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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

EFFECT OF RAINFALL ON TREE STABILITY

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

NANYANG TECHNOLOGICAL UNIVERSITY

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**SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY**

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ABSTRACT

Trees are “living structures”. They all possess an above ground superstructure as well as a below ground anchoring structure. The objective of this research was to study the loads applied to the trees, and the structural and geotechnical mechanisms that can lead to uprooting of trees in Singapore.

A new shallow root model (SRM) was developed and verified with field testing data from past literature. The SRM required the field greenwood moduli of rupture (MOR) to be measured for different tree species. A four-point bending and a three-point bending apparatuses were designed and built to measure greenwood MOR for eight species of trees. The saturated and unsaturated soil properties were also required for the SRM and determined using laboratory (triaxial) and field testing.

To determine the tree superstructure, a new tree structural survey method (TSSM) was developed to digitize trees regardless of species. The TSSM provided above ground tree data like tree mass, centroid and drag area. This TSSM was used to survey five trees at two sites in Singapore. Laser scans were used to verify the TSSM surveys.

At the two sites (Silat Avenue (SA) and Telok Blangah Rise (TBR)) instrumentation was installed to measure climatic, soil and tree deflection data in real time. This instrumentation provided data that were used to calculate the changes in the resistance to uprooting of the trees due to changes in flux boundary conditions and climatic parameters. The SRM and the existing heart root model (HRM) were used in conjunction with the TSSM data to calculate these changes. During the monitoring period it was observed that the wind speeds that were measured were small compared to the calculated critical wind speeds required to uproot the trees or cause trunk basal failures.

Parametric studies were performed numerically using EXCEL, SVFLUX, SIGMA/W and ANSYS software. Using the HRM in EXCEL, it was found that based on soil strength alone, tree resistance to uprooting was reduced dramatically by small amounts of rainfall, the raising of groundwater table as well as changes in root architecture. Using the SRM in EXCEL, it was found that resistance to uprooting was

more influenced by greenwood MOR, root cross-sectional area (CSA) and sinker root size and depth than soil properties. Through SIGMA/W analyses it was found that greenwood yield strains (<5%) were often exceeded before soil yield strains (>15%) were experienced. The ANSYS analysis showed that the effective area and depth of the shallow root responsible for resistance to tree uprooting was limited to a small volume around the tree trunk. The ANSYS analysis also showed that tension root cutting was most detrimental to tree stability followed by cutting of compression and perpendicular roots in that order.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	iii
ABSTRACT.....	iv
TABLE OF CONTENTS.....	vi
LIST OF TABLES.....	xiii
LIST OF FIGURES.....	xvi
LIST OF SYMBOLS.....	xxxvii
 CHAPTER 1 Introduction.....	 1
1.2 Structural analysis of trees.....	3
1.3 Objective.....	3
1.4 Scope of Works.....	4
1.5 Organization	5
 CHAPTER 2 Literature Review	 7
2.1 Wood found in trees	7
2.1.1 Structure of wood.....	9
2.1.2 Bending failure modes for branches and stems	12
2.1.3 Reaction wood	17
2.1.4 Modulus of rupture (MOR).....	17
2.2 Trees in urban environments	18
2.2.1 Factors affecting trees in Singapore.....	21
2.3 Tree Roots and Stability.....	23
2.3.1 Stability of trees with shallow roots or root plates	26
2.3.2 Heart root model.....	48
2.4 Structural analysis of trees	55

2.4.1 Structural mechanics used when performing engineering and structural simulations in ANSYS	57
2.4.1.1 Stress-strain relationships	61
2.4.1.2 Failure criteria for materials in ANSYS.....	61
2.5 Resisting moments of trees to static pull tests.....	67
2.6 Wind on trees.....	74
2.6.1 Drag estimation and wind tunnel tests.....	78
2.7 Geology of Singapore and drainage	83
2.8 Water balance in the vadose zone	89
2.9 Unsaturated soil mechanics	93
2.9.1 Soil-water characteristic curve	93
2.9.2 Unsaturated permeability	95
2.9.3 Seepage analyses and modelling of water flow in unsaturated soil	97
2.9.4 Unsaturated shear strength of soil.....	98
CHAPTER 3 Theory.....	101
3.1 Tree winching.....	101
3.2 Shallow root uprooting theory	105
3.3 Proposed three dimensional (3D) shallow root uprooting theory.....	111
CHAPTER 4 Research Program and Methodology.....	117
4.1 Introduction	117
4.2 Outline of research programme.....	118
4.3 Greenwood testing.....	119
4.3.1 Four-point flexural test	120
4.3.2 Three-point flexural test.....	128

4.4	Site selection, investigation, lab testing and field testing/instrumentation .	132
4.4.1	Pore-water pressure measurements.....	134
4.4.2	Volumetric water content and soil temperature measurements	138
4.4.3	Ground water table measurements.....	141
4.4.4	Tree movement and sway	143
4.4.5	Weather station and mast	147
4.4.6	Field determination of surface infiltration rate (Double-ring infiltrometer ASTM 3385-03)	153
4.4.7	Soil sampling and testing	155
4.5	Laser scanning of trees and surrounding features	168
4.6	Tree structural survey method (TSSM)	171
4.7	Numerical modelling and model verification.....	175
4.7.1	Numerical modelling using Microsoft EXCEL	175
4.7.2	Numerical modelling using SVFLUX	176
4.7.3	Numerical modelling using SIGMA/W	177
4.7.4	Numerical modelling using ANSYS.....	180
CHAPTER 5 Presentation of Results		183
5.1	Greenwood testing	183
5.1.1	Four point flexural testing.....	183
5.1.2	Three point flexural testing.....	183
5.2	Site investigation results from Silat Ave (SA) and Telok Blangah Rise (TBR)	193
5.3	Typical site instrumentation results from Silat Ave (SA) and Telok Blangah Rise (TBR).....	198
5.3.1	Pore-water pressure, volumetric water content, air/soil temperature,	

groundwater table and rainfall	198
5.3.2 Potential evaporation from flux boundary parameters	208
5.3.3 Field wind load measurements at Silat Ave and Telok Blangah Rise	216
5.4 Results of tree 3D laser scanning	241
5.5 Digitizing tree architecture using the new method (TSSM) to perform structural surveys on trees	246
5.6 Numerical modelling	261
5.6.1 Two dimensional shallow root model (shallow root model) verification...	262
5.6.2 Effects of canopy geometries and shapes on wind loads (EXCEL)	265
5.6.3 Effects of root plate thickness and groundwater table on tree resisting moments using the heart root model (EXCEL)	271
5.6.4 Effects of root plate extent, thickness and groundwater table depth on lateral root/trunk stresses and strains (SIGMA/W)	278
5.6.5 Flux boundary conditions (SVFLux)	281
5.6.6 Effects of soil properties and flat (shallow) root architecture on tree stability (ANSYS)	285
CHAPTER 6 Discussion	311
6.1 Greenwood testing	311
6.2 The proposed shallow root tree stability model	319
6.3 3D visualization of trees using laser scanning	322
6.4 Analyzes of the structural surveyed trees using the shallow root model	323
6.5 Comparing the wind characteristics of Silat Ave and Telok Blangah Rise	331
6.6 Numerical modelling on combined effects of canopy geometries, shapes and groundwater table on overturning and resisting moments (EXCEL)	333
6.7 Heart root model dimensions for soil failure (EXCEL)	335
6.8 Using the heart root model and numerical modelling in SIGMA/W to determine the controlling failure mode	337

6.9	Effect of flux boundary conditions on soil pore-water pressures and moisture contents (SVFLux)	340
6.10	Numerical modelling on root architecture and soil conditions	342
6.10.1	Number of evenly spaced sinker roots per lateral root	342
6.10.2	Depth of sinker roots within the critical structural root zone	343
6.10.3	Variation in lateral root diameter	346
6.10.4	Variation in the soil resilience or elastic modulus	348
6.10.5	Effect of tree root cutting on maximum equivalent stresses and total deformations.....	350
6.11	Summary of discussion of results.....	352
CHAPTER 7 Conclusions and recommendations		353
7.1	Conclusions from greenwood testing	353
7.1.1	Recommendations from greenwood testing	353
7.2	Conclusions from the proposed new shallow root uprooting models.....	354
7.2.1	Recommendations from the proposed new shallow root uprooting models.....	354
7.3	Conclusions from the visualization of trees using laser scanning	355
7.3.1	Recommendations from the visualization of trees using laser scanning	355
7.4	Conclusions from the new method used for the structural surveys of trees	355
7.4.1	Recommendations from the new method used for the structural surveys of trees (TSSM)	356
7.5	Conclusions from comparing the wind characteristics of Silat Ave and Telok Blangah Rise.....	356
7.5.1	Recommendations from comparing the wind characteristics of Silat Ave and Telok Blangah Rise.....	356
7.6	Conclusions from Numerical modelling on combined effects of canopy geometries, shapes and groundwater table on overturning and resisting moments (EXCEL).....	357

7.6.1 Recommendations from Numerical modelling on combined effects of canopy geometries, shapes and groundwater table on overturning and resisting moments (EXCEL).....	357
7.7 Conclusions from the effect of groundwater table depth and root plate dimensions on failure mechanisms (SIGMA/W)	357
7.7.1 Recommendations from the effect of ground water table depth and root plate dimensions on failure mechanisms (SIGMA/W)	358
7.8 Conclusions from the effect of flux boundary conditions on soil pore-water pressures and moisture contents (SVFLux).....	358
7.8.1 Recommendations from effect of flux boundary conditions on soil pore-water pressures and moisture contents (SVFLux).....	358
7.9 Conclusions from numerical modelling on root architecture and soil conditions (ANSYS)	359
7.9.1 Recommendations from numerical modelling on root architecture and soil conditions	359
REFERENCES.....	360
APPENDIX I.....	376
APPENDIX II	389

LIST OF TABLES

Table 1.1 Climatic and environmental values provided by trees (Moore, 2011).....	2
Table 2.1 Some values of k_0 for different soils (from Boresi, 2002)	41
Table 2.2 The recorded tree pulling results for the different fill materials (from Rahardjo et.al, 2009).....	74
Table 2.3 Summary of drag coefficients for simple shapes determined in ANSYS (from Lim et al., 2013).....	82
Table 4.1 Specifications for Approved Soil mixture (ASM) (from NParks, 2009)...	157
Table 4.2 Net confining pressures used for the CU tests	164
Table 4.3 Parameters based on past research literatures and experimental data	178
Table 5.1 Average values recorded during the four-point flexural testing performed for several species of common roadside trees in Singapore	183
Table 5.2 Laboratory measured soil properties at Silat Ave.....	195
Table 5.3 Laboratory measured soil properties at Telok Blangah Rise.....	196
Table 5.4 Field measurements of saturated permeability at Silat Ave and Telok Blangah Rise using double ring infiltrometers.	196
Table 5.5 The coordinates used to generate the three dimensional representation of the tree as a series of cylinders	247
Table 5.6 the geometrical attributes obtained from the three dimensional figure.	249
Table 5.7 The coordinates used to generate three dimensional representation of the Silat Ave <i>Syzygium grande</i> 2	252
Table 5.8 The geometrical attributes obtained from the three dimensional figure....	253
Table 5.9 the coordinates used to generate three dimensional representation of the Silat Ave <i>Samanea saman</i>	255
Table 5.10 The geometrical attributes obtained from the three dimensional figure..	256
Table 5.11 The coordinates used to generate three dimensional representation of the Telok Blangah <i>Samanea saman</i> 1	258
Table 5.12 The geometrical attributes obtained from Figure 5.76	259
Table 5.13 the coordinates used to generate three dimensional representation of the Telok Blangah <i>Samanea saman</i> 2.....	260
Table 5.14 the geometrical attributes obtained from Figure 5.78.....	261

Table 5.15 Shallow root model input parameters from field testing of greenwood and laboratory soil tests. a) <i>Samanea saman</i> MOR and MOE. b) Soil strength properties.	263
Table 5.16 The measured CSA and failure pulling forces (Rahardjo et. al., 2010) together with the corresponding calculated failure pulling forces using the shallow root model	264
Table 5.17 Parameters based on past research literatures	273
Table 5.18 Resisting moments for tree of root plate of 0.25 m thick and B= 3 m	273
Table 5.19 Resisting moments for tree of root plate of 0.25 m thick and B=4 m	274
Table 5.20 Resisting moments for tree of root plate of 0.25 m thick and B= 5 m	274
Table 5.21 Resisting moments for tree of root plate of 0.5 m thick and B= 3 m	275
Table 5.22 Resisting moments for tree of root plate of 0.5 m thick and B= 4 m	275
Table 5.23 Resisting moments for tree of root plate of 0.5 m thick and B= 5 m	276
Table 5.24 Resisting moments for tree of root plate of 1 m thick and B=3 m	276
Table 5.25 Resisting moments for tree of root plate of 1 m thick and B= 4 m	277
Table 5.26 Resisting moments for tree of root plate of 1 m thick and B=5 m	277
Table 5.27 Summary of numerical analysis (SIGMA/W) results.....	280
Table 5.28 Input greenwood parameters used for ANSYS analyses derived from the average values from Section 5.1	285
Table 5.29 The elastic modulus or the subgrade modulus estimated for the different matric suctions at 50 kPa confining pressures.	286
Table 5.30 Results of the the parametric study on the variation of number of evenly spaced sinker roots.....	291
Table 5.31 Results of the the parametric study on the variation of depth of two sinker roots per lateral root.....	296
Table 5.32 Results of the parametric study on the variation of the diameter of lateral roots with two evenly spaced sinker roots (3 m depth) per lateral root.	300
Table 5.33 Soil properties varied to perform tree stability study.	301
Table 5.34 The results of the parametric study on the effect of the variation of the elastic modulus and compressive yield strength of the soil on stresses and deformations.	304
Table 5.35 Maximum equivalent stress and deformations from perpendicular, tension and compression root cutting.	310

Table 6.1 Summary of “yield” stress and strain values and toughness for the eight tested species with increasing toughness	318
Table 6.2 Summary of the resistance to bending for Silat Avenue <i>Syzygium grande</i> 1 using the shallow root model	323
Table 6.3 Summary of the resistance to bending for Silat Avenue <i>Syzygium grande</i> 2 using the shallow root model	326
Table 6.4 Summary of the resistance to bending for Silat Avenue <i>Samanea saman</i> (rain tree) using the shallow root model.	327
Table 6.5 Summary of the resistance to bending for Telok Blangah Rise <i>Samanea Saman</i> 1 using the shallow root model	328
Table 6.6 Summary of the resistance to bending for Telok Blangah Rise <i>Samanea Saman</i> 2 using the shallow root model	329
Table 6.7 Dimensions used in the parametric study for lateral loads	333
Table 6.8. Predicted failure mechanisms for a tree with a root plate thickness of 0.25 m and a radius of 4 m.....	339

LIST OF FIGURES

Figure 2.1 Outline of biomechanical considerations to tree above ground stability (from Spatz et al., 2000)	8
Figure 2.2 Helical arrangement of xylem vessels. a) The helically wound pattern arrangement of the cellulose microfibrils in the secondary cell wall (from Abraham et al., 2012) b) Scanning electron micrograph of a cross-section through a vascular bundle (vessels and tracheid's) showing helical thickening of xylem walls (from Cutler et al., 2005)	9
Figure 2.3 Wood anisotropy in three directions a) Longitudinal (L), Transverse (T) and Radial (R) b) A cube cut along a ray showing the arrangement of the (from Reiterer et al., 2002).....	10
Figure 2.4 Branch connections cause knots to form (Photo B. Chanson from Thibaut et al., 2001).	11
Figure 2.5 The pattern of stresses in beams loaded in pure bending. (a) Longitudinal stresses rise linearly either side of the neutral axis, the outer convex surface being loaded in tension and the concave inner surface being loaded in compression. (b) Transverse stresses rise to a maximum at the neutral axis, being compressive when the bending tends as here to increase curvature (from Ennos et al., 2010)	13
Figure 2.6 Patterns of bending failure predicted for branches. An initially curved branch (a) may split longitudinally down the centerline if it is subjected to a force tending to straighten it. By contrast an initially straight branch made of light wood (b) may buckle transversely inwards, its section flattening out when bent. A straight cylindrical branch of reasonably dense wood (c) may break half-way across before splitting along its length at its midpoint, while a tapered branch (d) should break half-way across then split distally (Reiterer et al., 2002).	14
Figure 2.7 The structure of a branch (a) 80% of the wood volume is composed of tightly packed tracheids or fibers, which are oriented longitudinally, while rays in which the cells are oriented radially constitute around 20%. As a consequence mechanical tests on oriented samples (b) show that tangentially (T) wood is weaker than radially (R) and much weaker than longitudinally (L). Wood is readily split or	

sheared along the center-line along which the rays and tracheids provide no reinforcement. (from Reiterer et al. 2002)	15
Figure 2.8 The two main growth habits (from ISA, 2012)	19
Figure 2.9 Common natural tree shapes. a) <i>Terminalia catappa</i> (Tiered), b) <i>Gnetum gnemon</i> (Columnar), c) <i>Myristica fragrans</i> (Pyramidal), d) <i>Mimusiodora elengi</i> (Round), e) <i>Mekakuca cajuouti</i> (Oval), f) <i>Samanea saman</i> (Umbrella) (from NParks, 2009)...	20
Figure 2.10 Common tree shapes. a) <i>Leptospermum brachyandrum</i> (Weeping), b) <i>Callerya atropurpurea</i> (hemispherical), c) <i>Azadirachtea excels</i> (open) and d) <i>Casuarina equisetifolia</i> (Conical) (from Nparks, 2009).....	21
Figure 2.11 Various factors affecting tree stability	22
Figure 2.12 The different types of tree root systems. (a) Tap-root - Provides main support of the juvenile tree by anchoring it firmly in the ground. (b) Lateral roots – Help support and anchor trunk, may extend far out, beyond crown spread. (c) Fibrous feeder roots – Masses of fine feeding roots close to ground surface. (d) Sinker or descending roots – Grow downwards from lateral roots (from USDA, 1970).....	23
Figure 2.13 A typical distribution of roots with maturity: a) Sapling with a stable symmetrical radiation of lateral roots. b) Sapling with an unstable non-symmetrical radiation of lateral roots. c) The mature tree with a stable symmetrical radiation of lateral roots using sinker roots to provide additional tie down and anchorage. d) The mature tree with a unstable non-symmetrical radiation of lateral roots using additional thickening of lateral roots and sinker roots to provide stability (adapted from Danjon et al., 2009)	25
Figure 2.14 A typical root structure just below the soil surface (Nicols, et al., 1996)	26
Figure 2.15 Tree adaptations at the root collar for stability. a) Buttresses found on tall trees experiencing high loads. b) A well- defined root flare that spreads out the loads experienced by the tree.	27
Figure 2.16 Diagrammatic view of a shallow-rooted tree, showing the four components of the anchorage which resist overturning or bending moments (from Coutts, 1983a).....	28
Figure 2.17 Mattheck’s model for the function and development of buttresses which can be extended to lateral roots. If a tree is pushed over by the wind (a) the bending force is transmitted smoothly to lateral sinker roots by the buttresses. Windward sinkers resist upward forces and the windward buttresses are put into tension.	

Leeward sinkers and buttresses are in compression. (b), (c) and (d) show the successive stages in Mattheck's simulation of buttress development. When the trunk is laterally loaded, stress is concentrated at the top of the junction between the lateral root and the trunk (stippling). Growth in response to heavily stressed regions (b) results in the formation of buttresses (c and d) and a great reduction in stress concentrations (from Mattheck, 1991).....	29
Figure 2.18 The residual soil formations common to Singapore that are products of bedrock weathering (modified from Little, 1969)	32
Figure 2.19 Failure of a flat rooted or shallow rooted tree. a) Soil cracks develop and roots slide. b) The shallow root/root plate lifts up with almost no shearing rotating about the hinge formed by the yielded lateral root (from Mattheck and Breloer, 1994)	32
Figure 2.20 Schematic of a mature tree root system with secondary sinkers' when laterally loaded to the right by wind (guying zone has practically no moment arm to the hinge) (from Danjon et al., 2009)	33
Figure 2.21 a) In widely spreading root systems with sinker roots (e.g. many trees and some herbaceous dicots), the system rotates up around a leeward hinge (from Crook and Ennos, 1996). b) The load displacement graph also shows a buildup of uprooting force to a maximum, followed by a series of rapid decreases as lateral, sinker and other fine roots break in series.	34
Figure 2.22 Excavation and air spading to show the complete root systems of two common wayside tree species found in Singapore a) <i>Samanea saman</i> (from Rahardjo et al., 2010) b) <i>Samanea saman</i> (from Rahardjo et al., 2009) c) <i>Syzygium grande</i> (from Ghani et al., 2009) d) <i>Syzygium grande</i> (from Ghani et al., 2009).....	36
Figure 2.23 The tree root plate can be modelled by point loaded infinite beam supported by an infinite series of springs. (from Kolitzus, 1984). This type of foundation response is referred to as the Winkler foundation.	37
Figure 2.24 Infinite beam on an elastic foundation and loaded at the origin 0 (from Boresi, 2002).....	38
Figure 2.25 The free body diagram of a beam element with all the forces and moments (from Boresi, 2002)	39
Figure 2.26 Values of functions $A\beta z$, $B\beta z$, $C\beta z$ and $D\beta z$ (Boresi, 2002).....	42

Figure 2.27 Reductions in k to k_1 cause a $(k/k_1)^{0.25}$ increase to M_1 from M , where M is the maximum bending moment in the beam for spring constant of $1.0k$. This is dimensionless and serves to highlight changes in maximum values of M_x with changes in k . Values of k will never reach zero.	43
Figure 2.28 A bending moment about the origin O can be represented by a force P_1 at a distance δ from O (from Boresi, 2002).	44
Figure 2.29 Curves showing, a) The deflections in direction y . b) The bending moment about the x axis (from Boresi, 2002).	45
Figure 2.30 Stylized view from above of three different tree root zones (not to scale and indicative only): 1) Structural roots that define the root plate effective width; 2) Woody transport roots; 3) Absorbing root fans. The dotted line representing crown projection on the soil (drip line) contains $\sim 65\%$ of roots found on average sites (from Coder, 2009).	45
Figure 2.31 The compressive portion of the q curve determines the effective root plate limit (from Coder, 2009 and Boresi, 2002).	46
Figure 2.32 The hinge joint forms at the point where the bending moment exceeds the bending capacity of the root plate (from Coder, 2009 and Boresi, 2002).	47
Figure 2.33 The heart rooted tree with strong branching roots that extend in all directions, deep within the soil (Dobson, 1995)	49
Figure 2.34 Failure mechanism of a heart rooted tree a): Soil cracks develop b): Roots pull out c): The root/soil ball shears/slides d): Roots break at the surface of shearing surface and the toe (Mattheck and Breloer, 1994)	49
Figure 2.35 The symmetrically raked pile group that can approximate the ideal heart root	50
Figure 2.36 The radius of the shearing surface from a symmetrical heart root system. The centre of the half circle is the black dot labeled O . The semi-circle is then cut into slices.	50
Figure 2.37 The top view shows the slices as a series of prisms to approximate the shearing surface	51
Figure 2.38 The forces acting on each slice (Rahardjo et al., 2009). Added is the self-weight of the tree as a uniformly distributed load WT . WT is reduced to WT_n by using the 2:1 slope ratio for area	52
Figure 2.39 A 2:1 stress distribution used to determine WT_n with depth	54

Figure 2.40. Branch joint of a tree, with finite element representation to visualize stress distribution (from Mattheck, 1990).....	56
Figure 2.41 Stress components at a point in loaded body.....	57
Figure 2.42 General deformed body (ANSYS, 2011).	59
Figure 2.43 Stress components showing changes from face to face along with body force per unit volume including inertial forces (ANSYS, 2011).	60
Figure 2.44 The ductile tensile test is very easily and quickly performed but it is not possible to know what is happening on the various scales that contribute to the macro scale results (from ANSYS, 2011).....	62
Figure 2.45 Yield surface of the Tresca (Tresca, 1864) failure criterion in stress space. a) Two-dimensional. b) Three-dimensional (from ANSYS, 2011).	63
Figure 2.46 Yield surface of the von mises (von Mises, 1913) criterion in stress space. a) Two-dimensional. b) Three-dimensional (from ANSYS, 2011).	65
Figure 2.47 Stress-strain diagram for a typical brittle material (from ANSYS, 2011).	67
Figure 2.48 Possible yield surfaces for brittle materials (ANSYS, 2011).	67
Figure 2.49 The combined resisting moment as a function of angle of inclination to the vertical for a tree which is considered typical of many found in tree pulling experiments (from England et al., 2000).	68
Figure 2.50 Static tree pull results. Maximum overturning moment is 350 KNm. Pull related to formula $(H \times DBH^2)$ to predict stability and failure (from Cucchi et al., 2004).	69
Figure 2.51 Stem failure was seen in 29 out of 164 <i>Pinus radiata</i> in NZ. The maximum stem failure resistive bending moments (KNm) were compared to theoretical values calculated using stem volume (from Moore, 2000).	70
Figure 2.52 The tree plots with different soil types with reference to the nearest landmark IMM mall (from Rahardjo et. al, 2009).....	71
Figure 2.53 Maximum pulling forces against root plate volume (from Rahardjo et. al, 2009)	72
Figure 2.54 Maximum pulling force against CSA (Root cross-sectional area) (from Rahardjo et. al, 2009).....	73

Figure 2.55. A histogram showing the contribution to the total bending moment made by one meter height increments of a pine tree of height 16m, DBH 22.5 cm at a wind speed of 17 m s ⁻¹ (from Petty & Swain, 1985).	77
Figure 2.56. Drag values for a red cedar (height 1.6m) in wind tunnel tests (Rudnicki et al., 2004).	80
Figure 2.57 Using computational fluid dynamics (CFD), a tree with a spherical canopy shape under constant wind speed experienced an increase in the drag coefficient to a peak value corresponding to a critical porosity before decreasing with increasing porosity (from Lim et al., 2013).	81
Figure 2.58 The overview geological map of Singapore Island (from Lee et al., 2009)	87
Figure 2.59 Typical unconfined ground water features (from Linsley et al., 1992)....	89
Figure 2.60 Water balance in the vadose zone (from Blight, 1997)	90
Figure 2.61 The relationship between the ratio of actual evaporation and potential evaporation against water availability (from Van Bavel et al., 1976)	93
Figure 2.62 A typical SWCC and the various features (Goh et al., 2011).....	94
Figure 2.63 Illustration for boundary drying and wetting curves and scanning curves of the SWCC of an unsaturated soil (from Pham et al., 2003)	95
Figure 2.64 Extended Mohr-Coulomb failure envelope for a unsaturated soil (from Fredlund & Rahardjo, 1993a).....	100
Figure 3.1 Schematic diagram showing the setup of the tree-pulling experiment performed in 2008 (from Rahardjo et al., 2009).....	101
Figure 3.2 Typical characteristics of the trees during the uprooting process. a) The point of rotation or hinge is always formed near the leeward side of the trunk in the direction of the force. b) The windward side laterals and sinker root (tension tie downs) furthest from the hinge break first as the strains are the largest. c)The heaved and exposed windward root plate can be small or be large as in d), depending on the root architecture.	103
Figure 3.3 Tree winched to failure a) Tree bole bends and no soil heave b) Soil starts to heave and rotation of the root plate starts c) Peak force recorded and highly apparent soil heave with root breakages observed d) Tree rotates about 90 degrees and rests on ground (note broken lateral roots that provided little restraint in c) and d)).	104

Figure 3.4 A shallow root system is basically a “flattened” tree root system (from Dobson, 1995).....	106
Figure 3.5 Different lateral roots with each making a different angle to the direction of the lateral load. Each lateral root contribution is a function of the cosine of that angle.	107
Figure 3.6 Shallow root failure model a) Tree without lateral load b) Tree under failure lateral load showing rotation about point B.	110
Figure 3.7 The dotted line perpendicular to the solid line representing the direction of the lateral load separates the lateral roots into the tension and compression lateral roots.....	111
Figure 3.8 Each lateral root in the compression zone makes an angle α_n to the direction of the lateral load	113
Figure 3.9 Similar to roots in the compression zone (Figure 3.8), the lateral roots in tension also make a contribution proportional to the cosine of the angle β_m	114
Figure 4.1 Scope of the research program	118
Figure 4.2 Four-point bending flexural shape, load, support reactions and the associated shear force and bending moment diagram.....	121
Figure 4.3 A simple and lightweight four-point bending rig designed and fabricated by Wong & Sim (2012).....	123
Figure 4.4 The modified four point bending apparatus a) the schematic of the modified four point bending rig. b) The photograph of the modified four point test apparatus.	124
Figure 4.5 The data logger and power pack used together as the data acquisition system for the four point bending rig. a) The Campbell Scientific CR1000 Data logger. B) The Campbell Scientific PS100 12V power supply	125
Figure 4.6 Field deployment of the four point bending apparatus.....	126
Figure 4.7 Typical four-point bending stress strain curve of a <i>Samanea saman</i> sample.....	127
Figure 4.8 The three-point bending rig a) the schematic of the three-point testing apparatus b) the associated shear force and bending moment diagrams	129
Figure 4.9 The three point bending apparatus after testing a <i>Khaya senegalensis</i> branch sample with the dial gauge measuring center deflection and digital pressure gauge mounted to the hand jack.....	131

Figure 4.10 Typical three-point bending stress strain curve of a <i>Samanea saman</i> sample	131
Figure 4.11 Location map with tree locations at Silat Avenue (www.googlemaps.com, 2012)	132
Figure 4.12 Location map with tree locations at Telok Blangah Rise (www.googlemaps.com, 2012)	133
Figure 4.13 Site operation overview of a typical site (www.envault.com.sg, 2012). 134	
Figure 4.14 The pore-water pressures at various depths are measured using tensiometers. a) Jet-fill tensiometer with bourdon gauge for manual readings (Soil Moisture Equipment Corp, 2012). b) Installed Jet-fill tensiometer with attached pressure transducer for automatic datalogging	135
Figure 4.15 Vacuum applied to tensiometers before installation to check saturation and condition of ceramic cups.	136
Figure 4.16 Special coring tool for the tensiometer installation.....	137
Figure 4.17 The jet-fill tensiometers with its attached transducers required protection from human interference and outdoor conditions. a)Jet-fill tensiometers of 0.5m, 1.0m and 1.5m depths in their protective PVC housings with lids closed. b)Jet-fill tensiometer and pressure transducer within the protective PVC housing.....	137
Figure 4.18 CS650 moisture probe from Campbell Scientific	139
Figure 4.19 CS650 moisture probes installed in a hand dug pit at 0.5m, 1.0m and 1.5m depths	140
Figure 4.20 Soil temperature probe 108-L with a range of -5°C to 95°C	140
Figure 4.21 Casagrande piezometer tip with filter material within to prevent fines from entering the piezometer.	141
Figure 4.22 a) Casagrande tip attached to PVC pipe b) Tip wrapped in sand and netting c) Taped up before lowering d) Inserted to borehole and backfilled with 1 m of sand e) Bentonite pellets inserted to seal sand layer f) Borehole topped up with bentonite slurry.	142
Figure 4.23 LVDTs placed along the length of a known section can detect the movement in real time	144
Figure 4.24 Real-time LVDT readings a) LVDT 1. b) LVDT 2	144
Figure 4.25 LVDTs 1 and 2 plotted together show the recorded motion of the acrylic tube/LVDT setup shown in Figure 4.24	145

Figure 4.26 <i>Syzygium grande</i> 1 at Silat Avenue instrumented with two LVDTs (LVDT 1 and 2) at 62° apart from each other and at azimuths 334° and 268°, respectively from magnetic north	146
Figure 4.27 <i>Samanea saman</i> at Telok Blangah Rise instrumented with two LVDTs (LVDT 1 and 2) at 83° apart from each other and at azimuths 90° and 7°, respectively from magnetic north.....	146
Figure 4.28 The Campbell Scientific TB4 tipping bucket rain gauge	147
Figure 4.29 TB4 rain gauge deployed at Silat Avenue.....	148
Figure 4.30 The CS300 Apogee silicon pyranometer for measuring solar radiation.	149
Figure 4.31 The HMP60 temperature and relative humidity probe and the field mount in a solar radiation shield.	150
Figure 4.32 CS106 barometric pressure sensor	150
Figure 4.33 The concrete footing constructed before mast erection.....	151
Figure 4.34 Lycopole 10 m mast erected over the footing at Telok Blangah Rise site	152
Figure 4.35 The Young's 05103 wind monitor and deployed on the mast top in the field	153
Figure 4.36 Double-ring infiltrometer at Silat Avenue. The organic material around and surrounding the rings were removed prior to ring installation and testing was conducted according to ASTM 3385-03.....	154
Figure 4.37 Drilling rig deployed at the Silat Avenue site. a) The drilling rig performing wash boring to 3m. b) A disturbed sample from the wash boring.....	155
Figure 4.38 The stainless steel tubes used for undisturbed sampling before sealing with paraffin wax.....	156
Figure 4.39 Testing equipment used to obtain the soil water characteristic curve of soil samples for different matric suction ranges. a) Tempe cells (0 – 100 KPa matric suction). b) Pressure plates (100 – 500 KPa).....	158
Figure 4.40 Schematic diagram of the modified Tempe cell test (from Indrawan et al., 2006)	160
Figure 4.41 Schematic diagram of the pressure plate test (from Indrawan et al., 2006)	161
Figure 4.42 Triaxial setup used for measuring K_{sat} and consolidated undrained shear strength.....	162
Figure 4.43 Schematic layout of the apparatus used for triaxial CU, and permeability tests (from Goh et al., 2011)	163

Figure 4.44 Triaxial unsaturated consolidated drained shear strength test apparatus	166
Figure 4.45 Schematic of the triaxial apparatus used for unsaturated soil testing (from Goh et al, 2011).....	168
Figure 4.46 Laser scanning procedure used in the initial scanning	170
Figure 4.47 Point cloud of a target tree, displayed left to right from different views (front, back, right, left and bottom, top)	170
Figure 4.48 Annotation system for designating a unique number to each tree branch that both describes its position and the order within the tree.....	172
Figure 4.49 Branch elevation a) darker lines designate the branches and light arrows show direction of magnetic north, the angles measured are the azimuths. b) Darker lines designate the branches and light arrows show direction of horizontal, the angles measured are the elevations	172
Figure 4.50 the darker line designates the branch to be measured.	173
Figure 4.51 Estimating feature dimensions using relative distances and image dimensions	174
Figure 4.52 1-D numerical seepage model used in SVFLux (Soilvision Ltd, 2009). 177	
Figure 4.53. Schematic diagram of model used in numerical modeling in SIGMA/W a) Groundwater table (dotted line), soil restraints (fixed at boundaries). b) Variation of root elastic modulus with distance from the bole (trunk)	179
Figure 4.54 A three dimensional tree drawn and rendered in ANSYS for the purpose of performing the static structural analyses required for the parametric study a) The root model comprising of trunk, lateral roots and sinker roots. b) The root model inserted into the soil block.	181
Figure 4.55 The deformed and un-deformed shapes of the root plate model used in the root plate parametric study with the locations and magnitude of the stress concentrations highlighted.	182
Figure 5.1 Three point bending tests obtained stress-strain properties of <i>Syzygium grande</i> charted using boxplots (42 samples).	184
Figure 5.2 Three point bending tests obtained stress-strain properties of <i>Khaya senegalensis</i> charted using boxplots (39 samples).....	185
Figure 5.3 Three point bending tests obtained stress-strain properties of <i>Samanea Saman</i> charted using boxplots (38 samples).....	185

Figure 5.4 Three point bending tests obtained stress-strain properties of <i>Tabebuia rosea</i> charted using boxplots (33 samples).....	186
Figure 5.5 Three point bending tests obtained stress-strain properties of <i>Peltophorum pterocarpum</i> charted using boxplots (31 samples).....	186
Figure 5.6 Three point bending tests obtained stress-strain properties of <i>Syzygium polyanthum</i> charted using boxplots (38 samples).....	187
Figure 5.7 Three point bending tests obtained stress-strain properties of <i>Pterocarpus indicus</i> charted using boxplots (38 samples).....	187
Figure 5.8 Three point bending tests obtained stress-strain properties of <i>Swietenia macrophylla</i> charted using boxplots (38 samples).....	188
Figure 5.9 Boxplots of the peak recorded flexural stress (MOR) for the eight common wayside tree species.....	189
Figure 5.10 Boxplots of the recorded strain at the peak recorded MOR.....	189
Figure 5.11 Boxplots of the calculated secant modulus of elasticity to MOR.....	190
Figure 5.12 Box plots of the wet or greenwood densities for the eight tested species obtained from three-point flexural testing.	191
Figure 5.13 Box plots of the oven dried densities for the eight tested species obtained from three-point flexural testing.	191
Figure 5.14 Box plots of the moisture contents as a percentage of wet mass, for the eight tested species obtained from three-point flexural testing.	192
Figure 5.15 Box plots of the moisture contents as a percentage of dry mass, for the eight tested species obtained from three-point flexural testing.	192
Figure 5.16 Trial pit dug at Silat Ave showing the presence of tree roots above the 0.5m depth volumetric water sensor and the water table found at the 1.5m mark. ...	193
Figure 5.17 Grain size distribution of the soil obtained from Silat Ave.....	194
Figure 5.18 Grain size distributions of the soil from Telok Blangah Rise.	194
Figure 5.19 Laboratory measured SWCC of the soil sample obtained from Silat Ave (SA) with the Fredlund & Xing (1994) fitted curve in green using a correction factor of 1 suggested by Leong & Rahardjo (1997) to better fit the low suction range used in the measurements.....	197
Figure 5.20 Laboratory measured SWCC of the soil sample obtained from Telok Blangah Rise (TBR) with the Fredlund & Xing (1994) fitted curve in green using a	

correction factor of 1 suggested by Leong & Rahardjo (1997) to better fit the low suction range used in the measurements	198
Figure 5.21 Pore-water pressure comparison against rainfall graph (SA).....	199
Figure 5.22 Water content comparison against rainfall graph (SA)	200
Figure 5.23 Soil temperature comparison against rainfall graph (SA)	201
Figure 5.24 Soil and air temperature comparison against rainfall graph (SA)	202
Figure 5.25 Pore-water pressure comparison against rainfall graph (TBR)	203
Figure 5.26 Water content comparison against rainfall graph (TBR)	204
Figure 5.27 Soil temperature comparison against rainfall graph (TBR)	205
Figure 5.28 Soil and air temperature comparison against rainfall graph (TBR)	205
Figure 5.29 1 year of water content monitoring with the accumulative rainfall at SA	206
Figure 5.30 1 year of water content monitoring with groundwater elevation at SA.	206
Figure 5.31 1 year of water content monitoring with the accumulative rainfall at TBR	207
Figure 5.32 1 year of water content monitoring with groundwater elevation at TBR	207
Figure 5.33 Total monthly rainfall in TBR Site.....	209
Figure 5.34 Total monthly rainfall in SA site	209
Figure 5.35 Monthly average, maximum and minimum temperature in TBR	211
Figure 5.36 Monthly average, maximum and minimum temperature in SA	211
Figure 5.37 Monthly average, maximum and minimum relative humidity in TBR ..	212
Figure 5.38 Monthly average, maximum and minimum relative humidity in SA.....	212
Figure 5.39 Monthly average, maximum and minimum (zero) average-windspeed in TBR.....	213
Figure 5.40 Monthly average, maximum and minimum (zero) average-windspeed in SA	213
Figure 5.41 Monthly average, maximum and minimum (zero) solar radiation in TBR	214
Figure 5.42 Monthly average, maximum and minimum (zero) solar radiation in SA	214
Figure 5.43 Monthly average daily potential evaporation calculated from monthly average meteorological data for TBR	215

Figure 5.44 Monthly potential evaporation calculated from monthly average meteorological data for SA.	215
Figure 5.45 The resultant wind force F_R and wind speed plotted for the month of December 2013	218
Figure 5.46 The wind rose and the tree movement directions for the Silat Ave <i>Syzygium grande</i> in the month of December, 2013.	219
Figure 5.47 a) for the month of December, the daily total wind produces a proportional tree movement detected by the LVDTs b) when resolved to the north and east directions, the resolved easterly winds have approximately 2.5 times more effect on tree movements in the wind direction than the northerly winds.	220
Figure 5.48 Basal diameter reduction to 0.167m from 0.731m required to fail under the maximum experienced wind load in December 2013 for the <i>Syzygium grande</i> at Silat Ave.....	222
Figure 5.49 The resultant wind force F_R and wind speed plotted for the month of January, 2014.	222
Figure 5.50 The wind rose and the tree movement directions for the Silat Ave <i>Syzygium grande</i> in the month of January, 2014.	223
Figure 5.51 a) for the month of January, 2014, the daily total wind produces a proportional tree movement detected by the LVDTs b) when resolved to the north and east directions, the easterly winds have approximately 2.9 times more effect on tree movements in the wind direction than the northerly winds due to the layout of the site at SA.....	224
Figure 5.52 Layout of the instrumentation site where the Layout of the instrumentation site where the <i>Syzygium grande</i> that had the LVDTs installed were shielded from winds from the north and northwest directions	225
Figure 5.53 Total wind and tree reactions on a monthly basis. a) Total wind, total wind East and total wind North. b) Total tree reaction, total tree reaction East and total tree reaction North.	226
Figure 5.54 Wind and tree reaction distributions from December, 2013 to July, 2014.	228
Figure 5.55 The resultant wind force F_R and wind speed plotted for the month of December 2013	229

Figure 5.56 The wind and the tree movement directions presented in the rose format for the Telok Blangah Rise <i>Samanea saman</i> in the month of December, 2013.	229
Figure 5.57 Total wind and tree reaction for the month of December, 2013 a) for the month of December, the daily total wind produces a proportional tree movement detected by the LVDTs b) when resolved to the north and east directions, the easterly winds have approximately 2.2 times more effect on tree movements in the wind direction than the northerly winds.	231
Figure 5.58 Basal diameter reduction to 0.249 m from 1.2 m required to fail under the maximum experienced wind load in December 2013 for the <i>Samanea saman</i> at Telok Blangah Rise.	232
Figure 5.59 The resultant wind force F_R and wind speed plotted for the month of December 2013 a) For the period of 1 st to 20 th of December. b) For the period of 21 st to 31 st of December.	234
Figure 5.60 The wind and the tree movement directions presented in the rose format for the Telok Blangah Rise <i>Samanea saman</i> in the month of January, 2014.	235
Figure 5.61 Total wind and tree reaction for the month of December, 2013 a) for the period of 1 st to 20 th January, 2014. b) for the period of 21 st to 31 st January, 2014. The daily total wind produces a proportional tree movement detected by the LVDTs. c&d) when resolved to the north and east directions, the easterly winds have approximately 1.91 times more effect on tree movements in the wind direction than the northerly winds.	237
Figure 5.62 Layout of the instrumentation site at TBR where the layout of the instrumentation site where the <i>Samanea saman</i> that had the LVDTs installed were shielded from winds from all directions except the East and West directions	238
Figure 5.63 Total recorded wind run and tree reaction. a) Total wind and resolved to East and North. b) Total tree reaction and resolved to East and North (the months of April to July experienced data acquisition problems with the LVDTs)	239
Figure 5.64 Wind and tree reaction distributions from a) December, 2013 b) January, 2013 c) February, 2014 d) March, 2014 e) April, 2014 f) May, 2014 g) June, 2014 h) July, 2014 (the months of April to July experienced data acquisition problems with the LVDTs)	241
Figure 5.65 Photo realistic point cloud from the 3D laser scan of the <i>Syzygium grande</i> 1 at Silat Ave shown from the various views	241

Figure 5.66 the same point cloud (<i>Syzygium grande</i> 1) meshed using triangular elements mesh. a) Resulting mesh scaled to enable simple dimensioning b) Tree height (18.7m). c) Trunk diameter (0.56m).	242
Figure 5.67 Non-colored point cloud of <i>Syzygium grande</i> 2 at Silat Ave capturing the co-dominant stems rising early from the base of the trunk.....	243
Figure 5.68 The meshed two <i>Syzygium grande</i> and one <i>Samanea saman</i> at SA.....	244
Figure 5.69 Scene of SA. a) A photo of SA. b) Captured point cloud of the same scene in SA.	245
Figure 5.70 Silat Ave <i>Syzygium grande</i> 1 3D model.....	248
Figure 5.71 The circle traced out by the height of Silat Ave <i>Syzygium grande</i> 1 with the arrow showing the azimuth of the centroid from magnetic north.....	250
Figure 5.72 Silat Ave <i>Syzygium grande</i> 2 three dimensional model	251
Figure 5.73 The circle traced out by the height of Silat Ave <i>Syzygium grande</i> 2 with the arrow showing the azimuth of the centroid from magnetic north.....	253
Figure 5.74 Silat Ave <i>Samanea saman</i> 1 three dimensional model	254
Figure 5.75 The circle traced out by the height of Silat Ave <i>Samanea saman</i> 1 with the arrow showing the azimuth of the centroid from magnetic north.....	256
Figure 5.76 Telok Blangah Rise <i>Samanea saman</i> 1 three dimensional model.....	257
Figure 5.77 the circle traced out by the height of Telok Blangah <i>Samanea saman</i> 1 with the arrow showing the azimuth of the centroid from magnetic north.....	259
Figure 5.78 Telok Blangah <i>Samanea saman</i> 2 three dimensional model.....	260
Figure 5.79 Good correlation between maximum pulling forces (bending resistance) and root CSA for all trees measured in the pull out tests (Rahardjo et al., 2010)	262
Figure 5.80 Wind force on a triangular canopy a) A tree with a triangular shaped canopy (e.g. Pine). b) Representation in Excel with the canopy height/width and trunk diameter/height.	266
Figure 5.81 Moment acting on tree canopy with variations in the canopy (Triangle) height and base.....	267
Figure 5.82 Wind force on an elliptical shaped canopy a) A tree with a elliptical shaped canopy (e.g. <i>Khaya senegalensis</i>). b) Representation in Excel with the elliptical canopy height/width and trunk diameter/height.	268
Figure 5.83 Moment acting on tree canopy with variations in the canopy (Ellipsoid) height and width.....	269

Figure 5.84 Wind force on a cylindrical shaped (2D rectangular) canopy a) A tree with a cylindrical shaped canopy (e.g. <i>Khaya grandifoliola</i>). b) Representation in Excel with the cylindrical canopy height/width and trunk diameter/height.	269
Figure 5.85 Moment acting on tree canopy with variations in the canopy (cylindrical) height and length.....	270
Figure 5.86 Summary of moment acting on tree for the three tree shapes	271
Figure 5.87 Assumptions made for the analysis a) mechanism of heart root tree throw b) assumed positive and negative soil pore-water pressure profiles.....	272
Figure 5.88. Critical failure point due to trunk break	279
Figure 5.89. Critical failure points due to root break.....	279
Figure 5.90 Meteorological data recorded in the site (Silat Ave (SA)) in the period of numerical modeling	281
Figure 5.91 Measured pore-water pressure in the period of the numerical modeling (Silat Ave (SA))	283
Figure 5.92 Measured volumetric water contents in the period of the numerical modeling (Silat Ave (SA))	283
Figure 5.93 Simulated and measured pore-water pressure in the period of the numerical modeling (Silat Ave (SA))	284
Figure 5.94 Simulated and measured volumetric water content in the period of the numerical modeling (Silat Ave (SA))	284
Figure 5.95 Triaxial stress strain curves for three values of matric suction ($u_a - u_w$); 25, 50 and 100 kPa for a confining pressure of 50 kPa (Silat Ave).....	286
Figure 5.96 Variation of number of evenly spaced sinker roots without the soil attached a) No sinker roots and the orientation of the reference axes. b) 4 sinker roots c) 8 sinker roots d) 12 sinker roots e) 16 sinker roots f) 20 sinker roots	288
Figure 5.97 Model with no sinker roots showing windward lateral root lift off (soil hidden). a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in leeward lateral root. b) Maximum total deformation experienced by the tip of the trunk.....	289
Figure 5.98 Model with 4 sinker roots showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.....	290

Figure 5.99 Model with 8 sinker roots showing additional restraint by the additional 4 sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.....	292
Figure 5.100 Variation of depth of 2 numbers of evenly spaced sinker roots per lateral root without the soil attached a) 0.5 m and the orientation of the reference axes. b) 1 m c) 2 m d) 3 m e) 4 m f) 5 m.....	293
Figure 5.101 Model with 8 sinker roots 0.5 m depth showing little restraint by the short 0.5 m sinker roots (soil hidden). a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in leeward lateral roots. b) Maximum total deformation experienced by the tip of the trunk	294
Figure 5.102 Model with 8 sinker roots 5 m depth showing high by the restraint sinker roots a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in leeward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.....	295
Figure 5.103 Variation of the diameter of lateral roots with two evenly spaced sinker roots (3 m depth) per lateral root without the soil attached a) 0.2 m and the reference axes. b) 0.4 m c) 0.6 m d) 0.8 m e) 1.0 m f) 1.2 m	297
Figure 5.104 Model with 4 lateral roots 0.2 m diameter still showing significant restraint by the sinker roots a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.....	298
Figure 5.105 Model with 4 lateral roots 1.2 m diameter still showing significant restraint by the sinker roots a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in trunk. b) Maximum total deformation experienced by the whole body (pure settlement of soil due to gravity)	299
Figure 5.106 Effect of change (-50%) in the elastic modulus (7.9 MPa) and compressive yield stress (188 kPa) of the soil. a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole body.	302
Figure 5.107 Effect of change (+50%) in the elastic modulus (23.7 MPa) and compressive yield stress (564 kPa) of the soil. a) Maximum equivalent von-Mises	

(von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole body.	303
Figure 5.108 An “idealized” perfectly concentric tree with four laterals and soil (hidden) model with the reference axes.	305
Figure 5.109 The “idealized” tree shown in Figure 5.108 after applying gravity and bending moment of 200 kNm. a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.	306
Figure 5.110 After cutting the root of the perfectly concentric “idealized” tree (red arrow) that is perpendicular to the bending direction. a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.	307
Figure 5.111 After cutting the compression root of the perfectly concentric “idealized” tree (red arrow) that is in line with the bending direction (about x-axis). a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.	308
Figure 5.112 After cutting the tension root of the perfectly concentric “idealized” tree (red arrow) that is in line with the bending direction. a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.	309
Figure 6.1 Six order polynomial fitted to the median points of the stress-strain data for <i>Syzygium grande</i>	312
Figure 6.2 Six order polynomial fitted to the median points of the stress-strain data for <i>Khaya senegalensis</i>	312
Figure 6.3 Six order polynomial fitted to the median points of the stress-strain data for <i>Samanea saman</i>	313
Figure 6.4 Six order polynomial fitted to the median points of the stress-strain data for <i>Tabebuia rosea</i>	313
Figure 6.5 Six order polynomial fitted to the median points of the stress-strain data for <i>Peltophorum pterocarpum</i>	314
Figure 6.6 Six order polynomial fitted to the median points of the stress-strain data for <i>Syzygium polyanthum</i>	314
Figure 6.7 Six order polynomial fitted to the median points of the stress-strain data for <i>Pterocarpus indicus</i>	315

Figure 6.8 Six order polynomial fitted to the median points of the stress-strain data for <i>Swietenia macrophylla</i>	315
Figure 6.9 definition of an elasto-viscous material “toughness” is the area under the stress-strain curve to the first stationary point defined by the MOR	316
Figure 6.10 Plot of the calculated maximum winching forces using the shallow root model from the field measured root CSA against the field measured winching forces with the linear regression line almost superimposing on the 45° line	320
Figure 6.11 A simple geometry inserted into the point cloud to take the place of a single point block.....	322
Figure 6.12 Using the shallow root root model, a reduction in the root CSA and greenwood modulus of rupture of Silat Avenue <i>Syzygium grande</i> 1 corresponds to a reduction in critical wind speed (vwc).....	325
Figure 6.13 With a smaller sail area and a lower center of gravity compared to <i>Syzygium grande</i> 1, <i>Syzygium grande</i> 2 displays a much higher critical wind speed of 238km/h for MOR of 50MPa.....	326
Figure 6.14 with a much larger sail area, lower MOR and a similar center of gravity height compared to <i>Syzygium grande</i> 1 and 2, the surveyed rain tree at Silat Avenue displays a much lower critical wind speed of 106.5km/h for a greenwood MOR of 38KPa.....	327
Figure 6.15 With a larger sail area and higher center of gravity compared to the trees at Silat Ave, the maximum critical wind speed was calculated to be only 86km/h for the same root CSA values	329
Figure 6.16 The high center of area of the Telok Blangah Rise <i>Samanea saman</i> 2 reduces maximum critical wind speed to 86km/h even as sail area is very much smaller compared to <i>Samanea saman</i> 1.....	330
Figure 6.17 Comparison of total recorded wind in kilometers at Silat Ave and Telok Blangah Rise for the same period with the line showing as a percentage of total wind recorded at Silat Ave over the total wind recorded at Telok Blangah Rise.	331
Figure 6.18 Wind speed and groundwater table level comparison for different canopy shapes and soil conditions at SA.....	334
Figure 6.19 Wind speed and groundwater table level comparison for different canopy shapes and soil conditions at TBR.	335

Figure 6.20 Variation of slip surface circumferences for different root plate dimensions	336
Figure 6.21 Failure wind load vs. depth of water table for different root plate dimensions	337
Figure 6.22 $F_{\%}$ for the tree of root plate of 0.25 m thick and 3 m.....	338
Figure 6.23 Chart of the maximum equivalent stresses in the model tree root with the number of evenly spaced sinkers (2 m depth) on each lateral root.....	342
Figure 6.24 Chart of the maximum total deformation in the model tree root (taken from the tip of the trunk) with the number of evenly spaced sinkers (2 m depth) on each lateral root.....	343
Figure 6.25 Chart of the maximum equivalent stresses in the model tree root with variation in the depth of two evenly spaced sinkers on each lateral root.	344
Figure 6.26 The three dimensional critical zone of influence is highlighted by the light line cylinder 2 m radius and 3 m depth.....	345
Figure 6.27 Chart of the maximum total deformation in the model tree trunk tip with variation in the depth of two evenly spaced sinkers on each lateral root.	346
Figure 6.28 Chart of the maximum equivalent stresses in the model tree root with variation in the diameter of the lateral roots with two sinker roots of 3 m depth.	347
Figure 6.29 Chart of the maximum total deformation in the model tree root measured from the trunk tip with variation in the diameter of the lateral roots with two sinker roots of 3 m depth.	348
Figure 6.30 Chart of the maximum equivalent stresses in the model tree root with variation in the soil elastic modulus with two sinker roots of 3 m depth.	349
Figure 6.31 Chart of the maximum total deformation in the model tree root measured from the trunk tip with variation in the soil elastic modulus with two sinker roots of 3 m depth.....	349
Figure 6.32 Summary of the effects of cutting the different roots in comparison to the intact root model. a) Maximum equivalent stresses. B) Maximum total deformations.	351

LIST OF SYMBOLS

α_1	is the angle from the horizontal from the observer to the beginning of the branch
α_2	is the angle from the horizontal from the observer to the end of the branch
α_3	is the elevation of the branch from the horizontal
α_n	is the angle the normal stress N makes with the vertical
β_m	is the angle that the tension roots make to the lateral load
δ_1	is the measured linear displacement by LVDT1
δ_2	is the measured linear displacement by LVDT2
ϵ_1	is the axial strain measured by LVDT1
ϵ_2	is the axial strain measured by LVDT2
ε	is the maximum surface strain,
Γ	is the slope of the saturation vapor pressure versus temperature curve at the mean temperature of the air (mmHg/°C)
γ	is the unit weight of the soil
γ'	is the unit of the soil above the level of the groundwater table
γ_w	is the unit weight of water
γ_{sub}	is the submerged unit weight
η	is the psychrometric constant
ϕ	is the friction angle of the soil
ϕ'	is the effective friction angle of the soil
ϕ^b	is the rate of increase in cohesion with respect to soil matric suction
ρ	is the density of air
ρ_a	is the density of air at 25°C
σ	is the MOR or modulus of rupture obtained from the four point bending tests
σ_1	is the average flexural stress on the outermost fiber experienced by the section measured by LVDT 1
σ_2	is the average flexural stress on the outermost fiber experienced by the section measured by LVDT 2
σ_n	is the normal stress of the soil

$(\sigma_n - u_a)$ is the net normal stress

θ is the slope of the beam deflected shape

θ_1 is the azimuth angle that LVDT1 makes to magnetic north

θ_2 is the azimuth angle that LVDT2 makes to magnetic north

θ_{FR} is the resultant direction

$(u_a - u_w)$ is the matric suction value of the soil

ΔS is water stored in soil

A_{rh} is the inverse of the relative humidity at the soil surface

A_s is the cross-sectional area of the sample

BM_{max} is the maximum resistive moment

B_{cmax} is the maximum bending resistance

B_{net} is the net bending resistance

B_p is the width or diameter of the pile

B_{total} is the total bending resistance of the root plate

C_D is a dimensionless drag coefficient

C_d is the drag coefficient which is dimensionless and taken as 1

C_z is the center of area of the tree measured in the vertical axis

D_1 is the distance of the observer to the beginning of the branch

D_2 is the distance of the observer to the end of the branch

D_3 is the length of the branch

D_c is the equivalent diameter of the CSA assigned to the circular section of the leeward member,

D_f is the distance from the feature

D_{min} is the minimum depth of penetration

D_n is the compressive lateral root of diameter

D_r is the distance from the reference feature

D_{tt} is the equivalent diameter assigned to the tension tie member

E_a is $f(u) e_a (B-A)$

E_v is the rate of evaporation (mm/day)

F_1 is the wind force in the direction of LVDT1

F_{1E}	is the wind force F_I in the direction of east
F_{1N}	is the wind force F_I in the direction of north
F_2	is the wind force in the direction of LVDT2
F_R	is the resultant force
F_{max}	is the maximum applied pulling force
F_s	is the factor of safety
H_1	is the average height of LVDT1 above the ground
H_2	is the average height of LVDT2 above the ground
I_1	is the average second moment of area of the length of section measured by LVDT 1
I_2	is the average second moment of area of the length of section measured by LVDT 2
I_c	is the second moment of area
I_f	is the image height of the feature
I_n	is the second moment of area of each compressive lateral root
I_r	is the image height of the reference feature
I_x	is the second moment of area about the x axis
L_1	is the measured length of LVDT1
L_2	is the measured length of LVDT2
L_n	is the moment arm to point O (the rotational point) can be estimated as R for all the slices
M_1	is the bending moment experienced by the section measured by LVDT1
M_2	is the bending moment experienced by the section measured by LVDT2
M_{CN}	is the maximum bending strength of the compressive
P_w	is the wind pressure in Pa
P_{wc}	is the critical wind pressure
Q_n	is the net radiation at the soil surface (mm/day of water)
R_1	is the average radius of the tree at the measured section of LVDT1
R_2	is the average radius of the tree at the measured section of LVDT2
R_{ech}	is water lost by groundwater recharge
T_n	is the total shear resistance from this slice

T_{tmax}	is the maximum tensile force in the tension tie down
T_{ttm}	is the tensile strength of the (tension tie down) sinker root
WT_n	is the vertical stress from the self-weight of the tree at slice n
W_n	is the self-weight of soil slice n
Z_c	is the as the center of area in the z axis
d_h	is the horizontal diameter of the root being measured
d_v	is the vertical diameter of the root being measured and
e_a	is the vapor pressure of of the air in the atmosphere above the water surface (mmHg or kPa)
e_s	is the saturation vapor pressure of water at the surface temperature (mmHg or kPa)
h_w	is the hydraulic head or total head
k_0	is the spring constant per unit width
k_s	is the water coefficient of permeability of soil at saturated condition
k_w	is the Darcy coefficient of permeability (Water coefficient of permeability)
k_w	is the water coefficient of permeability of soil
k_{wx}	is the coefficient of permeability with respect to water as a function of matric suction, in x-direction
k_{wy}	is the coefficient of permeability with respect to water as a function of matric suction, in y-direction
m_w^2	is the coefficient of volume change with respect to a change in matric suction (i.e. slope of the soil-water characteristic curve)
q_t	is the total flow rate through the cross-sectional area
s_u	is the undrained shear strength of soil
u_a	is the pore air pressure
u_a	is the soil pore-air pressure
u_r	is the known wind speed at a reference height z_r .
u_w	is the pore water pressure
u_w	is the soil pore-water pressure
v_w	is the velocity of air in m/s

x_1	is the distance of the tension tie down member to the edge of the windward edge of the trunk,
τ_{ff}	is the stress on the failure line
A_f	is the actual dimension of the feature
A_r	is the actual dimension of the reference feature
h	is the head loss
A	is the frontal area of the trunk and crown presented to the wind
B	is the inverse of the relative humidity in the air
D	is the vertical deflection of the sample measured with increasing applied load
E	is the median field measured, greenwood modulus of elasticity for the tree species
ET	is water lost by evapotranspiration
F	is the factor varying from 0 (fully submerged soil) to 1 (water table at or below the failure surface)
I	is water intercepted by vegetation
L	is the support span
N	is the resolved normal stress with contribution from W_n and WT_n
P	is precipitation
R	is surface run-off
V	is the lateral force
W	is the applied load
b	is the uniform width of the beam in the x direction
c	is the total cohesion or intercept of the shear stress for the various matrix suction planes in the extended Mohr-Coulomb failure envelope.
c'	is the effective cohesion or intercept of the extended Mohr-Coulomb failure envelope
d	is the sample diameter
e	is the height of V above the ground surface
$f(u)$	is the turbulent exchange function which depends on the mixing characteristics of the air above evaporating surface
i	is the hydraulic gradient

m	is the straight line portion of the load deflection curve
q	is the dynamic air pressure applied to the frontal area A .
q	is the applied flux at the boundary
t	is the time
u	is the wind speed (in metres per second) at height z (in metres),
v	is the flow velocity
v	is the wind velocity
w	is the diameter of the trunk.

CHAPTER 1 Introduction

1.1 Background

Singapore is an island city-state with an area of only 710 square kilometers. Located on the Equator at the southern tip of the Malaysian Peninsula, the climate of Singapore is tropical with a mean annual rainfall of 2360mm (NEA, 2008). The average relative humidity of Singapore is 84% (NEA, 2008) and the mean annual temperature is 26.7°C (NEA, 2008). The wind system in Singapore comprises roughly of two systems, the North-East Monsoon lasting from late November to March (1 – 4.3 m/s) and the Southwest Monsoon lasting from late May to September (2.4-3.7 m/s) (NEA, 2008).

Singapore's mild tropical climate makes Singapore a suitable locale for trees to flourish. The initial vision of a "Garden City" led the authorities to plant two million trees in addition to the local trees. The objective was to soften the urban sprawl and create "green lungs". Often taken for granted, trees have become an important national resource. Table 1.1 highlights the functions or values that trees provide that are often overlooked by the general public.

The value of trees in Singapore cannot be overstated. However with a population of 5.4 million (Singapore Government Department of Statistics, 2014) in a highly urbanized and organized society, there are often "conflicts" with the tree population due to fallen branches and tree failures. Tree failure events are rare statistically, much in part due to the highly competent efforts of the National Parks Board in the maintenance and care of the trees. Yet when tree failures do happen, much inconvenience is caused due to human traffic blockage and infrastructure damage. Danger can also be caused to the general public due to failed branches and trees.

Table 1.1 Climatic and environmental values provided by trees (Moore, 2011)

Climate related values	Environmental values
<ul style="list-style-type: none"> • Shade • Shelter from the wind • Thermal insulation • Temperature modification • Reduction in Glare • Humidification of the air • Filtration of polluted air • Interception of rainfall • Reduced water runoff • Reduced stream turbidity • Altered effective precipitation 	<ul style="list-style-type: none"> • Production of Oxygen • Fixing of Carbon Dioxide • Reduced soil erosion • Edaphic (soil) environment • Protecting watersheds • Ameliorating wind flow • Improving air quality • Altering ambient temperature • Noise abatement • Wildlife habitat • Create ecosystems

A normal roadside tree in Singapore is between 20-30m in height and can weigh many tons. Due to the high self-weight of the tree, an uprooting failure has the highest potential for causing damage and thus this type of failure poses the greatest danger to the general public. In the densely populated tropical island city of Singapore, 2 million planted trees (Tee et al., 2009) share the small land area with 5.40 million people (Singstats, 2014). Mature trees provide shade, wind protection, glare reduction, rainfall interception, noise reduction and pollution reduction (Table 1.1). However, mature trees are also large structures each weighing from many hundreds to thousands of kilograms. Therefore upon the onset of instability, each mature or large tree presents a zone of potential damage or danger defined by a circle with the height of the tree taken as the radius (Toupin et al., 2005). In Singapore the frequent thunderstorm events (Sumatran squalls) that bring the associated heavy rainfall intensities are often perceived to induce matured tree failures.

In this research, the loads experienced by the urban trees and the mechanisms that provide the trees with resistance against uprooting in the Singapore environment were investigated using applied engineering techniques.

1.2 Structural analysis of trees

Trees are “living structures”. They all possess an above ground superstructure as well as an anchoring sub-structure. Biologists and subsequently arborists and other practitioners have long used stochastic observations to define the behavior of both healthy and failed/failing trees. These stochastic observations have been explained and classified with biological processes like reproduction, growth, adaptation, infection and death etc. The ever changing environment (which is true of all biological systems) that the typical tree is exposed to and its unique responses to these changes does not allow simple definitions to be made of these responses. However, all organisms including trees must obey the laws of physics (Niklas, 1992). As trees grow in size and height, the added biomass develops greater self-loading, and also exposes the upper reaches of the tree to higher wind speeds, which develop larger bending moments at its base, (Niklas & Spatz, 2000). The growth of trees is largely determined by physiological constraints, particularly those affecting photosynthesis and water transport, but if these are optimal, limitations of size and shape are still imposed by biomechanical constraints (Spatz and Bruechert, 2000).

An urban tree needs to be able to withstand all the self-weight and climatic loads applied to it for as long a period as possible. Wind forces, the growing environment and topography provide the most persistent challenges that urban trees are subjected to. However as climate change becomes an accepted reality, wind loads can become ever increasing in magnitudes and frequencies. Strong roots and good soil provide urban trees better chances of resisting wind throw in an increasingly hostile wind environment.

1.3 Objective

The objective of this research was to study the mechanisms leading to uprooting of urban trees in Singapore. The approaches covered will include geotechnical, structural, fluid dynamics, tree/root architectures and greenwood/soil properties.

1.4 Scope of Works

This research covered laboratory work, field work and numerical analyses.

For laboratory work, soil characterization of field and laboratory soils were performed using index tests, permeability tests, shear strength tests and tests to obtain soil-water characteristic curves. These tests provided the engineering properties of the soils that were used as input parameters for numerical analyses and model verifications. An innovative four-point flexural testing apparatus and subsequently, three-point flexural testing apparatus was designed and built to test and classify greenwood for eight common wayside tree species.

For field work, two sites were instrumented to provide real-time data of tree movement, soil moisture/suctions, ground water depth, wind speed/direction, rainfall, solar radiation, open-channel flow and soil temperature. Tree scanning was also performed using a portable three dimensional laser scanner mounted to a tripod to obtain a three dimensional point cloud of the trees under study together with the surrounding area. A new method of surveying the architecture of any tree was also formulated using a laser rangefinder with elevation and azimuth readings. Soil sampling and double ring infiltration tests were also performed.

For numerical analyses, rainfall, infiltration, seepage and evaporation was modelled using SVFLux and compared to the field results. A new model for shallow rooted trees was developed and verified against past tree pulling data. Parametric studies were also performed using EXCEL, SIGMA/W and ANSYS. In EXCEL, the 2D shallow root model was parametrically studied against tree sail area and canopy shape. In SIGMA/W, the effects of changes in the soil water contents were studied parametrically with regard the stresses and strains in the soil. In ANSYS, lateral root and sinker root architectures were parametrically studied together with soil properties.

1.5 Organization

This thesis is organized as follows:

Chapter 1

This chapter firstly describes the background on the Singapore climate, urban trees and structural analysis of urban trees. This chapter then describes the research objective and the scope of the research.

Chapter 2

This chapter presents a review on the existing theories, works conducted by other researchers on greenwood properties, trees in urban environments, tree roots and stability (shallow root and heart root model), structural simulations and failure criteria, static pull tests on trees, wind loads on trees, the geology of Singapore, the water balance in the vadose zone (unsaturated zone) and unsaturated soil mechanics.

Chapter 3

This chapter presents the relevant equations and theory that were proposed and used in the study of the shallow rooted tree resistance to uprooting (shallow root or root plate model).

Chapter 4

This chapter describes the research program that incorporated greenwood testing, field instrumentation, tree surveys, laboratory works, numerical modelling, shallow root model development and parametric studies.

Chapter 5

The chapter describes the results of the research program. These results include the results of the greenwood testing, the field instrumentation results, tree survey results, laboratory results, numerical modelling and parametric study results.

Chapter 6

This chapters provides the discussion of the results presented in Chapter 5. The discussion includes greenwood testing, the performance of the proposed shallow root

tree stability model, tree surveys, parametric studies, comparing wind characteristics between the two sites and numerical modelling.

Chapter 7

This chapter presents the conclusions and recommendations of the discussions in the following order; greenwood testing, shallow root uprooting models, tree surveys, wind characteristics and numerical modelling

CHAPTER 2 Literature Review

This literature review covered the topics of wood properties, above ground tree architecture, below ground tree root architecture and failure modes; past static pull tests, lateral loads on trees due to wind and finally a review of the geological and drainage properties of Singapore Island.

2.1 Wood found in trees

Wood is a material that has evolved over millions of years to be the structural material for trees. Trees are the largest of the plant structures; certain species can be more than 100 m in height, while at the same time, support large complex canopies. Trees have been known to live for hundreds to thousands of years and survive extreme changes in environments and weather.

Growth of trees is determined largely by environmental constraints (e.g. soil, climate and available space), physiological requirements (e.g. photosynthesis and water/nutrient transport) and biomechanical constraints (e.g. wood strength, wood density and genetic pre-dispositions).

Gravitational loads by the tree's own weight or by additional water and snow/ice loads as well as wind loads will induce bending moments and torsional loads on the branches, trunk and roots (Spatz et al., 2000). These loads are highlighted in Figure 2.1. Engineers understand beam theory to a high degree of sophistication (Timoshenko and Goodier, 1970; Stephens, 1994). Before applying this to trees, it has to be realized that greenwood differs from normal isotropic engineering materials in several important aspects. The first aspect is that greenwood is an anisotropic composite material, which possesses mechanical properties that is different in the longitudinal, radial and tangential directions (as defined by the geometry of the tree). When greenwood undergoes bending, modulus of elasticity, i.e. the measure of stiffness, depends not only on the amount of the different tissues, but also on their distribution with respect to the neutral axis. (Rowe & Speck, 1998). The second aspect is that greenwood failure is not an all or none process. Samples, branches or

even entire stems can be bent far beyond the range of linear elasticity and still be stable. This may lead to a reduction in wood quality, but from a biological point of view this mechanical behaviour is of great advantage, since the previously over bent tree structure may eventually recover its structural strength by wood growth. As biological materials differ from most engineering materials, so do design principles. Conventional engineered structures are mostly required to be stiff, while nature's response to mechanical loads is flexibility. It is, therefore, not always justified to use the simplification of small deflections and linear responses.

Figure 2.1 Outline of biomechanical considerations to tree above ground stability
(from Spatz et al., 2000)

Plant biomechanics has been developed, among others, by Schwendener (1874) and Rasdorsky (1928). A monograph (Niklas, 1992) covers the entire field. Several contributions of which only a selection can be given here (Metzger, 1893;

Esser, 1946a, b; McMahon and Kronauer, 1976; King and Loucks, 1978; Morgan and Cannell, 1987; Bertram, 1989; Mattheck, 1992; Morgan and Cannell, 1994; Wood, 1995; Peltola, 1996; Moulia and Fournier-Djimbi, 1997; Niklas, 1998; Spatz et al., 1998a) treat the stability of trees.

2.1.1 Structure of wood

Figure 2.2 Helical arrangement of xylem vessels. a) The helically wound pattern arrangement of the cellulose microfibrils in the secondary cell wall (from Abraham et al., 2012) b) Scanning electron micrograph of a cross-section through a vascular bundle (vessels and tracheid's) showing helical thickening of xylem walls (from Cutler et al., 2005)

Wood is a composite, anisotropic material that comprises of cellulose, lignin, hemicelluloses and other materials bound together within a cellular structure (USDA, 2010). Wood possesses an excellent combination of mechanical properties that leads to high toughness (Jeronimidis, 1979). The toughness of wood has been shown to be due to the helically wound pattern arrangement of the cellulose microfibrils in the secondary cell wall (Figure 2.2 a & b) that induce buckling failure in tension, which in turn produces an elastic behaviour followed by high ductility (Jeronimidis, 1979).

a)

b)

Figure 2.3 Wood anisotropy in three directions a) Longitudinal (L), Transverse (T) and Radial (R) b) A cube cut along a ray showing the arrangement of the (from Reiterer et al., 2002).

Different species of trees possess variations in the characteristics and proportions of these components. Differences in cellular structure of the wood from each species account for their variation in strength, stiffness and density (USDA, 2010). Figure 2.3a & b illustrates the anisotropic nature of wood in a cross-section of

a trunk. The axes are L (Longitudinal), T (Tangential) and R (Radial). The longitudinal axis L is parallel to the fiber (grain). The radial axis R is normal to the growth rings (perpendicular to the grain in the radial direction). The tangential axis T is perpendicular to the grain but tangent to the growth rings (USDA, 2010). Wood is perpendicular direction. This is because about 80% of the total wood volume is composed of fiber cells (trachieds) (Figure 2.3b) that run in the longitudinal direction (Reiterer et al., 2002)

In wood, there are three orthotropic elastic constants for each axis; there are nine orthotropic elastic constants in total. At low stress levels, and when loaded for short periods of time, wood behaves as an elastic material, but at higher stress levels and when loaded for longer periods, wood behaves as a viscoelastic material (Dinwoodie, 1975 and Schniewind et al., 2007).

Figure 2.4 shows that a branch often causes a knot to build up at the connection. The younger branch's connection causes non-continuity in the older branch's longitudinal fibers and creates a v-shaped notch that can be a point of stress concentration and thus weakness in bending along the L-axis (Figure 2.3).

Figure 2.4 Branch connections cause knots to form (Photo B. Chanson from Thibaut et al., 2001).

2.1.2 Bending failure modes for branches and stems

When describing the loading regime in beams when they are subjected to pure bending, engineering textbooks often emphasise on the longitudinal stresses that are set up. When a beam of uniform cross-section is bent, the concave surface is subjected to longitudinal compression and the convex surface is subjected to longitudinal tension, the stress increasing linearly away from the neutral axis which is located at the centroid of the cross-section (Figure 2.5a). The resistance of each element to bending is proportional to the square of its distance from the neutral axis; this is because it is both stretched more when further away from the neutral axis, and because its moment arm about the neutral axis is greater. The flexural rigidity R of a beam is therefore given by the expression;

$$R = EI \quad (2.1)$$

Where;

E is the stiffness or Young's modulus of the material and

I is the second moment of area of the beam's cross-section under consideration

The longitudinal stress σ_L in a part of the beam positioned a distance y from the neutral axis, when a bending moment M is applied is given by the expression.

$$\sigma_L = \frac{My}{I} \quad (2.2)$$

The maximum stress, σ_{Lmax} , occurs at the inner and outer edges of the beam and is given by the expression;

$$\sigma_{Lmax} = \frac{My_{max}}{I} \quad (2.3)$$

where y_{max} is the greatest distance from the neutral axis. For a cylindrical beam of radius r the maximum longitudinal stress σ_{Lmax} can be readily calculated:

$$\sigma_{Lmax} = \frac{4Mr}{\pi r^3} \quad (2.4)$$

A beam is expected to fail when this maximum stress exceeds the breaking stress of the material of which the beam is composed, at which point the bending moment M is given by the expression;

$$M = \frac{\sigma_{max}\pi r^3}{4} \quad (2.5)$$

In typical engineering materials such as metals, ceramics and plastics, which are stiff and isotropic and have low breaking strains, this analysis is perfectly adequate. Beams made of brittle metals and ceramics will fail on the tension side and then simply break right across, while those composed of ductile metals will instead bend irreversibly when the yield stress of the metal is reached, conserving their cross-section.

Figure 2.5 The pattern of stresses in beams loaded in pure bending. (a) Longitudinal stresses rise linearly either side of the neutral axis, the outer convex surface being loaded in tension and the concave inner surface being loaded in compression. (b) Transverse stresses rise to a maximum at the neutral axis, being compressive when the bending tends as here to increase curvature (from Ennos et al., 2010)

Young twigs of many herbaceous plant stems have been observed to buckle inwards and bend readily without actually breaking (Figure 2.6). By contrast, the curved branches seen in some trees tend to split along their length if an attempt is made to straighten them (Mattheck & Kubler, 1995). Finally, many green branches and twigs (Currey, 2002) only break half-way across when bent; the structure then splits lengthwise at its midpoint, and the unbroken half continues to bend while the split extends (Figure 2.6).

Figure 2.6 Patterns of bending failure predicted for branches. An initially curved branch (a) may split longitudinally down the centerline if it is subjected to a force tending to straighten it. By contrast an initially straight branch made of light wood (b) may buckle transversely inwards, its section flattening out when bent. A straight cylindrical branch of reasonably dense wood (c) may break half-way across before splitting along its length at its midpoint, while a tapered branch (d) should break half-way across then split distally (Reiterer et al., 2002).

If the materials making up a beam are anisotropic, meaning, being much stronger and stiffer longitudinally than transversely, the transverse stresses set up in bending can cause beams to fail even when the radius of bending curvature is large. Wooden branches and trunks are the most important of such beams. Wood is much stronger longitudinally than transversely because 80 per cent of the volume is composed of long narrow tracheids or fiber cells that are orientated longitudinally (Reiterer et al., 2002). In the radial direction wood is also strengthened somewhat by

the rays which comprise some 20 per cent of the wood volume, and in which the cells are oriented radially. However, there are no cells oriented in the tangential direction, so it is weakest in this direction; wood can be split or sheared readily along its central axis as tracheid cells and rays are simply split apart or sheared laterally (Figure 2.7).

Figure 2.7 The structure of a branch (a) 80% of the wood volume is composed of tightly packed tracheids or fibers, which are oriented longitudinally, while rays in which the cells are oriented radially constitute around 20%. As a consequence mechanical tests on oriented samples (b) show that tangentially (T) wood is weaker than radially (R) and much weaker than longitudinally (L). Wood is readily split or sheared along the center-line along which the rays and tracheids provide no reinforcement. (from Reiterer et al. 2002)

In a beam loaded to a curvature, the tension in the outer half of the beam will set up an inward pressure on the material inside it. Similarly the compression in the inner half will set up outward pressure on the material outside it. Transverse stresses will therefore be set up within the beam, rising to a maximum at the neutral axis (Figure 2.5). By contrast if the beam is bent in such a way as to decrease curvature, transverse tensile stresses will be set up within the beam.

As Mattheck & Kubler, 1995, have pointed out, transverse forces can be a real problem for curved branches, which they describe as forming a 'hazard beam'. If such curved beams are bent in such a way as to straighten the beam (such as when a downward force is applied to a beam that has been curved upwards by reaction wood), tensile stresses will tend to split the branch along its length. Tests by Reiterer

et al., 2002, have shown that the tangential tensile strength of green oak and ash, at around 8 MPa, are some 35 per cent lower than the radial tensile strength. Other authors give rather lower values down to 2 MPa (Panshin & de Zeeuw, 1980). These values are between a fifth and one-twentieth of the longitudinal compressive yield strength of wood, which is around 40 MPa (Panshin & de Zeeuw, 1980), and an even smaller fraction of the tensile strength (70–140 MPa). A strongly curved branch will therefore split before longitudinal compressive yield of the wood occurs. Failure will occur exactly along the midpoint where the transverse tensile stresses are greatest and along the line where the transverse tensile strength of the wood is least. Splitting will start to occur before compressive failure when the lateral stress is between a twentieth and a fifth of the longitudinal stress, so when so the radius of curvature is between 0.8 and 3.5 times the diameter of the beam.

In fact, even straighter branches can split along their length, because wood does not break in compression, even after it has yielded; instead, as the tracheid cells on the compression side are compressed further they will tend to densify like other cellular solids (Gibson & Ashby, 1999) and the wood's compressive resistance will increase to above the value for tensile strength (70–140 MPa). Therefore even rods with rather a lower degree of curvature, above between 1.3 and 9 times diameter should split along their length.

It might be thought that changes in wood structure on either side of the center of a hazard beam might help prevent splitting. Mattheck & Kubler (1995) found higher transverse strength close to the center of their hazard beams, probably due to greater ray development. However, since the wood actually splits precisely along the centerline where there is no possibility of ray-reinforcement, this growth response cannot prevent splitting.

If a straight branch is bent, compressive transverse stresses will be set up in the branch as its curvature increases. However, since the longitudinal compressive yield strain of wood is less than 1 per cent, the radius of curvature of the rod when the wood starts to yield will be more than 100 times the radius. The transverse stresses set up will therefore be less than one-three hundredth of the longitudinal stress, far too small for transverse compressive failure to occur. However, once the wood has

yielded, and buckles longitudinally on the compression side, the branch can be bent much further, with greater areas of wood on the concave side buckling in compression and being densified. Consequently, the transverse compressive strain in the wood will rise rapidly, while longitudinal strain and stress will only increase slowly.

2.1.3 Reaction wood

Trees adapt to the environments as they mature. In situations (external loads and self-weight) demanding orientation changes in growth directions, trees produce the so-called reaction wood. Reaction wood is defined by the International Association of Wood Anatomists (IAWA, 1957) as: “wood with distinctive anatomical and physical characteristics, formed typically in parts of leaning or crooked stems and in branches, that tends to restore the original position of the branch or stem when it has been disturbed; also known as tension wood in deciduous trees or angiosperms and compression wood in conifers or gymnosperms”.

This definition combines a functional and a structural aspect of reaction wood, but also refers indirectly to the problems associated with reaction wood occurrence: namely heterogeneity of physical and mechanical properties within wood (even within a single tree). The laying of reaction wood by a tree due to growth responses, can also account for the different failure modes.

2.1.4 Modulus of rupture (MOR)

The modulus of rupture (MOR) reflects the maximum load-carrying capacity in bending and is proportional to the maximum moment borne by a tested wood sample. Modulus of rupture is an accepted criterion of strength, although it is not a true stress because the formula by which it is calculated is valid only within the elastic range. The ratio of compressive strength to tensile strength varies for different parts of the tree. Therefore, the measured MOR is usually intermediate between tensile and compression strengths parallel to the grain. As all trees will have branches that break in the different modes of failure (greenstick or buckling), there will be a wide band of values when measuring MORs for a particular tree species. The measured medians or statistically obtained MORs give us a way to gauge tree species' general wood

strength and stiffness without the need to distinguish between the different modes of failure, be it greenstick or buckling.

2.2 Trees in urban environments

A tree is defined as a woody plant with an erect perennial stem at least 4 meters tall, a diameter measured at breast height (1.3 meters) of at least 7.5 centimeters, and a distinct crown of leaves or leafy branches (NParks, 2009).

There is an above-ground shoot system comprising the stem (trunk) and branches bearing the leaves, buds, flowers and fruits. Together, the branches and foliage make up the crown. The outer edge of the crown marks the drip line of the tree.

There is also a below-ground root system which plays important structural and functional roles in the growth and development of the tree. The junction at which the stem enters the ground and merges with the root system is called the root collar.

The architecture of a tree is often described in terms of its size and crown shape. The latter is determined by the growth habit, shoot construction and branching patterns. In an urban setting, trees may be arbitrarily classified as small, medium or large, on the basis of height and crown spread. Small trees generally grow to a height of 10 meters. Medium sized trees are between 10 to 20 meters tall (NParks, 2009). Large species can reach heights beyond 20 meters. Trees exhibit both excurrent and decurrent growth habits. Figure 2.8 illustrates both growth habits.

Trees exhibiting the excurrent growth habit have a dominant stem called a leader that suppresses growth of the lateral branches. The strong apical dominance of the central leader results in a conical shaped crown.

Trees that exhibit a decurrent growth habit lack a central leader. Instead, several primary branches or scaffold branches develop with almost similar prominence. This gives rise to secondary and tertiary branches, resulting in a spreading or round-headed crown.

Figure 2.8 The two main growth habits (from ISA, 2012)

The common tree shapes are conical, tiered, columnar, pyramidal, oval, umbrella shaped, weeping, open and hemispherical. Figure 2.9 and Figure 2.10 show examples of trees with different shapes. Where pruning of trees is carried out on a regular basis, the shape of the trees may be altered from their natural form. However, if left to themselves they will generally try to resume their natural shapes (NParks, 2009).

The value of mature trees in an urban environment cannot be overstated. Mature trees provide shade, wind protection, glare reduction, rainfall interception, noise reduction and pollution reduction. However, mature trees are also large structures each weighing from many hundreds to thousands of kilograms. Therefore upon the onset of instability, each mature or large tree presents a zone of potential damage or danger defined by a circle with the height of the tree taken as the radius (USDA, 2008). A good example of a city with many urban trees is the densely populated tropical island city of Singapore. In Singapore, 2 million planted trees (NParks, 2009) share 710 square kilometers with 5.18 million people (Singapore Government Department of Statistics, 2011). Therefore, with such close interaction between trees and the urban inhabitants, any failure is taken very seriously.

a)

b)

c)

d)

e)

f)

Figure 2.9 Common natural tree shapes. a) *Terminalia catappa* (Tiered), b) *Gnetum gnemon* (Columnar), c) *Myristica fragrans* (Pyramidal), d) *Mimusiops elengi* (Round), e) *Mekakuca cajuouti* (Oval), f) *Samanea saman* (Umbrella) (from NParks, 2009)

a)

b)

c)

d)

Figure 2.10 Common tree shapes. a) *Leptospermum brachyandrum* (Weeping), b) *Callerya atropururea* (hemispherical), c) *Azadirachtea excels* (open) and d) *Casuarina equisetifolia* (Conical) (from Nparks, 2009)

2.2.1 Factors affecting trees in Singapore

Trees in Singapore are exposed to a myriad of environmental factors. One of the factors is the tropical climatic factor that includes high annual total precipitation and frequent thunderstorm events. These thunderstorm events are often preceded by strong wind gusts. Another important environmental factor is the urban factor which includes frequent branch pruning, mechanical damage to root systems by construction activities, restrictive planting spaces and pollution. Lastly, the trees are also affected by their location within the geological and hydrological landscape. The exposure to

these factors must be taken into account when considering the structural stability of the trees, from individual branch stability to overall tree stability.

To consider overall tree stability, tree-root plate models must be devised to take into account the effects of the key environmental factors on tree stability. The tree-root plate models should include the tree root architecture and greenwood mechanical properties. A tree-root plate model that takes into account the complex interaction of all key environmental factors, tree-root architecture and greenwood material properties will provide a much more accurate model of any tree stability in its planted location at any one time (Figure 2.11).

Figure 2.11 Various factors affecting tree stability

Past research works on the role of root architecture in influencing tree stability have found that the maximum moment required to fail the tree is proportional to root plate volume and not the depth (Papesch et al. 1997). Trees also have the ability to adaptively respond to prevailing wind loads via preferential secondary thickening or growth of tree trunks and roots (Ray and Nicoll, 1998). Increasing soil moisture that leads to reducing soil strength was also found to negatively affect tree stability (Fraser, 1962; Lohmander and Helles, 1987 and Frederickson et al., 1993). Conversely, the presence of adequate soil drainage was found to increased tree stability by up to 25% (Fraser, 1962 and Frederickson et al. 1993). Tree stability has also been found to be affected by tree stand distribution, geographical location and

topography (Frederickson et al. 1993, Peltola et al., 2000 and Nykanen et al., 1997). Moore (1999) also highlighted that the location of the tree exposed the tree to different soil types which could affect root anchorage strength. Smiley (2008b) showed that manmade factors like construction activities that affected the roots of the tree had a detrimental effect on root anchorage.

2.3 Tree Roots and Stability

The below ground portion of a tree is called the root system. It performs several important functions such as providing anchoring and support for the tree, absorption and conductance of water and minerals, food storage, and the production of plant growth regulators (NParks, 2009).

Figure 2.12 The different types of tree root systems. (a) Tap-root - Provides main support of the juvenile tree by anchoring it firmly in the ground. (b) Lateral roots – Help support and anchor trunk, may extend far out, beyond crown spread. (c) Fibrous feeder roots – Masses of fine feeding roots close to ground surface. (d) Sinker or descending roots – Grow downwards from lateral roots (from USDA, 1970)

Most dicotyledonous (group of flowering plants whose seed typically has two embryonic leaves or cotyledons) trees start with taproot system in the sapling stage (Figure 2.12a). In this case, the primary tap-root continues its downward growth into the soil, forming a vertical main root with lateral roots (Figure 2.12b) growing out

from the sides. As the lateral roots radiate outwards, they branch out and also give rise to sinker roots (Figure 2.12d) that provide additional anchorage. In most trees, the taproot will not develop further. The main functions such as anchorage are then carried out by the lateral roots, which undergo secondary thickening while absorption of water and nutrients are performed by fine roots called feeder roots (Figure 2.12c). The lateral root systems of dicotyledonous trees may extend for great distances beyond the drip line; however, they often do not penetrate deeper than the top 1 meter depth of soil (NParks, 2009).

Figure 2.13 shows the influence of root system architecture types on tree stability against lateral loading. Heterogeneity in the radial distribution of lateral roots can be compensated for by the presence of sinker roots. In the juvenile stages of the tree, the sapling will normally possess a dominant tap-root (shown in Figure 2.13a and Figure 2.13b) that will provide additional stability and anchorage in the soil. As the tree matures, lateral roots radiate out and provide additional stability. Figure 2.13a shows a stable configuration of lateral roots while Figure 2.13b shows the unstable configuration. With maturity, many shallow rooted trees (species dependent) see a major reduction in the prominence of the tap-root within the root system (Figure 2.13c and Figure 2.13d). The lateral roots begin to become more important. The unstable configuration of the lateral roots compensates for the reduction in tap-root anchorage by growing sinker roots to effectively “tie-down” the lateral roots. Root systems that are severely restricted in lateral root radiation can further compensate by increasing the diameter of the lateral roots and sinker roots and depth of sinker root penetration into the soil (Figure 2.13d).

Figure 2.13 A typical distribution of roots with maturity: a) Sapling with a stable symmetrical radiation of lateral roots. b) Sapling with an unstable non-symmetrical radiation of lateral roots. c) The mature tree with a stable symmetrical radiation of lateral roots using sinker roots to provide additional tie down and anchorage. d) The mature tree with a unstable non-symmetrical radiation of lateral roots using additional thickening of lateral roots and sinker roots to provide stability (adapted from Danjon et al., 2009)

2.3.1 Stability of trees with shallow roots or root plates

Figure 2.14 A typical root structure just below the soil surface (Nicols, et al., 1996)

Trees which are shallow rooted form a “plate” like rooting system. This root plate can spread over large areas near the surface of the soil. In order for shallow rooted trees with no significant tap-root to achieve anchorage, the roots must transfer forces that the tree experiences into the soil (Stokes et.al, 1996). The two main forces are:

- 1) The gravity loads from the tree
- 2) The bending moments due to eccentricity in gravity loads and lateral wind loads (uplift forces)

The tree adapts to these loads by growing a flaring stump and lateral roots (Figure 2.15). Buttresses are additional structures found on some species that comprise of distinctly flat plates of wood formed at the junction of the stem (Trunk) with the lateral roots. Produced by secondary growth, they extend along the ground and also up the trunk. Root flares are often found on big trees with large crowns as they help to distribute the loads experienced by the tree over a much wider area (NParks, 2009).

a)

b)

Figure 2.15 Tree adaptations at the root collar for stability. a) Buttresses found on tall trees experiencing high loads. b) A well- defined root flare that spreads out the loads experienced by the tree.

Trees are normally subjected to horizontal forces by the action of wind on the canopies (resulting in bending moments that can result in overturning), which are in turn transmitted to the root systems by the stems, causing rotation of the root plates.

Figure 2.16 shows a view of a shallow rooted anchorage system of a tree. The windward lateral roots must be able to transmit rotational torque to the soil by resisting upward forces. The windward fibrous and sinker root systems (Figure 2.12d) that are so good at preventing vertical uprooting will help the trees resist rotation. Resistance to rotation requires at least one rigid element at the base of the stem to act as a lever; this can be provided by a tap-root, or the lateral root systems, or both (Ennos & Fitter, 1992).

Figure 2.16 Diagrammatic view of a shallow-rooted tree, showing the four components of the anchorage which resist overturning or bending moments (from Coutts, 1983a).

Trees commonly develop a root plate system (Coutts, 1983) consisting of large diameter lateral roots which radiate almost horizontally from the base of the trunk before tapering and branching (Figure 2.14). These thick, horizontal roots may, in turn develop 'sinker' roots which grow vertically downwards. In such systems the resistance of the soil to downwards movement of the roots is high because of their large area and high resistance to compression of the soil. There are four main components to the anchorage of such systems (Figure 2.16): i) The bearing capacity of the soil; ii) The resistance of the leeward hinge to bending, iii) The resistance of the windward roots, especially the sinkers, to uprooting; and iv) The mass of the root plate-soil plate (Coutts, 1986; Ennos, 2000). The leeward side of the root-soil plate acts as a cantilevered beam, and as a force is applied on the windward side so upward movement of the root-soil plate on that side occurs accompanied by sequential breakage of sinker roots and uplift of the root plate. Eventually the tree overturns with a characteristically elliptical shaped root-soil plate attached; damage to leeside roots occurs nearer to the stem base (Coutts, 1983).

Figure 2.17 Mattheck's model for the function and development of buttresses which can be extended to lateral roots. If a tree is pushed over by the wind (a) the bending force is transmitted smoothly to lateral sinker roots by the buttresses. Windward sinkers resist upward forces and the windward buttresses are put into tension.

Leeward sinkers and buttresses are in compression. (b), (c) and (d) show the successive stages in Mattheck's simulation of buttress development. When the trunk is laterally loaded, stress is concentrated at the top of the junction between the lateral root and the trunk (stippling). Growth in response to heavily stressed regions (b) results in the formation of buttresses (c and d) and a great reduction in stress concentrations (from Mattheck, 1991).

Buttress roots are deep stiff cantilever beams that help spread the self-weight of the tree over a larger area, and more importantly help the tree resist lateral loads efficiently. (Mattheck, 1991 & 1993) has suggested that, in trees which develop buttresses, this function is performed by sinker roots which grow out from superficial lateral roots and down into the soil well away from the trunk. Large buttresses ensure that the sinker roots are far apart. This make the sinker roots well placed to anchor the tree, the windward roots resisting upward forces and the leeward roots resisting downward forces. In such as system, the beneficial function of buttresses is clear. Without buttressing, the lateral roots would be subject to large bending forces and might either snap or split at their junction with the trunk (Mattheck, 1991). Buttresses prevent such failure by bracing the roots to the trunk like angle brackets and smoothly transmitting tension to the windward sinkers and compression to the leeward sinkers (Figure 2.17a). Buttresses therefore act as both props and guy ropes to support the tree and together with the sinker roots, make up an efficient anchorage system.

In experiments with Sitka spruce on a peaty gley soil, Coutts (1986) found that the relative importance of the factors influencing anchorage changed with time. With a small horizontal force applied, the soil resistance was dominant, but with a large force, components of anchorage were in this order of importance:

Roots > mass of plate > hinge resistance > soil resistance

The importance of the laterally growing roots on the windward side in conferring stability to the tree grew as the tree became heavier and taller with time.

From these considerations it is apparent that the stability of trees will be affected considerably by the depth of soil available for sinker roots to exploit, and by the architecture of the root system. Therefore predicting the anchorage failure of tree root systems is a complex matter. The stability of shallowly rooted trees can be strongly influenced by the symmetry of the root system, and where woody lateral roots are poorly developed or absent, stability will be reduced (Coutts et al., 1999). Trees deploy various modifications during their development to limit their susceptibility to overturning. On shallow soils, the flexing of structural roots near the surface increases as the height of the tree increases, therefore taller trees will sway

more. To limit this movement, the size of the root-soil plate increases, both in area and thickness. According to Nicoll & Ray (1996) and Ray & Nicoll (1998), there is an inverse relation between the plate area and plate depth. Thin root plates which develop over shallow water-tables have greater surface areas than thicker plates that have developed where the water tables are deeper. They also found that anchorage was related to the rigidity of the plate, which affected the resistance to soil failure. Increasing rigidity had the effect of extending the leeway hinge away from the trunk and therefore increasing the stability of the tree. Trees also respond to mechanical stresses (thigmomorphogenetic responses). For example, increased root biomass may be allocated in the direction parallel to the direction of the prevailing wind, i.e. there are thickened lateral roots in the windward and leeward direction to provide uplift and bending resistance respectively. Buttressing is also a growth response to mechanical stresses resulting in the increased stiffness of the lateral roots and increased distance of the leeward hinge formation from the trunk.

The vast majority of trees in Singapore are shallow rooted. High annual precipitation rates means that tree roots do not have to go deep into the soil for water. The residual soils; soils whose origins come from parent underlying rock (Figure 2.18), with low permeability are commonly found in Singapore. This also means that the tree roots cannot penetrate the soil to considerable depths (not greater than 2 m) nor survive in a low oxygen environment. The topsoil forms a thin layer above this residual soil and is where most of the roots actually grow.

Figure 2.18 The residual soil formations common to Singapore that are products of bedrock weathering (modified from Little, 1969)

Mattheck and Breloer (1994), have a pictorial explanation (Figure 2.19) that visually illustrates the failure process in a shallow rooted tree. In Figure 2.19 it can be observed that there is very little or no compression side roots exposed after uprooting failure has occurred for shallow rooted trees. A hinge is formed at the compression side just next to the leeward side of the trunk. The tree superstructure and tensile root system rotate about this hinge.

Figure 2.19 Failure of a flat rooted or shallow rooted tree. a) Soil cracks develop and roots slide. b) The shallow root/root plate lifts up with almost no shearing rotating about the hinge formed by the yielded lateral root (from Mattheck and Breloer, 1994)

Figure 2.20 shows a schematic of a shallow rooted mature tree with sinkers (Danjon et al., 2009). This shows that the compression hinge formed is in agreement with the schematic by Mattheck & Breloer (1994) shown in Figure 2.19. In Figure 2.20 there is another two restraining components highlighted. These are the guying zone and the root plate weight. However, the guying zone has a very small moment arm to the hinge and cannot contribute much restraint. Similarly, the weight of the root plate is only defined by the distance between the compression and tension flexion hinge with the restraining moment arm which is only half of this distance. The biggest contribution to the restraint against toppling is the magnitude of the compression hinge restraint.

Figure 2.20 Schematic of a mature tree root system with secondary sinkers' when laterally loaded to the right by wind (guying zone has practically no moment arm to the hinge) (from Danjon et al., 2009)

Figure 2.21 shows another simple but effective schematic of the uprooting of a shallow rooted tree by Ennos (2000). There is the same definition of the leeward hinge as with Figure 2.19 and Figure 2.20. However there is also another restraint to uprooting defined by the breakages in the sinker roots. Each sinker root relies on its diameter, strength properties and more importantly, its distance to the leeward hinge for the restraint moment arm. The likely load displacement chart is shown in Figure

2.21b where the total elastic restraint is first overcome. This is followed by a plastic phase where permanent deformation is encountered. A series of reductions in the uprooting force and increases in displacement signify root breakages of the shallow root system.

Figure 2.21 a) In widely spreading root systems with sinker roots (e.g. many trees and some herbaceous dicots), the system rotates up around a leeward hinge (from Crook and Ennos, 1996). b) The load displacement graph also shows a buildup of uprooting force to a maximum, followed by a series of rapid decreases as lateral, sinker and other fine roots break in series.

The contributions of the individual roots to anchorage depend on the mechanical properties of the roots and their physical dimensions (Coutts, 1983). The bending stiffness of the root is related to the fourth power of its diameter if it is

approximated by a circular beam. In tension, the tensile strength of a root is related to a square of its diameter. Thus, the presence of numerous smaller diameter lateral roots may not provide the same restraint as a single large diameter root. The angular arrangement of the main lateral roots with respect to the lateral force direction will also affect their ability to resist the force, both in tension through the sinker roots and the weight of the soil/root mass, and in compression through the leeward lateral roots against the soil.

There have been many empirical models developed to quantify root plate anchorage. Field observations have led Elie & Ruel (2005) to state that the total root plate anchorage is contributed by the windward roots growing beyond the root plate edge, however, root plate mass and leeward roots did not provide an explanation of the mechanism leading to uprooting. Coutts et al. (1999) stated that tree anchorage resistance factor of safety against wind throw was a function of the product of the tree mass, root plate mass and the root plate radius divided by the product of the wind load and the height to the crown center of the wind load force. The function by Coutts et al. (1999) was based on the conservation of forces but made no mention of greenwood properties, root dimensions, anchorage mechanisms and soil properties. Fourcaud et al. (2008) also stated that tree anchorage was observed to be the product of root plate mass and leeward hinge distance from the stem base. However, the hinge formation due to rupture of the leeward lateral roots and the effects of sinker roots were not accounted for. Anderson et al. (1989) observed that uprooting resistance was a function of the square of the root plate radius divided by the wind load. Lundstrom et al. (2008) provided an equation, stating that the root plate volume contributing to anchorage was a function of the root plate diameter parallel to the wind direction multiplied by the root plate diameter perpendicular to wind direction multiplied by an empirical factor.

The root plate concept is valuable in understanding and educating practitioners about root anchorage. An accurate model must improve the current models by accounting for greenwood strength, lateral root dimensions and distributions, sinker root dimensions and distributions, failure root plate shapes and soil shear strength.

The model must be verified using past tree pulling data that also provided excavated and dimensionally detailed root architecture. The model must also account for the shape and form of the root plate from its intact form to the failed form.

Figure 2.22 Excavation and air spading to show the complete root systems of two common wayside tree species found in Singapore a) *Samanea saman* (from Rahardjo et al., 2010) b) *Samanea saman* (from Rahardjo et al., 2009) c) *Syzygium grande* (from Ghani et al., 2009) d) *Syzygium grande* (from Ghani et al., 2009)

Viewing of the shallow root systems can be destructively performed through excavation and air spading. The shallow root systems of two common wayside tree species widely planted in Singapore (*Samanea saman* and *Syzygium grande*) are shown in Figure 2.22. Common to these four trees is that there are both large and small lateral roots radiating and branching horizontally from the root collar. The presence of small sinker roots and other fine roots is also seen in the figures. The depth of the entire root plate does not exceed 1m but the diameter of the root plate can

extend to great horizontal distances away from the trunk. The responsibility of resisting uprooting failure in shallow rooted trees is mainly held by the complex interaction between the lateral roots, sinker roots and the soil. Tap-roots were not found within the root systems and were deemed to have receded with maturity.

2.3.1.1 Shallow root behaviour described as a flat slab with varying soil supports (Winkler foundation)

The elastic foundation reaction from the soil to the trees' self-weight can be shown in two dimensions as a point loaded beam supported by an infinite series of springs (Figure 2.23). The deflected shape is dependent on the foundation modulus, the stiffness of the root plate/beam and the magnitude of the point load F .

Figure 2.23 The tree root plate can be modelled by point loaded infinite beam supported by an infinite series of springs. (from Kolitzus, 1984). This type of foundation response is referred to as the Winkler foundation.

The response of a beam resting on an elastic foundation can be described by a single differential equation. The boundary conditions for the beam depend on how the beam is supported at its ends. To remove these boundary conditions, an infinite beam is used that is attached along its entire length to an elastic foundation (Figure 2.24). Figure 2.24 shows the origin of the Cartesian coordinate system (x , y , z) that is located at the centroid of the beam cross-section. The z axis is along the length of the beam, the x axis is out of the paper towards the reader and the y axis is normal to the elastic foundation. The load P causes the beam to deflect. This deflection in turn causes an elastic response from the foundation. Thus relative to the beam, the stiffness of the foundation produces a laterally distributed force q (force per unit length) on the beam (Figure 2.24).

The distributed force q is taken as positive when it reacts up against the beam. The downward deflection of the beam is taken as positive. When the deflection is upward (negative), tension is induced in the supporting medium; this means that it pulls down on the beam (q is negative). This accurately depicts the root plate as fibrous roots and sinkers will grow throughout the root plate and hold it down to the supporting soil.

Figure 2.24 Infinite beam on an elastic foundation and loaded at the origin 0 (from Boresi, 2002).

The free body diagram of a beam element shown in Figure 2.25 with the sign conventions that is used for the following equations. The beam cross-section vertical faces are assumed to remain vertical for small deflections.

Figure 2.25 The free body diagram of a beam element with all the forces and moments (from Boresi, 2002)

In Figure 2.24c the shape of the slope θ is shown.

$$\theta = \frac{dy}{dz} \quad (2.6)$$

where:

θ is the slope of the beam deflected shape

The moment about the x axis,

$$M_x = -EI_x \frac{d^2y}{dz^2} \quad (2.7)$$

where:

E is the root plate bending modulus

I_x is the second moment of area about the x axis

The shear stress in the y direction,

$$V_y = \frac{dM_x}{dz} = -EI_x \frac{d^3y}{dz^3} \quad (2.8)$$

The elastic foundation reaction q ,

$$q = \frac{dV_y}{dz} = -EI_x \frac{d^4y}{dz^4} \quad (2.9)$$

For a linearly elastic foundation or subgrade, q can also be defined to be linearly proportional to the deflection of the beam. The spring constant of the soil is denoted as, k (some examples in Table 2.1). Therefore;

$$q = ky \text{ or } q = bk_0y \quad (2.10)$$

where,

b is the uniform width of the beam in the x direction

k_0 is the spring constant per unit width

Substituting q for both expressions 2.8 and 2.9,

$$EI_x \frac{d^4y}{dz^4} = -ky = -bk_0y \quad (2.11)$$

Using the notation:

$$\beta = \sqrt[4]{\frac{k}{4EI_x}} \quad (2.12)$$

The general solution is given by,

$$y = e^{\beta z}(C_1 \sin \beta z + C_2 \cos \beta z) + e^{-\beta z}(C_3 \sin \beta z + C_4 \cos \beta z) \quad (2.13)$$

This solution represents the general solution for the response of an infinite beam on an elastic foundation subjected to a concentrated vertical load. The constants of integration C_1 , C_2 , C_3 and C_4 are determined by the boundary conditions. The deflection of the beam goes to zero for large positive values of z , therefore constants C_1 and C_2 can be taken as zero and the equation for the beam deflection y reduces to,

$$y = e^{-\beta z}(C_3 \sin \beta z + C_4 \cos \beta z) \text{ for } z \geq 0 \quad (2.14)$$

As the beam deflection (Figure 2.24c) is symmetrical about the origin O, $y(-z)=y(z)$.

Table 2.1 Some values of k_0 for different soils (from Boresi, 2002)

Soil type	Range of k_0 [N/mm ³]
Loose sand	0.005–0.016
Medium sand	0.010–0.080
Dense sand	0.063–0.126
Clayey sand (medium)	0.031–0.080
Silty sand (medium)	0.024–0.048
Clay, $q_u < 0.2$ N/mm ²	0.012–0.024
Clay, 0.2 N/mm ² $< q_u < 0.4$ N/mm ²	0.024–0.048
Clay, $q_u > 0.4$ N/mm ²	> 0.048

Source: Data adapted from Bowles (1995).

Using boundary conditions, the two constants of integration C_3 and C_4 can be determined. The boundary conditions are:

- 1) At the origin O, the slope θ or $\frac{dy}{dz} = 0$.

Therefore $C_3 = C_4 = C$ and $y = Ce^{-\beta z}(\sin \beta z + \cos \beta z)$ for $z \geq 0$

- 2) $2 \int_0^\infty ky dz = P$ (due to symmetry about the origin (Figure 2.24c) and force equilibrium)

$$\text{Therefore } C = \frac{P\beta}{2k} \text{ and } y = \frac{P\beta}{2k} e^{-\beta z}(\sin \beta z + \cos \beta z) \text{ for } z \geq 0 \quad (2.15)$$

For $z < 0$, $y(-z)=y(z)$ can be used due to symmetry.

$$\text{Taking } A_{\beta z} = e^{-\beta z}(\sin \beta z + \cos \beta z), \quad (2.16)$$

$$y = \frac{P\beta}{2k} A_{\beta z} \text{ for } z \geq 0$$

Taking $B_{\beta z} = e^{-\beta z}(\sin \beta z)$,

$$\theta = \frac{dy}{dz} = -\frac{P\beta}{2k} B_{\beta z} \text{ for } z \geq 0 \quad (2.17)$$

Taking $C_{\beta z} = e^{-\beta z}(\cos \beta z - \sin \beta z)$,

$$M_x = -EI_x \frac{d^2 y}{dz^2} = \frac{P}{4\beta} C_{\beta z} \text{ for } z \geq 0 \quad (2.18)$$

Taking $D_{\beta z} = e^{-\beta z}(\cos \beta z)$,

$$V_y = -EI_x \frac{d^3 y}{dz^3} = -\frac{P}{2} D_{\beta z} \quad (2.19)$$

Figure 2.26 Values of functions $A_{\beta z}$, $B_{\beta z}$, $C_{\beta z}$ and $D_{\beta z}$ (Boresi, 2002)

For a tree root plate modeled as a point loaded infinite beam of width B (Figure 2.24) on an elastic foundation of spring constant k , the length of the effective root plate in compression can be considered as $\frac{3\pi}{4\beta}$ for $z \geq 0$ (Figure 2.24c) and

therefore $\frac{3\pi}{2\beta}$ for the whole tree. The maximum bending moment, M_x is $\frac{\pi}{4\beta}$. The maximum shear stress in the y direction V_y , is $\frac{P}{2}$. Reductions in the value of k (e.g, due to excessive infiltration and thus reductions in soil matric suctions) will cause values of M_x to increase shown in Figure 2.27. The maximum value of y will also increase with a reduction in k.

Figure 2.27 Reductions in k to k_1 cause a $(k/k_1)^{0.25}$ increase to M_1 from M , where M is the maximum bending moment in the beam for spring constant of 1.0k. This is dimensionless and serves to highlight changes in maximum values of M_x with changes in k. Values of k will never reach zero.

Trees under lateral loads like wind experience an extra overturning bending moment about the root plate. This bending moment can be represented by an extra force P_1 at a distance δ from the origin O. Figure 2.28 shows this representation. The effect of these two forces can be super imposed on each other to get the resultant shape of the deflection, bending moment, shear force and bending moment curves.

Figure 2.28 A bending moment about the origin O can be represented by a force P_1 at a distance δ from O (from Boresi, 2002).

$$y = \frac{P\beta}{2k} A_{\beta z} \text{ and } M_x = \frac{P}{4\beta} C_{\beta z} \text{ for } z \geq 0$$

By superposition,

$$y = -\frac{P_1\beta}{2k} A_{\beta(z+\delta)} + \frac{P_2\beta}{2k} A_{\beta z} \quad (2.20)$$

$$\text{and } M_x = -\frac{P_1}{4\beta} C_{\beta(z+\delta)} + \frac{P_2}{4\beta} C_{\beta z} \text{ for } z \geq 0 \quad (2.21)$$

If $|P_1| = |P_2| = P$ and multiplying by $\frac{\delta}{\delta}$

$$y = -\frac{(P\delta)\beta}{2k} \left[\frac{A_{\beta(z+\delta)} + A_{\beta z}}{\delta} \right] \quad (2.22)$$

$$\text{and } M_x = -\frac{P\delta}{4\beta} \left[\frac{C_{\beta(z+\delta)} + C_{\beta z}}{\delta} \right] \quad (2.23)$$

Letting $P\delta \rightarrow M_0$ and $\delta \rightarrow 0$ we the definition of the derivative is obtained,

$$y = -\lim_{\delta \rightarrow 0} \left\{ \frac{(P\delta)\beta}{2k} \left[\frac{A_{\beta(z+\delta)} + A_{\beta z}}{\delta} \right] \right\} = -\frac{M_0\beta}{2k} \left[\frac{dA_{\beta z}}{dz} \right] = -\frac{M_0\beta^2}{2k} [B_{\beta z}] \text{ for } z \geq 0 \quad (2.24)$$

$$\text{and } M_x = -\lim_{\delta \rightarrow 0} \frac{P\delta}{4\beta} \left[\frac{C_{\beta(z+\delta)} + C_{\beta z}}{\delta} \right] = -\frac{M_0}{4\beta} \left[\frac{dC_{\beta z}}{dz} \right] = \frac{M_0}{2} [D_{\beta z}] \text{ for } z \geq 0 \quad (2.25)$$

The deflected shapes are shown in Figure 2.29a.

Figure 2.29 Curves showing, a) The deflections in direction y. b) The bending moment about the x axis (from Borezi, 2002).

Figure 2.30 shows the zones where the roots perform different functions. The effective root plate is in zone 1. Assuming a perfectly symmetrical root plate, the point of hinge formation traces a circle around the tree.

Figure 2.30 Stylized view from above of three different tree root zones (not to scale and indicative only): 1) Structural roots that define the root plate effective width; 2)

Woody transport roots; 3) Absorbing root fans. The dotted line representing crown projection on the soil (drip line) contains ~ 65% of roots found on average sites (from Coder, 2009).

Figure 2.30a when combined with the deflection curve of Figure 2.24(b and c), Figure 2.31 is obtained and the effective structural root plate limit can be defined. At failure, the hinge point can be defined with Figure 2.32 where the moment curve of Figure 2.31b is combined with Figure 2.32b. The hinge point will be determined once the bending capacity of the root plate is exceeded by the applied moment.

Figure 2.31 The compressive portion of the q curve determines the effective root plate limit (from Coder, 2009 and Boresi, 2002).

Figure 2.32 The hinge joint forms at the point where the bending moment exceeds the bending capacity of the root plate (from Coder, 2009 and Boresi, 2002).

Section 2.3.1.1 describes the use of a Winkler foundation to describe the action of a thin extensive root plate founded on soil. The use of the Winkler foundation provides a basis for assuming that only the immediate lateral roots around the trunk are responsible for restraining the tree against lateral loads (Figures 2.29 a &

b). The Winkler foundation discussed in Section 2.3.1.1 also makes the case for the shallow root model shown in Chapter 3 and the numerical modelling in SIGMA/W (Section 4.7.3) and ANSYS (Section 4.7.4). As soil is much stronger in compression than in tension, the case can be made for the fact that the bearing capacity of soil on the leeward side is less critical than the tension failure of soil on the windward side. Section 2.3.1.1 thus provides the basis for a hinge forming in the compression roots and uplift of the tension side lateral roots (Shown in the shallow root model in Section 3.2).

2.3.2 Heart root model

The heart rooted tree shown in Figure 2.33 is the most commonly held image by the public regarding a tree's rooting system. The heart root is only possible if the soil is sufficiently fertile, is porous (aeration) and has high enough water content to a depth similar to the radius of the lateral root spread. The resulting root system is "heart shaped" and thus the name. Strong roots of large diameters radiate from the base of the trunk.

Figure 2.34 shows the failure mechanism of the heart root (Mattheck and Breloer, 1994). The primary mechanism initiating failure is the pulling out of the windward side roots from the soil. This is similar to a raked pile group designed to resist lateral loads (Figure 2.35). The main benefit of the raked pile group or a heart root is the depth of penetration, where a deeper penetration leads to a larger shearing surface and therefore bigger resistance to overturning.

Figure 2.33 The heart rooted tree with strong branching roots that extend in all directions, deep within the soil (Dobson, 1995)

Figure 2.34 Failure mechanism of a heart rooted tree a): Soil cracks develop b): Roots pull out c): The root/soil ball shears/slides d): Roots break at the surface of shearing surface and the toe (Mattheck and Breloer, 1994)

Figure 2.35 The symmetrically raked pile group that can approximate the ideal heart root

Tree stability analysis for heart rooted trees can be performed using the ordinary method of slices (Figure 2.36) (Rahardjo et al., 2009). The ordinary method of slices is performed over a half-cylindrical section or part-of. This is a significant simplification to define the heart rooted tree critical uprooting failure mode to be a soil only failure mode. The half-cylindrical shearing surface is first defined using the average length of the radiating lateral roots as the radius and the width of the half cylinder. The ordinary method of slices dictates that the half circle is split into slices joined by straight lines. Figure 2.37 shows the top view of the half cylinder of soil. The free body diagram of each slice is shown in Figure 2.38.

Figure 2.36 The radius of the shearing surface from a symmetrical heart root system. The centre of the half circle is the black dot labeled O. The semi-circle is then cut into slices.

Figure 2.37 The top view shows the slices as a series of prisms to approximate the shearing surface

The half circle cylindrical shearing surface is divided into n equal width slices

W_n is the self-weight of soil slice n

WT_n is the vertical stress from the self-weight of the tree at slice n

α_n is the angle the normal stress N makes with the vertical

T_n is the total shear resistance from this slice

L_n is the moment arm to point O (the rotational point) can be estimated as R for all the slices

N is the resolved normal stress with contribution from W_n and WT_n

WT_n can be calculated using a simple method to compute the distribution of stress with depth for a loaded area. The method uses a 2: 1 area distribution with depth. The self- weight of the tree is distributed over an increasing area with depth (Figure 2.39)

Figure 2.38 The forces acting on each slice (Rahardjo et al., 2009). Added is the self-weight of the tree as a uniformly distributed load WT . WT is reduced to WT_n by using the 2:1 slope ratio for area

The depth used to determine the WT_n stress distribution will be the average of the two sides of the trapezium (D_n and D_{n-1}).

$$WT_n = WT \left(\frac{4R^2}{(2R+D)^2} \right) \quad (2.26)$$

The horizontal distance of each D_n from D_0 , B_n is as follows:

$$B_n = \left(\frac{R}{\Sigma n}\right)n \quad (2.27)$$

The height of each slice, D_n is calculated as follows:

$$D_n = \sqrt{R^2 - B_n^2} \quad (2.28)$$

The area of each slice (A_n) is assumed to be trapezoidal and calculated as follows:

$$A_n = \frac{(D_{n-1} + D_n)}{2} \times \frac{R}{\Sigma n} \quad (2.29)$$

The weight of each slice (W_n) is given by:

$$W_n = \rho g A_n (1m) \quad (2.30)$$

where :

$\rho = \text{soil density (Mg/m}^3\text{)}$

$g = \text{gravitational acceleration (m/s}^2\text{)}$

Normal force N acting on the chord length S_n is given by:

$$N = W_n \cos \alpha_n + W T_n B S_n \cos \alpha_n \quad (2.31)$$

where S_n is length where the normal force N acts on (Figure 2.38).

Figure 2.39 A 2:1 stress distribution used to determine WT_n with depth

$$S_n = \sqrt{(D_n - D_{n-1})^2 - B^2} \quad (2.32)$$

$$\tau_n = c' + \left(\frac{N}{S_n}\right) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (2.33)$$

where c' is the effective cohesion of the soil

ϕ' is the friction angle of the soil

u_a is the pore air pressure in the soil at the depth of the shearing surface

u_w is the pore water pressure in the soil at the depth of the shearing surface

$\tan \phi^b$ is the rate of increase of shear strength with increasing $(u_a - u_w)$

The resisting shear force for a particular slice is T_n where:

$$T_n = \tau_n S_n \quad (2.34)$$

$$\text{Total resistive moment is } M_r = 2R \sum T_n R \quad (2.35)$$

$$\text{The factor of safety against a driving moment } M_d \text{ is given by } \frac{M_r}{M_d} \quad (2.36)$$

2.4 Structural analysis of trees

Structural analysis is the determination of the response of a structure to applied loads. If the applied load is constant, the response of the structure will also be constant and a static analysis is sufficient to determine deflections and stresses. For trees, high constant load situations would be due to various combinations of their own self-weight, rainwater interception loads, snow/ice loads or sustained wind loads.

In discussing the storm-resisting features of the design of trees, Vogel, 1996 highlighted that nature uses flexible and ductile structures like leaves, branches, trunks, soil and roots to change shape and absorb energy. Simply applying an engineering analysis of rigid structures to trees may not provide the required solutions. The flexible and ductile structures and materials of trees not only twist and bend but do other things like absorb and either store or dissipate energy (Vogel, 1996).

There has been considerable study of tree structures using static analyses (Sugden, 1962; Gardiner, 1992; Mayhead, 1973; Oliver & Mayhead, 1974; Blackburn et al., 1988; Bell et al., 1991; Roodbaraky et al., 1994; Lilly & Davis Sydnor, 1995; Rodgers et. al. 1995; Wessolly, 1995; Neild & Wood 1999; Brüchert et al., 2000; England et al., 2000; Silins et al., 2000; Moore, 2000, Peltola et al., 2000; Ilic, 2001; Brudi, 2002; Cucchi & Bert, 2003b; Cucchi et al., 2004; Fraser & Gardiner, 1967; Herajarvi, 2004; Peltola, 2006; Bergeron, 2009). The history of plant biomechanics is summarised by Niklas (1992) who describe how the basic principles of structural engineering theory are applicable to the study of plant forms including trees. Niklas, (1992) cautions that care must be taken because applying well developed engineering beam theory to trees may not accurately describe how the tree responds under wind loading. Often assumptions are made in order to simplify the mathematical calculations. One frequently used simplification is to treat a tree as a beam or a tapered pole without considering any of the branches. This would miss the major structural contributions from branches. Live trees and living greenwood differs from normal engineering material in several important aspects. Wood is a composite material that is both anisotropic and heterogeneous, and mechanical behaviour at failure is not an all or none process, (Spatz & Bruechert, 2000). Structural analysis

has used both static and dynamic methods but in general dynamic analysis is more complex. Care needs to be taken when applying any simplifying assumptions to make sure they are valid.

As trees are three dimensional indeterminate structures, a method of expressing displacements and stresses is through the finite element method. It is applicable to all structures and can require high computing power due to the complex calculations; especially when dealing with three dimensions and time domain. Using the finite element method, the structure under analysis is divided into an appropriate number of meshed elements (2D or 3D) whose size may vary, and the sides of each element (nodes) become the generalised coordinates with boundary conditions and interaction formulae. The deflection of the complete structure can then be expressed in terms of generalised coordinates due to the aggregate behaviour of the elements. This method is good for three dimensional structures and has the advantages of being able to select the desired number of generalised coordinates by dividing the structure into the appropriate number of segments. For uniform materials and symmetrical structures, interpolation functions of each segment may be identical and computations are simplified. Applying this method to trees should require taking into account the heterogeneous qualities of material and shape, the complex three dimensional structures, interactions with soil and require complex mathematical solutions. The method has been applied to a tree branch and is described by Mattheck (1990) and a branch section is shown in Figure 2.40.

Figure 2.40. Branch joint of a tree, with finite element representation to visualize stress distribution (from Mattheck, 1990)

2.4.1 Structural mechanics used when performing engineering and structural simulations in ANSYS

Engineering simulations were conducted using ANSYS to perform a parametric study on the effect of root architecture and soil modulus on the shallow root stresses and deformations. The parametric study is described in Section 4.7.4 and the results presented in Section 5.6.6.

An engineering simulation refers to the process of finding the responses of a problem domain subject to environmental conditions. A structural simulation refers to the process of determining the responses of bodies subject to environmental conditions, where the bodies are described by geometries and materials. The environmental conditions include support and loading conditions while the responses to these conditions can be described by displacements, strains and stresses.

The displacement vector $\{u\}$ of a particle found within the body under study is formed by connecting the positions of the particle before and after deformation in three dimensions (ANSYS, 2011):

$$\{u\} = \{u_x \ u_y \ u_z\} \quad (2.37)$$

Figure 2.41 Stress components at a point in loaded body

The stress tensor $\{\sigma\}$ defines the axial and shear stresses on any face of a particle. The stress field defines the stress state of the particle (Figure 2.41) (from ANSYS, 2011).

$$\{\sigma\} = \begin{pmatrix} \sigma_x & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_y & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z \end{pmatrix} \quad (2.38)$$

As $\sigma_{xy} = \sigma_{yx}$, $\sigma_{yz} = \sigma_{zy}$ and $\sigma_{xz} = \sigma_{zx}$

$$\{\sigma\} = \{\sigma_x \sigma_y \sigma_z \sigma_{xy} \sigma_{yz} \sigma_{zx}\} \quad (2.39)$$

The strains caused by the stress tensor acting on a point of the body are defined using the same axes. Therefore the normal strain ϵ_{xx} is the percentage of stretch or compression of a fibre along the x- direction. The shear strain ϵ_{xy} is the angle change in radians of two fibres lying on the XY-plane and originally forming a right angle (ANSYS, 2011).

$$\{\epsilon\} = \begin{pmatrix} \epsilon_x & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_y & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_z \end{pmatrix} \quad (2.40)$$

As $\epsilon_{xy} = \epsilon_{yx}$, $\epsilon_{yz} = \epsilon_{zy}$ and $\epsilon_{xz} = \epsilon_{zx}$

$$\{\epsilon\} = \{\epsilon_x \epsilon_y \epsilon_z \epsilon_{xy} \epsilon_{yz} \epsilon_{zx}\} \quad (2.41)$$

The governing equations for bodies are three equilibrium equations, six strain-displacement equations and six stress-strain equations.

When performing a structural analysis on a deformable body, differential equations of motion for a deformable solid body are necessary (differential equations of equilibrium if the deformed body has zero acceleration). These equations are needed when the theory of elasticity is used to derive load-stress and load deflection

relations for a member. When considering a general deformed body, a differential volume element at point 0 in the body as indicated in Figure 2.42.

Figure 2.42 General deformed body (ANSYS, 2011).

The form of the differential equations of motion depends on the type of orthogonal coordinate axes employed. The chosen rectangular coordinate axes (x , y , z) has directions are parallel to the edges of the volume element. For small displacements there is no need to distinguish between coordinate axes in the deformed state and in the undeformed state (Boresi & Chong, 2000). Six cutting planes bound the volume element shown in the free-body diagram of Figure 2.43. In general, the state of stress changes with the location of point 0. In particular, the stress components undergo changes from one face of the volume element to another face. Body forces (B_x , B_y , B_z) are included in the free-body diagram. Body forces include the force of gravity, electromagnetic effects and inertial forces for accelerating bodies.

Figure 2.43 Stress components showing changes from face to face along with body force per unit volume including inertial forces (ANSYS, 2011).

To write the differential equations of motion, each stress component must be multiplied by the area on which it acts and each body force must be multiplied by the volume of the element as (B_x, B_y, B_z) have dimensions of force per unit volume. The equations of motion for the volume element in Figure 2.43 are then obtained by summation of these forces and summation of moments. The summation of forces in the x, y and z directions give (ANSYS, 2011):

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \frac{\partial \sigma_{zx}}{\partial z} + B_x = 0 \quad (2.42)$$

$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zy}}{\partial z} + B_y = 0 \quad (2.43)$$

$$\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + B_z = 0 \quad (2.44)$$

2.4.1.1 Stress-strain relationships

For isotropic, linear elastic material, the Young's modulus (E) and Poisson's ratio (ν) can be used to fully describe the stress strain relations. This material model is called Hooke's law. If the temperature changes (thermal loads, the coefficient of thermal expansion (α) must be included. If inertia forces are involved, mass and density parameters must be included. The stress-strain relationships including thermal loads are shown below (ANSYS, 2011):

$$\varepsilon_x = \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} - \nu \frac{\sigma_z}{E} \quad (2.45)$$

$$\varepsilon_y = \frac{\sigma_y}{E} - \nu \frac{\sigma_z}{E} - \nu \frac{\sigma_x}{E} \quad (2.46)$$

$$\varepsilon_z = \frac{\sigma_z}{E} - \nu \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} \quad (3.48)$$

$$\varepsilon_{xy} = \frac{\sigma_{xy}}{G} \quad (2.47)$$

$$\varepsilon_{yz} = \frac{\sigma_{yz}}{G} \quad (2.48)$$

$$\varepsilon_{zx} = \frac{\sigma_{zx}}{G} \quad (2.49)$$

2.4.1.2 Failure criteria for materials in ANSYS

Material failure is defined as any action to separate the material, or to create new free surfaces, depending on the geometrical scale (Boresi, 2002). The failure criteria of an engineering material are required so that material scientists and engineers can determine the cause of failure by describing the failure process and to suggest measures of preventing the failure from recurring. Material failures lead to structural failures. Structural failures can be defined as any action leading to the loss of the designed structural function/integrity to sustain load, which is frequently due to the inability of the structural members. Structural members can be columns, beams, panel/plates, shells etc.

The scale of the structural member under study is important when considering the failure criteria. The various scales are macroscopic (body forces and deformations), mesoscale (represented by the characteristic size of voids), micro scale ($\sim 10^{-6}$ m, e.g., dislocations, which is the scale limitation for the validity of continuous mechanics) and nano/atomic (Angstrom units (A), where, $1\text{A}=10^{-10}$ m). For example, when constructing a stress-strain curve using a tensile test, the macro scale stress-strain curves are the result of many complicated physical processes happening on the meso, micro and nano scales (Figure 2.44).

There are two basic material groups; ductile materials and brittle materials. Ductile materials exhibit a large amount of strain before it fractures, whereas brittle materials only undergo small strains before fracture. The fracture strain is a measure of ductility.

For a typical ductile material (Figure 2.44), there often exists an obvious yield point, beyond which the deformation would be too large so that the material is no longer reliable or functional. Failure is accompanied by excess deformation. Therefore for ductile materials, the most important point is not the rupture or fracture stress but the yield stress. The yielding of ductile materials is mostly due to shear failure. The typical yield criteria used for ductile materials are the Tresca criterion (Tresca, 1864) and the von Mises criterion (von Mises, 1913).

Figure 2.44 The ductile tensile test is very easily and quickly performed but it is not possible to know what is happening on the various scales that contribute to the macro scale results (from ANSYS, 2011).

The Tresca (Tresca, 1864) failure criterion states that the failure of a ductile material is a shear failure. When a ductile material yields it is because it has experienced a shear stress higher than the shear strength of the material.

Figure 2.45 Yield surface of the Tresca (Tresca, 1864) failure criterion in stress space.
a) Two-dimensional. b) Three-dimensional (from ANSYS, 2011).

If σ_a and σ_b represent orthogonal stresses, for σ_a and σ_b with the same sign, the maximum shear stress,

$$\tau_{max} = \frac{|\sigma_a|}{2} \text{ or } \frac{|\sigma_b|}{2} < \frac{\sigma_{yield}}{2} \quad (2.50)$$

$$|\sigma_a| < \sigma_{yield} \text{ or } |\sigma_b| < \sigma_{yield} \quad (2.51)$$

where,

σ_{yield} is the yield stress on the stress-strain curve.

for σ_a and σ_b with the opposite signs, the maximum shear stress,

$$\tau_{max} = \frac{|\sigma_a - \sigma_b|}{2} < \frac{\sigma_{yield}}{2} \quad (2.52)$$

$$\text{Or } |\sigma_a - \sigma_b| < \sigma_{yield} \quad (2.53)$$

The von Mises (von Mises, 1913) criterion (Maximum distortion energy criterion) states that yielding occurs when the deviatoric strain energy density reaches a critical value. The structural component of interest yields when the distortion energy per unit volume (u_d) is more or equal than that occurring in a tensile test specimen at yield (u_y), i.e.,

$$u_d \geq u_y \quad (2.54)$$

$$u_y = \frac{(1+\nu)\sigma_{yield}^2}{3E} \quad (2.55)$$

The distortion energy per unit volume is:

$$u_d = \frac{1+\nu}{6E} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (2.56)$$

The criterion reduces to yielding to occur when,

Figure 2.46 Yield surface of the von mises (von Mises, 1913) criterion in stress space.

a) Two-dimensional. b) Three-dimensional (from ANSYS, 2011).

$$\sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \geq \sigma_{yield} \quad (2.57)$$

In Equation 2.58, the term on the left is the von mises (von Mises, 1913) stress or effective stress and denoted by σ_e ; in ANSYS it is also referred to as equivalent stress,

$$\sigma_e = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (2.58)$$

The equivalent strain or effective strain ε_e is defined by

$$\varepsilon_e = \frac{\sigma_e}{E} \quad (2.59)$$

For a brittle material, there usually is no obvious yield stress and therefore the fracture or rupture stress is much more important. The fracture of brittle materials is mostly due to tensile failure (Figure 2.47). The structural component that is made up of a brittle material is safe as long as the maximum normal stress is less than the ultimate strength of a tensile test specimen. The Mohr-Coulomb criterion can be used to predict the effect of a given state of plane stress on a brittle material.

Case 1: $\sigma_a \geq 0, \sigma_b \geq 0$

Case 2: $\sigma_a \geq 0, \sigma_b \leq 0$

Case 3: $\sigma_a \leq 0, \sigma_b \geq 0$

Case 4: $\sigma_a \leq 0, \sigma_b \leq 0$

Figure 2.47 Stress-strain diagram for a typical brittle material (from ANSYS, 2011).

Figure 2.48 Possible yield surfaces for brittle materials (ANSYS, 2011).

2.5 Resisting moments of trees to static pull tests

The resisting moments of the tree have been measured for Sitka spruce (*Picea sitchensis*) (Coutts, 1986) and found to depend on the resistance of the hinge at the base of the trunk, the soil tension, the soil shear, the strength of the windward roots, and the weight of the root-soil plate. The combined resisting moment as a function of angle of inclination to the vertical is shown in Figure 2.49 and the curve is considered to be typical of many found in tree pulling experiments (England et al., 2000).

Figure 2.49 The combined resisting moment as a function of angle of inclination to the vertical for a tree which is considered typical of many found in tree pulling experiments (from England et al., 2000).

In order to predict tree failure, there was an attempt to correlate critical turning moment to tree size and particularly to stem weight or volume for Maritime pine. The best predictive variable used the expression $(H \times DBH^2)$; (H was height and DBH was trunk diameter at breast height) which was also used by Moore (2000). This variable was used as the x axis in Figure 2.50 but could not completely explain the variability in the critical turning moment. The slenderness ratio of the forest trees ranged from 54 to 82.

Figure 2.50 Static tree pull results. Maximum overturning moment is 350 kNm. Pull related to formula $(H \times DBH^2)$ to predict stability and failure (from Cucchi et al., 2004).

Ten Sitka spruce trees (*Picea sitchensis*) from a 22 year-old plantation in Scotland were winched to failure by Blackburn et al., 1988 to determine critical bending moments and compare values to maximum wind speeds. Wind throw or uprooting was considered as a static process and the maximum values measured ranged from 3.24 to 14.14 kNm for trees with a slenderness ratio varying from 51 to 101. The critical wind speeds to cause uprooting were calculated using measured wind profiles and assuming the wind acted as a statically applied load. The results from these tests found that the static pull test over-estimated the bending moments needed to cause failure and estimated critical wind speeds greatly exceeded real wind speeds recorded during a gale which caused tree damage.

The static pull method was used on a similar 22 year-old Scottish plantation of *Picea sitchensis* to determine elasticity and the vertical distribution of stress. A static analysis using simple beam theory found Young's modulus values to vary from 2 to 6.4 GPa (Milne & Blackburn, 1989).

Tree pulling tests in Finland on Scots pine, Norway spruce and birches in frozen and unfrozen soil were conducted by Peltola et al. (2000) to evaluate mechanical stability. The maximum resistive bending moment before failure was most significantly and positively correlated with diameter at breast height (DBH) and tree height (H). The best predictor of BM_{max} for uprooting was the relationship $H \times DBH^2$, and the best predictor of BM_{max} for stem breaking was the relationship $H \times DBH^3$.

Figure 2.51 Stem failure was seen in 29 out of 164 *Pinus radiata* in NZ. The maximum stem failure resistive bending moments (KNm) were compared to theoretical values calculated using stem volume (from Moore, 2000).

Tree pull tests were conducted on 164 radiata pine tree (*Pinus radiata* D. Don) in NZ on six different soil types (Moore, 2000). Trees were pulled with a hand winch and maximum resistive bending moments were recorded when the trees failed. Three failure modes were observed, stem failure, root failure and uprooting with a maximum bending moment value of 300 kN m being recorded (Figure 2.51). Trees with a high taper (low slenderness ratio) had higher maximum resistive bending moment than trees with low taper. There was a positive correlation for bending moment with tree height, diameter at breast height and stem volume. Using the relationships between

DBH and *H* to predict the uprooting/wind throw failures did not describe the mechanisms of uprooting.

In June 2005, there was an extensive tree planting exercise performed of 20 trees of the same species (*Samanea saman*) on different soil types in Singapore in an effort to determine the effect of different growing mediums on the health and vitality of the trees (Rahardjo et. al, 2009). Each tree was planted in a hole, 2.5 x 2.5 m² in area and 1 m in depth. The soil mediums used were in-situ (IIF), Topsoil (TIF), 80% gravel chips with 20% topsoil (80GC-20TS) and 50% gravel chips with 50% topsoil (50GC-50TS).

Figure 2.52 shows the arrangement of the field plots. The idea behind the exercise was to determine if an engineered fill material could be used enhance the stability of the tree while maintaining root growth. The normal engineered material used for normal day to day new plantings in Singapore is the Approved Soil Mix (ASM) which is represented by the TIF mix in Figure 2.52.

Figure 2.52 The tree plots with different soil types with reference to the nearest landmark IMM mall (from Rahardjo et. al, 2009)

The final part of the study (carried out in March 2009) involved pulling the trees with a horizontal force until failure. The parameters measured were the

maximum pulling force for complete uprooting, displacement in the direction of the pulling force, the root plate volume and the root cross-sectional area (CSA). The maximum pulling force and pulling energy were found to be roughly proportional to the root plate volume and CSA while no real correlation was found with the type of engineered fill material. Figure 2.53 shows the experimental results plotted for maximum pulling force against root plate volume. Note that the intercept of the line to the y axis was not zero and could have represented the value of the pulling force required to uproot the tree without lateral roots, relying on the vertical tap-root effect (piled foundation) only. The correlation of the maximum pulling force against the root area (CSA) also showed a good correlation. The results are shown in Figure 2.54.

Figure 2.53 Maximum pulling forces against root plate volume (from Rahardjo et. al, 2009)

Figure 2.54 Maximum pulling force against CSA (Root cross-sectional area) (from Rahardjo et. al, 2009)

The stress strain curves were also recorded and the areas under the curves were measured to yield the total strain energy or pulling energy. Table 2.2 shows the maximum pulling forces and pulling energies of trees planted in the IIF, TIF, 50GC-50TS and 80GC-20TS respectively.

It appeared that the total pulling energy was sometimes not proportional to the maximum pulling force. After viewing pictures of the tree pulling exercise, the pulling force was determined to be proportional to the disturbed soil volume mobilized.

Table 2.2 The recorded tree pulling results for the different fill materials (from Rahardjo et.al, 2009)

Tree No	Max pulling force (kN)	Pulling energy (kJ)	Tree No	Max pulling force (kN)	Pulling energy (kJ)
4	7.45	3.70	1	11.56	1.97
10	6.27	-	5	9.21	2.27
14	15.29	10.45	8	6.86	4.71
16	11.17	3.12	13	7.64	4.14
19	20.78	9.88	18	4.51	0.47
Mean	12.19	6.79	Mean	7.96	2.71

Tree No	Max pulling force (kN)	Pulling energy (kJ)	Tree No	Max pulling force (kN)	Pulling energy (kJ)
2	1.96	0.57	7	6.27	0.83
3	2.94	0.94	9	10.58	2.40
6	16.27	3.24	12	3.14	0.28
11	10.19	5.50	17	0.59	-
15	3.53	1.15	20	19.40	-
Mean	6.98	2.28	Mean	8.00	1.17

2.6 Wind on trees

A static analysis of how a tree responds in the wind is a simplification which may result in incorrect analysis (Mayhead, 1973b). The static analysis hypothesizes that a tree remains rigid, does not deform and the sail area directly responsible for wind throw does not change. The static analysis also assumes that trees deflect to a point of failure; either by trunk snap or uprooting when a critical constant wind speed is experienced.

Tree failure has been reported at wind speeds less than those predicted by static pull tests (Hassinen et al., 1998, Fraser & Gardiner, 1967, Gardiner, 1995, Oliver & Mayhead, 1974), presumably because trees do not have the same resistance to critical bending moments in all directions and static pull tests do not take into account rooting mechanisms and soil strengths.

The tree is a flexible structure that under wind loading will change the exposed canopy area by realignment and streamlining as the wind speed increases. Drag forces are difficult to assess accurately and may not vary to the square of the

wind speed as in rigid engineering structures but at some lesser rate, and even in a linear manner as suggested by Mayhead (1973b).

Wind speed and direction can be measured but it is not easy to directly measure the wind force that is distributed over the canopy of a tree. When the wind acts on a tree, the net resultant of the aerodynamic forces generate an overturning moment at the base which is resisted by the root base (England et al., 2000). It is this base bending moment that gives a measure of the wind loading on a tree and is a product of the wind force (kN) multiplied by the height at which the force acts (m). The two useful measures are therefore wind speed (ms^{-1}) and wind load (kNm). The wind speeds at which tree failure begins to occur are known as critical wind speeds.

The wind loads measured in base bending moments are not easily measured and have required purpose built instruments to be made for tree studies. Only a few studies have taken this approach (Rodgers et al., 1995, Guitard & Castera, 1995, Gardiner et al., 1997, Peltola et al., 2000, Moore et al., 2005). Most previous studies of tree dynamics have used more readily available instruments, usually located in the upper part of the tree to measure tree response parameters such as displacement, tilt, accelerations which were used as estimates of wind loading.

The wind speed at which tree failure begins to occur is called the critical wind speed and has been studied by (Oliver & Mayhead, 1974; Petty & Swain, 1985, Coutts, 1986; Blackburn et al., 1988; Peltola & Kellomaki, 1993; Hedden et al., 1995; Peltola, 1996b; England et al., 2000; Zhu et al., 2000; Gardiner et al., 2000 & 2008; Cullen, 2002; Zeng et al., 2007; Schelhaas, 2008; Wood et al., 2008).

This contrasts with an engineering approach which considers wind forces on inflexible and non-deforming buildings known as bluff bodies and the dynamic effects of gusts and eddies due to vortex shedding (Davenport, 1960). Buildings are rigid and built without flexibility so that occupants do not feel uncomfortable on moving floors, so there is a difference in design concept between buildings and trees. Wind engineering theory applied to very large buildings uses an aerodynamic admittance function (Holmes, 2007) to allow for gusts impacting on the windward face and this may have application to large trees. Currently in the engineering wind

standards trees are not considered. Usually wind excitation on buildings is of interest to evaluate the response as measured by deflection at some height up the building or by using accelerometers.

Topography was found to have a marked effect on wind speed in a study by Sagar & Jull, 2001. Wind speeds in forest areas in British Columbia were measured over a five year period, 1995 to 2000 in ten locations. Ten towers, each of height 9.1m were erected and one second wind records were taken using an anemometer and wind vane (Young Model 05130). Extreme wind events were defined as 1 second wind speed exceeding 20 m s^{-1} (72 km/h). Such extreme wind events occurred at 3 sites with the maximum value of 28 m s^{-1} (100 km/h). Spatial and temporal distribution of extreme wind events was very dependent on local topography and the wind was very gusty in nature. Critical wind speeds causing tree failure were determined from data obtained during a gale in southern Britain on Monday, 2 April 1973 (Oliver & Mayhead, 1974). Gusts of wind were estimated to be 15 m across and of 5 s duration based on observations of the swaying tree patterns.

Terrain roughness effects over forests contributed to a reduction in average wind speed compared to wind speeds over flat surfaces of a RAF base which were 170% higher. The gust speeds were not so affected by roughness as they were only 130% higher over the smoother RAF base surface. For an aerodynamically rough surface the maximum gust can be estimated as approximately twice the calculated maximum hourly mean wind speed. Critical wind speeds were estimated at 17 m/s at tree top when some trees failed in the forest. Comparison of this figure was made with critical wind speed estimates based on static pull tests which predicted that wind speeds of 40-45 m/s were necessary for overturning. This implies that the static pull tests considerably over estimate the critical wind speeds needed to cause some tree failures.

Wind loads are the largest loads on trees (Petty & Swain, 1985; Mattheck & Bethge, 1998). Bending moments about the base of trees were calculated (Petty & Swain, 1985) by dividing the stem into segments of one metre lengths and determining the moment contribution due to stem weight, crown weight and wind force exerted on the crown. Typical results (Figure 2.55) show that wind contributes

the largest component of bending moment which was 15 kNm for a 16 m high pine tree at a wind speed of 17 m/s. The authors noted that if a common assumption that the wind acted on the centre of pressure of the canopy was used, the bending moment value changed to 23 kNm. This is a marked difference that would be even greater for trees with less localized crowns.

Figure 2.55. A histogram showing the contribution to the total bending moment made by one meter height increments of a pine tree of height 16m, DBH 22.5 cm at a wind speed of 17 m s⁻¹ (from Petty & Swain, 1985).

Peltola & Kellomaki (1993) modeled Scots pines on the edge of a forest stand to determine critical wind speeds and critical overturning moments. Crown streamlining was taken as a function of wind speed with a reduction of 20% area for wind speeds less than 10 m/s, and a 60% reduction for wind speeds more than 20 m/s. Constant wind speeds were used to evaluate bending moment. Total turning moments needed to uproot trees of various sizes were calculated with a critical turning moment of 76 kNm determined for a 20 m tree with a slenderness ratio of 70.

2.6.1 Drag estimation and wind tunnel tests

A crucial factor in determining the forces on a tree in high wind is the drag force. Drag is the link between the wind speed and the force on a tree (Wood, 1995) and its value is determined by defining a drag coefficient C_D . A major determinant of drag is the exposed surface area which in broad leaved trees is presented by its leaves. Typically leaves are borne in the canopy far above the base and are exposed to the highest winds. It is therefore the upper part of the canopy which greatly contributes to the turning moment about the base. Deciduous broad leaved trees seem to more commonly suffer wind-throw when leaved than when bare.

Solid objects, known as bluff bodies have been used by engineers to study drag forces, often under controlled conditions such as in wind tunnels (Holmes, 2007). The objects are not flexible and can be scaled down to give indicative results that can then be applied to full sized objects. Bluff bodies have a fixed frontal area exposed to the wind and a fixed shape which has a set value of streamlining. When scaling up wind effects on large objects such as tall buildings, additional factors such as the aerodynamic admittance function may need to be considered (Holmes, 2007). These methods may not be suitable for flexible objects such as trees because the response of small scale models under constant wind speed conditions may not represent the response of large trees under actual wind conditions (Mayhead, 1973b).

Trees and their canopies of leaves are flexible and the surfaces realign themselves in high winds. This occurs in two ways. First the exposed area decreases as the wind increases, due to the leaves turning and reconfiguring their shape as well as the total canopy area reducing. The second flexible change is that the whole canopy bends and changes shape and becomes more streamlined which reduces drag (Rudnicki et al., 2004). The streamlining depends on the mechanical and aerodynamic properties of stems, branches and foliage (Niklas, 1992). The effect of flexibility on drag is usually detrimental and may be far higher than for a flat rigid object. Vogel (1989) compares a rigid flat plate such as a weather vane to a flexible flag which flutters in the wind and states that the drag forces on a flag are much higher due to its flexibility. The effect of flexibility on the value of the drag is far from self-evident (Vogel, 1980).

Several studies assumed a constant frontal area (Mayhead, 1973b; Smith et al., 1987; Peltola & Kellomaki, 1993; Hedden et al., 1995) which leads to an under-estimate of drag. Attempts have been made to allow for the change in frontal area (Wood, 1995; Spatz & Brüchert, 2000) by estimating branch deflection under load. Estimates of crown streamlining were provided by Hedden et al., 1995 but there have been few studies where crown drag and streamlining have been measured simultaneously (Rudnicki et al., 2004).

The drag coefficient reflects the combined effects of the skin friction as the air moves over the surface of the drag element and the pressure differential between the windward and leeward sides of the element (Vollsinger et al., 2005). Canopies are porous so that the total drag coefficient is the sum of the pressure and skin-friction components of leaves and branches (Niklas, 1992). In tree studies the drag has been studied for individual leaves (Vogel, 1989) and of whole trees (Mayhead, 1973b; Gardiner et al., 1997; Rudnicki et al., 2004; Vollsinger et al., 2005).

Wind tunnels have been used to study the effect of wind on trees by a number of authors, (Mayhead, 1973b; Vogel, 1989; Gardiner et al., 1997 & 2005; Tevar Sanz et al., 2003; Rudnicki et al., 2004; Vollsinger et al., 2005 and Gromke & Ruck, 2008). Several wind tunnel studies have investigated forest trees in order to assess wind damage, by finding the wind speed at which structural damage begins to occur. These values are then used in predictive formulae or models to calculate the point at which failure occurs by estimating a critical tree height (Mayhead, 1973b) or a critical wind speed (Rudnicki et al., 2004). Several wind tunnel studies have established drag coefficients of trees but of necessity they use models (Tevar Sanz et al., 2003) or small juvenile trees (Rudnicki et al., 2004, Vollsinger et al., 2005) and the drag coefficient values need to be verified for mature standing trees.

Small trees, 2.5 to 5 m high, were tested in a wind tunnel with wind speeds ranging from 4 to 20 m s⁻¹ (Rudnicki et al., 2004). Crowns were cut to a height of 1.9m, the lower branches were trimmed, and trees were mounted inside a wind tunnel that had a maximum height of 1.65 m. Trees were subject to progressive wind speeds and instruments at the base of the tree recorded wind loads. The results were

converted to drag values using the standard drag equation and the results for red cedar are presented in Figure 2.56.

Figure 2.56. Drag values for a red cedar (height 1.6m) in wind tunnel tests (Rudnicki et al., 2004).

Drag coefficients at 20 m s^{-1} were 0.22, 0.47 and 0.47 for western red cedar (*Thuja plicata*), Western hemlock (*Tsuga heterophylla*), and lodgepole pine (*Pinus cordata*) respectively. Rudnicki et al., 2004 examined the effect of streamlining and the change in frontal area as wind speed increased. An interesting result was noted in that the frontal area increased slightly as the wind speed changed from 0 to 4 m s^{-1} . This was explained by the way branches realigned themselves, especially those branches facing the wind or perpendicular to the wind. These branches bent a small amount in light winds and actually increased the frontal surface area, but as wind speeds increased the branches bent more severely and aligned themselves with the wind stream so that the area then decreased. At wind speeds above 4 m s^{-1} streamlining reduced frontal area by 54% for red cedar, 39% for hemlock and 36% for lodgepole pine. Streamlining results in variable drag coefficients and a near linear relationship between drag and the product of branch mass and wind speed was found. Between-species differences in drag relationships reflect differences in streamlining, within-crown sheltering, and foliage shape.

Figure 2.57 Using computational fluid dynamics (CFD), a tree with a spherical canopy shape under constant wind speed experienced an increase in the drag coefficient to a peak value corresponding to a critical porosity before decreasing with increasing porosity (from Lim et al., 2013).

Lim et al. (2013) ran CFD analysis using ANSYS on idealised tree shapes and found that, in addition to the wind speed, the porosity of trees was important for determining the drag coefficient of trees (Figure 2.57). Lim et al. (2013) also found that drag coefficient was independent of wind speed beyond a threshold value. Lim et al. (2013) concluded that the drag coefficient and frontal area reductions due to aerodynamic streamlining and variation in porosity had a limit; and this limit had to be determined for a tree to calculate the drag force at the critical wind speed. Lim et al. (2013) also ran simple non porous geometrical shapes in ANSYS to determine the average-steady state drag coefficients (Table 2.3).

Table 2.3 Summary of drag coefficients for simple shapes determined in ANSYS
(from Lim et al., 2013)

Model	Greatly Simplified
Conical	0.47
Sphere	0.34
Cylinder	1.05

2.6.2 Calculating wind forces on trees

The conventional aerodynamic drag equation is shown in Equation 2.37. This equation uses the dynamic pressure portion ($\frac{1}{2}\rho v^2$) of the Bernoulli's pressure equation to calculate the drag force of any body. This conventional equation is found widely in scientific and engineering literature. Mayhead (1973b) used data from previous wind tunnel tests on trees to measure the drag coefficient by measuring the wind force on the trees. Several wind tunnel tests have established drag coefficient values using model trees (Tevar Sans et al., 2003) or junveile trees (Rudnicki et al., 2004 and Vollsinger et al., 2005).

$$F_{wind} = \frac{1}{2}\rho v^2 AC_D \quad (2.37)$$

where;

ρ is the density of air

v is the wind velocity

A is the frontal area of the trunk and crown presented to the wind

C_D is a dimensionless drag coefficient

Removing the frontal area, A and the dimensionless drag coefficient C_D , which are parameters associated with the body under study, we arrive at;

$$q = \frac{1}{2} \rho v^2 \quad (2.38)$$

Where q is the dynamic air pressure applied to the frontal area A .

The drag equation q is a useful tool in urban tree risk management as arborists and urban foresters are concerned with public safety. The notion that the exponent of v determines the shape and slope of a curve of wind force values, found with Equation 2.38, over a range of velocity seems to assume that A and C_D must be constant. Bonser & Ennos (1998) note that the “hypothesis is based on the assumption that trees do not deform and, hence, their drag coefficient remains constant.” Niklas (2003) observes that this may be a common assumption. Mattheck & Breloer (1994) explicitly consider C_D a constant. In fact, C_D is not constant with v (Sinn & Wessolly, 1989; Niklas, 1992, Vogel 1994). Mayhead (1973), the classically cited source for the “linear” argument, reported that actual A is expected to decrease as V increases. If reference A (for $v = 0$) remains constant in Equation 2.38, then C_D would also be expected to decrease as v increases. Ezquerro and Gil (2001) noted a “non-uniform” decrease with increasing v in Mayhead’s C_D data. Gaffrey and Kniemeyer (2002) described a “parabolic decrease” in Mayhead’s C_D data.

To circumvent the variability of C_D and A with different wind speeds, measurements of wind force on the canopy could be performed by measuring the strains on the tree trunk. This way, using measured elastic modulus of different species of trees and the section properties of the trunk at the point of measurement, wind force can be estimated.

2.7 Geology of Singapore and drainage

Trees in Singapore are large living structures founded on natural and engineered soils. The topography of the location; drainage and strength characteristics of the underlying soil are important for determining tree rooting depth, spread and

anchorage. Therefore there is a structural significance to their location within the Singaporean geology.

Singapore Island is moderately low lying. The highest point, Bukit Timah hill, is only about 163 meters above sea-level. The tropical climate associated with equatorial countries creates hot and humid conditions with an annual rainfall of 1,600mm in the southwest to 2,500mm in the central regions. Under these conditions, the rocks are deeply weathered and the drainage has developed to a stage where the rivers are of low gradient with a mature profile. The drainage patterns found in Singapore are either;

- 1) Consequential : A river system that follows a normal downhill pattern along a pre-existing land surface; or,
- 2) Structurally Controlled: A river system resulting from structural control joints or faults in the bedrock.

According to the latest edition (2009) of the Geology of Singapore by Lee et al. (2009), there are seven discrete physiological areas that can be recognized on the main Singapore Island.

The discrete areas are described in (Lee et al., 2009) as the following;

- Area 1, covering grounds to the north and west of Nanyang Technological University (NTU) and including the pronounced Pasir Laba Ridge, is an area of moderate relief with hills rising to a maximum of 85 meters above sea level. The hills are aligned to the geological structure and are steep but covered with soil. Drainage is influenced by its geological structure.
- Area 2, covering grounds to the east and south of Area 1, is of low relief and had rolling hills rising to about 28 meters above sea-level. The area is crossed by a northwesterly trending line of hills which reaches 70 meters above sea-level. Drainage is partly consequent and partly controlled by structure.
- Area 3 is the low-lying Sungei Jurong River Valley. It has a flat relief and a consequent drainage pattern modified by man.

- Area 4 is the largest physiographic area defined for Singapore. It is an area of higher relief. Slopes are generally steep. Drainage is controlled by the faults and joints in the granite and by the folds, faults and cross-joints in the Triassic sedimentary rocks to the south. A belt of relatively low relief cuts across the southern end of this area in a northwest direction along the line of Singapore River and Sungei Ulu Pandan.
- Area 5 lies in the central north area and has similar characteristics to those of Area 2. Most of the area is below the 20 meter contour. Drainage is consequent to the northeast.
- Area 6 is the low-lying Kallang River Basin and it shows similar characteristics to Area 3.
- Area 7 lies to the east and southwest of Paya Lebar Air Base. It can be described as a deeply dissected plateau. The relief is high with steep slopes with a well-developed dendritic drainage pattern consequent on the surface. The highest point of 46 meters above sea-level is found just east of the Paya Lebar Airbase.

Generally, due to the topography of the Singapore Island, low lying areas between the areas of higher elevations are natural drainage paths and collection zones (Alluvial) for precipitation, ground water and also act as natural stream/river basins. In Singapore these areas are represented by the Kallang Formation. The formation is named after the Kallang River Basin where it is the most extensive. The formation is found along the coastline and extends into the headwaters of the rivers draining Singapore. It's most extensive development is found around Sungei Kallang, Kranji Reservoir, Sungei Kallang, Sungei Jurong, Kranji Reservoir, Sungei Serangoon, and Lower Seletar Reservoir. The formation also includes reef deposits exposed to the south and southwest of Singapore at low tides. The majority of the formation is found at elevations less than or equal to four meters above sea level. The Kallang Formation is a recent formation, it is generally shallow. Lee et al. (2009) states that the Kallang Formation can be broadly characterized into five groups, they are the,

- Marine Member (Km): Predominantly a blue-grey clayey mud. Peat and sand horizons are also present. The member is usually unconsolidated but lightly consolidated beds do occur.
- Alluvial Member (Ka): A variable terrestrial sediment ranging from pebble beds through sand, muddy sand, and clay to peat. The member is usually unconsolidated but lightly consolidated beds do occur.
- Littorial Member (KI): Well sorted unconsolidated beach and near-shore quartz sand with minor lateritic, shell and lithic (pieces of other rocks that have been eroded down to sand size and now are sand grains in a sedimentary rock) fragments. Iron-cemented beach rock is also included in this member.
- Transitional Member (Kt): Unconsolidated black to blue-grey estuarine mud, muddy sand or sand, often with high organic content and peat layers.
- Reef Member (Kr): Coral, unconsolidated calcareous sand and lesser quartz, ferruginous (Having the color of iron rust; reddish-brown) and lithic sand.

In Figure 2.58, Ka, KI and Kt represent the different portions of the Kallang Formation. Due to the rapid urbanization, planted foliage and trees plus the use of an efficient concrete lined drainage system, this formation is generally hidden from view and evidences of its existence are only seen from boreholes and excavations. Ka, KI and Kt members form the majority of the Kallang Formation.

The Ka member of the Kallang Formation is found as valley fills throughout Singapore and as a thin layer on the floor of the Kallang and Jurong River Basins. It has a varied composition ranging from pebble beds, sands, muddy sands and clays to peat. Lightly or unconsolidated in nature, permeability can be high with low shear strength. Alluvial deposits that makeup the Ka members continue to be deposited on the valley floors of the rivers to present day.

The Littorial Member (KI) comprises of beach, immediate offshore and tidal deposits. The depth is normally only to five meters below the surface and it can be

found as terraces up to a height of 2.8 meters above sea level. The KI member comprises mainly clean sand and pebbly sand.

Figure 2.58 The overview geological map of Singapore Island (from Lee et al., 2009)

The transitional member (Kt) is found in the river mouths and tidal swamps surrounding Singapore. The Kt member is derived from sediments deposited in a low energy environment. The member is made up of unconsolidated black to blue-grey mud, muddy sands, or sand with a high organic content.

The common property of the Kallang Formation seen from its constituents is the lightly/unconsolidated nature of its members. According to Holtz (1991) under-consolidation of soils can occur, for example, in soils that have only been recently deposited, either geologically or by human activity, and are still consolidating under their own weight. If pore-water pressures are measured for under-consolidated soils, they can be in excess of hydrostatic. Conversely if valley overlaid by alluvial deposits are consistently wetted from seepage flow from higher ground or are always

submerged, they may be continuously exposed to pore-water pressures in excess of hydrostatic and never consolidate. Structures like trees that rely on good soil strength to spread loads to a larger area may find constantly wetted alluvial formations detrimental to their stability.

Singapore is a highly urbanized island; the drainage system has been optimized to carry away runoff in the most efficient manner. Most of the canals and drains are concrete lined to reduce the friction and the slope of these water channels has been designed to be sufficient for self-cleaning. However, the drainage and waterway system is still largely designed to be gravity driven and thus follows the original topography of the land. That means that the pathways and locations of the original natural waterways and flood plains have been re-used with performance upgrades. The geology of Singapore indicates the existence of recent alluvial deposits along the low points and flood plains. Thus it can be assumed that in those areas, the ground water table is shallow and fluctuating according to rainfall patterns, seepage flow and tidal cycles at the coastal areas. Figure 2.59 shows the typical ground water profile with different topographical and hydrological features.

Figure 2.59 shows that drainage features at higher elevations are often influent and those found at lower elevations are often effluent. The average depth of the ground water table from the surface is also proportional to the elevation above sea level. If the deposited alluvial layer is of a high enough permeability in comparison to the residual soil, it may play a big role in flowing infiltrated ground water to lower elevations via seepage flow and finally out to the sea.

Figure 2.59 Typical unconfined ground water features (from Linsley et al., 1992)

The main source of groundwater is precipitation, which may infiltrate into the soil directly as groundwater or may enter surface streams and percolate from these channels to the groundwater. In terms of the total amount of water from precipitation, groundwater typically makes up the smallest fraction. Interception, depression storage, and soil moisture must be satisfied before any large amount of water can percolate to the groundwater. Except where sandy soils exist (e.g. alluvial deposits like the Kallang Formation and old Alluvium found in Singapore), only prolonged periods of heavy precipitation can supply large quantities of water for groundwater recharge. Groundwater recharge is an intermittent and irregular process. Closely spaced rainfall events of sufficient intensity contribute to a large increase in groundwater level. The total rainfall per event seems to be less relevant than the threshold event frequency in dictating ground water levels. The groundwater levels rise and fall rapidly after a closely spaced series of rainfall events.

2.8 Water balance in the vadose zone

Soil water balance consists of two main basic inputs, namely: atmospheric water balance and surface radiation balance. Blight (1997) stated that the soil water balance controls the state of moisture in the unsaturated soil. Figure 2.60 shows the component of water balance in the vadose zone as proposed by Blight (1997).

Blight (1997) proposed a soil water balance formula where water input is equal to water output and water stored in the soil. Water input or infiltration can be defined as the amount of precipitation minus the water intercepted by the vegetation and the surface runoff. The water output can be defined as water lost by the evapotranspiration and the groundwater recharge. Water stored in the soil can be defined as the total change in moisture in the soil. The Blight equation can be written as:

$$P - (I + R_{off}) = ET + R_{ech} + \Delta S \quad (2.39)$$

Where:

P is precipitation

I is water intercepted by vegetation

R is surface run-off

ET is water lost by evapotranspiration

R_{ech} is water lost by groundwater recharge

ΔS is water stored in soil

Figure 2.60 Water balance in the vadose zone (from Blight, 1997)

2.8.1 Evaporation process

Evaporation is a change in water state from liquid to vapor due to an increase of water kinetic energy. During evaporation, hydrogen bonds break down and the water vapor diffuses from higher to lower vapor pressures, i.e., from the ground surface to the atmosphere. Evaporation from soil is an important flux boundary condition that should be defined to calculate the soil water balance.

Evaporative flux modeling has been limited to methods that predict the unit flux evaporation rate based on a potential evaporation (*PE*) value. The potential evaporation term introduced by Thornthwaite (1948) is defined as the upper limit or maximum rate of evaporation from a saturated ground surface under given climatic conditions. The potential rate of evaporation may be computed using the Dalton-type equation as follows (Gray, 1970):

$$E = f(u)(e_s - e_a) \quad (2.40)$$

where:

E is the rate of evaporation (mm/day)

e_s is the saturation vapor pressure of water at the surface temperature (mmHg or kPa)

e_a is the vapor pressure of the air in the atmosphere above the water surface (mmHg or kPa)

$f(u)$ is the turbulent exchange function which depends on the mixing characteristics of the air above evaporating surface

Equation 2.40 has become the basis of widely used Penman equation (1948) for PE calculation. It is well known that the rate of actual evaporation (AE) is only equals to potential evaporation (PE) when the soil is saturated. The AE decreases as the soil surface become unsaturated and the supply of water become limited (Gray, 1970). Figure 2.61 shows a typical relationship for the ratio of actual and potential evaporation (AE/PE) against the water availability for the sand surface. The shape of the curve is described by Van Bavel et al. (1976). There are three stages of drying. Stage I is the maximum rate of drying that occurs when the soil surface is near

saturation. Stage II is when the conductive properties of soil become so low that restrict sufficient flow of water to the surface and the maximum rate of evaporation cannot be maintained. Stage III is after the soil surface becomes desiccated and the liquid-water phase becomes discontinuous. It can be seen that the actual rate of evaporation is controlled by both climatic conditions and also the soil properties such as hydraulic conductivity and vapor diffusivity.

Wilson (1990) proposed a method for the calculation of evaporation rate from unsaturated soil surface. The method is based on modification of the Penman (1948) equation. The equation is as follow:

$$E = \frac{\Gamma Q_n + \eta E_a}{\Gamma + \eta A} \quad (2.41)$$

where:

Γ is the slope of the saturation vapor pressure versus temperature curve at the mean temperature of the air (mmHg/°C)

Q_n is the net radiation at the soil surface (mm/day of water)

η is the psychrometric constant

E_a is $f(u) e_a (B-A)$

B is the inverse of the relative humidity in the air

A is the inverse of the relative humidity at the soil surface

Figure 2.61 The relationship between the ratio of actual evaporation and potential evaporation against water availability (from Van Bavel et al., 1976)

The Wilson equation (1990) reduces to conventional Penman (1948) equation when the surface is saturated as the soil will have a relative humidity of 100% and A of one. The relative humidity of the soil surface is evaluated by simultaneously solving the coupled moisture and heat flow.

2.9 Unsaturated soil mechanics

Tree roots experience varying pore-water pressures in the soil. The pore-water pressures range from hydrostatic (saturated) to negative (unsaturated). Changes in the pore-water pressures of the soil affect the engineering properties within the soil. These properties include shear strength, modulus of subgrade reaction, bearing capacity and permeability.

2.9.1 Soil-water characteristic curve

The soil-water characteristic curve or SWCC is one of the most important soil parameters that can be used to characterize the hydraulic properties of the soil. The SWCC for a soil is the relationship between volumetric water content θ_w , and matric suction ($u_a - u_w$). When soil dries, it experiences a reduction in the volumetric water content θ_w and also, u_w . This leads to an increase in the matric suction of the soil.

Figure 2.62 A typical SWCC and the various features (Goh et al., 2011).

The SWCC for a soil can be determined through laboratory testing or via field measurements. Figure 2.62 A typical SWCC and the various features (Goh et al., 2011). The AEV or air entry value of a soil is defined as the matric suction at which air first enters the largest pores of a soil during drying process (Brooks and Corey, 1964, 1966). It can be determined by finding the intersection point between the tangent line at the beginning of the SWCC, which is always taken as a horizontal line from the saturated volumetric water content, and the tangent line at the SWCC in the transition zone. This technique has been widely used and adopted in various literature (e.g. Fredlund and Xing, 1994, Vanapalli et al. 1996b, Leong and Rahardjo, 1997, Fredlund, 2002, Yang et al., 2004, Fredlund, 2006, Ng and Menzies, 2007, etc.).

The drying curve that starts from saturation (zero matric suction) is commonly called the initial drying curve. This drying cycle causes a permanent change in the soil particle arrangement or stress state. Subsequent drying and wetting curves are scanning curves that occur within the defined boundary curves (Figure 2.63).

Figure 2.63 Illustration for boundary drying and wetting curves and scanning curves of the SWCC of an unsaturated soil (from Pham et al., 2003)

2.9.2 Unsaturated permeability

The unsaturated permeability of soils can be estimated using a permeability function. There have been various permeability functions proposed in the past. Amongst them is one proposed by Leong & Rahardjo (1997a). Using the function proposed by Leong & Rahardjo (1997a), the unsaturated permeability of soils at different matric suctions can be estimated if the SWCC of the soil is first determined.

Leong & Rahardjo (1997a) suggested an empirical permeability relationship using the SWCC to estimate the water coefficient of permeability of an unsaturated soil. The permeability function is as follows:

$$k_w = k_s(\theta^p) \quad (2.42)$$

Where,

k_w = water coefficient of permeability of soil

k_s = water coefficient of permeability of soil at saturated condition

θ = normalized volumetric water content

p = fitting parameter

Fredlund et al. (2001) conducted a study to determine the typical values for the fitting parameter, p that was used in the Leong & Rahardjo (1997a) permeability function using a large data set of 300 measured SWCCs and permeability functions.

Using this function, the water coefficient of permeability of a soil can be estimated down to zero water content provided the complete SWCC of the soil is available. When a soil has matric suction values beyond the residual suction threshold, it should be noted that in the function may be more indicative of vapour flow rather than fluid flow (Fredlund et al., 2001). Thus, it may be more reasonable to assume the coefficient of permeability as a constant after residual matric suctions have been exceeded.

The water coefficient of permeability of an unsaturated soil can be calculated using Darcy's Law (Childs & Collis-George, 1950; Fredlund & Rahardjo, 1993a). Darcy's law is written as:

$$q_t = vA = k_w i A = k_w \frac{h}{L} A \quad (2.43)$$

where,

q_t is the total flow rate through the cross-sectional area

v is the flow velocity

A is the cross-sectional area of the sample

k_w is the Darcy coefficient of permeability (Water coefficient of permeability which is a function of soil suction)

i is the hydraulic gradient

h is the head difference, where the head can be positive or negative

L is the sample length

2.9.3 Seepage analyses and modelling of water flow in unsaturated soil

Steady state and transient water flow in soil through unsaturated soil can be analyzed by solving the governing equations of water flow. The equation can be solved using the finite element method (FEM). The procedures involved in the solving process are:

1. Discretization of the area or geometry into elements.
2. Determination of permeability matrix for each element.
3. Construction of matrix for the entire problem.
4. Boundary condition implementation.
5. Solving the equation.
6. Calculation of results.

The finite element formulation of water flow can be written using the water-flow governing equation used for solving a transient and two dimensional seepage analyses (Geo-slope International, 2007a):

$$m_w^2 \gamma_w \frac{\partial h_w}{\partial t} = \frac{\partial}{\partial x} \left(-k_{wx} \frac{\partial h_w}{\partial x} \right) + \frac{\partial}{\partial y} \left(-k_{wy} \frac{\partial h_w}{\partial y} \right) + q \quad (2.44)$$

where:

m_w^2 is the coefficient of volume change with respect to a change in matric suction (i.e. slope of the soil-water characteristic curve)

γ_w is the unit weight of water

h_w is the hydraulic head or total head

t is the time

k_{wx} is the coefficient of permeability with respect to water as a function of matric suction, in x-direction

k_{wy} is the coefficient of permeability with respect to water as a function of matric suction, in y-direction

q is the applied flux at the boundary

The SWCC and the permeability functions are the two primary soil properties required in the seepage analysis. The above equation is only applicable in an isothermal condition. For a non-isothermal condition, additional terms are introduced to incorporate water flow due to diffusion and advection processes (Wilson, 1990).

2.9.4 Unsaturated shear strength of soil

For the calculation of the ultimate bearing capacity and resistance to pull out of the sinker root (tension tie down), matric suctions will have to be determined. The soil surrounding the sinker root (tension tie down) will experience varied pore water pressures (both positive and negative) with depth and environmental/climatic factors. Furthermore, roots participate in transpiration where large matric suctions can develop as water is drawn up to the leaves. In its natural state, soils located above the groundwater table are normally in an unsaturated condition. Unlike a saturated soil, the shear strength of an unsaturated soil depends on two independent stress-state variables. These variables are net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$. Fredlund et al., 1978 proposed an equation to describe the shear strength of unsaturated soils in terms of the two stress state variables.

The failure envelope for an unsaturated soil can be described in a similar way as that for a saturated soil. The failure envelope for an unsaturated soil is plotted using Mohr circles in three dimensions. This three dimensional failure surface is an extension of two dimensional Mohr-Coulomb failure envelope for a saturated soil. The third dimension is the axis for matric suction, $(u_a - u_w)$. The shear strength of an unsaturated soil can be represented by an Extended Mohr-Coulomb Failure Criterion (Fredlund et al., 1978). The rate of increase in τ with respect to $(\sigma - u_a)$ is defined by the effective friction angle or ϕ' . At the same time the rate of increase of τ with respect to $(u_a - u_w)$ is defined by the effective friction angle or ϕ^b . The shear strength of unsaturated soil increases as the net normal stress or matric suction increases. The equation for the line of intercept of the failure envelope of shear strength versus matric suction in the extended Mohr-Coulomb failure envelope is as follows:

$$c = c' + (u_a - u_w) \tan \phi^b \quad (2.45)$$

where:

c is the total cohesion or intercept of the shear stress for the various matric suction planes in the extended Mohr-Coulomb failure envelope.

The resulting extended Mohr-Coulomb failure envelope (Figure 2.64) is defined as:

$$\tau_{ff} = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (2.46)$$

Where

τ_{ff} is the stress on the failure line

c' is the effective cohesion or intercept of the extended Mohr-Coulomb failure envelope

σ is the normal stress

u_a is the pore air pressure

ϕ' is the effective friction angle

u_w is the pore water pressure

ϕ^b is the angle that controls the rate of shear increase due to matric suction

$(\sigma - u_a)$ is the net normal stress

$(u_a - u_w)$ is the matric suction

Matric suction or negative pore water pressures ($u_a = 0$ at atmospheric pressure) causes the contact stresses between particles to increase and therefore, a higher shear strength will develop. Figure 2.64 shows the relationship between matric suction, shear strength and net normal stress.

As an unsaturated residual soil approaches the saturated state, the pore-air pressure, u_a approaches u_w . Therefore, $(u_a - u_w)$ becomes zero, and Equation 2.46 reduces to Equation 2.47, which is the well-known Mohr-Coulomb strength criterion for saturated soils. The general Mohr-Coulomb strength criterion is (Terzaghi, 1943):

$$\tau_{ff} = c' + (\sigma - u_w) \tan \phi' \quad (2.47)$$

Limited tests data are available to describe parameter ϕ^b and Leong et al. (2002) suggested that in general the ϕ^b is expected to vary from $0.5\phi'$ to ϕ' . Research on local granitic and sedimentary residual soil indicated that ϕ^b can vary with matric suction ($u_a - u_w$) (Gasmo et al., 2000) and there is evidence that show ϕ^b can exceed ϕ' at low matric suctions. Values of ϕ^b that have been reported by other work (Lim, 1995; Gasmo, 1997; Hritzuk, 1997) ranges from 27° to 35° for Jurong Formation residual soils. For Bukit Timah residual soil a general ϕ^b value was 27.5° given by Leong et al. (2003).

Figure 2.64 Extended Mohr-Coulomb failure envelope for a unsaturated soil (from Fredlund & Rahardjo, 1993a).

CHAPTER 3 Theory

In this chapter, tree shallow root models are proposed. These tree root models are based on some of the dominant root architectures observed in trees. These tree root models also mimic the failure modes and the shapes of the failed tree roots. A method for artificially pulling trees to failure is also presented.

3.1 Tree winching

Tree winching is a common technique where trees are tied to a specific height and pulled until the tree is uprooted or the trunk breaks. The winching force is constantly measured using a dynamometer and the angular rotation is measured by measuring the length of the cable that has been retracted at a constant winching rate. Tree winching is efficient and consistent as each tree is winched using the same setup. Figure 3.1 shows the tree winching setup that was used by Rahardjo et al. (2009) for the pulling tests conducted in 2008.

Figure 3.1 Schematic diagram showing the setup of the tree-pulling experiment performed in 2008 (from Rahardjo et al., 2009)

The maximum resistive moment (BM_{max}) is calculated from the maximum applied pulling force (F_{max}) multiplied by the height of the pulling rope attachment to the tree from the ground.

$$BM_{max} = F_{max} \times \text{cable attachment height} \quad (3.1)$$

For each winching test, the effect of the change in the center of mass of the tree inducing additional bending moment to BM_{max} is reduced by removing, or heavily pruning the crown prior to winching.

Rahardjo et al. (2009) performed winching tests on 20 rain trees (*S. saman*) in March 2008. The trees were initially planted as big saplings in 2005 from a nursery then planted to an experimental plot in 2006. The trees were winched at a time when there was little rainfall and thus the average gravimetric soil moisture throughout the depth of rooting was low, measuring between 9% and 20% from samples taken at 0.5m and 0.8m, respectively. The cable attachment point to all the trees was placed at a height of 1.3m and the setup for the winching test is shown in Figure 3.1.

Uprooting was the only mode of tree failure observed in all the 20 rain trees. The typical uprooting failure was characterized by the windward side root plate lifting out of the soil due to a rotational motion about a point at the leeward side of lateral roots, just next to the trunk. Figure 3.2 shows some of the tree uprooting failures at the point when this happened.

Each of the tree winching exercises could be described as follows:-

- 1) Tree trunk starts to bend (Figure 3.3a), but there is no noticeable root movement (pulling force increases rapidly and somewhat linearly)
- 2) Tree bends further (Figure 3.3b). Some root movements described as root plate heave on the windward side and there is no noticeable movement on the leeward side (peak pulling force is reached)
- 3) Tree trunk does not bend further but rotates about the leeward side (pulling cable side) of lateral roots, causing the windward side root plate to pull free of the soil (Figure 3.3c) (pulling force decreases rapidly).

- 4) Tree comes to rest on its side (pulling force drops to 0kN) (Figure 3.3d).

a)

b)

c)

d)

Figure 3.2 Typical characteristics of the trees during the uprooting process. a) The point of rotation or hinge is always formed near the leeward side of the trunk in the direction of the force. b) The windward side laterals and sinker root (tension tie downs) furthest from the hinge break first as the strains are the largest. c) The heaved and exposed windward root plate can be small or be large as in d), depending on the root architecture.

a)

b)

c)

d)

Figure 3.3 Tree winched to failure a) Tree bole bends and no soil heave b) Soil starts to heave and rotation of the root plate starts c) Peak force recorded and highly apparent soil heave with root breakages observed d) Tree rotates about 90 degrees and rests on ground (note broken lateral roots that provided little restraint in c) and d)).

Following each winching test, the entire root plate of the tree was excavated and air spaded to reveal the root architecture and structure. The failed uplifted root volumes were small compared to the entire excavated root system (mostly left in place during failure) which often extended horizontally beyond the drip line of the canopy. The root cross sectional area (CSA) at 0.5m distance from the trunk was measured (Equation 3.2).

$$\text{Root CSA} = \frac{\pi d_v d_h}{4} \quad (3.2)$$

where,

d_v is the vertical diameter of the root being measured and

d_h is the horizontal diameter of the root being measured

The root CSA measured included the lateral roots and the sinkers. However, the proportions of each were not specified.

3.2 Shallow root uprooting theory

The flat or shallow root system is by far the most common tree rooting system. The shallow root system is basically a root system constrained by poor, infertile, low porosity (aeration) soils, urban constraints and surface access to water. The resulting root system is a “flattened” root (Figure 3.4).

The depth of rooting in a shallow root system is only a fraction of the height of the tree (Figure 3.4). As the shallow rooting system is shallow and covers a wide area (often beyond the drip line of the canopy), the term “root plate” is often used to describe the system. The tree with a shallow root system is like a cantilever structure (trunk) supported by long lateral beams radiating from the trunk resting on a visco-elastic foundation (soil).

Figure 3.4 A shallow root system is basically a “flattened” tree root system (from Dobson, 1995)

The performance of the shallow root system is highly dependent on the shallow root’s ability to resist the load and spread out the load onto the foundation soil. The softer the supporting soil and/or the larger the load, the stronger and stiffer the shallow root must be to spread the load over more of the supporting soil. The shallow root’s stiffness is a function of lateral root thickness and the material elastic modulus while the rupture strength is a function of the material strength.

The most representative way to describe the bending resistance performance of a shallow rooted tree is that of a shallow large thin circular footing resting on soil with tension tie-downs. A tree’s shallow rooting system consists of three major components:

- 1) The horizontal tree root components (lateral roots) that serve to spread the heavy weight of the trunk and crown across as large an area of soil as possible and thus reduce the induced vertical stresses to the foundation soil.
- 2) The vertical tree root component (diagonally and vertically penetrating roots) that help to tie the tree down to the foundation soil and increase the resistance to lateral loads.

- 3) The soil component that interacts with the horizontal and vertical tree root components and deforms according to the stresses induced by the tree root system (1 and 2). Its own strength and modulus of elasticity can be increased or reduced by variations in pore water pressures.

The shallow root system radiates from the trunk. The bending resistance of a tree in a particular direction can be determined by the directional distribution of the root CSA in relation to the direction of the lateral force. Figure 3.5 illustrates that the angle at which a lateral root makes to the direction of the applied lateral load determines the effectiveness of that root in resisting the applied lateral load.

Figure 3.5 Different lateral roots with each making a different angle to the direction of the lateral load. Each lateral root contribution is a function of the cosine of that angle.

The shallow root model shown in Figure 3.6 makes the following assumptions;

- 1) The 360° measured root CSA is equally split into two with one half for the windward (tension) and one half for the leeward (compression) sides.

- 2) The windward and leeward CSAs are converted to an equivalent circular section, from which the lateral root diameters are derived.
- 3) Half the windward CSA is then assigned to the tension tie component as an equivalent circular section of which a diameter is derived
- 4) The length of the tension tie is assumed to be 2m or whatever depth deemed appropriate. 2m can be considered to be reasonable to account for the maximum vertical penetration of small sinker roots (tension tie downs) in residual soil in Singapore.
- 5) The maximum tension force provided by the tension tie down is the smaller of its breaking strength and the friction resistance between the tension tie and the soil. The mass of the retained soil of the uplifted windward root is taken into account by the shear strength of the tension tie.
- 6) The maximum bending resistance provided by the leeward member is the bending resistance of the member calculated from the section properties and the modulus of rupture (MOR).
- 7) A rotational plastic hinge forms at the leeward member next to the trunk.
- 8) There is no leeward soil failure.
- 9) The maximum bending resistance provided by the tension tie is calculated from the maximum tension force in 5) and the perpendicular distance that the force acts to the hinge (Figure 3.6a).
- 10) As this is a small strain static model, the horizontal force T (Figure 3.6b) from the rest of the root system has no or a small lever arm to the hinge B and therefore is not considered.

In the shallow root model, the hinge forms at the leeward member next to the trunk. The leeward member or compressive member will have a maximum bending resistance. This resistance B_{cmax} is given by;

$$B_{cmax} = \frac{2\sigma_c I_c}{D_c} \quad (3.3)$$

where,

D_c is the equivalent diameter of the CSA assigned to the circular section of the leeward member,

I_c is the second moment of area and is given by;

$$I_c = \frac{\pi D_c^4}{64} \quad (3.4)$$

σ is the MOR or modulus of rupture obtained from the four point bending tests.

The windward side member has a tension tie down. The maximum tensile force (T_{max}) in the tension tie down is limited to the smaller of the following:

- 1) The tensile strength of the tension tie or (T_u), or,
- 2) The total skin friction between the tension tie down and the soil.

$$T_u = \frac{\sigma \pi D_u^2}{4} \quad (3.5)$$

D_u is the equivalent diameter assigned to the tension tie member

The total skin friction between the tension tie down and the soil (T_{uf}) is given by:

$$T_{uf} = \tau L_u \pi D_u \quad (3.6)$$

where:

L_u is the length of the tension tie down

$$\tau = c' + (\sigma' - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (3.7)$$

where:

c' is the effective cohesion of the soil

σ' is the effective stress of the soil

u_a is the soil pore-air pressure

u_w is the soil pore-water pressure

ϕ' is the effective friction angle of the soil

ϕ^b is the slope of the variation of the shear strength with matric suction

Figure 3.6 Shallow root failure model **a)** Tree without lateral load **b)** Tree under failure lateral load showing rotation about point B.

The bending moment provided by the tension tie down member (B_{tmax}) is given by taking moments about the hinge as formed at the leeward compressive member:

$$B_{tmax} = T_{tmax} (x_1 + w) \quad (3.8)$$

where:

x_l is the distance of the tension tie down member to the edge of the windward edge of the trunk,

w is the diameter of the trunk.

The total bending resistance of the root plate (B_{total}) is given by;

$$B_{total} = B_{lmax} + B_{cmax} \quad (3.9)$$

3.3 Proposed three dimensional (3D) shallow root uprooting theory

To enhance the accuracy of the shallow root model, a 3D model can be created to take into account the 3D spatial distribution of the lateral and sinker roots (tension tie downs).

Figure 3.7 The dotted line perpendicular to the solid line representing the direction of the lateral load separates the lateral roots into the tension and compression lateral roots

Figure 3.7 shows the dotted line that separates the shallow root plate into a compressive zone and a tension zone. This line is perpendicular to the direction of the lateral load. Each lateral root in the compression zone makes an angle α_n to the lateral load direction (Figure 3.8). If there are n compressive lateral roots, and each compressive lateral root will have a diameter D_1 to D_n . Each lateral root will have a modulus of rupture (MOR) and a modulus of elasticity (MOE). The angle α_n is measured as a positive angle from $0 - 90^\circ$ to the left or the right (anti-clockwise or clockwise) of the lateral load.

The second moment of area (I_n) of each compressive lateral root is given by,

$$I_n = \frac{\pi D_n^4}{64} \quad (3.10)$$

This assumes that the lateral root is circular in cross sectional shape. The second moments of areas of other shapes can also be used. The maximum bending strength (M_{cn}) of the lateral root in the compression zone of diameter D_n is given by,

$$M_{cn} = \frac{2\sigma I_n}{D_n} \quad (3.11)$$

where σ is the modulus of rupture (MOR) in MPa

The contribution of the lateral root n in the compression zone in resisting the moment imposed by the lateral load is given by,

$$M_{cn} \cos \alpha_n \quad (3.12)$$

The summation of all the maximum bending strengths of the lateral roots in the compression zone is given by,

$$\sum_1^n M_{cn} \cos \alpha_n \quad (3.13)$$

Figure 3.8 Each lateral root in the compression zone makes an angle α_n to the direction of the lateral load

Similar to the roots in the compression zone, Figure 3.9 shows the plan view of the root plate, highlighting the lateral roots in the tension zone. Each lateral root in the tension zone makes an angle β_n to the applied lateral load. Similar to the lateral roots in the compression zone, the tension zone lateral roots contribute to resisting the applied lateral load depending on the angle each root makes to the lateral load. This passive resistance is provided for by the vertical or sinker root component of each tensile lateral root and is also called the tension tie down. When the tree does not experience lateral loads, the tension tie down or sinker root does not experience tensile stress. Figure 3.6 shows the elevation view of the tensile lateral root with the equivalent sinker root (tension tie down) resisting the lateral force. The tension tie down forces multiplied by the distances to the rotational hinge as formed in the lateral roots in the compression zone is the bending resistance contributed by the lateral roots in the tension zone of the root plate.

Figure 3.9 Similar to roots in the compression zone (Figure 3.8), the lateral roots in tension also make a contribution proportional to the cosine of the angle β_m

The sinker root (tension tie down) for each lateral root is modeled as an equivalent diameter frictional anchor. The resistance of the tension tie is limited by,

- 1) The tensile strength of the sinker root (tension tie down) $m (T_{tm})$
- 2) The shear strength of the soil restraining the sinker root (tension tie down) (τ)

$$T_{tm} = \frac{\sigma \pi D^2 t m}{4} \quad \text{and} \quad (3.14)$$

$$\frac{\sigma \pi D^2 t m}{4} \quad \text{or} \quad \tau L_m \pi D_{tm} \quad (3.15)$$

where,

τ is defined by Equation 3.7.

This is because if the tension tie down is insufficient in strength to overcome the skin friction from the soil, it will rupture and its length below the rupture will be left behind. Conversely, if the shear strength of the soil is less than the tensile strength of the tie down, the entire tie down or sinker root will be pulled out of the ground with the attached soil mass. The soil mass pulled out with the tension tie down component is proportional to the shear strength of the soil/tension tie down interface.

Each lateral root in the tension zone will provide a resisting moment in the direction of the lateral load as given by the following,

$$T_{mttmax}(\cos \beta)(x_m + w) \quad (3.16)$$

The summation of all the resisting moments from the sinker roots (tension tie downs) to overturning is,

$$\sum_{m=1}^m T_{mttmax} \cos \beta_m (x_m + w) \quad (3.17)$$

The ground water table position and the effective stress of the soil affect the calculation of the soil shear strength, τ . The depth of the ground water table is assumed to induce a hydrostatic matric suction profile above the water table. The effective stress of the soil σ_n is dependent on the depth and the density of the soil. Figure 3.6 shows the deformed shape of the shallow rooted tree at its limit state. The deformations are assumed to be small enough that the resulting changes induced by the lateral load to the geometry of the whole structure are negligible. The total resistance to the applied lateral load as afforded by the lateral roots in compression and tension can be summed up as follows:

$$\sum_1^n M_{cn} \cos \alpha_n + \sum_{m=1}^m T_{mttmax} \cos \beta_m (x_m + w) \quad (3.18)$$

The contribution of each root component can be seen in Equation 3.18. For trees with a shallow sinker root (tension tie down) root depth, the contribution from the sinker roots (tension tie downs) is small. The majority of the tree resistance to the applied lateral load is borne by the compressive lateral roots.

CHAPTER 4 Research Program and Methodology

4.1 Introduction

A comprehensive research programme was planned and carried out to study the mechanisms used by trees to resist uprooting forces due to the external loads that they faced in the field. The research programme concentrated on developing new tree stability models as well as developing new methods to measure key model input parameters that were not previously available.

The key information gaps identified were;

- 1) Greenwood properties. Tropical greenwood properties were relatively unknown in the literature. To address this information gap, flexural bending equipment was designed and fabricated to determine the flexural strength properties of branch greenwood (Section 4.3).
- 2) Wind loads on trees. The actual wind loads on trees could be estimated by correlating wind speed and direction measurements using meteorological stations to tree response measuring the strain along the trunk using Linear Variable Differential Transducers (LVDTs) (Section 4.4.4).
- 3) Climatic parameters of relative humidity, air temperature, solar radiation and wind speed/direction for the purpose of flux boundary analyses (Section 4.4.5).
- 4) Soil properties and measured parameters. Soil properties that needed to be determined included shear strength, soil water characteristic curves and permeability functions (Sections 4.4.7) Measured parameters required for geotechnical analysis included pore-water pressures (Section 4.4.1), volumetric water contents (Section 4.4.2) and groundwater table measurements (Section 4.4.3). Surface infiltration rate (Section 4.4.6).
- 5) Tree above ground architecture. This was performed using laser scanning (Section 4.5) and a newly developed survey method for estimating the architecture of the trees in three-dimensional space to provide tree canopy areas for wind drag estimation and self-weight (Section 4.6).
- 6) Theoretical tree root models (Section 4.7)

The overview of the research programme and the data flow is shown in Figure 4.1.

Figure 4.1 Scope of the research program

4.2 Outline of research programme

The research program consists of six main parts:

1) Branch greenwood testing

The modulus of rupture, modulus of elasticity, moisture content and specific gravity were measured to provide input parameters for the tree stability models and numerical modelling.

2) Site selection, investigation, lab testing and field testing/instrumentation

The basic properties tests and standard properties tests such as soil index properties, saturated permeability tests, saturated consolidated drained (CD) triaxial tests, saturated consolidated undrained (CU) triaxial tests and Soil-Water Characteristic Curve (SWCC) tests were conducted on the soil samples obtained from the field. These tests were carried out in the laboratory. In the field, double-ring infiltrometer tests were also carried out. Instrumentation installed in the field included tensiometers, volumetric water content sensors, Casagrande piezometers, rain gauges,

anemometers, temperature sensors, solar radiation sensors, trunk strain sensors and relative humidity sensors

3) Laser scanning of selected trees and surrounding features

A total station laser scanner was used to attempt to capture the three dimensional details of selected trees and the surrounding landscape.

4) Structural survey of selected trees

A new method was devised to capture the three dimensional branch architectures of trees. Five trees from two sites were surveyed.

5) Numerical modelling

Numerical modelling was performed in EXCEL, SVFLUX, SIGMA/W and ANSYS. Parametric studies were performed using these softwares.

6) Tree root model development and parametric studies

Developing closed form engineering models to approximate uprooting mechanisms. These models were used for performing parametric studies.

4.3 Greenwood testing

Green wood describes recently cut wood that still retains the internal moisture content and material properties that occur in the living tree. As of present, green wood properties of common tropical planted tree species in Singapore remain largely unknown. The analyses of the above and below ground tree architecture model require the determination of the input parameters of green wood properties. The key green wood properties needed as input parameters are green wood flexural stress-strain curves and specific gravity.

The main requirement for greenwood testing is that the wood being tested retains its natural moisture content. This means that there is an advantage to design and fabricate a portable testing apparatus that can be easily transported to the sites for tests to be carried out on freshly cut samples.

One of the major problems encountered in measuring the mechanical properties of materials softer than metals is that of securing the test sample. This is particularly pronounced in the tensile testing of unidirectional materials like wood where fibers are arranged in a parallel fashion within a binding matrix.

In wood, the high ratio that exist between tensile and shear strengths makes gripping of the sample difficult. A premature shear failure in the region of the grips may occur before the tensile strength can be measured. This difficulty can be overcome by means of special consideration of the test sample's dimensions. This requires careful machining of the test sample by milling and cutting. The machining of the greenwood sample to obtain a sample with a large enough gripping surface is can take a long time, during which, the moisture content of the wood sample may change. The machining of the sample may also create stresses and faults in the wood sample, especially if the tension area is very small in comparison to the gripping area (may be the case with weaker and lower density wood from trees like *Samanea saman*).

To obtain the “aggregate” flexural strength of the tree member (MOR), the entire member should also be used for testing. Branches of difference sizes can be tested to provide a good indicator of flexural strength (MOR) for each species. Testing apparatus portability and size constraints also mean that the larger branches or the trunk cannot be tested. The field conditions at the testing locations required that the apparatus be designed to be self-contained in terms of power supply and data logging with some forms of weather proofing.

The two most commonly used methods for performing flexural tests are the four point and the three point flexural tests. Both are described in ASTM-143D-09. Field testing equipments were fabricated to test the samples immediately after cutting from the tree.

4.3.1 Four-point flexural test

The four-point flexural test is conducted by loading a test sample that is supported over a specified span. The load is applied to the sample through two load

points within the support span. Figure 4.2 shows the flexural shape of the sample and the associated bending moment and shear force diagrams.

Figure 4.2 Four-point bending flexural shape, load, support reactions and the associated shear force and bending moment diagram

Figure 4.2 shows that between the load points, the moment is constant and the shear force is zero. The advantages of the four-point bending test are:

- Since the sample undergoes pure bending between the inner pair of load points, there is no shear component in this area.
- Pure bending results in uniform stress and strain along the sample surface between the loading points.
- Because of the uniformity of stress, a much larger area of sample is effectively under test and the results are more representative.

In the four-point bending test (Figure 4.2), the total length, L , is given by

$$L = 2(l_1 + l_2) \quad (4.1)$$

The modulus of elasticity E is given by

$$E = \frac{W}{6ID} l_1^2 (l_1 + 3l_2) \quad (4.2)$$

where I is the second moment of area of the samples, D is the vertical deflection of the sample measured with increasing applied load and W is the applied load.

The maximum surface strain, ε which is uniform over the sample region B to B' may be determined by;

$$\varepsilon = \frac{3dD}{2l_1(l_1 + 3l_2)} \quad (4.3)$$

where d is the diameter of the specimen, and

The stress at the outer most fiber, σ over the span BB' is given by;

$$\sigma = \frac{Wdl_1}{4I} \quad (4.4)$$

The first effort to design and fabricate a portable flexural testing apparatus was made by Wong et al. 2012. The resulting test apparatus was a lightweight four-point bending rig to perform flexural testing in the field. Figure 4.3 shows the four-point bending apparatus which consists of a hand actuated hydraulic piston attached to a steel channel as the main reaction beam. The two U-clamps acted as the two end supports. Another steel channel attached to the moving piston had two steel rods attached to it at a designed spacing to provide the two centre loading points.

In addition to being very lightweight, the portable four point bending rig was also simple to operate. A hydraulic jack provided high pressure fluid to one square inch area piston with a seven inch stroke. The force of the piston or W was measured by viewing the analog pressure gauge for the maximum pressure at breakage but D (Equation 4.2) was not measured as there was no provision to perform that measurement in the initial design. The initial design of the four point bending rig was found to work well with small branches but there was great difficulty in reading the

maximum pressure in the analog gauge that corresponded to the breaking of the test samples.

Figure 4.3 A simple and lightweight four-point bending rig designed and fabricated by Wong & Sim (2012)

To obtain the greenwood properties of modulus of rupture (MOR), elastic modulus and stress strain curves, a load cell to measure W and a long stroke (10cm) LVDT (Linear Variable Differential Transformer) to measure D were added. Steel legs were also welded onto the rig for upright stability. The whole revised setup is shown in Figure 4.4a. The U-clamps were also replaced with stainless circular section steel bars of the same diameter as the loading bars and the new bars were held down by threaded rods. Figure 4.4 shows the four point testing apparatus after modification.

a) Schematic

b) Photograph

Figure 4.4 The modified four point bending apparatus a) the schematic of the modified four point bending rig. b) The photograph of the modified four point test apparatus.

The load cell and LVDT were connected to a Campbell Scientific CR-1000A data logger and a Campbell Scientific 12V lead power pack (Figure 4.5) for portable power and data recording and the data sampling interval was set at the minimum value of 1 second. This sampling rate was deemed to be adequate for the tests to be carried

out. Calibration of the load cell using a load ring and dial gauge was carried out, while the LVDT was calibrated using a micrometer based LVDT calibrator.

FIGURE 2.1-1. CR1000 Wiring Panel

a)

b)

Figure 4.5 The data logger and power pack used together as the data acquisition system for the four point bending rig. a) The Campbell Scientific CR1000 Data logger. B) The Campbell Scientific PS100 12V power supply

During testing, a constant loading rate of one stroke per second was applied using a hydraulic jack. The load and deflection readings were captured using a Campbell Scientific CR1000 data logger and downloaded to a computer for further

processing. Figure 4.6 shows a field deployment of the four point bending apparatus and failure of a *Samanea saman* branch sample.

Figure 4.6 Field deployment of the four point bending apparatus.

The four point testing procedures were as follows:

- 1) Identify tree species for testing.
- 2) Cut at least thirty samples of branches of about 340 mm long and at between 20 to 30 mm in diameter (branches should be as straight as possible with minimum bend).
- 3) The cut branches are marked for upper surface and lower surface orientation and sample number.
- 4) The branch sample is inserted with the correct surface orientation according to the original branch orientation in the tree.
- 5) The hand jack is pumped at 1 stroke per second and the load, W and displacement D are recorded until failure of the branch occurs.
- 6) Two cross-section samples are cut from each test branch. The bark of the samples is removed and tested for wood density (wet and oven dried) and moisture content.
- 7) The process is repeated for all the samples.

From the results, it was observed that there was usually a linear portion of the curve followed by a rounding peak and then a plateau stage where snapping sounds were heard. A sudden failure was then experienced where the applied stress was

quickly reduced with a large increase in strain. A typical stress strain curve of the four-point test performed for *Samanea saman* samples is shown in Figure 4.7.

Figure 4.7 Typical four-point bending stress strain curve of a *Samanea saman* sample

During the preliminary testing conducted using the four-point testing apparatus, there were some difficulties encountered during the use of the initial design of the modified four-point bending apparatus. They were,

- 1) The four-point geometry limited the magnitude of the bending moments applied to the test samples, severely limiting the maximum diameter size of the test samples that could be tested using the testing frame and loading jack.
- 2) The Campbell Scientific data logger, power pack, LVDT, load cell and notebook computer required significant electrical power, providing a working period of only two to three hours in the field.
- 3) The numerous electronic instruments and their associated cabling and connections provided multiple points of critical failure that could disrupt any testing. Lack of weather proofing also meant that field testing was only possible weather permitting.

4.3.2 Three-point flexural test

With all the limitations of the four-point bending design, it was then decided to streamline the equipment and apparatus to a more simple and robust three-point testing apparatus. The hydraulic hand pump and piston were retained but a more robust frame was designed to apply higher bending loads to the samples using a longer span, reinforced steel load frame and three point bending geometry. The use of the data logger, LVDT, load cell and computer notebook was also removed to increase reliability and eliminate the limiting factor of power supply. In their place a magnetically mounted dial gauge and digital pressure gauge were used. Pressure gauge recording was performed manually with every 1 mm compression of the dial. The schematic of the three-point testing apparatus and the associated bending moment and shear force diagrams are shown in Figure 4.8.

The three-point flexural test concentrates stress on the center loading point of the sample. This enables the failure point to be clearly defined. With a larger support length (L), compared to the four-point testing apparatus, larger samples could be tested on the three point testing apparatus as the bending moments applied are much higher for the same applied piston force.

In the three-point bending test, the modulus of elasticity E is given by

$$E = \frac{L^3 m}{4d^4} \quad (4.5)$$

where,

m is the straight line portion of the load deflection curve

L is the support span

d is the sample diameter

The maximum surface strain ε may be determined by;

$$\varepsilon = \frac{6dD}{L^2} \quad (4.6)$$

where d is the diameter of the sample, and

D is the vertical deflection of the sample measured with increasing applied load.

The flexural stress at the outermost fiber of the circular section, σ over the span AA' is given by;

$$\sigma = \frac{8FL}{\pi d^3} \quad (4.7)$$

10a)

10b)

Figure 4.8 The three-point bending rig a) the schematic of the three-point testing apparatus b) the associated shear force and bending moment diagrams

The three-point testing procedures were as follows:

- 1) Identify tree species for testing.
- 2) Cut at least thirty samples of branches of about 600mm long and at between 20 to 70mm in diameter (branches should be as straight as possible with minimum bend).
- 3) The cut branches are marked for upper surface and lower surface orientation and sample number.
- 4) The three point bending apparatus has a dial gauge to replace the previous LVDT and a pressure gauge to replace the load cell.
- 5) Branch sample is inserted with the correct surface orientation that reflects the branch sample's original orientation on the tree.
- 6) The hand jack is applied at 1 stroke per second and the pressure gauge reading is manually recorded at every 1mm compression recorded by the dial gauge. This is carried out to failure of the branch or when the peak pressure has been reached and the pressure starts to drop appreciably.
- 7) The pressure is converted to a jacking force using the piston area.
- 8) Two cross-sectional branch samples are cut from each test branch, with bark removed and tested for wood density (wet and oven dried) and moisture content. The bark is removed as is assumed not to contribute to the strength of the greenwood.
- 9) The process is repeated for all the branch samples.

Figure 4.9 shows the three point bending apparatus in the field. To compare the three-point bending test with the four-point bending test, tests were also conducted on *Samanea saman* branch samples. A typical stress strain curve of the three-point test performed for *Samanea saman* branch samples is shown in Figure 4.10. The three-point bending test was also able to capture the stress strain properties of the branch samples without using the fast data sampling rate used for the four point bending test. By using a strain related to sampling rate rather than a time-based sampling rate, the three-point bending apparatus was able to produce less data noise in the resulting curves without sacrificing the key properties like maximum force and strain.

Figure 4.9 The three point bending apparatus after testing a *Khaya senegalensis* branch sample with the dial gauge measuring center deflection and digital pressure gauge mounted to the hand jack.

Figure 4.10 Typical three-point bending stress strain curve of a *Samanea saman* sample

4.4 Site selection, investigation, lab testing and field testing/instrumentation

In collaboration with NParks (National Parks Board), two sites were instrumented with a variety of sensors. The objective of the project was to determine the effects of rainfall on tree stability. The two selected sites were Silat Avenue (Figure 4.11) and Telok Blangah Rise (Figure 4.12).

The location criteria set were the following;

- 1) Flood prone area (low elevation).
- 2) Open channels nearby for hydrological flow measurements.
- 3) Trees were matured common roadside tree species.
- 4) Trees were wayside trees.
- 5) There was past history of tree uprooting failures

Figure 4.11 Location map with tree locations at Silat Avenue (www.googlemaps.com, 2012)

Figure 4.12 Location map with tree locations at Telok Blangah Rise
(www.googlemaps.com, 2012)

After the locations were selected, the parameters to be measured were decided upon. The parameters with instrument types in brackets that were needed to be monitored in real time for the study were:

- 1) Pore-water pressure (Tensiometers)
- 2) Volumetric water content (Time Domain Reflectometers)
- 3) Ground water depth from the surface (Casagrande Piezometers)
- 4) Soil Temperature (Temperature Probe)
- 5) Tree trunk deflection (Linear variable differential transformers (LVDT))
- 6) Rainfall (Tipping Bucket Rain gauge)
- 7) Solar radiation (Apogee Silicon Pyranometer)
- 8) Wind speed (Wind Monitor)
- 9) Wind direction (Wind Monitor)
- 10) Air temperature (Temperature Probe)
- 11) Relative humidity (Relative humidity Probe)

A screenshot of the homepage of the monitoring website is shown in Figure 4.13. The monitoring website provided real time tracking and charting of readings from instruments with recording of historical data.

Figure 4.13 Site operation overview of a typical site (www.envault.com.sg, 2012)

4.4.1 Pore-water pressure measurements

The measurement of pore-water pressures was performed using tensiometers. The typical tensiometer and its field installation are shown in Figure 4.14. The jet-filled tensiometers relied on a saturated ceramic cup with a high air-entry value to act as an interface between the de-aired water filled plastic tube and the soil. The installed tensiometers could measure negative and positive pore-water pressures in the soil. The measurement of the pore-water pressures was performed automatically using a powered electrical pressure transducer attached to the tube and measuring the air pressure within the tube. Typically, for tensiometers, the less water movement between the water in the tube and the soil, the more accurate the reading and the faster the response time. Osmotic potential was not measured as only pore-pressure difference could equalize across the ceramic cup and not ionic concentrations.

Figure 4.14 The pore-water pressures at various depths are measured using tensiometers. a) Jet-fill tensiometer with bourdon gauge for manual readings (Soil Moisture Equipment Corp, 2012). b) Installed Jet-fill tensiometer with attached pressure transducer for automatic datalogging

For good performance from tensiometers, air was not allowed to be dissolved in the water. Bubbles must also be flushed from the tensiometer by application of vacuum and the ceramic cup was kept saturated at all times. Before field installation, the tensiometers were first checked for saturation by using a vacuum pump to ensure that negative pressures could be maintained. Figure 4.15 shows the vacuum being applied to the tensiometers. For tensiometers, the limiting magnitude of negative pore-water measurements is about 100 kPa before water cavitation occurred.

Figure 4.15 Vacuum applied to tensiometers before installation to check saturation and condition of ceramic cups.

Good contact was also ensured between the tensiometer and the soil, firstly to keep water from the surface from running down the external tube wall, and to ensure a fast equilibrium time with the soil. This was achieved by using a steel pipe that is of the same diameter as the tensiometer shaft to core a tightly fitting hole for the tensionmeter to be inserted. Figure 4.16 shows the coring tool in action. The tensiometers were protected by PVC housings (Figure 4.17).

Figure 4.16 Special coring tool for the tensiometer installation

a)

b)

Figure 4.17 The jet-fill tensiometers with its attached transducers required protection from human interference and outdoor conditions. a) Jet-fill tensiometers of 0.5m, 1.0m and 1.5m depths in their protective PVC housings with lids closed. b) Jet-fill tensiometer and pressure transducer within the protective PVC housing.

4.4.2 Volumetric water content and soil temperature measurements

For measurements of soil water content, time domain reflectometers (TDR) were used. The CS650 Water Content Reflectometer (Figure 4.18) measured the volumetric water content of porous media using time domain measurement methods that were sensitive to dielectric permittivity. The probe consisted of two 30 cm long stainless steel rods connected to a printed circuit board. Each circuit board was encapsulated in epoxy, and a shielded four-conductor cable was connected to the circuit board to supply power, enable probe, and monitor the output. The probe rods could be inserted from the surface or the probe could be buried at any orientation to the surface.

The differentially-driven probe rods formed a transmission line with a wave propagation velocity that was dependent on the dielectric permittivity of the medium surrounding the rods. Nanosecond rise-times produced waveform reflection characteristics of an open-ended transmission line. The return of the reflection from the ends of the rods triggered a logic state change which initiated propagation of a new wave front. Since water has a dielectric permittivity significantly larger than other soil constituents, the resulting oscillation frequency was dependent upon the average water content of the medium surrounding the rods. The megahertz oscillation frequency was scaled down and easily read by a data logger.

The signal propagating along the parallel rods of the CS650 was attenuated by free ions in the soil solution and conductive constituents of the soil mineral fraction. In most applications, the attenuation was not enough to affect the CS650 response to changing water content, and the response was well described by the standard factory calibration which was used. However, in soil with relatively high soil electrical conductivity levels, compacted soils, or soils with high clay content, the calibration could be adjusted for the specific medium.

Figure 4.18 CS650 moisture probe from Campbell Scientific

Figure 4.19 shows the CS650 moisture probes installed on site. A pit had to be hand dug to install the moisture probes at depths of 0.5m, 1.0m and 1.5m. In addition to water content measurements, the CS650 probes also measured soil temperature. To measure the soil temperature near the soil surface, a temperature probe was installed just 10 cm below the soil surface. Figure 4.20 shows the Campbell Scientific soil temperature probe 108-L with measurement range of -5°C to 95°C . The pits were backfilled to ensure that a false drying surface at the pit wall did not prevail. The pits dug were also backfilled and compacted in layers. As much as possible, all the soil that was removed was put back in place. The CS probes were also inserted to the “undisturbed” soil of the pit wall. The readings were commenced after a period of a month had elapsed to allow for completion of settlement. In the future, vertical probes can be used.

Figure 4.19 CS650 moisture probes installed in a hand dug pit at 0.5m, 1.0m and 1.5m depths

Figure 4.20 Soil temperature probe 108-L with a range of -5°C to 95°C

4.4.3 Ground water table measurements

For measuring the depth of the water table from a datum, a Casagrande piezometer tip was used in the standpipe that was drilled in each location. Figure 4.21 shows the tip of the steel Casagrande type piezometer tip used on site with the filter material within the tip. The Casagrande tip was connected to lengths of PVC pipe and installed in the borehole with a zone of sand surrounding the tip (the piezometer response zone). A bentonite seal was placed above the sand to isolate the piezometer response zone. The borehole above the bentonite seal was backfilled to the surface (with cement-bentonite grout) to prevent the penetration of water down the hole. The top of the PVC pipe at the surface was fitted with a vented cap, and physically protected. The water level in the PVC standpipe was measured using an electrical pressure transducer. These measurements were used to calculate piezometric pressures or groundwater levels. The sequence of installation is summarised in Figure 4.22.

Figure 4.21 Casagrande piezometer tip with filter material within to prevent fines from entering the piezometer.

Figure 4.22 a) Casagrande tip attached to PVC pipe b) Tip wrapped in sand and netting c) Taped up before lowering d) Inserted to borehole and backfilled with 1 m of sand e) Bentonite pellets inserted to seal sand layer f) Borehole topped up with bentonite slurry.

4.4.4 Tree movement and sway

It was observed that the wind loads on trees had the effect of causing the tree trunk to bend and apply an overturning moment at the root plate of the tree. It was also observed that, as the trunk bent, the trunk (idealized as circular) also obeyed the mechanics of a simple geometrical cross-section. The outer fibres elongated (tension) on the windward side and shorten (compression) on the leeward side of the trunk. Instruments that measure this fibre elongation were attached to the trunk, near the base of the tree and recorded the trunk bending response to wind loading. To estimate the wind force on the tree or the drag coefficient of the tree, an indirect way was to measure the axial strains of the tree at a point along the trunk of the tree. The strains, together with the material properties of the greenwood (obtained from greenwood testing) and the dimensions of the trunk and the wind speed would provide a good estimation of the wind drag forces on the tree.

Axial strain measured in real time in different directions along a length of a member of known cross-sectional and material properties had the potential to indirectly measure the forces acting on the member and the movements resulting from the forces. To test this concept, two 50 mm stroke linear variable differential transformers (LVDTs) were installed on a 25mm diameter acrylic tube orthogonal to each other in the laboratory and the output of the LVDTs was recorded at 10 Hz (Figure 4.23).

The acrylic tube was clamped at one end and the other end was hand excited over a period of time. At the same time, a video of the oscillations were captured. The acrylic tube was observed to oscillate freely with little damping and frequencies (1-2 Hz) much higher than trees. The LVDTs recorded the oscillations well by measuring the axial strains. From the output of the 2 LVDTs (Figure 4.24(a) and (b)), the axial strains were adequately captured. The summations of the movements recorded by LVDTs 1 and 2 are shown in Figure 4.25. The recorded movements by the LVDTs matched the recorded video well.

Figure 4.23 LVDTs placed along the length of a known section can detect the movement in real time

a) LVDT 1

b) LVDT 2

Figure 4.24 Real-time LVDT readings a) LVDT 1. b) LVDT 2

Figure 4.25 LVDTs 1 and 2 plotted together show the recorded motion of the acrylic tube/LVDT setup shown in Figure 4.24

As the LVDTs used in the laboratory were not ruggedized for field deployment, suitable models of LVDTs had to be selected that were designed to operate under field conditions and also to be accurate enough to record small changes in trunk elongation. In order to measure the dynamic response of the tree the data rate needs to be fast enough and after some initial testing this was chosen to be 3 Hz. This data speed resulted in smooth curves in the time domain and was faster than the 2.5 Hz sampling rate of Moore and Maguire, 2004. They used a similar principle of measuring outer fibre strain to detect tree movement, but with an instrument of a different design and a sampling rate of 2.5 Hz. This was adequate for comparing with the wind speed measurements which had a similar sampling rate.

For deployment in the field, the LVDTs selected for the measurement of axial deformations were the Solartron S series AS/5 high performance displacement sensors. The AS/5 LVDTs had a measuring range of $\pm 5\text{mm}$ with a linearity of $\pm 0.2\%$ of full scale and a voltage output of $\pm 5\text{V}$. The LVDTs had a stainless steel construction and were rated at IP67 for ingress protection. To increase the sensitivity of the LVDTs in the field to capture sway motion of the trees from light winds that were commonly found in Singapore, the L_0 (nominal distance between mounting

points of the LVDTs) was increased using guided aluminum rods. Figure 4.26 and Figure 4.27 show the LVDTs setup in the field at Silat Avenue and Telok Blangah Rise, respectively. The LVDTs could not be installed orthogonally to each other as the trunk surfaces were uneven and suitable vertical surfaces had to be found.

Figure 4.26 *Syzygium grande* 1 at Silat Avenue instrumented with two LVDTs (LVDT 1 and 2) at 62° apart from each other and at azimuths 334° and 268° , respectively from magnetic north

Figure 4.27 *Samanea saman* at Telok Blangah Rise instrumented with two LVDTs (LVDT 1 and 2) at 83° apart from each other and at azimuths 90° and 7° , respectively from magnetic north

At Silat Avenue the LVDTs were installed onto *Syzygium grande* 1 while at Telok Blangah Rise, the LVDTs were installed onto a *Samanea saman* 1. To reduce the amount of zero value data recorded by the LVDTs during no wind periods, a threshold value of wind speed (3m/s) was required before recording of the LVDTs were initiated.

4.4.5 Weather station and mast

The sites at Silat Avenue and Telok Blangah Rise were each instrumented with fully equipped weather stations. The parameters measured were rainfall, solar radiation, relative humidity, air temperature, barometric air pressure and wind speed/direction. The wind speed and direction measurements made at the sites was used in conjunction with structural surveys of the selected trees found on site instrumented with the LVDTs. Together, these measurements were used to estimate the wind forces on the tree and at the same time observe the tree response to different wind loads.

Rainfall events are recorded using a tipping bucket rain gauge. Figure 4.28 shows the rain gauge used in both sites.

Figure 4.28 The Campbell Scientific TB4 tipping bucket rain gauge

The TB4 measured rainfall in 0.01-inch increments. These raingauges funnelled rain into a mechanism that tipped when filled to the calibrated level. Each tip was marked by a dual reed switch closure that was connected and recorded by a datalogger pulse count channel. After measurement, the water drained through two orifices in the base, allowing the measured water to be collected in a separate container. The TB4 tipping buckets were ideal for locations where intense rainfall events occurred. They include a siphoning mechanism that allowed the rain to flow at a steady rate regardless of rainfall intensity. The siphon reduced typical rain bucket errors and produced accurate measurements over a range of 0 to 19.69-inches per hour (50 cm per hour). Figure 4.29 shows the TB4 raingauge deployed in the field at Silat Avenue.

Figure 4.29 TB4 rain gauge deployed at Silat Avenue

To obtain evaporation and transpiration rates, input parameters had to be measured and the results calculated using established models. The input parameters required were solar radiation, relative humidity, air temperature and barometric

pressure. Solar radiation was measured using the Campbell Scientific CS300 Apogee Silicon Pyranometer (Figure 4.30). The CS300 used a silicon photovoltaic detector mounted in a cosine-corrected head to provide solar radiation measurements for solar, agricultural, meteorological, and hydrological applications. Calibrated against a Kipp & Zonen CM21 thermopile pyranometer, the CS300 accurately measured sun plus sky radiation for the spectral range of 300 to 1100 nm. For accurate measurements, the CS300 require mounting to a level base plate.

Figure 4.30 The CS300 Apogee silicon pyranometer for measuring solar radiation.

Relative humidity and air temperature were measured in the field using a HMP60 sensor by Campbell Scientific. Figure 4.30 shows the HMP60 and the field deployment of the sensor mounted under a solar radiation shield. The HMP60 sensor, measured air temperature with a range of -40°C to 60°C, and relative humidity for the range of 0 to 100% RH. It used the INTERCAP® capacitive RH chip. This field-replaceable chip eliminated the downtime typically required for the recalibration process.

Figure 4.31 The HMP60 temperature and relative humidity probe and the field mount in a solar radiation shield.

Barometric pressures are measured using a CS106 barometric pressure sensor. The CS106 Barometer used Vaisala's BAROCAP silicon capacitive sensor to measure barometric pressure over a 500 to 1100 millibar range. Figure 4.32 shows the CS106.

Figure 4.32 CS106 barometric pressure sensor

Figure 4.33 The concrete footing constructed before mast erection

To provide data on wind speed and direction at the tree canopy level, a 10m high mast was deployed in the field. The mast used was the Lycopole 10 m galvanized mast. The mast required a concrete footing to be constructed for pole stability. The footing is shown in Figure 4.33. The mast was then erected only after the concrete of the footing had cured for a week. Figure 4.34 shows the mast erected.

Figure 4.34 Lycopole 10 m mast erected over the footing at Telok Blangah Rise site

On top of the mast (Figure 4.35), the wind speed and direction monitor was deployed together with a solar panel (for powering the datalogger and instruments), lightning protection rod and the pyranometer (for measuring solar radiation). The wind speed and direction monitor was the Young's 05103. RM Young's Wind Monitors were selected because of their light-weight construction and also because they measured both wind speed and direction. Their design emphasizes simplicity and lightweight construction. The wind monitors were made out of ruggedized materials and the moving parts were precision made to optimize response times. The wind monitors used a helicoid-shaped, four-blade propeller that was optimized to respond quickly to changing wind speeds. Rotation of the propeller produced an ac sine wave signal that had a frequency directly proportional to wind speed. The ac signal was induced in a transducer coil by a six-pole magnet mounted on the propeller shaft. The coil resided on the non-rotating central portion of the main mounting assembly, eliminating the need for slip rings and brushes. The wind monitors used a potentiometer to measure wind direction. The data logger applied a known precision excitation voltage to the potentiometer element. The output signal was an analog voltage directly proportional to the azimuth angle.

Figure 4.35 The Young's 05103 wind monitor and deployed on the mast top in the field

4.4.6 Field determination of surface infiltration rate (Double-ring infiltrometer ASTM 3385-03)

Surface saturated hydraulic conductivity can be very different from laboratory triaxial saturated conductivity. This is because of the presence of vegetation on the surface and their roots penetrating into the soil to a significant depth. At the two sites, surface saturated conductivity was measured using the double-ring infiltrometer according to ASTM 3385-03.

The double-ring infiltrometer is a widely used apparatus for conducting field infiltration tests to obtain field infiltration rates that are used in many applications. The infiltrometer consists of two concentric metal rings, which are driven into the soil. The double-ring infiltrometer requires a wooden piece or something similar in order to drive the rings into the soil. Other equipment needed include a large hammer, buckets, a measuring jug, stopwatch, equipment for writing records, measuring tape, washcloth, and water.

The measurements were taken in the inner cylinder; the outer cylinder was used only as a tool to ensure that water from the inner cylinder will flow vertically

(downwards) and not laterally (one-dimensional flow). Figure 4.36 shows the double-ring infiltrometer equipment deployed at Silat Avenue.

Figure 4.36 Double-ring infiltrometer at Silat Avenue. The organic material around and surrounding the rings were removed prior to ring installation and testing was conducted according to ASTM 3385-03

Two marking points of different lengths were marked on the folding ruler. These points were used for observation of decreasing water level during the infiltration. Both (inner and outer) cylinders were driven into the soil (to a depth of 10-20 cm). As recommended in the standard procedures, the turf around the rings' periphery was cut, so that the soil was less disturbed during the driving of the rings. After the rings were driven into the soil, water was poured into both cylinders with the water level in the inner cylinder reaching the upper marking point. At this moment the stopwatch was started and the time needed for the water level to drop from the upper mark point to the lower mark point was measured and recorded. After this elapsed time, a certain amount of water was infiltrated (in this case 500 cm³). When the water level reached the lower nail point, the time was recorded and the same amount of water was poured back from a prepared graduated bottle (500 cm³). The water level in the outer cylinder was kept at the same level as the water level in the inner cylinder so that there was no differential head.

4.4.7 Soil sampling and testing

Geotechnical information about each site was obtained by drilling boreholes. At both sites, boreholes were drilled to a sufficient depth to define the soil profile (10 m). Undisturbed and disturbed samples were obtained for classification and laboratory testing. After the samples were retrieved, each borehole was instrumented with the Casagrande piezometer (Section 4.4.3). Figure 4.37 shows the drilling rig performing wash boring to 3m depth for disturbed samples before stainless steel tubes (Figure 4.38) were pushed into the ground to obtain the undisturbed samples.

Figure 4.37 Drilling rig deployed at the Silat Avenue site. a) The drilling rig performing wash boring to 3m. b) A disturbed sample from the wash boring.

The tree root models described in Chapter 3 required soil characterization and shear strength testing to be performed for the field soil samples. The undisturbed sampling was performed at depths >3 m. This was below the root zone that was within the first 1.5 m depth of the soil. Therefore laboratory tests were performed on reconstituted samples taken from the disturbed sampling depth <1.5 m depth (which was determined to be representative of the soil in the failure or root zone). The required input parameters were grain size distribution, Atterberg Limits, shear strength

(saturated and unsaturated), saturated permeability and finally soil-water characteristic curves (SWCC).

Figure 4.38 The stainless steel tubes used for undisturbed sampling before sealing with paraffin wax.

The first series of laboratory tests comprised of the following tests to characterize the soil found within the sites that will be instrumented. They included:

- 1) Atterberg limits (Index properties)
- 2) Organic content
- 3) Grain size distribution
- 4) Saturated permeability (K_{sat})
- 5) Consolidated, undrained triaxial shear strength (CU)
- 6) Unsaturated, consolidated, drained triaxial shear strength (CD)
- 7) Soil water characteristic curves (SWCC)

Before the site investigation of the first two sites was performed, a series of preliminary tests were conducted on two samples of NParks Approved Soil Mix (ASM). These tests were carried out to establish baseline range of values for

comparison purposes to field samples taken from the sites. ASM could be used as a comparison soil as it was an engineered planting soil commonly used by contractors employed by NParks for the planting of roadside trees and other roadside greenery purposes. The ASM specifications were provided by NParks and are shown in Table 4.1.

Table 4.1 Specifications for Approved Soil mixture (ASM) (from NParks, 2009)

Parameters	Required Range/Value
pH	6.5 – 7.5
Electrical Conductivity	Less than 2.0 dS/m
Organic Matter	Minimum 10% by dry weight
Cation Exchange Capacity	Greater than 10meq/100g soil by dry weight
Bulk Density	Greater than 0.8 Mg/m ³
Soil Texture Composition	Sand (0.05 – 2.00mm) Max 75% Min 20% Silt (0.002 – 0.05mm) Max 60% Min 5% Clay (less than 0.002mm) Max 30% Min 5%
Heavy Metal Concentration	To comply with national standards under public health and pollution control, whenever such standards are applicable
Organic Contaminants	To comply with national standards under public health and pollution control, whenever such standards are applicable
Pathogens	To comply with national standards under public health and pollution control, whenever such standards are applicable

Investigation of soil basic properties included measurements of soil specific gravity, grain-size distribution analyses, Atterberg limit tests and saturated permeability. The measurement of soil specific gravity was performed following

ASTM D-854. The grain-size analyses, which involved wet sieve, dry sieve analyses and hydrometer analyses, were performed in accordance with ASTM D-1140 and ASTM D-422, respectively. The wet sieve tests were conducted in order to measure accurately the fine contents of the soils. Once the wet-sieve analyses were performed, the dry-sieve tests were conducted on the remaining coarser-grained materials. The Atterberg limit tests were performed in accordance with ASTM D-4318 in order to obtain the liquid and plastic limits of the fine-grained soils. Once the liquid and plastic limits of the soils and the grain-size distributions were obtained, the soil was classified in accordance with the unified soil classification system (USCS) following ASTM D-2487.

4.4.7.1 Soil-water characteristic curve

The soil-water characteristic curves of the soils were measured in Tempe cells and pressure plate tests (Figure 4.39). The test procedures of the Tempe cell and pressure plate tests are explained below.

Figure 4.39 Testing equipment used to obtain the soil water characteristic curve of soil samples for different matric suction ranges. a) Tempe cells (0 – 100 KPa matric suction). b) Pressure plates (100 – 500 KPa)

The Tempe cell tests were conducted using a Tempe pressure cell manufactured by Soilmoisture Equipment Corporation, CA, USA. The Tempe cell consists of three main components, which are the top and base caps, the 60 mm high, and 84 mm diameter brass cylinder, and the 1 bar high-flow high-air entry ceramic disk. The saturated high air-entry ceramic disk allows water to flow freely across it, but it stops air flow as long as the disk is fully saturated.

A required amount of dry soil specimen was placed on the brass cylinder and compacted to a target density and water content. The outlet tube, which was provided in the water compartment beneath the ceramic disk, was then connected to a burette filled with water for saturation of the soil specimen. After saturation, the top and the base caps were tightened together. In order to maintain the saturation of the ceramic disk during the test, which allowed soil water to flow out easily through the ceramic disk, the Tempe cell was placed in a support ring that was placed in a pan filled with water.

Water pressure was maintained at an atmospheric pore-water pressure or 0 kPa (gauge pressure) at the bottom of the soil specimen in the Tempe cell during the test. An applied air pressure to the soil specimen gives a matric suction value as matric suction is the difference between pore-air pressure (u_a) and pore-water pressure (u_w). Air pressure was supplied through the inlet tube on the top plate. Once the air pressure was applied, water in the specimen started draining out through the ceramic disk until equilibrium was reached. The change of water volume in the soil specimen was measured by weighing the Tempe cell periodically. In the initial stage of matric suction application, generally, the water flowed out rapidly and the volume of water in the soil specimen decreased. As time elapsed, water continued flowing out at a slower rate. Once the decrease in the volume of water became insignificant, the measurement of volume of water under the applied matric suction value was stopped and the air pressure was subsequently increased to a higher value. In order to confirm the equilibrium condition in each of the applied matric suction, the volume of water in the soil specimen was plotted against logarithm of time during the test. The procedure was repeated at higher matric suctions. Once the highest air pressure had been applied, the

soil specimen was then moved to a pressure plate apparatus for measurements at matric suction values higher than 100 kPa.

The Tempe cell tests started at a very small matric suction value as the air-entry values of the soils used in this research were anticipated to be very low (i.e., less than 1 kPa). Since the minimum air pressure supplied through the pressure gauge was only accurate to 10 kPa, the air pressure system was then modified and a water head was used to control the air pressure applied to the soil. As shown in Figure 4.40, the provided valves could release some of the air pressure, so that even a small air pressure of 0.1 kPa (i.e. equals to 1 cm water pressure head) could be controlled by balancing the water in the manometer tube.

Figure 4.40 Schematic diagram of the modified Tempe cell test (from Indrawan et al., 2006)

In order to obtain the drying SWCC at higher matric suction values, the soil specimens were removed from the Tempe cell and then placed on a 5 bar high-flow, high-air entry ceramic plate inside a pressure plate apparatus.

The pressure plate apparatus consists of a chamber containing a 5 bar high-flow, high-air entry ceramic plate and a water compartment and a burette as shown in Figure 4.39. Before starting the test, the 5 bar high-flow, high-air entry ceramic plate was submerged in water in a vacuum container for saturation. Once the ceramic plate

had become saturated, the soil and the brass cylinder, which were weighed in advance, were placed on the saturated ceramic plate. A weight was placed on the soil sample to ensure an intimate contact between the soil and ceramic disk. Then, the container and the lid were tightened by the clamping bolts. A schematic diagram of the pressure plate apparatus is shown in Figure 4.41.

Figure 4.41 Schematic diagram of the pressure plate test (from Indrawan et al., 2006)

During the test, the high air pressure inside the container forced pore-water in the soil to flow out through the pores in the ceramic plate. Similar to the Tempe cell test, the change of water volume in the soil specimen was measured by weighing the soil together with the brass cylinder, periodically. In order to confirm the equilibrium condition under each of the applied matric suction, the volume of water in the soil specimen was also plotted against log time during the test. Once the highest matric suction had been applied, the soil specimen was then removed from the pressure plate and the final water content of the soil specimen was measured by oven drying. This water content, together with the previous changes in mass, were used to back-calculate the water contents corresponding to different matric suctions. The water contents were then plotted against their corresponding matric suctions to give the soil-water characteristic curve.

Tempe cell and pressure plate tests could only provide a limited set of points for the SWCC curve. In order to obtain a continuous and wide range of data, the experimental data were fitted with the equation from Fredlund & Xing, 1994 using the correction factor, $C(\psi)$, equal to 1 as recommended by Leong and Rahardjo, 1997a. Results of the SWCC curve can be found in Chapter 5.

4.4.7.2 Triaxial consolidated undrained (cu) shear strength and saturated permeability

The soil samples from both sites were also tested in the triaxial cell. The triaxial cell setup is shown in Figure 4.42. Multi-stage CU and permeability tests were conducted using the triaxial apparatus shown in Figure 4.42.

Figure 4.42 Triaxial setup used for measuring K_{sat} and consolidated undrained shear strength

As shown in Figure 4.43 , the confining pressure was applied and controlled through valve A, pore-water pressure was applied and controlled through valve B. A pressure transducer was installed at valve D to monitor the pore-water pressure of the soil specimen. Valve D was opened during flushing when de-aired distilled water was supplied from Valve C with an applied water pressure of 30 kPa.

Reconstituted statically compacted soil specimens from Silat Ave and Telok Blangah Rise of 50 mm in diameter and 100 mm in height were used for permeability and CU triaxial tests. The soil specimen was saturated by applying back pressure and cell pressure. Upon saturation, the soil specimen was isotopically consolidated to the designated net confining pressure, $(\sigma_3 - u_w)$. During consolidation, the pore-water pressure was monitored by the pressure transducer at valve D while the pore-water volume change of the specimen was measured by the volume change indicator. The completion of the consolidation process was indicated by the equilibrium of pore-water volume and the lack of excess pore-water pressure above the cell pressure.

Figure 4.43 Schematic layout of the apparatus used for triaxial CU, and permeability tests (from Goh et al., 2011)

After consolidation was complete, the specimen was sheared by applying an axial load through the loading-ram at a constant strain rate of 0.0009 mm/min. Valve A was kept opened during the shearing stage while Valve B was kept closed to keep

an un-drained condition. The pore-water pressure was monitored using the pressure transducer at valve D, the pore-water volume change of the specimen was measured by the volume change indicator through Valve B and the axial load and axial displacement was measured through the load ring and dial gauges. Shearing was terminated when failure was imminent by looking for movement in the dial gauge with no additional axial load. The specimen was then unloaded and consolidated to a higher effective confining pressure and the same procedures were repeated. In the final stage, the specimen was sheared until the deviator stress reached a constant value or a significant shear plane in the specimen was observed. The maximum strain was limited to 20%. The specimen was then unloaded and all the pressures were released. The soil specimen was dismantled from the pedestal and the rubber membrane was removed after the cell water was drained out. Finally, the water content of the specimen was determined.

Table 4.2 Net confining pressures used for the CU tests

Soil Specimen	Net Confining Pressure (kPa)		
	15	30	60
Silat Avenue	✓	✓	✓
Telok Blangah Rise	✓	✓	✓

The saturated permeability tests under different net confining pressures were also conducted for the soil specimens. Constant head permeability test procedure (D2434-68 (1997)) as described in the ASTM (1997) soil testing standard was used. Saturated triaxial apparatus (Figure 4.43) and digital pressure and volume controller (DPVC) were also used in the test. Three different net confining pressures were chosen for the saturated permeability test in order to compare and understand the effects of net confining pressure on the saturated permeability of the specimens.

After consolidating the soil specimens to the targeted effective confining pressure, valve C was opened. De-aired distilled water with a constant pressure 10 kPa higher than the pore-water pressure inside the soil specimen was applied and controlled by DPVC through valve C while the back pressure with a constant pressure of 10 kPa lower than pore-water pressure inside the soil specimen was applied and

controlled by the volume change indicator through valve B. Thus, water was made to flow upward through the column of soil specimen under the application of 20 kPa constant pressure difference. The test was stopped when the flow rate was constant for a given period of time. The soil specimen was then consolidated to a higher effective confining pressure and the same procedures were repeated in order to measure the permeability of the soil under higher effective confining pressures.

The results of the CU and the permeability tests are presented in Chapter 5.

4.4.7.3 Triaxial unsaturated consolidated drained shear strength

Figure 4.44 shows the triaxial setup for the unsaturated consolidated drained test (CD) to attain the measured ϕ' and ϕ^b . A transparent triaxial cell, modified pedestal, ceramic disks, top cap and constant rate compression machine, two linear variable differential transformers (LVDT), a digital pressure and volume controller (DVPC-1) for pore-water pressure, a digital pressure and volume controller (DPVC-2) for confining pressure, pore-air control system, three pressure transducers, data acquisition system and a personal computer were the components of the triaxial equipment. The axis-translation technique (Hilf, 1956) was used in order to prevent cavitation as negative pressures approached -100 kPa. Pore air pressure (u_a) and pore water pressure (u_w) were controlled using the DVPC-1 and pore-air control system to apply a matric suction ($u_a - u_w$) to the soil specimens. The schematic of the modified triaxial apparatus for unsaturated soil testing is shown in Figure 4.45.

All specimens were saturated at the beginning of the testing in order to have a uniform initial condition and to reduce the matric suction to a low value. Before starting the saturation, valves C and G were joined and connected to back pressure line which was connected to DPVC-1 to supply water as well as to control water pressure into the specimen through porous metal from top and bottom of the soil specimen simultaneously. The porous metal has much higher permeability than the 5-bar high air-entry ceramic disk, thus the saturation time could be shortened. Cell pressure (confining pressure) was applied and controlled through valve D, which was connected to DPVC-2. Pore-water pressure was measured by the pressure transducers at valve B. Figure 4.45 shows the schematic diagram of the triaxial apparatus. The soil

specimen was saturated by applying a cell pressure, σ_3 , and a back pressure, u_w , with a net confining pressure, $(\sigma_3 - u_w)$, of 10 kPa until the pore-water pressure parameter B value was larger than 0.95 as proposed by Head (1986). Pore-water pressure parameter, B value is defined as the ratio of a change in pore-water pressure to a change in the confining pressure as described by the following equation,

$$B = \frac{\Delta u}{\Delta \sigma_3} \quad (4.8)$$

where,

Δu is the pore-water change after the increment of confining pressure

$\Delta \sigma_3$ is the increment of confining pressure

Figure 4.44 Triaxial unsaturated consolidated drained shear strength test apparatus

In the beginning of saturation, 40 kPa of back pressure and 50 kPa of cell pressure were first applied to the soil specimen. After equilibrium, both valves C and G were closed and cell pressure (confining pressure) was increased to 100 kPa. So, the pore-water pressure of the specimen built up due to the increment of the confining pressure. After the pore-water pressure reached equilibrium, the pore-water pressure

value was noted and used for calculating the B value. If the B value was lower than 0.95, back pressure was then increased to 90 kPa. After both pressures reached equilibrium, both valves C and G were closed and the cell pressure was then increased by 50 kPa, to 150 kPa. These procedures were repeated until the B value was larger than 0.95. The total volume change and pore-water volume change of the soil specimen were measured by DPVC-2 and DPVC-1, respectively.

After the saturation was completed, the soil specimen was isotopically consolidated to the designated net confining pressure. During consolidation, the back pressure (pore-water pressure) line was connected to valve C and valve G while the cell pressure (confining pressure) line was connected to valve D. Valves A, B, E and F remained closed. The pore-water pressure and the cell pressure were applied and controlled by DPVC-1 and DPVC-2, respectively, at the designated values. The pore-water pressure was monitored by the pressure transducer at valve B. The completion of consolidation was reached when there was no excess pore-water pressure and the pore-water volume reached equilibrium.

Valves A, C, D, F and G were remained open during the shearing stage. Both pore-air and pore-water phases were in a drained condition and were maintained at the same pressures as the pressures before the shearing started. A slow strain rate was applied such that excess pore-water pressure is zero to maintain the same pore-air and pore-water pressures throughout the shearing process. In Rahardjo et al. (2004) study, the strain rate of 0.0009 mm/min was used for the CD triaxial test of compacted residual soil from the Jurong Sedimentary Formation of Singapore. The same strain rate, 0.0009 mm/min, was reported to be used in the study of Thu et al. (2006) for the CD triaxial test of compacted kaolin. Since the sand-kaolin mixture used in this research had similar properties (i.e. saturated permeability, plasticity index, fine contents) as the soils used in both studies, the strain rate of 0.0009 mm/min was adopted for the CD triaxial tests in this research. Shearing was terminated when the deviator stress reached a constant value or a significant shear plane in the soil specimen was observed. The maximum axial strain was limited to 20 %. The soil specimen was then unloaded and all the pressures were released. The soil specimen was dismantled from the triaxial cell, and the final water content of the soil specimen was obtained. All the measurements, e.g. pore-air pressure, pore-water pressure, total

and water volume changes, applied load, displacement as well as cell and ambient temperatures were automatically recorded using the acquisition program via the computer.

Figure 4.45 Schematic of the triaxial apparatus used for unsaturated soil testing (from Goh et al, 2011).

4.5 Laser scanning of trees and surrounding features

Unlike typical man-made structures, the above ground architecture of trees is irregular, hard to define and measure. After evaluating different methods of defining actual tree dimensions for the above ground tree model, three dimensional laser scanning was chosen to accurately and rapidly obtain a detailed three dimensional model of the tree. Laser scanning provided high resolution/detail that could not be replicated by other methods. With the correct setup and sufficient practice, laser scans

could be quickly performed with reasonable productivity. The resulting data clouds could also be cleaned up to produce the required three dimensional point clouds of the targets in the computer.

The laser scanner used was the Leica ScanStation C10. The C10 is a compact, all-in-one platform. Its built in features include a laser scanner, battery, controller, data storage and video camera. The ScanStation C10 provides high-accuracy; long range scanning and can perform full dome interior scanning.

Laser scanning using the Leica C10 can only be performed on static (non-moving) structures. The three dimensional representation of the scan is presented in a point cloud form (Three dimensional series of dots). Each point captures the line of sight distance, elevation and the azimuth from the Leica C10. Also captured is the coloration of the instantaneous target. Trees are ideal candidates for laser scanning because of their irregular shapes. On a calm day every single detail on the tree in the line of sight of the laser will be picked up and recorded as a point cloud.

To ensure that the target trees, be captured with reasonable detail, the weather had to be calm and windless during the scanning to eliminate the tree target swaying and leaf flutter. While capturing the target tree in its three dimensional form, background features will also be captured. The resulting cloud of data points have to be cleaned up to isolate the background features from the target trees.

The scanning procedure used for preliminary scans is shown below in Figure 4.46. The targets that are set up at the beginning of the scan are for used for location registration and reference points for moving the C10 to another location. Typically, at least two scans are required to capture the target tree in three dimensions. Therefore the targets that are initially set up have to take into consideration visibility from the subsequent scan locations. A typical point cloud of a target tree without the background clutter is shown in Figure 4.47.

Figure 4.46 Laser scanning procedure used in the initial scanning

Figure 4.47 Point cloud of a target tree, displayed left to right from different views (front, back, right, left and bottom, top)

4.6 Tree structural survey method (TSSM)

To conduct analysis in finite element software, there was a requirement to reduce the complexity of the trees to the woody branches and the trunk. Using this new method of performing structural surveys of trees, the woody members of the surveyed tree could also be reduced to a hierarchical system of cylindrical cantilevers extending from the soil to the height and width of the tree. This led to the creation of a numbering system that could be used to annotate any branch on the tree regardless of its location in the branching hierarchy.

Any branch on a tree can be simplified as a single or a series of straight cylinders each having an azimuth (bearing from true north), an elevation (angle from the horizontal) and a diameter. The branches of a tree can be described as a system of higher order cantilevers extending out from lower order cantilevers. The end of lower order cantilevers is taken as the beginning of the next level of cantilevers. As there are usually never more than four higher order branches radiating from a lower order branch, a single digit can be used to annotate any branch. Figure 4.48 describes in two dimensions the system of branch annotation so that any branch will be assigned a unique number that both shows their order within the system.

A sketch of a tree to be surveyed was first drawn and unique numbers were assigned to each branch to be surveyed. For each branch number the azimuth, elevation, length and diameter are recorded.

The azimuth of each tree branch is recorded as a heading in degrees from magnetic north using a compass (0 – 360 degrees). This is done with reference to the trunk or point of connection to the soil. The elevation of the branch is taken as the angle from the horizontal. Figure 4.49a shows the orientation of the branches from plan view with reference to magnetic north and Figure 4.49b shows the side elevation of the same branches with reference to horizontal.

Figure 4.48 Annotation system for designating a unique number to each tree branch that both describes its position and the order within the tree

Figure 4.49 Branch elevation a) darker lines designate the branches and light arrows show direction of magnetic north, the angles measured are the azimuths. b) Darker lines designate the branches and light arrows show direction of horizontal, the angles measured are the elevations

To measure the azimuth of each branch, a handheld GPS (Garmin ETREX Vista) was used which had a built in compass with a digital readout for convenient readings. To obtain the elevations and lengths of each individual tree branch, a laser range finder with a built in inclinometer was used. The model used was the Leica Disto D8 which provided millimeter accuracy for distance measurements and elevation angles to one decimal place.

Figure 4.50 illustrates the measurements that have to be obtained using the laser range finder and inclinometer (D_1 , D_2 , α_1 and α_2) to calculate D_3 and α_3 ;

$$D_3 = \sqrt{(D_2 \sin \alpha_2 - D_1 \sin \alpha_1)^2 + (D_2 \cos \alpha_2 - D_1 \cos \alpha_1)^2} \quad (4.9)$$

$$\alpha_3 = \tan^{-1} \left(\frac{D_2 \sin \alpha_2 - D_1 \sin \alpha_1}{D_2 \cos \alpha_2 - D_1 \cos \alpha_1} \right) \quad (4.10)$$

D_1 = distance of the observer to the beginning of the branch

D_2 = distance of the observer to the end of the branch

α_1 = angle from the horizontal from the observer to the beginning of the branch

α_2 = angle from the horizontal from the observer to the end of the branch

D_3 = length of the branch

α_3 = elevation of the branch from the horizontal

Figure 4.50 the darker line designates the branch to be measured.

To measure the diameter of a branch up in the tree, an indirect method had to be used. Firstly, a calibration image of another feature of known height or width and distance was obtained. This image was then measured either with a ruler or a vernier. With the same focal length (zoom) the image was taken of the branch to be measured for the purpose of diameter determination. At the same time, using the laser rangefinder, the range from the observer to the branch was also taken. In place of a camera, the human eye was used as the fixed focus camera. A vernier or ruler was held at arm's length to measure the virtual dimensions of the target branch or reference feature. In the case of the conducted tree surveys, reference features like a steel post or concrete slabs were used. Figure 4.51 illustrates the concept of the determination of target dimensions using relative distances and dimensions.

Figure 4.51 Estimating feature dimensions using relative distances and image dimensions

Using the concept of relative distances and image dimensions, the feature dimensions that need to be determined are as follows;

$$A_f = \frac{I_f \times A_r \times D_f}{D_r \times I_r} \quad (4.11)$$

where,

D_r = distance from the reference feature

D_f = distance from the feature

A_r = actual dimension of the reference feature

A_f = actual dimension of the feature

I_r = image height of the reference feature

I_f = image height of the feature

Using the new surveying method to survey the trees, three dimensional trees comprising of the trunks and the main branches could be generated. Weight, volume, centroid and static bending moments could also be determined. It was also found that the time required to survey a tree was proportional to the number of major branches that had to be captured. The time required ranged from half an hour for a simple *Syzygium grande* to close to two hours for a more complex *Samanea saman*.

4.7 Numerical modelling and model verification

The numerical modelling of the shallow root plate was performed using Microsoft EXCEL, SVFLux, SIGMA/W and finally ANSYS. Microsoft EXCEL was used to perform modelling using the shallow root and heart root model mentioned in Chapters 2 & 3. SVFLux was used to model one dimensional infiltration, pore-water pressures and evapo-transpiration. SIGMA/W was used to model the effect of ground water table on tree stability. ANSYS was used to perform a three dimensional parametric study on the effects of root architecture on tree stability.

4.7.1 Numerical modelling using Microsoft EXCEL

The shallow root model described in Chapter 3 comprised a series of closed form equations (Equations 3.3 to 3.9) that were suited to modelling in Excel. The parameters used for input into the shallow root model were obtained using the results of the greenwood testing, structural surveys performed on the five trees at the two

sites, the soil tests performed on samples from the two sites, and assumptions of drag forces on the trees. Using the shallow root model, tree resistances to uprooting failure could be plotted with different root CSA for the different trees. The results are shown in Chapter 5 and discussed in Chapter 6. Also performed using the shallow root plate model was the modelling of past field tree pulling experiments. The results of the modelling were verified using the results from the field testing.

In addition to the shallow root model, the heart root model was also used in EXCEL to compare the effect of ground water depths, canopy shapes and root sizes on the tree's resistance to lateral loads.

4.7.2 Numerical modelling using SVFLUX

Seepage analysis was conducted using using SVFLUX (Soilvision Ltd, 2009). The objective of the numerical modelling was to obtain the complete profile of pore-water pressure for the field measurement time period. The results of the numerical model were then verified with data from the field measurements points. The results of the seepage analyses were then used as input for the tree stability analysis.

The model for the seepage analysis is shown in Figure 4.52. The seepage analysis was 1-dimensional (1-D) with a height of 5 m. The SWCC and permeability function were the main input data for the numerical modelling and the values were taken from the laboratory measurements described in the previous section. The boundary condition used at the bottom of the model was total head being equal to the initial water table and at the top of the model was the flux boundary condition which included rainfall and potential evaporation. The potential and actual evaporations in the model were calculated from the measured meteorological data using the Wilson et al., 1997 equation. Three measurement points similar to the field measurements points were chosen from the model for results comparison. The initial condition for the model was a water table at a depth of 0.96 m from the ground surface. The soil matric suction was varied hydrostatically below the ground water table and the above groundwater initial suctions were read from the field tensiometer readings.

Figure 4.52 1-D numerical seepage model used in SVFLux (Soilvision Ltd, 2009)

4.7.3 Numerical modelling using SIGMA/W

SIGMA/W was used to analysis the 2D stress and strain distribution parametrically within the tree trunk, its root plate and the soil due to lateral/wind loading. In this analysis, only two large diameter lateral roots were taken into consideration as a simplification of the tree architecture. Effects of anchor roots and tap roots to the tree's stability were neglected as the program SIGMA/W could not model the root and the soil as two separate entities. The parameters used in the numerical modeling were derived either from experimental results or based on past literatures (Table 4.3).

Table 4.3 Parameters based on past research literatures and experimental data

Parameters	Values	Sources
Tree Modulus of Elasticity	1400000 kPa	<i>Khaya grandifoliola</i>
Tree Modulus of Rupture	64700 kPa	<i>Khaya grandifoliola</i>
Tree Unit Weight	10 kN/m ³	<i>Khaya grandifoliola</i>
Tree Girth	1.75 m	NParks (2009)
Root Plate Thickness	0.25 – 1m	NParks (2009)
Tree Height	20 m	NParks (2009)
Root Plate Length	6 – 10 m	NParks (2011)
Force Lever Arm (20m tree)	13.08 m	Keong (2004), Rahardjo et al. (2009)

Figure 4.53a shows the schematic diagram used in the numerical modeling. In this analysis, the tree was simplified as a footing. The root plate was segmented into different regions of decreasing modulus of elasticity with increasing distance from the trunk (Figure 4.53b). This was to simulate the tapering effect of the lateral roots away from the trunk. One of the variations of modulus of elasticity along the root plate is shown in Figure 4.53b and the rest are shown in the Appendix. The soil was restricted in horizontal displacement on its side boundaries and both horizontal and vertical displacement at the base boundary. Tree failure was deemed to have occurred when the soil experienced more than 15% strain (ASTM D4767) or the tree or root plate experienced more than 5% strain at its extreme fibers (Lee, 2012). The point load to have caused tree failure at 13.08 m (Table 5.16) above ground level was recognized as the failure wind load. The simulation was run at varying depths of water table and root plate dimensions to determine their influence in tree stability. The soil pore water pressures were varied hydrostatically from the ground water table (positive and negative).

Figure 4.53. Schematic diagram of model used in numerical modeling in SIGMA/W
a) Groundwater table (dotted line), soil restraints (fixed at boundaries). b) Variation of root elastic modulus with distance from the bole (trunk)

Tree dimensions were assumed from past literature (Table 4.3). Properties of root and soil were obtained from works by Rahardjo et al. (2009), in which topsoil was selected in these analyses. Groundwater level at zero depth, i.e. at ground surface was assumed, to represent a critical condition.

As soil plays an important role in tree stability in regard to uprooting, maximum strain in the soil was the main failure criterion in this numerical model, i.e. 20% as outlined in ASTM D4767 (2011). However, a maximum strain of 15% was used in this project to be more conservative.

4.7.4 Numerical modelling using ANSYS

ANSYS was used to perform static structural analysis of three dimensional finite element root plate models. A parametric study was performed in ANSYS to determine the effects of variation in the different structural components of the tree root plate like lateral root spread, lateral root dimensions, sinker root number, sinker root depth and effects of cut roots on stresses and strains experienced by the root model. In addition to the root parameters, the soil elastic modulus and yield strengths were also varied parametrically to see the effects on maximum equivalent stresses and deformations in the root model.

The static structural module found within ANSYS was used because it could model the interaction between the soil and tree roots. The connection type between the roots and the soil could be modelled in ANSYS using a frictional sliding coefficient (0.6) akin to using the tangent of the friction angle ($\tan\phi'$) of about 30 degrees (SA soil ϕ' was 34° and TBR soil ϕ' was 32°) This frictional coefficient would be automatically used by ANSYS to calculate the amount of frictional restraint provided by the root-soil interface.

Figure 4.54a shows a three dimensional tree root model drawn without the soil in ANSYS for the purpose of performing the parametric study. Figure 4.54b shows the same tree root model together with the soil. The soil block was fixed on all sides. Gravity and the applied moment loads were applied in a ramped manner over one time step. Figure 4.55 shows an example of the loaded root plate model with the soil hidden from view, and the un-deformed shape shown as a shadow. The parameters used and the results are shown in Chapter 5.

a)

b)

Figure 4.54 A three dimensional tree drawn and rendered in ANSYS for the purpose of performing the static structural analyses required for the parametric study a) The root model comprising of trunk, lateral roots and sinker roots. b) The root model inserted into the soil block.

Figure 4.55 The deformed and un-deformed shapes of the root plate model used in the root plate parametric study with the locations and magnitude of the stress concentrations highlighted.

CHAPTER 5 Presentation of Results

5.1 Greenwood testing

Four-point and subsequently three-point flexural tests were performed on greenwood branch samples from several tree species obtained from the field. The four-point and three-point bending test results are presented in Sections 5.1.1 and 5.1.2 respectively.

5.1.1 Four point flexural testing

For *Samanea saman*, an average peak stress or modulus of rupture (MOR) of 37.7 MPa was recorded and the average secant modulus of elasticity was 791 MPa at peak stress. The average strain (Equation 4.3) where peak stress was observed was about 5%. Table 5.1 shows a summary of the three species tested to date using the four-point bending apparatus. The failure strain observed for all tree species were similar, however, the modulus of rupture (MOR) were different for all the species.

Table 5.1 Average values recorded during the four-point flexural testing performed for several species of common roadside trees in Singapore

Tree species	Average greenwood density (Mg/m ³)	Average oven dried wood density (Mg/m ³)	Moisture content (water as % of greenwood mass)	Moisture content (water as % of oven dry mass)	Average peak flexural stress MOR (MPa)	Average peak Strain (%)	Secant modulus of elasticity (MPa)	No. of samples
<i>Peltophoreum pterocarpum</i>	0.79	0.45	0.43	0.74	54.7	4.5	1215	31
<i>Samanea saman</i>	0.61	0.38	0.37	0.59	37.7	4.7	791	63
<i>Khaya grandifoliola</i>	0.68	0.41	0.40	0.66	64.7	4.6	1400	32

5.1.2 Three point flexural testing

Three point bending tests were carried out on eight species of common wayside tree species in Singapore. The data were analyzed using boxplots and

subsequently six order polynomials were fitted to the median stress strain curves to provide a median stress strain that could be utilized in any application that requires stress properties over a strain range.

Boxplots are a convenient way of graphically depicting groups of numerical data within ranges or categories through the use of their quartiles. They are also called box and whisker plots. The end of the upper whisker shows the maximum value within the data set for the range or category in the X-axis. The top of the box shows the 75% quartile value, the mid-box line shows the median value and the bottom of the box shows the 25% quartile value. The end of the bottom whisker shows the minimum value of the data set within the defined range. Boxplots of the stress strain curves help to filter the results so that different species can be compared, through the medians with the quartiles acting as the confidence intervals. The boxplot results for each species are presented from Figure 5.1 to Figure 5.8

Figure 5.1 Three point bending tests obtained stress-strain properties of *Syzygium grande* charted using boxplots (42 samples).

Figure 5.2 Three point bending tests obtained stress-strain properties of *Khaya senegalensis* charted using boxplots (39 samples).

Figure 5.3 Three point bending tests obtained stress-strain properties of *Samanea saman* charted using boxplots (38 samples).

Figure 5.4 Three point bending tests obtained stress-strain properties of *Tabebuia rosea* charted using boxplots (33 samples).

Figure 5.5 Three point bending tests obtained stress-strain properties of *Peltophorum pterocarpum* charted using boxplots (31 samples).

Figure 5.6 Three point bending tests obtained stress-strain properties of *Syzygium polyanthum* charted using boxplots (38 samples).

Figure 5.7 Three point bending tests obtained stress-strain properties of *Pterocarpus indicus* charted using boxplots (38 samples).

Figure 5.8 Three point bending tests obtained stress-strain properties of *Swietenia macrophylla* charted using boxplots (38 samples).

The average peak flexural stress (MOR), flexural strain at MOR and average secant modulus of elasticity (MOE) are also summarized using boxplots for the various species as shown from Figure 5.9 to Figure 5.11.

Figure 5.9 Boxplots of the peak recorded flexural stress (MOR) for the eight common wayside tree species

Figure 5.10 Boxplots of the recorded strain at the peak recorded MOR for the eight common wayside tree species obtained from three-point flexural testing.

Figure 5.11 Boxplots of the calculated secant modulus of elasticity to MOR for the eight common wayside tree species obtained from three-point flexural testing.

Generally, the failure strain at MOR for the eight different species was observed to decrease with rising MOR and secant modulus of elasticity to MOR with the exception of *Tabebuia rosea* (Figure 5.11). Higher MOR was also generally shown to be mirrored by higher secant modulus of elasticity.

As per the four-point flexural testing, the following greenwood properties were also recorded from freshly cut samples in the field.

- 1) Wet density (Figure 5.12)
- 2) Oven dried density (Figure 5.13)
- 3) Moisture content as a percentage of wet mass (Figure 5.14)
- 4) Moisture content as a percentage of dry mass (Figure 5.15)

Figure 5.12 Box plots of the wet or greenwood densities for the eight tested species obtained from three-point flexural testing.

Figure 5.13 Box plots of the oven dried densities for the eight tested species obtained from three-point flexural testing.

Figure 5.14 Box plots of the moisture contents as a percentage of wet mass, for the eight tested species obtained from three-point flexural testing.

Figure 5.15 Box plots of the moisture contents as a percentage of dry mass, for the eight tested species obtained from three-point flexural testing.

5.2 Site investigation results from Silat Ave (SA) and Telok Blangah Rise (TBR)

The testing of the soils found at both locations was confined to samples obtained within the depth of 1.5 m (root zone). This was because, observations from trial pits dug beside the trees at both sites, showed that the presence of tree roots was mostly found within the first 0.5m of soil. Figure 5.16 shows an example of a trial pit dug beside the *Syzygium grande* trees at Silat Ave showing the trees roots. Volumetric water content sensors were installed at 0.5, 1.0 and 1.5m. Few tree roots were seen below the 0.5m sensor. The perched water table was also found to be at about 1.5m for both sites.

Figure 5.16 Trial pit dug at Silat Ave showing the presence of tree roots above the 0.5m depth volumetric water sensor and the water table found at the 1.5m mark.

The soils from Silat Ave and Telok Blangah Rise were both generally classified as sandy clay (SC). The main differences in the soils found at both locations were in their gravel and sand contents. The soil obtained from Silat Ave was found to have significantly more sand than gravel in its soil distribution, whereas the soil

obtained from Telok Blangah Rise was found to have more gravel than Silat Ave. The % fines at both sites are relatively the similar at 50%. Figure 5.17 and Figure 5.18 show the grain size distribution of Silat Ave and Telok Blangah Rise respectively.

Figure 5.17 Grain size distribution of the soil obtained from Silat Ave.

Figure 5.18 Grain size distributions of the soil from Telok Blangah Rise.

Table 5.2 and Table 5.3 show the results of the laboratory tests to obtain the saturated hydraulic, strength and index properties of the soil at Silat Ave (SA) and Telok Blangah Rise (TBR) respectively.

Table 5.2 Laboratory measured soil properties at Silat Ave

Unified Soil Classification System	
Group name	Sandy Clay
Group symbol	SC-CL
Specific gravity G_s	2.67
Total density, ρ (Mg/m^3)	1.95
% Gravel	4.9
% Sand	44.6
% Fines	50.5
Atterberg Limits	
Liquid Limit, LL (%)	30
Plastic Limit, PL (%)	17
Plasticity Index, PI (%)	13
Permeability	
Laboratory Triaxial Saturated Coefficient of Permeability, k (m/s)	
	10^{-8}
Shear Strength	
Friction angle, ϕ' ($^\circ$)	34
Cohesion, C' (kPa)	0

Table 5.3 Laboratory measured soil properties at Telok Blangah Rise

Unified Soil Classification System	
Group name	Sandy Clay
Group symbol	SC-CL
Specific gravity G_s	2.46
Total density, ρ (Mg/m^3)	1.7
% Gravel	16.6
% Sand	30.5
% Fines	52.9
Atterberg Limits	
Liquid Limit, LL (%)	35
Plastic Limit, PL (%)	19
Plasticity Index, PI (%)	16
Permeability	
Laboratory Triaxial Saturated Coefficient of Permeability, k (m/s) (1.5 m depth)	10^{-8}
Shear Strength	
Friction angle, ϕ' ($^\circ$)	32
Cohesion, C' (kPa)	3

Separate field double o-ring infiltrometer tests were conducted at both sites to obtain the surface saturated permeability of the soil which often differ from the laboratory triaxial tests by a few orders. The results are shown in Table 5.4

Table 5.4 Field measurements of saturated permeability at Silat Ave and Telok Blangah Rise using double ring infiltrometers.

Silat Ave, (m/s)	4.37×10^{-4}
Telok Blangah Rise, (m/s)	1.13×10^{-3}

Figure 5.19 and Figure 5.20 present the soil-water characteristic curves (SWCC) of Silat Ave and Telok Blangah Rise respectively. The sample for Silat Ave

had an air entry value (AEV) of 25 kPa. Samples for TBR had an AEV of 15 kPa. However, since typically finer particles have a higher AEV (Fredlund and Rahardjo, 1993), therefore, it can be seen that SA soil had an air entry value of 25 kPa.

Figure 5.19 Laboratory measured SWCC of the soil sample obtained from Silat Ave (SA) with the Fredlund & Xing (1994) fitted curve in green using a correction factor of 1 suggested by Leong & Rahardjo (1997) to better fit the low suction range used in the measurements

Figure 5.20 Laboratory measured SWCC of the soil sample obtained from Telok Blangah Rise (TBR) with the Fredlund & Xing (1994) fitted curve in green using a correction factor of 1 suggested by Leong & Rahardjo (1997) to better fit the low suction range used in the measurements

5.3 Typical site instrumentation results from Silat Ave (SA) and Telok Blangah Rise (TBR)

This section shows some of the typical site results for both SA and TBR obtained from the instrumentation installed that is described in Chapter 4. The data of two time periods in 2013 are shown: 11th March – 18th March 2013 (low rainfall period) and 7th October – 14th October 2013 (high rainfall period).

5.3.1 Pore-water pressure, volumetric water content, air/soil temperature, groundwater table and rainfall

Figure 5.21 to Figure 5.24 show pore-water pressures, volumetric water content, air/soil temperatures and rainfall data for SA between 7th January and 14th January 2013. Figure 5.21 shows the comparison of pore-water pressure and rainfall through the week. Pore-water pressures through the week generally rose and fell

slightly due to the variation in the temperature between day and night; matric suctions rose in the day and dropped at night. However, during the three rainfall occurrences on the 8th of January, 11th and 12th of January 2013, a sharp spike in pore water pressures could be seen down to a depth of 1.5 m. The tensiometer at 1.5 m registered the smallest change in pore-water pressure throughout this period. This was consistent throughout the entire monitoring period, which shows that rainfall could affect the pore-water pressures in the soil at 1.5 m by building up the positive pore-water pressures at SA.

Figure 5.22 shows the comparison of water content measurements and rainfall. Similar observations of volumetric water contents could be seen showing little to no changes in water content measurements through the week except during the rainfall events. At 0.5m, the water content was generally below 40% when there was no rainfall, whereas at deeper depths, the water content was generally higher than 50%. The 1.5 m time domain reflectometer (TDR) also showed little change in water content during the rainfall. This confirmed that the water table was located close to the depth of 1.5 m at SA.

Figure 5.21 Pore-water pressure comparison against rainfall graph (SA)

Figure 5.22 Water content comparison against rainfall graph (SA)

Figure 5.23 shows the changes in soil temperature at various depths through the week. Observation shows that there were only changes in soil temperature at 0.5m according to time of day and during rainfall events. Beyond that, soil temperature was more or less constant at deeper depths. This showed that the soil was a very good insulator against variation in temperatures at depths deeper than 1m. This also implied that the temperature effects of infiltration, evaporation and transpiration (leading to heat exchange) occurred mainly near the surface. The changes in water content through the soil at depths greater than 1.0 m were mainly caused by groundwater level changes in depth, seepage from higher total head and by horizontal drainage to nearby drains and weep holes.

The stability of the volumetric water contents and temperature at depths greater than 1.0 m also could imply that the perched or permanent groundwater table could be located at that depth of 1.0 m.

Figure 5.23 Soil temperature comparison against rainfall graph (SA)

Figure 5.24 shows the comparison between soil, air temperatures and rainfall. The air temperature response is according to the sun's position in the sky. However, the temperature in the soil showed very little response ($< 1^{\circ}\text{C}$) to day and night effects and stays fairly constant and highly damped in its response. Air temperatures at the site dropped drastically during rainfall events (33°C to 24°C on the 8th of January) and Figure 5.24 highlights this observation. Air temperature recovery back to the mean value was observed to take place in a matter of hours whereas soil temperature at 0.5 m was seen to take as many as 3 days to recover after a heavy rainfall event. This was also mirrored in the time (3 days) taken for volumetric water content to recover to mean value at the 0.5 m depth. This discrepancy between temperature recovery times between air and soil could be explained firstly by the large differences when comparing the heat capacities of air to water/soil. Another explanation was that the temperature change (reduction) in soil was dependent on the rainfall amount rather than air temperature reduction. The recovery in the soil temperatures was dependent on the volumetric water content changes. The average air temperature recorded at SA was about 28°C which corresponded to the average soil temperature.

Figure 5.24 Soil and air temperature comparison against rainfall graph (SA)

Figure 5.25 to Figure 5.28 show the pore-water pressure, volumetric water content, air/soil temperatures and rainfall data for TBR between 7th January and 14th January 2013. Figure 5.25 compares the changes in pore-water pressure over the week. Similar to the results for the same period in SA, pore-water pressures through the week generally rose and fell slightly due to the temperature of the day; rising in the day and dropping at night. There were some problems with the 1.5m tensiometer on the 11th of January and the data ($>50\text{kPa}$) at this depth was considered as unreliable and should be disregarded. Otherwise, the other peaks in the pore-water pressure occurred only during rainfall events. The pore-water pressures at all the depths showed a reading close to 0 kPa for the period.

The constant pore-water pressures could be explained by the fact that the instrumented site at TBR was located at the toe of a steep hill. Therefore seepage from the hill could continue for many days after the rainfall event and lead to long periods (many days) of elevated pore-water pressures.

Figure 5.25 Pore-water pressure comparison against rainfall graph (TBR)

Figure 5.26 shows the changes in water content against rainfall through the week. Similar observations for SA also occurred at TBR. The rise in water content only during the rainfall events proved that the pore-water pressure readings at 1.5m to be higher than 40 kPa as shown in Figure 5.25 were false. There were problems taking pore-water pressure readings at that depth subsequently at both sites of SA and TBR. Also common to both sites was that the water content readings at SA and TBR never recovered sufficiently to go back to the mean values before the next rainfall event on the 11th January 2013. The slow rate of recovery in the negative pore-water pressures and volumetric water contents show that the soil at TBR and SA remained wet; and therefore, weaker for a long period of time after rainfall. Another observation was that the pore-water pressures at SA were slightly more negative compared to TBR. This meant that with similar soil properties, the soil at SA was in general stronger than at TBR.

Figure 5.26 Water content comparison against rainfall graph (TBR)

Figure 5.27 shows the changes in soil temperature in TBR in response to rainfall through the week. Similar observations to SA show that only soil near the surface (< 1.0 m) show changes in temperature due to rainfall events. Deeper soil was more or less constant in temperature readings. Interestingly, mean soil temperatures in SA (28 – 29 degrees Celsius) were slightly higher nearer the surface than in TBR (26 – 27 degrees Celsius). This can be explained by the slightly higher pore-water pressures seen in TBR compared to SA. As the soil at SA dried faster, the water content reduced more with consequential larger increases in air content. Air temperature showed higher variation and higher mean temperature. Therefore, the mean soil temperature at TBR will be lower than the mean air temperature while the soil temperature at SA will be closer to the mean air temperature.

Similar observations are shown in Figure 5.28 which shows the changes in air and soil temperatures in response to day and night effects and rainfall events. Peak and low air temperatures were similar in both SA and TBR.

Figure 5.27 Soil temperature comparison against rainfall graph (TBR)

Figure 5.28 Soil and air temperature comparison against rainfall graph (TBR)

Taking a longer view (slightly more than 1 year) of the monitoring period to observe the differences between normal and dry weather conditions Figure 5.29 shows that between rainfall events, time taken to recover to the equilibrium soil water contents was about 10 days. The first four months of 2014 was a period of dry weather, however there was only a small reduction in water content readings below

the equilibrium water contents for the 10 day recovery water contents. The peak readings of water contents at the 1.5 m depth was lower after the dry period as the groundwater table was depressed slightly (about 0.4 m lower) as a result of the dry period (Figure 5.30). The ground level of SA was 104.8 m and the measured groundwater elevation was between 103.0 – 103.5 m. This showed that the groundwater depth at SA was about 1.5 m depth

Figure 5.29 1 year of water content monitoring with the accumulative rainfall at SA

Figure 5.30 1 year of water content monitoring with groundwater elevation at SA.

A similar longer term view of TBR water contents was also plotted and shown in Figure 5.31. At TBR, the water contents were shown to be higher than SA for the 1.0 m depth and these readings were also closer to the 1.5m depth readings. However the 0.5m water content readings were much lower, going below 20% during the dry

spell. There was also a depressed groundwater table elevation after the dry spell (Figure 5.32). The elevation at ground level at TBR was measured at 125.5m. The recorded groundwater elevation was about 124.5m. The groundwater table at TBR was even shallower than at SA therefore the 1.0m and 1.5m water content readings were similar.

Figure 5.31 1 year of water content monitoring with the accumulative rainfall at TBR

Figure 5.32 1 year of water content monitoring with groundwater elevation at TBR

5.3.2 Potential evaporation from flux boundary parameters

Climatic parameters that determine flux boundary conditions in TBR and SA are described in this section. There are generally five climatic parameters that affected flux boundary conditions: rainfall (precipitation), air temperature, relative humidity, wind speed and solar radiations. These parameters were recorded at both sites as described in Chapter 4.

The total monthly rainfall in TBR and SA are presented in Figure 5.33 and Figure 5.34. The maximum total monthly rainfall for TBR was on the month of November 2012 of 175mm. The total amount of rainfall recorded in SA for the month of November 2012 was 181mm. However, the highest total monthly rainfall for SA was recorded in the month of February 2013 amounting to 248 mm. The trend of the monthly rainfall for TBR and SA were generally similar except for the month of February 2013. The variation of rainfall in the month of February 2013 was explained by Chatterjea, 1989. Chatterjea, 1989 reported that in Singapore, the variation of rainfall for different stations in the island could be quite significant. The maximum amount of rainfall occurred in November 2012 and February 2013 for TBR and SA Site, respectively. This was a bit different compared to the statistical data compiled by National Environmental Agency (NEA) (NEA, 2010). The statistical data showed that maximum rainfall usually occurred in the months of December and January. However, the amount of total monthly rainfall of around 200 mm was in the same order with the statistical data provided by NEA (NEA, 2010).

Figure 5.33 Total monthly rainfall in TBR Site

Figure 5.34 Total monthly rainfall in SA site

The monthly average, maximum and minimum temperature in TBR and SA Sites are shown in Figure 5.35 and Figure 5.36. The average, maximum and minimum temperature in both TBR and SA site was similar of around 27, 34 and 21°C, respectively. These values were almost similar to the values reported in Rahardjo et. al., 2012 except for the maximum and minimum values in Rahardjo et. al., 2013 was 31 and 24°C respectively. The difference could be attributed to the effects of climate change as reported by several researchers with regards to extreme temperature (Astrom et al, 2013).

The monthly average, maximum and minimum relative humidity in TBR and SA sites are shown in Figure 5.37 and Figure 5.38 respectively. The average, maximum and minimum relative humidity in both TBR and SA were 80%, 100% and 50% respectively. These values were also higher compared to the values reported in Rahardjo et. al., 2012. The monthly average, maximum and minimum wind speed in TBR and SA sites are shown in Figure 5.39 and Figure 5.40. The maximum wind speed could be as high as 10x the average wind speed. The average wind speed was in the range of 0.3-0.5 m/s while the maximum wind speed was in the range of 3-4 m/s.

The average, maximum and minimum solar radiation at both TBR and SA are shown in Figure 5.41 and Figure 5.42 respectively. The average solar radiation was considerably smaller than the maximum solar radiation because the majority of the radiation occurs only in the day (after sunrise to sunset). The maximum solar radiation recorded was in SA Site of approximately 1200 W/m². The average solar radiation from both sites was in the range of 150-200 W/m². Solar radiation is a key component for potential evaporation calculation. The potential evaporation calculated using Penman equation based on the climatic parameters recorded in TBR and SA are presented in Figure 5.43 and Figure 5.44. The trends of the potential evaporation for TBR and SA were similar. The trend followed the average solar radiation trend showed in Figure 5.41 and Figure 5.42. The highest potential evaporation was recorded in the month of September 2012 in TBR site of around 9 mm/day whereas the lowest potential evaporation rate was recorded in the month of February 2013 of around 4.2 mm/day.

Figure 5.35 Monthly average, maximum and minimum temperature in TBR

Figure 5.36 Monthly average, maximum and minimum temperature in SA

Figure 5.37 Monthly average, maximum and minimum relative humidity in TBR

Figure 5.38 Monthly average, maximum and minimum relative humidity in SA

Figure 5.39 Monthly average, maximum and minimum (zero) average-windspeed in TBR

Figure 5.40 Monthly average, maximum and minimum (zero) average-windspeed in SA

Figure 5.41 Monthly average, maximum and minimum (zero) solar radiation in TBR

Figure 5.42 Monthly average, maximum and minimum (zero) solar radiation in SA

Figure 5.43 Monthly average daily potential evaporation calculated from monthly average meteorological data for TBR

Figure 5.44 Monthly potential evaporation calculated from monthly average meteorological data for SA.

5.3.3 Field wind load measurements at Silat Ave and Telok Blangah Rise

The field wind load instrumentation (LVDTs) installed in the field at Silat Ave and Telok Blangah Rise is described in Section 4.4. The measurements of axial deformations were translated into strains, flexural stresses, bending moments and wind forces acting on the trees. The parameters used included the modulus of elasticity and rupture of the tree species, the tree trunk section properties, the tree architecture, wind directions and wind speeds.

5.3.3.1 Equations and assumptions

Two LVDTs were installed in each tree. The LVDTs were programmed to start measurements when wind speed was equal to or above 3m/s. The LVDTs were designated LVDT1 and LVDT2. The list of parameters is shown below:

θ_1 is the azimuth angle that LVDT1 makes to magnetic north

θ_2 is the azimuth angle that LVDT2 makes to magnetic north

L_1 is the measured length of LVDT1

L_2 is the measured length of LVDT2

δ_1 is the measured linear displacement by LVDT1

δ_2 is the measured linear displacement by LVDT2

ϵ_1 is the axial strain measured by LVDT1

ϵ_2 is the axial strain measured by LVDT2

I_1 is the average second moment of area of the length of section measured by LVDT 1

I_2 is the average second moment of area of the length of section measured by LVDT 2

σ_1 is the average flexural stress on the outermost fiber experienced by the section measured by LVDT 1

σ_2 is the average flexural stress on the outermost fiber experienced by the section measured by LVDT 2

M_1 is the bending moment experienced by the section measured by LVDT1

M_2 is the bending moment experienced by the section measured by LVDT2

C_z is the center of area of the tree measured in the vertical axis

H_1 is the average height of LVDT1 above the ground

H_2 is the average height of LVDT2 above the ground

R_1 is the average radius of the tree at the measured section of LVDT1

R_2 is the average radius of the tree at the measured section of LVDT2

E is the median field measured, greenwood modulus of elasticity for the tree species

F_I is the wind force in the direction of LVDT1

F_2 is the wind force in the direction of LVDT2

F_{IN} is the wind force F_I in the direction of north

F_{IE} is the wind force F_I in the direction of east

F_R is the resultant force

θ_{FR} is the resultant direction

By resolving the directions of the measured wind and measured tree strains to North and East, we can see the trees' responses in different directions. The equations presented are for LVDT1 and are the same for LVDT2 using LVDT2 parameters.

$$\epsilon_1 = \frac{\delta_1}{L_1} \quad (5.1)$$

$$\sigma_1 = E \times \epsilon_1 \quad (5.2)$$

$$M_1 = \frac{\sigma_1 I_1}{R_1} \quad (5.3)$$

$$F_1 = \frac{M_1}{C_z - H_1} \quad (5.4)$$

$$F_{1N} = F_1 \cos \theta_1 \quad (5.5)$$

$$F_{1E} = F_1 \sin \theta_1 \quad (5.6)$$

$$F_R = \sqrt{F_{1N}^2 + F_{1E}^2} \quad (5.7)$$

$$\theta_{FR} = \tan^{-1}\left(\frac{F_{1N}}{F_{1E}}\right) \quad (5.8)$$

Using Equations 5.1 to 5.8, the wind force could be charted against date and time.

5.3.3.2 Silat Avenue wind and tree (*Syzygium grande*) response characteristics

Figure 5.45 shows the wind force and wind speed charted against date for the month of December 2013.

Figure 5.45 The resultant wind force F_R and wind speed plotted for the month of December 2013

Figure 5.45 also shows that F_R does not track the wind speed exactly. However prolonged wind gust of higher speeds do produce larger responses from the tree. Figure 5.46 shows the frequency distribution of the wind direction and the tree

direction in the month of December 2013 presented in a wind rose format (Silat Ave *Syzygium grande* 1).

Figure 5.46 The wind rose and the tree movement directions for the Silat Ave *Syzygium grande* in the month of December, 2013.

Figure 5.46 shows that the tree moves predominately in the east west direction, even though the wind is coming from the NW-NNW direction. The accumulative movement of a tree can be plotted against the accumulative wind. Figure 5.47a shows that a daily total wind is proportional to the daily total tree movement. Figure 5.47b shows that when the wind speed and the tree movement is resolved to north and east, the easterly wind has a much higher effect on the tree than the northerly wind. The easterly wind has approximately 2.5 times the effect of the northerly wind in producing a tree movement in the direction of the wind.

a)

b)

Figure 5.47 a) for the month of December, the daily total wind produces a proportional tree movement detected by the LVDTs b) when resolved to the north and east directions, the resolved easterly winds have approximately 2.5 times more effect on tree movements in the wind direction than the northerly winds.

The recorded forces and wind speeds were low for the month of December with high factors of safety for the *Syzygium grande* 1 at Silat Ave. The tree at Silat Ave was relatively sheltered with many trees and structures surrounding it. The tree is the last tree in a row that is in the north south direction and this may account for the large amount of shielding from the winds originating from the north.

From the shallow root tree stability model for *Syzygium grande* 1 at Silat Ave, the maximum recorded wind speed of 6.3m/s (22.7km/h) in December 2013 saw the minimum root plate factor of safety to be always above unity (Critical wind speed 177.7km/h). With the basal diameter of 0.732 m, and a median modulus of rupture of (50MPa), the maximum allowable bending moment before rupture is 2041 kNm or . The tree experienced only a maximum bending moment of about 34.7 kNm giving a factor of safety against basal trunk snap of about 59. Figure 5.48 shows the reduction in basal diameter required for the tree to experience trunk basal failure due to the experienced wind load of 4239 N.

In January, 2014, the total wind increased considerably over the month of December, 2013. Figure 5.49 shows the wind speed and the force on the tree plotted with time. Although the total wind increased considerably, the peak force on the tree was still well below the capacity of the tree both in uprooting or trunk snap failures. The first ten days of January showed low wind speeds as the threshold of 3 m/s wind speed was not activated at all.

Figure 5.48 Basal diameter reduction to 0.167m from 0.731m required to fail under the maximum experienced wind load in December 2013 for the *Syzygium grande* at Silat Ave.

Figure 5.49 The resultant wind force F_R and wind speed plotted for the month of January, 2014.

The wind/tree movement rose is shown in Figure 5.50. Compared to the month of December, 2013, the tree showed an even more biased movement in the east west direction. The wind direction was still predominately the same in the NW and NNW direction.

Figure 5.50 The wind rose and the tree movement directions for the Silat Ave *Syzygium grande* in the month of January, 2014.

The threshold wind speed of 3m/s was breached more often in January, 2014 compared to December, 2013. Figure 5.51a shows that the wind speeds were consistent over the last 20 days of the month of January, 2014.

a)

b)

Figure 5.51 a) for the month of January, 2014, the daily total wind produces a proportional tree movement detected by the LVDTs b) when resolved to the north and east directions, the easterly winds have approximately 2.9 times more effect on tree movements in the wind direction than the northerly winds due to the layout of the site at SA.

Figure 5.52 shows the layout of the instrumentation site at SA where the *Syzygium grande* that had the LVDTs installed were shielded from winds from the north, northeast and northwest directions that were prevalent in the month of January, 2014. There was a gap between the embankment and trees, and the nursing home in the NNW orientation to the instrumented tree.

To summarise the data from the LVDTs and the anemometer installed at Silat Ave for the months of December, 2013 to July, 2014, Figure 5.53 a & b show the total wind run and total response of the tree on a month by month basis. Even though the month of February, 2014 had the highest total wind run, there was no corresponding highest total tree reaction. This was because of the shielding effects of the site. March, 2014 had a higher total wind than January, 2014 but the total tree reaction for March, 2014 was lower than that of January, 2014. Figure 5.54 a-h show the wind and tree reaction frequency distribution presented in roses.

Figure 5.52 Layout of the instrumentation site where the *Syzygium grande* that had the LVDTs installed were shielded from winds from the north and northwest directions

a)

b)

Figure 5.53 Total wind and tree reactions on a monthly basis. a) Total wind, total wind East and total wind North. b) Total tree reaction, total tree reaction East and total tree reaction North.

Looking at Figure 5.54b, the gap allowed wind from the NNW direction (January, 2014) through to affect the instrumented tree more. However due to the shielding effects of *Syzygium grande* 2, the instrumented tree only moved in the EW direction. Figure 5.53 and Figure 5.54 show that, a change in wind direction has a big effect on the tree reaction totals and directions. This is because of the wind shielding

effects of the site. When the prevailing winds came from the southern, southwest and southeast directions, the tree response was generally opposite to the wind direction Figure 5.54g & h.

a) December, 2013

b) January, 2014

c) February, 2014

d) March, 2014

e) April, 2014

f) May, 2014

Figure 5.54 Wind and tree reaction distributions from December, 2013 to July, 2014.

5.3.3.3 Telok Blangah Rise wind and tree (*Samanea saman*) response characteristics

Figure 5.55 shows the wind force and wind speed charted against date for the month of December 2013. The peak recorded wind speed of 8.81 m/s on the 6th of December generated a peak force of about 6400N on the tree. Like the *Syzygium grande* at SA shown in Figure 5.45, the tree movement does not track the wind directions exactly but tracked sustained higher wind speeds.

Figure 5.56 shows the frequency distribution of the wind direction and the tree direction in the month of December 2013 presented in a wind rose format (Telok Blangah Rise *Samanea Saman*).

Figure 5.55 The resultant wind force F_R and wind speed plotted for the month of December 2013

Figure 5.56 The wind and the tree movement directions presented in the rose format for the Telok Blangah Rise *Samanea saman* in the month of December, 2013.

Figure 5.56 shows that the prevailing wind directions originated from the North, North-North-West and South-South-West directions. The tree responded in an almost circular fashion slightly favoring the East and West directions. Figure 5.57 shows that there were two relatively windless periods in the month of December, 2013 (represented by the flat portions of the blue wind line). There were 3 days with above average daily total wind, shown by 6th, 28th and 31st of the month of December, 2013. Figure 5.57b shows that the instrumented *Samanea saman* also showed a higher propensity to respond to Easterly and Westerly winds. The *Samanea saman* was shown to have a 2.2 times higher response to East-West direction winds than North-South directions winds.

a)

b)

Figure 5.57 Total wind and tree reaction for the month of December, 2013 a) for the month of December, the daily total wind produces a proportional tree movement detected by the LVDTs b) when resolved to the north and east directions, the easterly winds have approximately 2.2 times more effect on tree movements in the wind direction than the northerly winds.

The recorded forces and wind speeds were low for the month of December with high factors of safety for the *Samanea saman* at Telok Blangah Rise. The tree at Telok Blangah Rise was sheltered by being part of a row of roadside trees running in the North-West direction. The tree is the second tree in the row. This may account for the large amount of shielding from the winds originating in the North-South directions.

Figure 5.58 Basal diameter reduction to 0.249 m from 1.2 m required to fail under the maximum experienced wind load in December 2013 for the *Samanea saman* at Telok Blangah Rise.

From the shallow root tree stability model for *Samanea saman* 1 at Telok Blangah Rise, the maximum recorded wind speed of 8.1m/s in December 2013 saw the minimum root plate factor of safety against uprooting to be always above unity. With the basal diameter of 1.2 m, and a median modulus of rupture of (37 MPa), the maximum allowable bending moment before rupture is 6276 kNm. The tree experienced only a maximum bending moment of about 56.5 kNm giving a factor of safety against basal trunk snap of about 111. Figure 5.58 shows the reduction in basal diameter required for the tree to experience trunk basal failure due to the maximum experienced wind load of 6342 N. The lower median MOR of *Samanea Saman* (37 MPa) means that compared to *Syzygium Grande* (53 MPa), a larger basal diameter is required.

Like the *Syzygium grande* at Silat Ave, there was higher recorded total wind at Telok Blangah in the month of January 2014 compared to December, 2013. Due to the limitations of Microsoft Excel in handling large number of rows of data (>1,000,000 rows), the data had to be split and charted in separate files. Figure 5.59a

shows the *Samanea saman* 1 responding to wind changes in the period of 1st to 20th of January, 2014. Figure 5.59b shows the same from the 21st to the 31st of the same month.

Figure 5.59a & b also shows that the force experienced by the tree is not governed by the peak wind speed of the event but by how sustained the wind event is. This is because the wind transfer force with time as momentum. This momentum transfer has to overcome the inertia of the tree which is represented by its mass and drag.

Figure 5.60 shows the frequency distribution of the wind direction and the tree direction in the month of January 2014 presented in a wind rose format (Telok Blangah Rise *Samanea Saman* 1). The frequency rose shown in Figure 5.60 shows that the wind direction changed from that of December, 2013 to a North-Westerly wind. This wind induced an East-West reaction from the tree.

Figure 5.61a-d show the total wind and tree reaction recorded for the month of January, 2014. The Easterly winds were shown to have a 1.91 times higher effect on tree reaction than the Northerly winds. This is similar to the month of December, 2013.

a)

b)

Figure 5.59 The resultant wind force F_R and wind speed plotted for the month of December 2013 a) For the period of 1st to 20th of December. b) For the period of 21st to 31st of December.

Figure 5.60 The wind and the tree movement directions presented in the rose format for the Telok Blangah Rise *Samanea saman* in the month of January, 2014.

a)

b)

c)

d)

Figure 5.61 Total wind and tree reaction for the month of December, 2013 a) for the period of 1st to 20th January, 2014. b) for the period of 21st to 31st January, 2014. The daily total wind produces a proportional tree movement detected by the LVDTs. c&d) when resolved to the north and east directions, the easterly winds have approximately 1.91 times more effect on tree movements in the wind direction than the northerly winds.

Figure 5.62 Layout of the instrumentation site at TBR where the layout of the instrumentation site where the *Samanea saman* that had the LVDTs installed were shielded from winds from all directions except the East and West directions

Figure 5.62 shows that the instrumented tree at TBR was sheltered from almost all directions except the East and West directions. Therefore, the prevailing wind directions shown in Figure 5.64 a-i mostly produced a circular motion except for the month of January, 2014 where a prevailing wind with a NWW component probably produced the EW response from the tree.

a)

b)

Figure 5.63 Total recorded wind run and tree reaction. a) Total wind and resolved to East and North. b) Total tree reaction and resolved to East and North (the months of April to July experienced data acquisition problems with the LVDTs)

Figure 5.63 a&b show the total wind run experienced by the *Samanea saman* at Telok Blangah Rise and the monthly total tree reaction. The months of April and May, 2014 were devoid of LVDT data as there were data acquisition problems. Figure

5.63a shows that March, 2014 was the month that the site recorded the highest total wind. The lowest total wind was recorded in the month of December, 2013.

Figure 5.64 a-i show the wind and tree reaction frequency distribution presented in roses. The *Samanea saman* moves in a more circular motion with a smaller East-West bias of movement than the *Syzygium grande* in Silat Ave.

Figure 5.64 Wind and tree reaction distributions from a) December, 2013 b) January, 2013 c) February, 2014 d) March, 2014 e) April, 2014 f) May, 2014 g) June, 2014 h) July, 2014 (the months of April to July experienced data acquisition problems with the LVDTs)

5.4 Results of tree 3D laser scanning

3D laser scanning of trees described in Chapter 4 were performed on five trees; Two *Syzygium grande* and three *Samanea saman* were scanned and the results are shown in Figure 5.65 to Figure 5.68. Laser scanning of the trees created high density point clouds of the target with the points numbering in the millions per tree. Color data was also captured and assigned to each dot leading to photo realistic three dimensional representations of the target trees. From the captured point clouds, dimensions like canopy width and height, trunk dimensions and tree shape could be measured and visualized.

Figure 5.65 Photo realistic point cloud from the 3D laser scan of the *Syzygium grande* 1 at Silat Ave shown from the various views

After the point clouds were collected, they were meshed together using triangular elements and the resulting mesh for the *Syzygium grande* 1 from Silat Ave shown in Figure 5.65 is shown in Figure 5.66.

Figure 5.66 the same point cloud (*Syzygium grande* 1) meshed using triangular elements mesh. a) Resulting mesh scaled to enable simple dimensioning b) Tree height (18.7m). c) Trunk diameter (0.56m).

The *Syzygium grande* 1 was meshed successfully. However the mesh could not be imported into finite element analysis software due to fact that the generated mesh was not closed. The mesh was not closed because there were many gaps and

voids within the point cloud data. Without a closed mesh, material properties and section properties could not be assigned.

Figure 5.67 shows the non-colored point cloud of *Syzygium grande* 2 at Silat Ave after removing the background clutter. Like the *Syzygium grande* 1 shown in Figure 5.65 and Figure 5.66, the tree was captured in great detail by the laser scanner. Highlighted by the scan were the co-dominant stems growing from the base of the trunk. Complex tree shapes can be captured by the laser scans, but the laser scans cannot differentiate between wood and leaves and therefore between the branches and leaf canopy.

Figure 5.67 Non-colored point cloud of *Syzygium grande* 2 at Silat Ave capturing the co-dominant stems rising early from the base of the trunk.

The processed laser scan point clouds and meshed rendering of two *Syzygium grande* and one *Samanea saman* are shown in Figure 5.68. Their relative positions and relative sizes can be seen. Also captured in the laser scan are the numerous epiphytes that commonly make wayside *Samanea saman* their home.

Figure 5.68 The meshed two *Syzygium grande* and one *Samanea saman* at SA.

Notwithstanding the limitations of the 3D laser scanning method to generate small scale finite element models, the main usefulness of this survey method was as a visualization and reference tool. Using the 3D laser scanning method, large landscapes can be captured and virtually built up in the computer to locate the trees and the features surrounding them. The features include topography and urban structures like buildings, roads, street lighting and shelters. Figure 5.69 shows the photo compared to point cloud of the same captured landscape at SA. The laser scans of TBR are shown in Appendix II.

a)

b)

Figure 5.69 Scene of SA. a) A photo of SA. b) Captured point cloud of the same scene in SA.

5.5 Digitizing tree architecture using the new method (TSSM) to perform structural surveys on trees

Using the new method described in Chapter 3 to perform structural surveys and digitizing the tree architecture, the same five trees that were laser scanned were also surveyed, digitized and analyzed.

Table 5.5 shows the results of the structural survey for *Syzygium grande* 1 at Silat Ave. The results were for the cartesian coordinates of the end of the member and the average radius of the member. The XY plane was the horizontal plane and the Z axis was the vertical axis of the tree. Figure 5.70 shows the plotting rendering of the tree in 3D using CAD (computer aided design) software. Using the CAD software, the attributes of the tree could be measured when drawn as a series of geometrical shapes. The geometrical and static structural attributes of the tree are presented in Table 5.6.

From Table 5.6, the geometrical attributes of obtained from the rendered three dimensional tree in the CAD software are presented. It can be seen that the static bending moment of the tree without external lateral loads was 8.6 kNm at a direction of about 196° from magnetic north. Using this direction, the stability of the tree will be affected most from external lateral loads acting in this direction. Using Google Maps™ to orientate the tree to its surroundings and using the height of the tree (18.5m) as its crown radius, Figure 5.25 shows the circle drawn by the radius of the tree and the arrow showing the direction of the centroid. This means that during the tree will show a preference to fall in the direction of the arrow due to the mass centroid bias. Comparing the dimensions measured using the laser scan for this tree; the height was almost the same (18.7 m vs 18.5 m). The trunk diameter recorded was also similar (0.6 m vs 0.6 m)

Table 5.5 The coordinates used to generate the three dimensional representation of the tree as a series of cylinders

Branch No.	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>
<i>1</i>	0.00	0.00	8.95	0.31
<i>11</i>	-2.66	-2.66	1.37	0.16
<i>12</i>	0.00	0.44	1.22	0.22
<i>121</i>	-0.46	-0.12	1.02	0.19
<i>1211</i>	-0.79	-0.21	0.82	0.13
<i>12111</i>	-1.97	0.31	0.72	0.05
<i>12112</i>	-2.58	-1.15	1.03	0.07
<i>1212</i>	0.00	0.00	1.83	0.15
<i>12122</i>	-0.34	1.37	1.41	0.05
<i>12121</i>	-1.31	1.56	2.04	0.07
<i>122</i>	1.11	0.84	2.41	0.16
<i>1221</i>	0.16	0.27	1.77	0.14
<i>12211</i>	0.19	0.33	2.18	0.07
<i>12212</i>	2.04	0.55	2.12	0.05
<i>1222</i>	2.18	-0.58	1.90	0.04
<i>13</i>	0.64	-0.99	4.39	0.16
<i>131</i>	-0.33	0.85	5.15	0.13
<i>132</i>	-1.44	-1.21	3.25	0.12
<i>1321</i>	0.70	0.34	1.35	0.08
<i>1322</i>	-0.16	-0.76	1.35	0.10
<i>133</i>	-1.49	-1.91	2.42	0.12

Figure 5.70 Silat Ave *Syzygium grande* 1 3D model

Table 5.6 the geometrical attributes obtained from the three dimensional figure.

Silat Ave <i>Syzygium grande</i> 1	
Height (m)	18.5
Canopy width (m)	6.2
Volume (m ³)	5.3
Density (kg/m ³)	900
Weight (kg)	4784
Centroid X (m)	0.0
Centroid Y (m)	-0.1
Centroid Z (m)	8.2
Azimuth of centroid (deg)	196
Static bending moment (kNm)	8.6

Figure 5.71 The circle traced out by the height of Silat Ave *Syzygium grande* 1 with the arrow showing the azimuth of the centroid from magnetic north

For the next tree survey using the same method, Silat Ave *Syzygium grande* 2, Figure 5.72 shows the three dimensional tree generated by the survey data. Table 5.7 shows the coordinates used to generate three dimensional representation of the tree. The *Syzygium grande* 2 shows a different shape from the first *Syzygium grande*. This is estimated by the survey method.

Table 5.8 shows that the tree is estimated to be almost concentric with a static bending moment of about 0.1kNm in the direction of about 350 degrees from magnetic north. Figure 5.73 shows the centroid of Silat Ave *Syzygium grande* 2.

Figure 5.72 Silat Ave *Syzygium grande* 2 three dimensional model

Table 5.7 The coordinates used to generate three dimensional representation of the
Silat Ave *Syzygium grande* 2

<i>No.</i>	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>
<i>1</i>	0.00	0.00	1.35	0.34
<i>11</i>	-0.42	0.34	6.12	0.20
<i>111</i>	-1.64	-0.91	0.33	0.04
<i>112</i>	-1.86	1.68	4.34	0.08
<i>113</i>	0.00	0.00	0.89	0.15
<i>1131</i>	-0.43	-0.39	3.29	0.10
<i>11311</i>	-1.52	-0.62	1.64	0.03
<i>11312</i>	-0.19	-0.17	1.48	0.10
<i>113121</i>	-0.98	-1.22	2.71	0.05
<i>113122</i>	0.53	2.75	2.80	0.03
<i>1132</i>	0.12	0.39	2.29	0.07
<i>11321</i>	0.02	0.08	0.94	0.05
<i>113211</i>	-0.79	0.85	2.00	0.05
<i>113212</i>	0.43	1.60	2.87	0.04
<i>12</i>	0.94	-0.32	5.65	0.20
<i>121</i>	-0.22	1.25	3.48	0.03
<i>122</i>	1.67	-0.58	10.05	0.11
<i>1221</i>	-0.54	0.97	1.92	0.03
<i>1222</i>	-0.43	0.02	2.41	0.04
<i>1223</i>	0.65	-0.55	2.35	0.04
<i>123</i>	0.34	-1.74	4.87	0.04

Table 5.8 The geometrical attributes obtained from the three dimensional figure.

Silat Ave <i>Syzygium grande</i> 2	
Height (m)	19.5
Canopy width (m)	5.2
Volume (m ³)	2.82
Density (kg/m ³)	900
Weight (kg)	2,521
Centroid X (m)	0.2
Centroid Y (m)	-0.0
Centroid Z (m)	6.1
Azimuth of centroid (deg)	350
Static bending moment (kNm)	0.1

Figure 5.73 The circle traced out by the height of Silat Ave *Syzygium grande* 2 with the arrow showing the azimuth of the centroid from magnetic north

The next tree surveyed was a *Samanea saman* (Rain Tree) at Silat Ave. The *Samanea saman* had an umbrella shaped canopy with much of the height of the tree made up of secondary branches. Compared to the two *Syzygium grande* at Silat Ave, the larger *Samanea saman* required more time to survey due to the complexity of the branching structure. Figure 5.74 shows the three dimensional model derived from the survey. Table 5.8 shows the coordinates used to generate the three dimensional representation of the Silat Ave *Samanea saman*. Table 5.9 shows the geometrical attributes obtained from the three dimensional figure. Figure 5.75 shows the direction of the centroid of the *Samanea saman* at Silat Ave.

Figure 5.74 Silat Ave *Samanea saman* 1 three dimensional model

Table 5.9 the coordinates used to generate three dimensional representation of the
Silat Ave *Samanea saman*

<i>No.</i>	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>	<i>No.</i>	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>
<i>1</i>	0.00	0.00	2.14	0.48	<i>12122</i>	1.52	-3.58	3.89	0.14
<i>11</i>	0.41	0.66	0.45	0.44	<i>12123</i>	-2.03	-1.96	2.83	0.21
<i>111</i>	1.86	2.98	2.95	0.21	<i>122</i>	-0.98	-2.84	5.20	0.27
<i>1111</i>	2.87	4.10	8.66	0.07	<i>1221</i>	4.89	-3.69	5.14	0.07
<i>1112</i>	2.24	-1.69	7.71	0.04	<i>1222</i>	-2.44	-3.90	3.86	0.06
<i>112</i>	0.00	0.00	3.00	0.17	<i>13</i>	-4.88	-1.78	3.00	0.07
<i>1121</i>	-3.24	7.64	1.46	0.17	<i>14</i>	-0.37	-0.83	1.95	0.34
<i>11211</i>	-1.12	1.49	0.33	0.03	<i>141</i>	0.11	-0.61	1.69	0.36
<i>1113</i>	-0.25	0.35	0.43	0.20	<i>1411</i>	4.73	-2.52	4.50	0.07
<i>11131</i>	-3.85	9.07	1.74	0.04	<i>14111</i>	0.00	0.00	3.10	0.03
<i>11132</i>	-0.90	1.28	8.86	0.08	<i>1412</i>	-1.21	-0.94	1.29	0.20
<i>1122</i>	0.38	0.35	0.61	0.17	<i>14121</i>	-5.62	-9.35	6.30	0.11
<i>11221</i>	1.68	2.58	8.46	0.08	<i>14122</i>	-4.06	-1.09	1.53	0.21
<i>11122</i>	2.34	-3.00	8.16	0.08	<i>141221</i>	0.00	0.00	6.86	0.11
<i>12</i>	0.21	0.00	2.39	0.32	<i>141222</i>	-1.97	0.10	0.35	0.07
<i>121</i>	0.55	0.66	2.35	0.32	<i>1412221</i>	0.00	0.00	4.00	0.07
<i>1211</i>	-4.73	5.25	7.07	0.12	<i>141223</i>	-3.73	-4.78	3.50	0.08
<i>12112</i>	0.76	2.85	2.95	0.09	<i>142</i>	-3.68	1.06	3.21	0.23
<i>121121</i>	-1.74	1.80	4.33	0.05	<i>1421</i>	-4.17	5.53	4.00	0.07
<i>121122</i>	0.91	2.98	3.11	0.04	<i>1422</i>	-1.96	0.92	-0.38	0.12
<i>121123</i>	2.75	1.46	3.11	0.04	<i>14221</i>	-3.48	3.86	3.00	0.05
<i>1212</i>	0.00	0.00	3.77	0.21	<i>1423</i>	-5.21	-3.65	6.36	0.12
<i>12121</i>	4.85	3.15	6.89	0.10					

Table 5.10 The geometrical attributes obtained from the three dimensional figure

Silat Ave <i>Samanea saman</i>	
Height (m)	21.3
Canopy width (m)	20.1
Volume (m ³)	14.2
Density (kg/m ³)	790
Weight (kg)	11,229
Centroid X (m)	-0.8
Centroid Y (m)	-0.1
Centroid Z (m)	6.8
Azimuth of centroid (deg)	266
Static bending moment (kNm)	9.0

Figure 5.75 The circle traced out by the height of Silat Ave *Samanea saman* 1 with the arrow showing the azimuth of the centroid from magnetic north.

The tree surveys were next carried out at Telok Blangah Rise where two *Samanea saman* (rain trees) were surveyed. Table 5.11 shows the data used to

generate the three dimensional figure shown in Figure 5.76. Like the *Samanea saman* at Silat Avenue, the *Samanea saman* shown in Figure 5.76 also has a large sail area compared to the *Syzygium grande*. Table 5.12 shows the geometrical attributes obtained from the three dimensional model. Figure 5.77 shows the centroid of Telok Blangah *Samanea saman* 1 with the arrow showing the azimuth of the centroid from magnetic north.

Figure 5.76 Telok Blangah Rise *Samanea saman* 1 three dimensional model

Table 5.11 The coordinates used to generate three dimensional representation of the
Telok Blangah *Samanea saman* 1

<i>No.</i>	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>	<i>No.</i>	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>
<i>1</i>	0.00	0.00	2.38	0.56	<i>131212</i>	-3.99	-3.01	8.66	0.05
<i>11</i>	4.53	0.80	3.86	0.25	<i>13122</i>	- 10.25	-2.75	10.6 1	0.05
<i>12</i>	-1.32	0.38	3.76	0.46	<i>132</i>	-2.74	0.00	7.52	0.15
<i>121</i>	-0.64	6.09	5.14	0.23	<i>1321</i>	0.00	0.00	1.50	0.16
<i>1211</i>	-7.78	- 0.54	4.50	0.12	<i>13211</i>	0.06	-0.68	1.88	0.13
<i>1212</i>	-7.91	3.52	5.00	0.07	<i>132111</i>	-5.79	-4.06	7.07	0.07
<i>1213</i>	-3.66	6.88	4.50	0.05	<i>132112</i>	5.45	-6.50	8.49	0.06
<i>1214</i>	-2.85	5.35	3.50	0.04	<i>13212</i>	-3.44	1.68	3.21	0.13
<i>122</i>	-0.72	- 3.39	2.00	0.19	<i>132121</i>	0.00	0.00	3.00	0.08
<i>123</i>	3.35	- 0.71	9.40	0.21	<i>1321211</i>	9.81	-7.13	7.00	0.06
<i>1231</i>	-3.32	7.81	8.49	0.09	<i>1321212</i>	0.00	0.00	12.0 0	0.09
<i>1232</i>	6.88	0.36	5.79	0.09	<i>132122</i>	-0.84	2.95	2.57	0.15
<i>13</i>	0.00	0.00	2.00	0.36	<i>1321221</i>	-5.81	8.62	6.00	0.05
<i>131</i>	4.10	1.10	4.24	0.25	<i>1321222</i>	0.00	0.00	4.00	0.06
<i>1311</i>	3.76	1.01	2.25	0.15	<i>131121</i>	-7.18	-4.84	5.00	0.05
<i>13111</i>	3.62	- 4.32	2.05	0.08	<i>131122</i>	0.79	11.2 5	4.10	0.05
<i>13111 1</i>	4.23	- 5.04	2.39	0.07	<i>14</i>	-2.89	-1.05	8.46	0.19
<i>13111 2</i>	6.55	- 0.57	2.39	0.04	<i>141</i>	- 10.80	3.93	9.64	0.10
<i>13112</i>	6.61	6.39	7.71	0.09	<i>142</i>	13.13	-6.12	3.88	0.05
<i>1312</i>	-2.05	- 1.23	6.58	0.12	<i>143</i>	1.10	-3.59	1.37	0.09
<i>13121</i>	0.36	- 0.77	2.35	0.10	<i>1431</i>	-0.61	-1.60	4.70	0.04
<i>13121 1</i>	4.70	- 5.04	5.79	0.05	<i>1432</i>	12.54	0.66	3.36	0.11

Table 5.12 The geometrical attributes obtained from Figure 5.76

Telok Blangah <i>Samanea saman</i> 1	
Height (m)	31.6
Canopy width (m)	29.4
Volume (m ³)	17.5
Density (kg/m ³)	790
Weight (kg)	13,838
Centroid X (m)	0.0
Centroid Y (m)	0.6
Centroid Z (m)	8.9
Azimuth of centroid (deg)	1.2
Static bending moment (kNm)	8.9

Figure 5.77 the circle traced out by the height of Telok Blangah *Samanea saman* 1 with the arrow showing the azimuth of the centroid from magnetic north

The final tree surveyed was another *Samanea saman* beside Telok Blangah *Samanea saman* 1. Table 5.13 shows the data used to generate the three dimensional figure shown in Figure 5.78.

Figure 5.78 Telok Blangah *Samanea saman* 2 three dimensional model

Table 5.13 the coordinates used to generate three dimensional representation of the
Telok Blangah *Samanea saman* 2

No.	<i>X (m)</i>	<i>Y (m)</i>	<i>Z (m)</i>	<i>Radius (m)</i>
<i>I</i>	0.00	0.00	2.00	0.32
<i>II</i>	8.30	1.76	8.49	0.15
<i>III</i>	-2.38	-3.82	7.79	0.06
<i>III2</i>	5.79	2.00	5.14	0.07
<i>II2</i>	-0.16	-0.68	3.94	0.16
<i>II21</i>	-0.77	-3.33	9.40	0.13
<i>II211</i>	4.69	-8.83	17.32	0.05
<i>II212</i>	3.30	-9.06	11.49	0.05
<i>II22</i>	-3.11	0.27	17.73	0.14
<i>I3</i>	-1.37	0.00	3.76	0.17
<i>I31</i>	15.40	2.17	15.56	0.14
<i>I32</i>	-2.80	-0.49	10.63	0.14
<i>I321</i>	5.61	-0.99	21.25	0.14

Table 5.14 the geometrical attributes obtained from Figure 5.78

Telok Blangah Samanea saman 2	
Height (m)	37.7
Canopy width (m)	17.7
Volume (m ³)	7.77
Density (kg/m ³)	790
Weight (kg)	6,107
Centroid X (m)	1.1
Centroid Y (m)	-0.4
Centroid Z (m)	13.4
Azimuth of centroid (deg)	341.6
Static bending moment (kNm)	7.3

5.6 Numerical modelling

In this section, EXCEL was first used to verify the shallow root model described in Chapter 3 using past tree pulling data. The results are presented in Section 5.6.1.

The following Section 5.6.1, Sections 5.6.2 to 5.6.7 show the results of the parametric studies performed using the various numerical modelling software described in Chapter 4. The parametric studies were performed in Microsoft EXCEL, SVFLux, SIGMA/W and ANSYS using the theory described in Chapter 3. The parametric studies were broadly categorized into the following:

- 1) Effects of canopy geometries and shapes on wind loads. (EXCEL).
- 2) Effects of root plate thickness and groundwater table on tree resisting moments (EXCEL).
- 3) Effects of root plate extents, thickness, lateral wind loads and groundwater table on resisting moments (SIGMA/W)
- 4) Flux boundary conditions (SVFLux)
- 5) Effects of soil properties and root architecture on tree stability (ANSYS)

5.6.1 Two dimensional shallow root model (shallow root model) verification

Figure 5.79 shows the winching results of 19 trees performed by Rahardjo et al., (2010) in 2009. This was described in Chapter 2. Although there were 20 trees that were pulled to uprooting failure, one tree was used as a trial run with no readings kept. The root CSA measured also did not have direction assigned to them. So for simplicity sake, the shallow root model described in Chapter 3 (Section 3.1) with all its assumptions could be used.

Figure 5.79 Good correlation between maximum pulling forces (bending resistance) and root CSA for all trees measured in the pull out tests (Rahardjo et al., 2010)

Table 5.15 shows the *Samanea saman* greenwood properties and soil properties used as input parameters in the shallow root model. Table 5.15 shows the field measured pulling forces and the calculated values using the shallow root model.

In this study, branch greenwood was tested using the flexural bending apparatus to obtain the mean modulus of rupture (MOR) and modulus of elasticity (MOE) for *Samanea saman*. Ideally, root greenwood should be tested. However, due to the tree pulling predating the greenwood testing by four years, root greenwood for *Samanea saman* of a statistically significant quantity was not available. Fortunel et al.

(2014) stated that wood specific gravity was a strong predictor of tree performance and that wood specific gravity was strongly correlated between branches and roots with low standard deviations observed.

Table 5.15 Shallow root model input parameters from field testing of greenwood and laboratory soil tests. a) *Samanea saman* MOR and MOE. b) Soil strength properties.

a)

<i>Samanea saman</i> Modulus of Rupture (MOR)/failure strain	<i>Samanea saman</i> Secant Modulus of Elasticity (MOE)
37.7 MPa / 4.8%	791 MPa

b)

Soil cohesion (c')	5 kPa
Soil effective friction angle (ϕ')	33°
ϕ^b Slope of the variation of the shear strength with matric suction (ϕ^b)	30°
Groundwater table depth	5 m

Table 5.16 The measured CSA and failure pulling forces (Rahardjo et. al., 2010) together with the corresponding calculated failure pulling forces using the shallow root model

<i>Tree no</i>	<i>Root CSA (cm²)</i>	<i>Measured failure pulling force (kN)</i>	<i>Calculated failure pulling force (kN)</i>
1	164	7.4	8.1
2	48	6.3	3.2
3	320	15.3	15.4
4	110	11.2	5.8
5	260	20.8	12.9
6	266	11.6	12.7
7	160	9.2	8.0
8	64	6.9	5.7
9	54	7.6	3.5
10	60	4.5	3.8
11	29	2	2.4
12	44	2.9	3.0
13	240	16.3	11.6
14	130	10.2	6.7
15	120	3.5	6.3
16	112	6.3	6.0
17	232	10.6	11.3
18	103	3.1	5.5
19	694	19.4	36.9

5.6.2 Effects of canopy geometries and shapes on wind loads (EXCEL)

A parametric study was conducted on different tree canopy shapes. The shapes were considered in three dimensions. The values for the drag coefficients for the different shapes were obtained from Table 2.3 in Chapter 2. The wind profile power law for estimating wind speed at different heights in the tree was used to estimate the wind force at every 0.5 m height slice of the tree.

The wind profile power law relationship is:

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^\alpha \quad (5.9)$$

where:

u is the wind speed (in metres per second) at height z (in metres),

u_r is the known wind speed at a reference height z_r .

The wind force on each slice was derived from Equation 5.9 and the bending moment was obtained by multiplying the wind force with the average height of the 0.5 m slice above the ground.

Figure 5.80a shows a tree with a conical canopy. Figure 5.80b shows the simulated geometry design used in the parametric study. A conical canopy was assumed to represent the canopy for a pine tree. The drag coefficient for a conical shaped canopy was 0.47 (Lim et. al., 2013) assuming it was a non-porous solid. The drag coefficient on the trunk was 1.05 (Lim et. al., 2013). Trunk diameter was kept at 1m and trunk height was 10m. A wind speed of 5m/s (18km/h) was assumed measured at 10 m.

Figure 5.80 Wind force on a triangular canopy a) A tree with a triangular shaped canopy (e.g. Pine). b) Representation in Excel with the canopy height/width and trunk diameter/height.

Figure 5.81 shows the moments acting on a triangle shaped tree canopy at different canopy dimensions. Keeping the height of the triangular canopy constant at 20 m, the base of the canopy was varied. The figure shows that changing the dimensions of the base of the triangle shaped canopy did not change the moment acting on the tree significantly. However, when the base of the canopy was kept constant (20 m) and the height of the canopy was varied; there was a larger increase in moment acting on the triangle shaped tree. This was due to the wind profile power law relationship (Equation 5.9). Increasing the base and height simultaneously also resulted in similar values in moment acting on the tree as increasing the height only.

Figure 5.81 Moment acting on tree canopy with variations in the canopy (Triangle) height and base.

Figure 5.82a shows a tree with an ellipsoid shaped canopy (*Khaya senegalensis*). Figure 5.82b shows the simulated elliptical tree used in the parametric study. An ellipsoid shaped canopy was assumed to represent the canopy for *Khaya senegalensis*. The drag coefficient for an ellipsoid shaped canopy was 0.34 (Lim et. al., 2013) assuming it was solid without porous media. The drag coefficient on the trunk was 1.05 (Lim et. al., 2013). Trunk diameter was kept at 1m and trunk height was 10m. A wind speed of 5m/s (18km/h) was assumed.

Figure 5.82 Wind force on an elliptical shaped canopy a) A tree with a elliptical shaped canopy (e.g. *Khaya senegalensis*). b) Representation in Excel with the elliptical canopy height/width and trunk diameter/height.

Figure 5.83 shows the moment acting on the ellipse shaped canopy at different canopy heights and width. The moments were also obtained by summing the product of the wind force for each 0.5 m slice with the height above the ground. When the height or width of the ellipse is kept constant (Figure 5.83), while increasing the other, there was a similar linear increase in moment acting on the tree. However, there is a slightly faster increase in moment acting on the tree when varying the width and height together.

Figure 5.84a shows a cylindrical shaped (2D rectangular) tree canopy. Figure 5.84b shows the simulated design used in the parametric study. A cylindrical shaped (2D rectangular) canopy was assumed to represent the canopy for the *Khaya grandifoliola*. The drag coefficient for a cylindrical shaped canopy was 1.05 (Lim, 2012) assuming it was solid without porous media. The drag coefficient on the trunk was 1.05. Trunk diameter was kept at 1m and trunk height was 10m. A wind speed of 5m/s (18km/h) was assumed.

Figure 5.83 Moment acting on tree canopy with variations in the canopy (Ellipsoid) height and width.

Figure 5.84 Wind force on a cylindrical shaped (2D rectangular) canopy a) A tree with a cylindrical shaped canopy (e.g. *Khaya grandifoliola*). b) Representation in Excel with the cylindrical canopy height/width and trunk diameter/height.

Figure 5.85 shows the moment acting on a cylindrical shaped (2D rectangular) tree canopy at different canopy heights. Keeping the height of the canopy constant at

20m, the length of the canopy was varied. The figure shows that changing the dimensions of the base of the rectangular shaped canopy linearly increased the moment acting on the tree. However, this was not as significant as increasing the height of the canopy. There was an exponential increase in moment acting on the rectangular shaped canopy when the height of the canopy was increased. Increasing the base and height simultaneously also resulted in similar values in moment acting on the tree as increasing the height only.

Figure 5.85 Moment acting on tree canopy with variations in the canopy (cylindrical) height and length.

Amongst the three shapes used, the cylindrical (2D rectangular) shaped canopy resulted in the highest moment acting on the tree as compared to the triangle and ellipse shaped canopies. This would mean that rectangular shaped canopies are more susceptible to wind loading effects as compared to the other shapes. Figure 5.86 shows the summary of moments acting on all three canopy shapes.

Figure 5.86 Summary of moment acting on tree for the three tree shapes

5.6.3 Effects of root plate thickness and groundwater table on tree resisting moments using the heart root model (EXCEL)

Using the heart root failure model highlighted shown in Figure 5.87a), the soil pore-water pressure profile assumed in Figure 5.87b) and the parameters shown in Table 5.17, the root plate thickness (D_o), breadth (B) and groundwater table depth were varied parametrically to study the resisting moments of a tree due to the shear strength of the soil using an excel spreadsheet. Table 5.18 to Table 5.26 show the changes in resisting moments of a tree with different root plate thicknesses and radii under varying depths of water table (Figure 5.87).

To compare the failure wind force for a certain ground water depth as a ratio of the failure wind force for 0 m ground water depth, the wind force ratio shown in Equation 5.10 was used. The wind force ratio is given as follows:

$$\text{Wind force ratio} = \frac{\text{Failure wind force for a certain groundwater table depth}}{\text{Failure wind force for zero groundwater table depth}} \quad (5.10)$$

Figure 5.87 Assumptions made for the analysis a) mechanism of heart root tree throw
b) assumed positive and negative soil pore-water pressure profiles

Table 5.17 Parameters based on past research literatures

Parameters	Values	Sources
Tree Modulus of Elasticity	1400000 kPa	<i>Khaya grandifolia</i>
Tree Modulus of Rupture	64700 kPa	<i>Khaya grandifolia</i>
Tree Unit Weight	10 kN/m ³	<i>Khaya grandifolia</i>
Tree Girth	1.75 m	NParks, 2009
Root Plate Thickness	0.25 – 1m	NParks, 2009
Tree Height	20 m	NParks, 2009
Root Plate Length	6 – 10 m	NParks, 2011
Force Lever Arm (R)	13.08 m	Keong, 2004, Rahardjo et al., 2009
ϕ'	33°	Rahardjo et al., 2009
c' (kPa)	5	Rahardjo et al., 2009
ϕ^b	30°	Rahardjo et al., 2009
Specific gravity	2.41	Rahardjo et al., 2009
γ (unit weight)	1.9 Mg/m ³	Rahardjo et al., 2009
γ (saturated unit weight)	2.1 Mg/m ³	Rahardjo et al., 2009

Table 5.18 Resisting moments for tree of root plate of 0.25 m thick and B= 3 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
248	19	1.0	0
935	72	1.9	1
1758	134	2.7	2
2582	197	3.2	3
3405	260	3.7	4
4228	323	4.1	5
5051	386	4.5	6
5875	449	4.9	7
6698	512	5.2	8

Table 5.19 Resisting moments for tree of root plate of 0.25 m thick and B=4 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
517	40	1.0	0
2138	163	2.0	1
4081	312	2.8	2
6022	460	3.4	3
7963	609	3.9	4
9905	757	4.4	5
11847	906	4.8	6
13788	1054	5.2	7
15730	1203	5.5	8

Table 5.20 Resisting moments for tree of root plate of 0.25 m thick and B= 5 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
946	72	1.0	0
4105	314	2.1	1
7889	603	2.9	2
11672	892	3.5	3
15456	1182	4.0	4
19239	1471	4.5	5
23022	1760	4.9	6
26806	2049	5.3	7
30589	2339	5.7	8

Table 5.21 Resisting moments for tree of root plate of 0.5 m thick and B= 3 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
216	17	1.0	0
501	38	1.5	1
927	71	2.1	2
1353	103	2.5	3
1779	136	2.9	4
2205	169	3.2	5
2631	201	3.5	6
3057	234	3.8	7
3482	266	4.0	8

Table 5.22 Resisting moments for tree of root plate of 0.5 m thick and B= 4 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
475	36	1.0	0
1138	87	1.6	1
2128	163	2.1	2
3117	238	2.6	3
4107	314	2.9	4
5097	390	3.3	5
6086	465	3.6	6
7076	541	3.9	7
8066	617	4.1	8

Table 5.23 Resisting moments for tree of root plate of 0.5 m thick and B= 5 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: <i>Wind force for G.W.T depth (m)</i> <i>Wind force for 0 m depth</i>	G.W.T Depth (m)
893	68	1.0	0
2176	166	1.6	1
4092	313	2.1	2
6007	459	2.6	3
7922	606	3.0	4
9837	752	3.3	5
11753	899	3.6	6
13668	1045	3.9	7
15583	1191	4.2	8

Table 5.24 Resisting moments for tree of root plate of 1 m thick and B=3 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: <i>Wind force for G.W.T depth (m)</i> <i>Wind force for 0 m depth</i>	G.W.T Depth (m)
211	16	1.0	0
295	23	1.2	1
537	41	1.6	2
779	60	1.9	3
1022	78	2.2	4
1264	97	2.4	5
1506	115	2.7	6
1749	134	2.9	7
1991	152	3.1	8

Table 5.25 Resisting moments for tree of root plate of 1 m thick and B= 4 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
468	36	1.0	0
651	50	1.2	1
1184	91	1.6	2
1717	131	1.9	3
2250	172	2.2	4
2784	213	2.4	5
3317	254	2.7	6
3850	294	2.9	7
4384	335	3.1	8

Table 5.26 Resisting moments for tree of root plate of 1 m thick and B=5 m

Resisting Moment (kN m)	Wind force (kN)	Wind force ratio: $\frac{\text{Wind force for G.W.T depth (m)}}{\text{Wind force for 0 m depth}}$	G.W.T Depth (m)
884	68	1.0	0
1227	94	1.2	1
2233	171	1.6	2
3238	248	1.9	3
4243	324	2.2	4
5248	401	2.4	5
6254	478	2.7	6
7259	555	2.9	7
8264	632	3.1	8

5.6.4 Effects of root plate extent, thickness and groundwater table depth on lateral root/trunk stresses and strains (SIGMA/W)

Using SIGMA/W, the loadings necessary to induce a failure strain in the soil (15%), root plate (5%) or tree (5%) are recorded in Table 5.27.

Critical points of failure are determined at nodes where the material first experiences the failure strain. Figure 5.88 and Figure 5.89 show the critical failure points under different failure mechanisms. CFP1 was selected due to the meshed element size in the trunk. 0.25 m above the lateral roots was the first node available for recording the maximum stress and strain in the trunk. CFP2 and 3 were selected as these two points were the nodes nearest the trunk/lateral roots interface for measuring stress and strain in the lateral roots. CFP2 and 3 also were the points where the maximum bending moments were exerted on the lateral roots (at the connections to the trunk).

Figure 5.88. Critical failure point due to trunk break

Figure 5.89. Critical failure points due to root break

Table 5.27 Summary of numerical analysis (SIGMA/W) results

Root plate						
Radius (m)	Thickness (m)	Groundwater table depth (m)	Failure wind load (kN)	Wind force ratio	Critical points of failure (CFP)	Failure mechanism
3	0.25	0	16.5	1.00	CFP 2, 3	Root flexural failure
		1	18.0	1.04		
		2	19.0	1.07		
		3	20.0	1.10		
		4	20.5	1.12		
		5	21.5	1.14		
		6	22.0	1.16		
		7	23.0	1.18		
		8	23.5	1.19		
4 & 5	0.25	0	18.5	1.00	CFP 2, 3	Root flexural failure
		1	20.0	1.04		
		2	21.0	1.07		
		3	22.0	1.09		
		4	23.0	1.12		
		5	24.0	1.14		
		6	24.5	1.15		
		7	25.5	1.17		
		8	26.0	1.19		
3 - 5	0.5	0 - 8	380.0	N.A	CFP 1	Trunk flexural failure
3 - 5	1	0 - 8	380.0	N.A	CFP 1	Trunk flexural failure

5.6.5 Flux boundary conditions (SVFLux)

There are five climatic parameters that affect flux boundary conditions: rainfall (precipitation), air temperature, relative humidity, wind speed and solar radiations. These parameters were recorded at the site (Silat Ave (SA)). This study presented the result of climatic parameters from 12 November 2012 to 19 November 2012. The period was chosen because several rainfalls occurred during the period and it was a typical week in a rainy season. The climatic parameters without rainfall are shown in Figure 5.90. The air temperature was in the range of 25-34°C. The relative humidity fluctuated between 60 to 95%, whereas the wind speed fluctuated between 0.5 to 2.0 m/s. The maximum solar radiation at 12 November 2012 was around 60 MJ/m²/hr. The solar radiation at the site sometimes had multiple peaks. This indicates that during the day, the solar radiation decreased and then increased. The multiple peaks could have been caused by rainfall or cloud cover on the days.

Figure 5.90 Meteorological data recorded in the site (Silat Ave (SA)) in the period of numerical modeling

Figure 5.91 shows that the pore-water pressure (PWP) at all depths increased significantly during rainfall due to water infiltration. When the rain stopped, the pore-

water pressure decreased again since water had infiltrated into deeper depths or evapo-transpiration had taken place. Similar trends were also observed in the variation of volumetric water content during dry and rainy periods. Figure 5.92 indicates that the volumetric water content (VWC) increased during rainfall and remained constant during dry period. The increase only occurred in the shallowest VWC measurement (W1 at 0.5 m) because the second and third VWC measurement sensors were positioned below the water table.

The PWP and VWC distributions at different depths obtained from the instrumentation readings and the results of numerical modeling are shown in Figure 5.93 and Figure 5.94, respectively. During rainfall, the PWP increased, showing the effect of rainfall on pore-water pressures at all depths. The VWC distributions also show a similar trend when compared to the instrumentation readings. However, the VWC values at the depths of 1.0 and 1.5 m deviated from the measurement data. The soils in these depths were in saturated condition. Therefore, the VWC results obtained from the measurement data were constant at around 0.52. W2 and W3 were located at the 1.0m and the 1.5m depth respectively. The groundwater table was also located at that depth (<1.0 m) and this is the reason for the consistency in readings. The numerical modeling results showed a constant value of around 0.42. The VWC values obtained from the numerical modeling were calculated based on the SWCC of the soils. The difference between the saturated VWC could be caused by the different densities of the soils at different depths compared to the soils tested in the laboratory. These differences could have been caused by disturbances during sampling, transportation and storage.

Figure 5.91 Measured pore-water pressure in the period of the numerical modeling (Silat Ave (SA))

Figure 5.92 Measured volumetric water contents in the period of the numerical modeling (Silat Ave (SA))

Figure 5.93 Simulated and measured pore-water pressure in the period of the numerical modeling (Silat Ave (SA))

Figure 5.94 Simulated and measured volumetric water content in the period of the numerical modeling (Silat Ave (SA))

5.6.6 Effects of soil properties and flat (shallow) root architecture on tree stability (ANSYS)

The tree root model described in Chapters 3 and 4 was modelled in ANSYS using the static structural module. Moderate non-failure loads were used in the ANSYS analyses as the purpose was to parametrically look at how variation in the root architecture affected the stresses and deformations in the model. From the analyses, an understanding was derived that the lateral roots near the trunk were responsible for most of the structural support. This finding was also supported by the Winkler foundation hypothesis (Section 2.3.1.1) and the SIGMA/W analyses (Section 5.6.4). This understanding was used as the basis for the shallow root model (Section 3.2) which worked fairly well to predict the tree pulling test results carried out in 2009. The analyses also explained why the tree pulling results were proportional to root CSA magnitude. There were five basic parameters that were varied to perform the parametric study in ANSYS. They were:

1. Number of evenly spaced sinker roots
2. Depth of sinker roots
3. Size of lateral roots
4. Elastic modulus of soil
5. Cutting of perpendicular, compression and tension roots.

The input greenwood parameters for the ANSYS analyses are shown in. These values represent the average values obtained from Section 5.1.

Table 5.28 Input greenwood parameters used for ANSYS analyses derived from the average values from Section 5.1

Modulus of rupture (MOR) (MPa)	50
Modulus of elasticity (MOE) (MPa)	1200
Greenwood density (Mg/m³)	0.9

The soil input parameters used for the input analyses were obtained from experimental data presented in Section 5.2. Figure 5.95 shows the stress strain curves for the suction range commonly found in the soil at Silat Ave.

Figure 5.95 Triaxial stress strain curves for three values of matric suction ($u_a - u_w$); 25, 50 and 100 kPa for a confining pressure of 50 kPa (Silat Ave).

From the saturated and unsaturated triaxial stress-strain curves, the elastic modulus or the subgrade modulus can be estimated for the different soils at 50 kPa confining pressures (σ_3). The elastic moduli are presented in Table 5.30.

Table 5.29 The elastic modulus or the subgrade modulus estimated for the different matric suctions at 50 kPa confining pressures.

Matric Suction ($u_a - u_w$) (kPa)	Secant modulus of elasticity (MPa)	Compressive yield stress (σ_1) (kPa)
0	5.9	134
25	10.1	248
50	15.8	376
100	23.8	574

Using the median value of 50 kPa for matric suction and confining stress, we can use the modulus of elasticity for the soil at 15.8 MPa and soil compressive yield stress of 376 kPa for the parametric study. The soil unit weight used for Silat Ave was 1.95 Mg/m^3 (Table 5.2). Figure 5.96 a-f shows the variation in the number of evenly spaced sinker roots for the flat root while hiding the soil mass. The X and Y axes (tree horizontal) are represented by the arrows within the lateral roots; the vertical arrow represents the Z or tree vertical direction (trunk). A bending moment of 200 kNm was applied on the 6 models shown in Figure 5.96 a-f, causing a rotation of the tree about the Y-axis (reference axes shown in Figure 5.96a). The soil properties were not changed throughout and the tree root and trunk material properties were kept constant. Besides the bending moment and earth gravity of acceleration 9.81 m/s^2 was applied in the negative Z direction. The bending moment resulted in flexural and tensile/compressive stresses to be experienced by the tree and the soil. Total deformation was also recorded for the whole model. The results are shown for the equivalent von-Mises stress and total deformations (Chapter 3) when carrying out this study variation of evenly spaced sinker roots.

The maximum stresses were always experienced by the leeward lateral root or the sinker roots. The nearer the sinker root is to the rotation edge of the leeward side of the trunk, the higher the stress experienced. Maximum total deformation was always experienced by the top of the trunk except for the case of the zero sinker root case where the lifting distance of the windward lateral root exceeded the rotational distance of the top of the trunk (Figure 5.97).

Figure 5.96 Variation of number of evenly spaced sinker roots without the soil attached a) No sinker roots and the orientation of the reference axes. b) 4 sinker roots c) 8 sinker roots d) 12 sinker roots e) 16 sinker roots f) 20 sinker roots

a)

b)

Figure 5.97 Model with no sinker roots showing windward lateral root lift off (soil hidden). a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in leeward lateral root. b) Maximum total deformation experienced by the tip of the trunk

The insertion of 1 sinker root per lateral root resulted in reduced maximum stresses and total deformations. The single sinker root also prevented complete lift off of the windward lateral root. Figure 5.98 shows the beneficial effects of inserting a single sinker root. Maximum stress is reduced from 7.5 MPa to 5.2 MPa and

maximum deformation of the top of the model trunk is reduced from 0.11 m to 0.083 m. This shows that the sinker roots nearest to the trunk have a large effect of reducing stresses and deformations.

a)

b)

Figure 5.98 Model with 4 sinker roots showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

The insertion of 2 numbers of sinker roots per lateral root resulted in further reductions in maximum stresses and total deformations. Figure 5.99 shows the results in stresses and total deformations. Compared to the model shown in Figure 5.97 with no sinker roots, stresses were further reduced from 7.4 MPa to 4.5 MPa. Maximum total deformation was further reduced from 0.11 m to 0.071 m. Subsequent increases in the number of evenly spaced sinker roots per lateral roots did not result in any significant reductions in stresses and total deformations. The results are shown in the Appendix I and discussed in Chapter 6.

The results of the parametric study on the variation of number of evenly spaced sinker roots are shown in Table 5.30.

Table 5.30 Results of the the parametric study on the variation of number of evenly spaced sinker roots

No. of Sinkers	Maximum von Mises (von Mises, 1913) stress (MPa)	Deformation (m)
0	7.44	0.11
1	5.17	0.08
2	4.46	0.07
3	4.09	0.067
4	3.83	0.067
5	4.08	0.067

The results of the study on the number of evenly spaced sinker roots per lateral root (Table 5.30) led to keeping the number of evenly spaced sinker roots to two numbers for the next study (no significant change in maximum total deformations and stresses after 2 sinker roots). In this study, the depth of the lateral roots was varied. The depths of the sinker roots was varied from 0.5 m to 5 m in 0.5m and 1 m increments. The models used in this study are shown in Figure 5.100 a-f

a)

b)

Figure 5.99 Model with 8 sinker roots showing additional restraint by the additional 4 sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

For the sake of contrast, the stresses and total deformations of 0.5 m depth and 5 m depth sinker roots are shown in Figure 5.101 a & b and Figure 5.102 a & b. The rest of the results are shown in Appendix I, summarised and discussed in Chapter 6.

Figure 5.100 Variation of depth of 2 numbers of evenly spaced sinker roots per lateral root without the soil attached a) 0.5 m and the orientation of the reference axes. b) 1 m c) 2 m d) 3 m e) 4 m f) 5 m

a)

b)

Figure 5.101 Model with 8 sinker roots 0.5 m depth showing little restraint by the short 0.5 m sinker roots (soil hidden). a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in leeward lateral roots. b) Maximum total deformation experienced by the tip of the trunk

Figure 5.101 and Figure 5.102 show that the depth of sinker root penetration affects the maximum stresses and deformations experienced by the tree root plate. On the windward side, short sinker roots are easily lifted out of the soil and long sinker roots provide much more restraint against lateral root lift off. On the leeward side or

compression side, the longer sinker roots stiffen the soil and reduce soil deformation. The results of the simulations are shown in Appendix I and discussed in Chapter 6.

Figure 5.102 Model with 8 sinker roots 5 m depth showing high by the restraint sinker roots a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in leeward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk

The results of the parametric study on the variation of depth of two evenly spaced sinker roots per lateral root are shown in Table 5.31. The maximum stress was seen to increase slightly with the 5.0 m depth from the 4.0 m depth as the maximum stress location was changed to the underside of the compressive lateral root/ sinker root connection. This shows that the long 5.0 m sinker root was resisting more of the compressive stresses from the lateral root due to its length.

Table 5.31 Results of the the parametric study on the variation of depth of two sinker roots per lateral root

Sinker depth (m)	Maximum von Mises (von Mises, 1913) stress (MPa)	Maximum Deformation (m)
0.5	5.40	0.08
1.0	5.02	0.08
2.0	4.46	0.07
3.0	3.69	0.064
4.0	3.59	0.064
5.0	3.71	0.063

The third study of the root architecture was variation in the diameter of the lateral roots. Using the same two evenly spaced sinker roots (3 m depth) per lateral root model from the Figure 5.100 d, the diameters of the lateral roots were uniformly varied from 0.2 m to 1.2 m in 0.2 m increments. 3 m depth was chosen as in Table 5.31, no significant change in maximum stress and deformation was seen after 3.0 m depth in the sinker roots. The models used in this study are shown in Figure 5.103 a-f.

Figure 5.104 and Figure 5.105 show that lateral root size have a significant role to play within the flat root architecture to reduce stress and total deformations experienced by the tree. Figure 5.105 shows that there was an interesting small lift off of the lateral roots (in Y-axis) due to soil deformation only. Another interesting observation for Figure 5.105 was that the maximum stress was in the tree trunk and not in the lateral roots or sinker roots. The maximum deformations seen in Figure 5.105 were only due to soil settlement. The results of the simulations are shown in Appendix I and discussed in Chapter 6.

Figure 5.103 Variation of the diameter of lateral roots with two evenly spaced sinker roots (3 m depth) per lateral root without the soil attached a) 0.2 m and the reference axes. b) 0.4 m c) 0.6 m d) 0.8 m e) 1.0 m f) 1.2 m

a)

b)

Figure 5.104 Model with 4 lateral roots 0.2 m diameter still showing significant restraint by the sinker roots a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

Figure 5.105 Model with 4 lateral roots 1.2 m diameter still showing significant restraint by the sinker roots a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in trunk. b) Maximum total deformation experienced by the whole body (pure settlement of soil due to gravity)

The results of the parametric study on the variation of the diameter of lateral roots with two evenly spaced sinker roots (3 m depth) per lateral root are shown in Table 5.32.

Table 5.32 Results of the parametric study on the variation of the diameter of lateral roots with two evenly spaced sinker roots (3 m depth) per lateral root.

Lateral diameter (m)	Maximum von Mises (von Mises, 1913) stress (MPa)	Maximum Deformation (m)
0.2	12.4	0.10
0.4	3.7	0.06
0.6	1.9	0.05
0.8	1.3	0.05
1.0	1.0	0.05
1.2	0.8	0.05

The fourth study was performed by varying the elastic modulus and shear strength of the soil in order to simulate the reduction of mechanical strength properties of the soil due to the increase in water content. Table 5.34 shows the elastic modulus and compressive yield stress changes in the soil used to perform the study. The root geometry used is shown in Figure 5.103d. The range was taken around the central elastic modulus of 15.8 MPa and compressive yield stress of 376 kPa as used in the previous analyses (Table 5.34).

Table 5.33 Soil properties varied to perform tree stability study.

No. (% Change in elastic modulus from 15.8 MPa)	Elastic modulus of soil (MPa)	Compressive yield strength (kPa)
1. (-50%)	7.9	188
2. (-20%)	12.6	301
3. (-10%)	14.2	338
4. (0%)	15.8	376
5. (+10%)	17.38	414
6. (+20%)	19.0	451
7. (+50%)	23.7	564

Figure 5.106 a & b and Figure 5.107a & b show that the two extremes of the study for the sake of contrast. The two figures show that for the elastic modulus of soil and compressive yield stress to increase by 200% the change in maximum stress is negligible. There is an improvement in the total deformation of the trunk top due to the reduction in soil deformation during the loading. The results of the simulations are shown in Appendix I and discussed in Chapter 6.

a)

b)

Figure 5.106 Effect of change (-50%) in the elastic modulus (7.9 MPa) and compressive yield stress (188 kPa) of the soil. a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole body.

a)

b)

Figure 5.107 Effect of change (+50%) in the elastic modulus (23.7 MPa) and compressive yield stress (564 kPa) of the soil. a) Maximum equivalent von-Mises (von Mises, 1913) stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole body.

The results of the parametric study on the effect of the variation of the elastic modulus and compressive yield strength of the soil on stresses and deformations are shown in Table 5.35. The results show that soil elastic moduli have only a small effect on maximum stresses and deformations. The root architecture is more important.

Table 5.34 The results of the parametric study on the effect of the variation of the elastic modulus and compressive yield strength of the soil on stresses and deformations.

No.	Maximum von Mises (von Mises, 1913) stress (MPa)	Maximum Deformation (m)
1. (-50%)	1.5	0.10
2. (-20%)	1.3	0.06
3. (-10%)	1.3	0.06
4. (0%)	1.3	0.05
5. (+10%)	1.2	0.05
6. (+20%)	1.2	0.04
7. (+50%)	1.1	0.03

The last simulation was performed to determine the effect of cutting a lateral root next to the trunk face. Figure 5.108 shows the perfectly concentric tree model four laterals and 16 sinker roots with an applied 200 kNm bending moment to the trunk. The tree and soil was provided a self-weight by applying normal earth gravity in a ramped manner. The resulting stresses and total deformations were only due to this self-weight and applied moment.

The resulting stresses and total deformations were only due to this self-weight and applied moment. The maximum equivalent stresses and the un-deformed shape are shown in Figure 5.109. The maximum stresses of 4.08 MPa was located at the lateral root connections. The un-deformed shape showed that the total deformation of 0.067 m was experienced by the end of trunk tip.

Figure 5.108 An “idealized” perfectly concentric tree with four laterals and soil (hidden) model with the reference axes.

After cutting the lateral root perpendicular to the bending direction, shown in Figure 5.110, there is an immediate increase in the maximum stresses (4.20 MPa) and minor increase in the maximum total deformations in the root model in the compression and tension lateral root connections to the trunk. The largest total deformations (0.068 m) are seen in trunk tip.

The response of the tree to a cut root is the same as that of a tree experiencing basal root decay. When a tree is experiencing detrimental changes in its basal root configuration, there will be a deformation response to the change. When there is increased deformation, there will be increased maximum equivalent stresses as demonstrated in Figure 5.109 and Figure 5.110 where the maximum equivalent stresses increased from 4.08 MPa to 4.20 MPa.

a)

b)

Figure 5.109 The “idealized” tree shown in Figure 5.108 after applying gravity and bending moment of 200 kNm. a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.

A tree with cut lateral roots at the same side to the lean direction (compression roots) will experience an increase in the deformations in the direction of the applied moments. This is demonstrated in Figure 5.111a where by changing the direction of the applied moment by 90° can simulate a cut compression root. Figure 5.111a shows the stresses in the root model with the cut compression root. Figure 5.111b shows the deformations in the root model with the cut compression root. The maximum stress

experienced by the tension lateral root is increased from 4.08 MPa to 4.83 MPa. The maximum deformation in the trunk tip is increased from 0.067 m to 0.09 m.

Figure 5.110 After cutting the root of the perfectly concentric “idealized” tree (red arrow) that is perpendicular to the bending direction. a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.

By changing the direction of the applied bending moment by a further 90°, the cutting the tension lateral root opposite the direction of the applied moment can be simulated (Figure 5.112). By cutting the tension root, the increase in deformation is even more than through the cutting of the compression roots. Maximum stress in the root model is increased from 4.08 MPa to 6.15 MPa. Maximum deformation is increased from 0.067 m to 0.09m.

Figure 5.111 After cutting the compression root of the perfectly concentric “idealized” tree (red arrow) that is in line with the bending direction (about x-axis). a)

Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree.

b) Total deformations experienced by the tree.

a)

b)

Figure 5.112 After cutting the tension root of the perfectly concentric “idealized” tree (red arrow) that is in line with the bending direction. a) Maximum equivalent von Mises (von Mises, 1913) stresses experienced by the tree. b) Total deformations experienced by the tree.

Table 5.36 shows the maximum equivalent stress and deformations from perpendicular, tension and compression root cutting. The maximum increase in maximum equivalent stress came from tension root cutting. The maximum increase in maximum total deformations came from compression root cutting. This shows that tension roots of the same diameter have a bigger effect on tree stability based on stresses than compression or perpendicular roots. However compression roots were more efficient at preventing rotational deformations than tension roots as they spread out the compressive forces over a wider area. Soil is weak in tension.

Table 5.35 Maximum equivalent stress and deformations from perpendicular, tension and compression root cutting.

Root state	Maximum von Mises (von Mises, 1913) stress (MPa)	Maximum Deformation (m)
Uncut	4.08	0.067
Perpendicular root cut	4.20	0.068
Compression root cut	4.84	0.095
Tension root cut	6.15	0.087

CHAPTER 6 Discussion

6.1 Greenwood testing

Four-point and three-point bending tests are the standard tests for measuring modulus of rupture (MOR) in a composite material. The development and field deployment of the lightweight four-point followed by the more robust and simple three-point flexural testing equipment show that field testing of greenwood samples is possible with low power requirements and without complicated and costly laboratory equipment. For field testing conditions, the three-point flexural testing apparatus was found to be simple to operate, portable, robust, flexible and sufficiently accurate to measure the modulus of rupture (MOR) and elasticity (MOE) for a wide range of sample sizes. Further development of the testing equipment can lead to improvements in testing productivity, equipment portability, sample clamping arrangement and simplicity of equipment that is often equated to robustness.

For the same species (*Samanea saman* and *Peltophoreum pterocarpum*), the three-point testing showed a slightly lower recorded MOR compared to the four point-test. This can be explained by the fact that for the four-point testing method, a larger volume of wood is under pure bending without shear. For the three point testing method, a smaller volume of greenwood is tested with shear.

The results of the four-point and three-point flexural testing showed that greenwood MOR for each species can show a wide variation within a species and even within a single tree. Boxplots of the stress strain curves help to filter the results so that different species can be compared, through the medians with the quartiles acting as the confidence intervals. The fitted stress strain curve through the medians for each species is useful and eight fitted curves are shown in Figure 6.1 to Figure 6.8. The reason for using a 6th order polynomial to fit the median data was so as to better capture the stress-strain relationship to the yield point (maxima point). After the yield stress/strain is reached, the greenwood is deemed to have failed and that the stress strain relationship beyond that point is not critical. Some species of greenwood could have been adequately fitted using a lower order polynomial. However for consistency, a 6th order polynomial was used

throughout. These curves can be easily updated as more testing is performed to provide larger sample data bases for each species.

Figure 6.1 Six order polynomial fitted to the median points of the stress-strain data for *Syzygium grande*.

Figure 6.2 Six order polynomial fitted to the median points of the stress-strain data for *Khaya senegalensis*.

Figure 6.3 Six order polynomial fitted to the median points of the stress-strain data for *Samanea saman*.

Figure 6.4 Six order polynomial fitted to the median points of the stress-strain data for *Tabebuia rosea*.

Figure 6.5 Six order polynomial fitted to the median points of the stress-strain data for *Peltophorum pterocarpum*.

Figure 6.6 Six order polynomial fitted to the median points of the stress-strain data for *Syzygium polyanthum*

Figure 6.7 Six order polynomial fitted to the median points of the stress-strain data for *Pterocarpus indicus*

Figure 6.8 Six order polynomial fitted to the median points of the stress-strain data for *Swietenia macrophylla*

Trees, like all living things will always try to operate within the elastic (recoverable) part of the stress-strain curves. The initial elastic range of the stress-strain curves along with the mass and density measurements can be used to provide an upper limit for different species on canopy sizes. Operating outside the elastic ranges can lead to irrecoverable strains that often show up in symptoms like droopy branches and leaning trunks. Damage to greenwood through decay will also be more easily detected if the trees are constantly maintained to operate within the elastic range of the greenwood properties. This is because material damage from decay due to infection will cause the greenwood to weaken and operate below the confidence (quartile) bands for the species. Using the results from the field testing, operational charts can be drawn to provide a visual aid to the arborists to reduce the risk of failure and improve the decision making processes with regard to tree maintenance.

One way to compare the greenwood stress-strain properties of one species to another is by comparing one fitted polynomial to another via their first stationary points (maximum) or where the first differential of the stress-strain curves equals zero (“yield criterion”) and the area under the curve to this point (work done to “yield” or “toughness”) (Boresi 1993).

Figure 6.9 definition of an elasto-viscous material “toughness” is the area under the stress-strain curve to the first stationary point defined by the MOR

The first maximum stationary point for a stress-strain curve signifies the first point where any increase in strain is not met with an increase in applied stress. The zero value of the first derivative of the fitted polynomial gives the strain value with the corresponding stress value (Figure 6.9). The values for the different species are shown in Table 6.1. The integral of the polynomial from the zero to the same strain value corresponding to the stationary point (MOR) provides the area under the curve and thus, the work done (energy) required per unit volume of the greenwood before the greenwood reaches “yield” condition. This is also referred to as the toughness of the greenwood material. The toughness of the species greenwood can be used to access the suitability for planting at reduced risk of failure by snapping. Table 6.1 also summarizes the toughness of the five species of trees tested.

Table 6.1 shows that data from field testing of greenwood can provide a good basis of comparing the greenwood material performances and properties for different species of trees. The moisture contents and greenwood density data were also plotted using boxplots in Chapter 5. An example of a way to utilize this data is to use wet or greenwood density in conjunction with the stress strain properties for designing tree maintenance regimes which incorporates structural risk analysis. For example, the bending stresses on the tree limbs and attachment points can be calculated using the geometrical and the wet density data corresponding to the tree species. These stresses can then be compared to the modulus of rupture measurements for structural risk analysis.

The shape and magnitude of the fitted stress strain curves also give practitioners and researchers a method to input the material properties for different tree species for more complex computer aided static or dynamic analysis. Using these data, complex finite element modelling like two-way fluid structural interaction using computational fluid dynamics (CFD) analyses can also be performed to understand the tree’s interaction with the micro or macro wind environment.

Table 6.1 Summary of “yield” stress and strain values and toughness for the eight tested species with increasing toughness

Tree Species	Fitted Polynomial $y = f(x)$ (y is the stress and x is the strain)	Strain (x) (%)	Stress (y) (MPa)	Toughness (J/m ³) x 10 ⁴
<i>Pterocarpus indicus</i>	$y = -0.0505x^6 + 0.84x^5 - 5.2261x^4 + 16.036x^3 - 31.559x^2 + 51.106x$ $R^2 = 0.9918$	2.7	46.2	88.99
<i>Samanea saman</i>	$y = 0.001x^6 - 0.0302x^5 + 0.3307x^4 - 1.4564x^3 + 0.3287x^2 + 15.418x$ $R^2 = 0.9837$	4.2	31.6	92.2
<i>Syzygium polyanthum</i>	$y = -0.0004x^6 + 0.0215x^5 - 0.2943x^4 + 2.007x^3 - 9.3401x^2 + 27.827x$ $R^2 = 0.9872$	3.7	35	94.65
<i>Tabebuia rosea</i>	$y = 0.003x^6 - 0.0831x^5 + 0.881x^4 - 4.166x^3 + 6.089x^2 + 13.471x$ $R^2 = 0.9948$	3.9	37.4	98.0
<i>Swietenia macrophylla</i>	$y = -0.0002x^6 + 0.0044x^5 - 0.0466x^4 + 0.3376x^3 - 2.5433x^2 + 13.765x$ $R^2 = 0.991$	6.1	30	130.6
<i>Syzygium grande</i>	$y = 0.0003x^6 - 0.0196x^5 + 0.3364x^4 - 2.1926x^3 + 2.948x^2 + 19.007x$ $R^2 = 0.958$	4.0	50.2	130.8
<i>Peltophorum pterocarpum</i>	$y = 0.0073x^6 - 0.1949x^5 + 1.9584x^4 - 8.7441x^3 + 13.435x^2 + 15.534x$ $R^2 = 0.998$	4.1	49.2	141.3
<i>Khaya senegalensis</i>	$y = -0.0003x^6 + 0.0086x^5 - 0.1263x^4 + 1.2104x^3 - 7.6392x^2 + 27.294x$ $R^2 = 0.9985$	4.8	40.1	144.1

It can be inferred from the field testing that the three-point test method utilizing the simplified data acquisition method is more suitable for providing greenwood flexural properties as a wider range of sample dimensions can be tested while keeping the apparatus testing frame small and portable. The three-point testing method also has the ability to test specific points along the branch for future tests on the effects of wood defects (knurls, knots and cuts etc.) on flexural strength (MOR). The lower values of average three-point testing MOR as compared to those of four-point testing are due to the smaller tested sample volumes. It also means that slightly more conservative numbers are used to derive arboricultural recommendations which can lead to safer practices. More research should also be performed to distinguish greenwood properties distribution for different parts of the tree for each species. The boxplots provide a useful statistical tool to help provide confidence intervals of the stress-strain data while filtering outliers. The fitted stress-strain polynomials and the areas under the represented curves also provide a means to obtain representative greenwood characteristics of individual tree species.

6.2 The proposed shallow root tree stability model

Figure 6.10 shows the plot of the winching force measured in the field tests and the calculated failure winching forces using the shallow root model. The shallow root model yielded a good representation of the field results with the regression line almost superimposing on the 45° line.

Figure 6.10 Plot of the calculated maximum winching forces using the shallow root model from the field measured root CSA against the field measured winching forces with the linear regression line almost superimposing on the 45° line

The results shown in Figure 6.10 show that the values calculated from the shallow root model can be used to estimate the bending resistance of shallow rooted trees. This shows that the bending resistance provided by the leeward compressive lateral roots becomes more important if there are fewer or shallow tension tie down roots (sinker roots). The passive nature of the sinker roots ensures that a significant strain at the leeward hinge precedes the activation of the maximum tensile force in the sinker roots. The depth of penetration of the sinker roots is far more important than the soil strength as the strong dense soil often cannot permit deep penetration due to constraints in permeability, shear strength and oxygen content. The shallow root model can also be adjusted to provide for more sinker roots and locate these sinker roots at different distances from the compression hinge. The shallow root model gives a good estimate of the resistance of a shallow rooted tree to uprooting but does not give an estimate of the directional strength as the 360° root CSA is measured and equally distributed between the windward and leeward members. To provide a directional variation of strength, the spatial distribution of the root CSA has to

be measured. This spatial variation can enable individual lateral and vertical tie down roots to be calculated for their contribution, either in a compressive or tensile capacity (Chapter 3: Three dimensional shallow rooted tree stability model).

Shallow rooted trees are uprooted due to the inadequate resistance of the root plate to flexural moments resulting from lateral loads. The direction of the lateral load separates the shallow root plate into compressive and tension lateral roots. The amount of contribution from the compressive and tension lateral roots can be determined by the spatial and directional distributions of the root CSA with respect to the lateral force direction. The shallow root model estimates the failure lateral force quite well with a 50%-50% separation of the measured root CSA between compressive and tensile lateral roots. For shallow rooted trees with few and shallow sinker roots, the importance of the lateral roots in compression far outweighs that of the sinker roots in tension. To increase the contribution of the lateral roots in tension to overall stability, the number of sinker roots has to increase, along with their diameters, their depth of penetrations and their locations along the lateral roots in tension. The stiffness (diameters) of the lateral roots in tension also dictate the ability for the sinker roots located further away from the trunk to be mobilized for stability against lateral loads in the opposite direction. The main difficulty of utilizing the shallow root model or any root model for the non-destructive prediction of failure lateral loads lies in the accurate assessment of the in situ distribution of the root CSA and the depth of rooting. However, with this in mind, risk models can be generated using this model coupled with canopy size, wind speeds and drag coefficients to better aid pruning methods and other operational decisions, like root cutting to make way for construction purposes. The effect of decay on the modulus of rupture of affected lateral roots can also be modeled using the shallow root model.

The described 3d shallow root model described in Section 3.3 should provide an even better estimation of the failure lateral force as it takes into account the directional distribution of the lateral roots. The 3d shallow root model will be able to cope with different geometries and ground conditions and topography to predict the failure lateral load magnitude in different directions. When using the shallow root or the 3d shallow root method to estimate the failure lateral loads of shallow rooted trees, non-destructive methods of estimating root CSA must first be developed. The effect of root confinements or obstructions within narrow planting strips must also be investigated.

6.3 3D visualization of trees using laser scanning

Chapter 5 presented the results for the laser scanning. Laser scanning was able to capture the selected trees and the surrounding area in great detail. Exact orientations of the tree, branches and canopy could be visualized in three dimensions when viewed in the computer. However as the laser scanner captures detail within the canopy as a series of scalar points, a surface cannot be generated. Furthermore, a surface cannot differentiate between the woody branches and the leaves. The resulting triangular mesh is not closed and does not define any geometrical properties like volume and area.

When scanning large structures with well-defined geometrical shapes (e.g. Buildings) a well refined surface mesh can be built up by inserting the appropriate geometrical shapes to take the approximate shape of the buildings and other structures. This is important for defining the landscape using three dimensional geometries that can be imported into computational fluid dynamics software or other finite element software. The interaction of wind with the trees can vary dramatically depending on the spatial orientation and geometry of manmade structures in relation to the trees.

Figure 6.11 shows the insertion of a simple geometrical shape to take the place of a point block within the point cloud landscape around the trees at Telok Blangah Rise.

Figure 6.11 A simple geometry inserted into the point cloud to take the place of a single point block.

Using the laser scans as a spatial reference, small scale areas can be built up using simple geometries and the effects of the urban landscape on the wind flow around the trees can be simulated.

6.4 Analyzes of the structural surveyed trees using the shallow root model

To analyze the structural surveyed trees (Chapter 5), values of root CSA and measured greenwood strength properties were assumed using literature and test data. This was due to the difficulty in non-destructively assessing a tree's true root CSA. From Ghani (2009), the root cross-sectional area (CSA) of *Syzygium grande* could be assumed at 0.5m from the trunk face. Ghani, 2009 estimated that the mean total CSA was 2373cm² for both lateral and sinker roots. Taking the input parameters of MOR (Chapter 5) and soil properties (Chapter 5), the shallow root model was used to estimate the resistance to uprooting. Table 6.2 shows a summary of the resistance to bending for Silat Avenue *Syzygium grande* 1 using the shallow root model.

Table 6.2 Summary of the resistance to bending for Silat Avenue *Syzygium grande* 1 using the shallow root model

Silat Avenue <i>Syzygium grande</i> 1	
<i>Diameter of trunk (m)</i>	0.620
<i>Sinker root depth (m)</i>	2.0
<i>Bending resistance (kNm)</i>	333.6
<i>Azimuth of centroid (deg)</i>	196.2
<i>Static bending moment (kNm)</i>	8.6
<i>Net Bending Resistance (kNm)</i>	325.0

Correlating the bending resistance to an equivalent wind speed, a uniform lateral pressure was applied to the three dimensional model at an azimuth of 196.2 degrees from magnetic north. With the total surface area of 54.2m² and due to the cylindrical nature of the branches, half the total area was always presented to the wind regardless of the wind direction.

Taking a drag coefficient of 1.0 for simplicity, the density of air is about 1.20 kg/m³ at 25°C.

$$P_w = 0.5 \times \rho_a \times v_w^2 \times C_d \quad (6.1)$$

where

P_w = wind pressure in Pa

ρ_a = density of air at 25°C

v_w = velocity of air in m/s

C_d = drag coefficient which is dimensionless and taken as 1

To calculate the critical wind speed (v_{wc}) the critical wind pressure P_{wc} needs to firstly be determined,

$$P_{wc} = \frac{2B_{net}}{AZ_c} \quad (6.2)$$

Where

P_{wc} = critical wind pressure

B_{net} = net bending resistance

Z_c = as the center of area in the z axis

For Silat Avenue *Syzygium grande* 1,

$$P_{wc} = 1,462 Pa$$

$v_{wc} = 49.3 m/s$ or 177.7km/h at 196.2 degrees from magnetic north (due to the static bending moment direction)

Figure 6.12 shows the variation of critical wind speed with changes in root CSA. As root CSA decreases, critical wind speed also decreases. Figure 6.12 also shows the variation of critical wind speed with wood MOR. Decreasing MOR also results in reduced critical wind speeds. Critical wind speeds decrease in rate of the square of root CSA and linearly to MOR.

Figure 6.12 Using the shallow root root model, a reduction in the root CSA and greenwood modulus of rupture of Silat Avenue *Syzygium grande* 1 corresponds to a reduction in critical wind speed (v_{wc})

For the trunk of diameter of 0.62m and the rupture modulus of *Syzygium grande*, the rupture bending moment was 1,170 kNm which was greater than B_{net} (325 kNm (Table 6.2)). Therefore, under lateral load, it is estimated that the tree would fail by uprooting when encountering a wind speed of 177.7km/h. Figure 6.12 shows the sharp drop in critical wind speed when root CSA is reduced by manmade or natural processes. Natural processes can include decay or root death and manmade processes can include construction activities resulting in root loss.

Using the same root CSA provided by Ghani (2009);

Table 6.3 shows the bending resistance of the second Silat Avenue *Syzygium grande* to lateral loads. Figure 6.13 shows that for the same root CSA, the second *Syzygium grande* shows a much higher failure wind speed due to its smaller sail area exposed to the wind. This could be a possible explanation of uprooting of single trees within an area where there are many trees of the same height and species. The center of area of a tree was also observed to be important to determine the resultant point of application of wind loads and as a result the bending moments applied to the roots.

Figure 6.13 With a smaller sail area and a lower center of gravity compared to *Syzygium grande* 1, *Syzygium grande* 2 displays a much higher critical wind speed of 238km/h for MOR of 50MPa

Table 6.3 Summary of the resistance to bending for Silat Avenue *Syzygium grande* 2 using the shallow root model

Silat Avenue <i>Syzygium grande</i> 2	
Diameter of trunk (m)	0.69
Sinker root depth (m)	2.0
Bending resistance (kNm)	329.0
Azimuth of centroid (deg)	349.9
Static bending moment (kNm)	0.101
Net Bending Resistance (kNm)	320.4
Total Surface Area (m ²)	40.0

For comparison sake to the *Syzygium grande* 1 and 2 at Silat Avenue, the same range of root CSA was used to calculate the critical wind speeds for the *Samanea saman* at Silat Ave. From the three point bending tests conducted on *Samanea saman*, the rain tree has a greenwood mean MOR of 38MPa. Table 6.4 shows the summary of resistance to bending for the Silat Avenue *Samanea saman* using the shallow root model for the same range of root CSA as the *Syzygium grande* 1 & 2. Figure 6.14 shows the comparison

between critical wind speed and root CSA for different greenwood modulus of rupture for Silat Avenue *Samanea saman*.

Table 6.4 Summary of the resistance to bending for Silat Avenue *Samanea saman* (rain tree) using the shallow root model.

Silat Avenue <i>Samanea saman</i> (Rain Tree)	
<i>Diameter of trunk (m)</i>	0.955
<i>Sinker root depth (m)</i>	2.0
<i>Bending resistance (kNm)</i>	311.0
<i>Azimuth of centroid (deg)</i>	266.1
<i>Static bending moment (kNm)</i>	9.0
<i>Net Bending Resistance (kNm)</i>	302.0
<i>Total Surface Area (m²)</i>	169.41

Figure 6.14 with a much larger sail area, lower MOR and a similar center of gravity height compared to *Syzygium grande* 1 and 2, the surveyed rain tree at Silat Avenue displays a much lower critical wind speed of 106.5km/h for a greenwood MOR of 38KPa

The next surveyed tree to be analyzed was the *Samanea saman* 1 at Telok Blangah Rise. Like the *Samanea saman* at Silat Ave, the *Samanea saman* 1 at Telok Blangah Rise also has a large sail area compared to the *Syzygium grande* 1 & 2. Table 6.5 shows a summary of the resistance to bending for the Telok Blangah Rise *Samanea saman* using the shallow root model.

From Table 6.5, the calculated root plate uprooting resistance was correlated to a critical wind speed using the above ground tree architecture. Using the average MOR of 38MPa (MOR of *Samanea saman*, the calculated critical wind speed was even lower than the Silat Ave *Samanea saman* at 86km/h (Figure 6.15). This shows that for the same root CSA, the variability of the above ground tree superstructure can cause big differences in the critical wind speed. Telok Blangah Rise site also experienced much higher total wind compared to Silat Ave (Figure 6.17). So a higher than average wind speed coupled with wind channeling amplification from nearby tall buildings can be part of the reason why Telok Blangah Rise experienced uprooting failure of a *Samanea saman* tree near the site in 2011.

Table 6.5 Summary of the resistance to bending for Telok Blangah Rise *Samanea Saman* 1 using the shallow root model

Telok Blangah <i>Samanea Saman</i> 1	
<i>Diameter of trunk (m)</i>	1.11
<i>Sinker root depth (m)</i>	2.0
<i>Bending resistance (kNm)</i>	337
<i>Azimuth of centroid (deg)</i>	1.2
<i>Static bending moment (kNm)</i>	8.9
<i>Net Bending Resistance (kNm)</i>	328.1
<i>Total Surface Area (m²)</i>	214.89

Figure 6.15 With a larger sail area and higher center of gravity compared to the trees at Silat Ave, the maximum critical wind speed was calculated to be only 86km/h for the same root CSA values

The final tree that was analyzed using the shallow root model was the *Samanea saman* 2 at Telok Blangah Rise. Table 6.6 shows a summary of the resistance to bending for the Telok Blangah Rise *Samanea saman* 2 using the shallow root model.

Table 6.6 Summary of the resistance to bending for Telok Blangah Rise *Samanea Saman* 2 using the shallow root model

Telok Blangah <i>Samanea Saman</i> 2	
Diameter of trunk (m)	0.637
Sinker root depth (m)	2.0
Bending resistance (kNm)	269
Azimuth of centroid (deg)	341.6
Static bending moment (kNm)	7.34
Net Bending Resistance (kNm)	261.7
Total Surface Area (m ²)	113.74

Figure 6.16 The high center of area of the Telok Blangah Rise *Samanea saman* 2 reduces maximum critical wind speed to 86km/h even as sail area is very much smaller compared to *Samanea saman* 1.

The analyses conducted on the five trees showed that the critical wind speed required for uprooting trees depend on sail area, sail height, location of center of area and root CSA. Therefore, to maximize tree resistance against uprooting while preserving reasonably large canopies for trees (large sail area), the canopy height must be minimized and the root CSA increased. The greenwood MOR was also shown to play a big part in preventing uprooting. If basal root decay takes hold in the trunk, lateral roots or sinker roots, greenwood MOR reduction can be used together with root CSA reductions to calculate the amount of reduction in net bending resistance. If partial decay of the root or trunk section was observed, reductions in the section sizes of the lateral roots or trunk can be performed to determine reductions in mechanical strength properties.

6.5 Comparing the wind characteristics of Silat Ave and Telok Blangah Rise

Figure 6.17 Comparison of total recorded wind in kilometers at Silat Ave and Telok Blangah Rise for the same period with the line showing as a percentage of total wind recorded at Silat Ave over the total wind recorded at Telok Blangah Rise.

Figure 6.17 shows that there was a big difference in the measured total wind run (wind speed multiplied by the time expressed in kilometers) between the two instrumented sites. The maximum monthly total winds recorded at Telok Blangah Rise also did not align with the maximum monthly total wind recorded at Silat Ave for the month of February. Telok Blangah Rise shows a distinct maximum monthly recorded total wind for the month of March. The percentage differences (Figure 6.17) between the two sites were amplified by overall reductions in total wind measured in the months of April to July. This showed that even a short distance between the sites of about 1 km shows a marked difference in total wind. The estimated elevation above sea level for Silat Ave site was about 7 m. After including the mast height of the anemometer at 10 m, the total estimated recording height

was 17 m above sea level at Silat Ave. The total estimated recording height at Telok Blangah Rise was about 40 m above sea level.

The wind profile power law is a relationship between the wind speeds at one height, and those at another. The wind profile of the atmospheric boundary layer (surface to around 2000 meters) is generally logarithmic in nature and is best approximated using the log wind profile equation that accounts for surface roughness and atmospheric stability. The wind profile power law relationship is often used as a substitute for the log wind profile when surface roughness or stability information is not available.

The wind profile power law relationship (Peterson et. al., 1978) is:

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^\alpha \quad (6.1)$$

where:

u is the wind speed (in metres per second) at height z (in metres),

u_r is the known wind speed at a reference height z_r .

The exponent (α) is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. For neutral stability conditions, α is approximately 1/7, or 0.143.

Using z and z^r as 40 m and 17 m respectively, Telok Blangah Rise was estimated to experience a 13% higher wind speed than in Silat Ave. The maximum recorded wind speed at Telok Blangah Rise was about 8.8 m/s while the maximum recorded wind speed at Silat Ave was about 7.9 m/s. This translates to an 11% difference. This shows that with an empirically derived coefficient (α), using more sites for calibration, wind speeds can be estimated for a location depending on the elevation of the location above sea level. The experienced total wind for a given location is a function of wind direction, topography and urban/natural structures layout and densities.

The low recorded wind speeds at Telok Blangah Rise and Silat Ave (presented in Chapter 5) showed that normal wind speeds experienced during thunderstorms form only a

part of the loads required for uprooting failures to occur. High factors of safety against trunk snap (Chapter 5, Figure 5.65) also showed that wind loads required for snapping healthy tree trunks are far greater than what is normally experienced. When defects in the tree structural components (roots, trunk and branches) start to manifest through natural wood death, decay, bad pruning practices or construction activities, these high factors of safety can be reduced to unity or lower depending on the applied wind speeds and soil conditions.

6.6 Numerical modelling on combined effects of canopy geometries, shapes and groundwater table on overturning and resisting moments (EXCEL)

A parametric study of SA and TBR was conducted in relation to the critical wind speed and groundwater depth with reference to different tree canopy shapes with the dimensions shown in Table 6.7. The heart root model was used in conjunction with the experimental soil properties.

Table 6.7 Dimensions used in the parametric study for lateral loads

Canopy shape	Dimensions (m)
Triangular	20 m base and 20 m height
Rectangular	20 m base and 20 m height
Ellipse	20 m radius

Figure 6.18 shows three canopy shapes and the corresponding critical wind speed at different groundwater table levels (GWT) for soil conditions at SA. When the groundwater table is at the surface (GWT = 0m), the moment required and wind speed required for failure to occur is at the lowest, with the ellipse shaped canopies requiring the lowest wind speed to fail followed by the rectangular shaped canopies then the triangular canopies. The deeper the groundwater table, i.e., as GWT increases in depth, the higher the wind speed required to cause tree failure.

Figure 6.18 Wind speed and groundwater table level comparison for different canopy shapes and soil conditions at SA.

Figure 6.19 shows three canopy shapes and its corresponding critical wind speed at different groundwater table levels (GWT) for soil conditions at TBR. Similarly, when the groundwater table is at the surface (GWT = 0m), the moment required and wind speed required for failure to occur is at the lowest, with the ellipse shaped canopies requiring the lowest wind speed to fail followed by the rectangular shaped canopies then the triangular canopies. The deeper the groundwater table, i.e., as GWT increases in depth, the higher the wind speed required to cause tree failure. However, the threshold wind speed required for tree failure is higher for TBR as compared to SA. This was because the heart root model only considered soil strength as the only restraining component of the root plate. The stronger soil (from experimental results shown in Chapter 5) found at TBR would mean that a tree with similar superstructure and root dimensions will fail at a lower critical wind speed in SA than in TBR.

The results from this section show that when considering tree stability against uprooting, soil strength or weakness can play a big part with variations in ground water table depths.

Figure 6.19 Wind speed and groundwater table level comparison for different canopy shapes and soil conditions at TBR.

6.7 Heart root model dimensions for soil failure (EXCEL)

In Section 6.6, the ground water table was varied in the theoretical analysis carried out in EXCEL for different canopy shapes using the soil parameters from the two sites. In this section, the root plate dimensions were varied together with ground water table depths in EXCEL. By considering only the shear resistance of the soil to resist the overturning moment by wind load, this analysis looks into wind throw failure of trees with different root plate dimensions.

Figure 6.21 shows the changes in failure wind load due as depth of water table varies for different root plate dimensions. In Figure 6.21, 't' refers to the root plate thickness while 'b' refers to the root plate radius (Figure 6.20).

In Figure 6.21, it is observed that a tree with the largest root plate thickness and smallest root plate radius is most vulnerable to tree throw. Having a smaller root plate radius (defined by b) means that the failure slip surface is smaller, resulting in a shorter path of mobilized soil resistance. Having a smaller root plate thickness also means that the failure slip surface is smaller. However, the difference is less significant compared to

having a smaller root plate radius. Figure 6.20 illustrates the changes in the failure slip surface as the root plate dimensions change. In Figure 6.20, the reduction in the circumference of the slip surface is only 0.23 m when the thickness of the root plate decreases by 0.75 m. However, the reduction in the circumference of the slip surface is large, i.e., 7.04 m when the root plate radius decreases by 2 m.

Even though having a smaller root plate thickness means that there is a reduction in the circumference of the slip surface, the tree modelled using the heart root model is able to resist a higher load given the same root plate radius. This is because when the root plate is thinner, it is assumed that the slip surface is also nearer to the ground level. This results in an increase in soil resistance due to higher matric suction in the soil found nearer the surface. Higher matric suctions lead to higher soil shear strengths. There is, however a sacrifice of lower shear strength due to lower net normal stress near the ground surface.

Figure 6.20 Variation of slip surface circumferences for different root plate dimensions

Figure 6.21 Failure wind load vs. depth of water table for different root plate dimensions

The results from this section illustrate the limitations considering only the soil shear strength as the root strength is not considered. In the next section, the root and trunk stresses and strains were considered together with the soil.

6.8 Using the heart root model and numerical modelling in SIGMA/W to determine the controlling failure mode

Section 5.6.3 shows that as the ground water table depth increases, the soil can become very strong. By estimating the resistive moments of the tree based on the heart root model, big overestimations of the tree's ability to resist lateral loads can occur due to the large slip surfaces used to calculate the resisting moments. Section 5.6.4 shows that the root size, stem (trunk) diameter and wood strength, can become more important than soil as these structures have been shown numerically to yield (<5% strain) before the soil (>15% strain). If the wind force required to break the root is divided by the wind force required to shear the soil via the heart root model and expressed as a percentage ($F_{\%}$), this percentage versus ground water depth can be plotted and is shown in Figure 6.22.

Soil properties and environmental conditions can vary such that the soil strength is reduced dramatically by high pore-water pressures from artesian springs, tidal variations or seepage flow. In those cases, the soil strength becomes much more important than the root/trunk dimensions.

Figure 6.22 $F_{\%}$ for the tree of root plate of 0.25 m thick and 3 m radius against ground water depth (m). $F_{\%}$ is the percentage of the wind load required to break the root compared to the wind load required to fail the soil calculated using the heart root model.

By quantifying the failure wind loads for various failure mechanisms at different depths of water table, the likely failure modes of a tree with a specified root plate thickness and radius can be predicted at varying depths of water table. Table 6.8 shows an example of the predicted failure mechanisms for a tree with a root plate thickness of 0.25 m and a radius of 4 m at various depths of water table. As shown in Table 6.8, as the depth of water table depth increases, the failure mechanism was tree root flexural failure. The tree material properties become the governing factor for tree failure as depth of water table increases.

It was observed that using the heart root model, the values of wind speed ratio are much higher compared to those obtained from SIGMA/W analyses. For a tree with a root plate thickness of 0.25 m and a radius of 4 m, an approximate increase of 550% in wind speed is required to fail the tree if the groundwater table depth increases from 0 to 8 m. This is way beyond the 20% increase in wind speed concluded in SIGMA/W analyses. This is because in theoretical analyses (heart root model), the tree stability is assumed to be heavily dependent on the soil resistance. A change in groundwater table depth

influences the matric suction in the soil and the corresponding shear resistance of soil. The larger the slip surface, the higher the effect of depth of water table on tree stability. From the SIGMA/W analyses, even though the soil played a large part in tree stability, the tree is deemed to have failed without soil failure. Thus, the effect of depth of water table on tree stability in the SIGMA/W analyses was lower than the analyses based on the heart root model.

Table 6.8. Predicted failure mechanisms for a tree with a root plate thickness of 0.25 m and a radius of 4 m

Depth of water table (m)	Failure mechanism	Failure wind load from soil shear failure (kN) (EXCEL)	Failure wind load from root/trunk failure (kN) SIGMA/W
0	Root failure	39.54	18.5
1	Root failure	163.49	20.0
2	Root failure	312.00	21.0
3	Root failure	460.38	22.0
4	Root failure	608.82	23.0
5	Root failure	757.26	24.0
6	Root failure	905.70	24.5
7	Root failure	1054.14	25.5
8	Root failure	1202.59	26.0

By incorporating the results from SIGMA/W and theoretical (heart root model) analysis, it could be deduced that a tree is most vulnerable to root break failure like what is shown in Section 5.6.4. As both kinds of failures involve interaction with the soil system, the depth of water table is important as it influences the properties of the soil. Trunk failure will only be encountered if the trunk dimensions were close to the lateral root dimensions.

6.9 Effect of flux boundary conditions on soil pore-water pressures and moisture contents (SVFLux)

The results of the flux boundary analyses confirmed that rainfall/groundwater table affect the soil pore-water pressures and therefore tree stability. Rainfall or a shallow ground water table decreases the negative pore-water pressure in the ground and hence decreased the shear strength of the soil. The decrease in soil strength due to increased pore-water pressures was also found in the study by Kamimura et al. (2012). This study supported the results of Samarakoon et al. (2013) and Rahardjo et al. (2009) that showed a decrease of 10-50% in overturning moment required to overturn a tree when the soil was wetted. The results also showed that the correct combination of wind, rainfall and groundwater depth can be a triggering factor for tree failure. It is also noted that rainfalls that eradicated the negative pore-water pressure were not very high (Figure 5.91). The possible reason for this phenomenon could be due to the very shallow ground water table as shown by the instrumentation results (<1.5 m depth). The shallow ground water table created a very low initial negative pore-water pressure. Therefore small rainfall events were sufficient to remove the small initial negative pore-water pressures. A different scenario may happen if the ground water table was in a deeper position. A deep ground water table could create a high negative pore-water pressure profile in the soil which results in a higher resisting moment for the tree. In addition, by having a deep ground water table and high negative pore-water pressure, the coefficient of permeability of the soil is lower hence the time for the water to infiltrate the soil is also longer.

The effect of transpiration or root water uptake from the tree was not taken into account in this study as a separate measurement. In this study the daily changes of negative pore-water pressure and the cyclical diurnal profile were small compared to the effects of rainfall or dry weather. This could be due to shallow depth of the water table, readily providing a stable source of ground water to the root system. The effects of increasing transpiration rates in the day and decreasing transpiration rates at night were too small to be detected from the pore-water pressure measurement data.

Soil mechanical properties are one of the major contributors to the trees' resisting moment against uprooting. In this study, there are two other soil properties that were seen

to be indirectly related to the stability of the trees. The first one was the coefficient of permeability and the second was the SWCC. These two properties affected the rate of water flow (drainage) in the soil and thus influenced the pore-water pressures in the soil. These pore-water pressures affected the shear strength properties (through the effective cohesion, effective friction angle and ϕ^b angle of the soil). In order to avoid large increases of pore-water pressure during rainfall, the soils should be able to drain the water efficiently. Therefore, the coefficient of permeability of the soil should be high enough to prevent high pore-water pressures from building up and at the same time low enough to retain water for root uptake. A soil type with a high coefficient of permeability such as sand usually has a lower water retention capacity whereas for fine clays, soil water-retention is high but permeability is low. Therefore, a soil mixture that balances between these two desired properties is desirable for tree stability. The soil commonly used for planting of roadside trees in Singapore is a mixture of sand, residual soil and organic matters. The proportion of these individual components can be altered in order to obtain the desired properties of top soil with high permeability and water retention. As the topsoil with modified hydraulic properties will have different properties from the in-situ soil, the design of the modified topsoil will need to take into account the hydraulic properties of the in-situ soil to prevent ponding of rainwater. Alternatively external drainage can be provided to give an outlet to the infiltrated water.

The top soil mixtures proportion will also affect the shear strength of the soil. Additional components such as gravel can be used to increase the soil strength as investigated by Raharadjo et al. (2009). One area that has not been well implemented on the arboricultural setting is the quality control of compaction and soil mixture in the field. It should be noted that the properties of the soil are dependent on the state of the soil (density, water content, loading history). Soils with the same density and water content can have different properties depending on whether the soil was compacted on wet or dry side of optimum (Holtz and Kovacs, 1981).

6.10 Numerical modelling on root architecture and soil conditions

Some results of the numerical modelling performed in ANSYS are shown in Section 5.6.6. To summarize all the modelling results for discussion, the maximum equivalent stresses (Equation 2.58 from Chapter 2) and total deformations (Equation 2.59 from Chapter 2) for each simulation are plotted as a point within the charts for each study; Figure 6.23 and Figure 6.24 show the study on the number of evenly spaced sinker roots per lateral root. Figure 6.25 and Figure 6.26 show the study on the depth of sinker roots within the critical structural root zone. Figure 6.28 and Figure 6.29 show the study on the variation in lateral root diameter. Figure 6.30 and Figure 6.31 for the study on the variation in the elastic modulus of the soil.

6.10.1 Number of evenly spaced sinker roots per lateral root

Figure 6.23 shows the variation of the maximum equivalent stress experienced by the model root system with increasing numbers of evenly spaced sinker roots per lateral root. The maximum stress decreased rapidly for the first two numbers of sinker roots. The maximum stress remained constant with two or more sinker roots. This shows that the effective zone of influence of the sinker roots is a small area around the tree trunk.

Figure 6.23 Chart of the maximum equivalent stresses in the model tree root with the number of evenly spaced sinkers (2 m depth) on each lateral root.

Figure 6.24 shows the variation of the maximum total deformation (measured by the tip of the trunk) experienced by the model root system with increasing numbers of evenly spaced sinker roots per lateral root. The total deformation chart shows similar characteristics to Figure 6.23. The decrease in total deformation is limited to the first two sinker roots beyond which there is hardly any variation.

Figure 6.24 Chart of the maximum total deformation in the model tree root (taken from the tip of the trunk) with the number of evenly spaced sinkers (2 m depth) on each lateral root.

Figure 6.23 and Figure 6.24 show that the radius of the circular critical zone around a tree trunk that affects tree resistance to uprooting is fixed by the root architecture within the zone. This critical zone, or the tree's resistance to uprooting, cannot be increased by increasing the lateral or radial spread of lateral roots. This however does not mean that cutting or reducing the lateral spread of the roots beyond this critical zone will not affect the overall health of the tree, as these roots may serve other non-structural purposes like for water or nutrient uptake.

6.10.2 Depth of sinker roots within the critical structural root zone

The simulation models used in Section 5.6.6 showed that the critical structural root zone around the tree was 2 m radius from the trunk center. The two sinker roots within this

zone were retained while the depth of the sinker roots was varied. The equivalent stress and total deformation for 0 m depth sinker root would coincide with the no sinker roots scenario in Figure 5.97. Therefore that point was ignored and instead a 0.5 m depth was used as the minimum depth in this parametric study.

Figure 6.25 Chart of the maximum equivalent stresses in the model tree root with variation in the depth of two evenly spaced sinkers on each lateral root.

Figure 6.25 shows that for this lateral root configuration and applied bending moment, the increase in the depth beyond 3 m of the sinker roots (two per lateral root) did not reduce the maximum equivalent stress. This means that in addition to the circular structural zone around the tree trunk, there is a cylindrical zone 2 m in radius and 3m depth below the ground that makes up the three dimensional critical zone of influence (Figure 6.26). The 2 m radius can be explained by the lack of stiffness in the lateral roots required to mobilize the sinker roots beyond 2 m away. The 3 m depth can be explained by the increasing spread of the compressive stresses due to the self-weight of the tree and the applied moment with increasing depth. At 3 m depth, the spread is enough to reduce compressive stresses to a small value.

Figure 6.26 The three dimensional critical zone of influence is highlighted by the light line cylinder 2 m radius and 3 m depth.

Figure 6.27 shows that even though Figure 6.25 indicates no increase in maximum stress after 3 m sinker depth, there is a continued improvement (reduction) in total deformations with up to 3 m sinker depth. This can be explained by the function of the longer leeward sinker roots as “friction piles” with a bigger surface for resisting the compression force from the leeward lateral root and increased resistance to a local bearing capacity failure at the tree trunk bottom. In this case, the differences in deformations between 2 and 3 m sinker depth is smaller at 8.6% compared to a 12.5% reduction in deformation between 1 m and 2 m sinker depth (Figure 6.27).

Figure 6.27 Chart of the maximum total deformation in the model tree trunk tip with variation in the depth of two evenly spaced sinkers on each lateral root.

6.10.3 Variation in lateral root diameter

In this parametric study, the diameters of the lateral roots were varied. The configuration of the sinker roots was two sinkers per lateral of 3 m depth as that was considered to be the controlling depth for controlling deformations. Figure 6.28 shows that with large increases in the lateral root diameter until 0.8 m, there is a large decrease in the maximum equivalent stress experienced by the root model. This simulation shows the efficacy of buttress roots in reducing the stresses in the lateral roots near the trunk edge. As the diameter of the lateral roots approach that of the trunk diameter (1 m) there is virtually no reduction in maximum equivalent stress.

Figure 6.28 Chart of the maximum equivalent stresses in the model tree root with variation in the diameter of the lateral roots with two sinker roots of 3 m depth.

Figure 6.29 shows that the increases in lateral roots size continue to reduce total deformations by spreading the load over a large area of soil and thus reducing soil deformations. This shows that large stiff root plates can have the biggest role to play in helping the tree resist uprooting. The root plate performs this role by activating windward sinker roots further away from the trunk to act as tension tie downs and by spreading compressive loads over a larger area of soil in the leeward side.

Figure 6.29 Chart of the maximum total deformation in the model tree root measured from the trunk tip with variation in the diameter of the lateral roots with two sinker roots of 3 m depth.

6.10.4 Variation in the soil resilience or elastic modulus

The last parametric study involved the variation of the soil elastic modulus. The soil elastic modulus is reduced with increasing water content and vice versa. Figure 6.30 shows the effect of the soil elastic modulus variation on the maximum equivalent stresses experienced by the tree root model. There are no significant changes in the maximum equivalent stress experienced by the tree root model when there is a $\pm 50\%$ range in soil elastic modulus variation. This shows that the maximum stress experienced by the tree will usually be a function of the root component geometries and arrangements. However if the soil is sufficiently weak enough to increase total deformations significantly, the centroid of the tree can shift enough to increase static bending moments to be applied and thus increase equivalent stresses.

Figure 6.30 Chart of the maximum equivalent stresses in the model tree root with variation in the soil elastic modulus with two sinker roots of 3 m depth.

Figure 6.31 Chart of the maximum total deformation in the model tree root measured from the trunk tip with variation in the soil elastic modulus with two sinker roots of 3 m depth.

Figure 6.31 shows that, even with little changes in the maximum stresses, there are significant changes in total deformations. This is mainly due to the reduction in settlement of the model with an increase in soil modulus. Increasing the soil elastic modulus reduces the deformations experienced by the soil. With no significant differences in the equivalent stresses experienced by the root model, all the reductions in the total deformations can be attributed to the increased resistance from the soil.

6.10.5 Effect of tree root cutting on maximum equivalent stresses and total deformations

Table 5.36 shows the results of the root cutting parametric study described in Section 5.6.6. Figure 6.32 summarizes and compared the effects of cutting the perpendicular root, the compression root and the tension root on the maximum equivalent stresses and total deformations in the root model. This shows that cutting the tension roots affects the stability of the root model the most as the resulting increases in maximum equivalent stresses are much higher but the resulting increases in total deformations are similar as compared to those resulting from the cutting of the compression roots. The compression and tension roots play the most part in restraining the tree against lateral loads. If a tree experiences a constant wind load in a certain direction, it may grow large compression and/or tension roots in this direction to brace the tree against wind in that direction. However, if the wind direction changes (up to $\pm 90^\circ$) and wind speed increases, the tree's growth responses may not be adequate to cater to this change in wind load and direction. This is due to the fact that the tension and compression roots may be in the perpendicular direction to the new wind direction.

Figure 6.32 also shows that cutting the tension roots of a leaning tree will pose the most danger to tree stability and followed by the cutting of the compression and lastly by the cutting of the perpendicular roots.

a)

b)

Figure 6.32 Summary of the effects of cutting the different roots in comparison to the intact root model. a) Maximum equivalent stresses. B) Maximum total deformations.

6.11 Summary of discussion of results

From the research program, the worst case scenario for uprooting failure could be summarized to be the sum of the following:

- 1) A shallow water table reducing soil strength and modulus and reducing sinker rooting depths (due to root death).
- 2) Compression and/or tension lateral roots are reduced by human activities or decay.
- 3) Asymmetrical tree rooting architecture that cannot respond to large changes in wind direction and magnitude.
- 4) Large canopy sail areas that induce high wind drag.
- 5) High canopy sail areas that are exposed to higher wind speeds.
- 6) Decay in the trunk base that can “disconnect” lateral roots from the trunk.

Any one of the listed causes can also cause uprooting failure. Due to the difficulty in detecting causes 1), 2), 3) and 6), measurements of permanent deformations like tree lean angle may prove to be a better diagnosis tool. A rapid progression of lean angle can provide a better indicator of impending failure than trying to diagnose each cause individually.

CHAPTER 7 Conclusions and recommendations

This chapter presents the conclusions and recommendations made from this study.

7.1 Conclusions from greenwood testing

It could be inferred from the field testing that the three-point test method utilizing the simplified data acquisition method was more suitable than the four-point testing method for performing field testing to obtain greenwood flexural properties. This was because a wider range of sample dimensions could be tested using the three-point test while keeping the apparatus testing frame small and portable. The three-point testing method also had the ability to test specific points along the branch for future tests to study the effects of wood defects (knurls, knots and cuts etc.) on flexural strength (MOR). The slightly lower values of the average three-point testing MOR as compared to those of four-point testing were due to the smaller tested sample volumes in the three-point testing method. It also meant that when using values derived from three-point testing, slightly more conservative values can be used to provide arboricultural recommendations which can also lead to safer practices.

7.1.1 Recommendations from greenwood testing

More research should also be performed to distinguish greenwood properties distribution for different parts of the tree for each species. More species of trees should be tested. The boxplots provide a useful statistical tool to help provide confidence intervals of the stress-strain data while filtering outliers. The fitted stress-strain polynomials and the areas under the represented curves also provide a means to obtain representative greenwood characteristics of individual tree species. Improvements to the three-point testing apparatus can also mean improved productivity and provide further improvements to the consistency of results.

7.2 Conclusions from the proposed new shallow root uprooting models

Shallow rooted trees are uprooted due to the inadequate resistance of the root plate to rotational loads caused by lateral loads. The eccentricity of the lateral load separates the shallow root plate into compressive and tension lateral roots. The amount of contribution from the compressive and tension lateral roots can be determined by the spatial and directional distributions of the root CSA with respect to the lateral force direction. The shallow root model estimates the failure lateral force quite well with a 50%-50% separation of the measured root CSA between compressive and tensile lateral roots. For shallow rooted trees with few sinker roots, the importance of the lateral roots in compression far outweighs that of the lateral roots in tension (due to little restraint from the sinker roots). To increase the contribution of the lateral roots in tension to overall stability, the number of sinker roots has to increase, along with their diameters, their depth of penetrations and their locations along the lateral roots in tension. The stiffness (diameter) of the lateral roots in tension also dictates the ability for the sinker roots located further away from the trunk to be mobilized for stability against lateral loads. The main difficulty of utilizing the shallow root model or any root model for the non-destructive prediction of failure lateral loads lies in the accurate assessment of the in situ distribution of the root CSA and the depth of rooting. However, with this in mind, risk models can be generated using this model coupled with canopy size, wind speeds and drag coefficients to better aid pruning methods and other operational decisions, such as root cutting to make way for construction purposes. The effect of decay on the modulus of rupture of the affected lateral roots can also be modeled using the shallow root model.

7.2.1 Recommendations from the proposed new shallow root uprooting models

The described 3D shallow root model described in Section 3.3 should provide an even better estimation of the failure lateral force as it takes into account the directional distribution of the lateral roots. The 3D shallow root model will be able to cope with different geometries and ground conditions and topography to predict the failure lateral load magnitude in different directions. When using the shallow root or the 3D shallow root models to estimate the failure lateral loads of shallow rooted

trees, non-destructive methods of estimating the three dimensional extents of tree root CSA must first be developed. The effect of root confinements or obstructions within narrow planting strips must also be investigated.

7.3 Conclusions from the visualization of trees using laser scanning

Laser scanning was able to capture the selected trees and the surrounding area in great detail. Exact orientations of the tree, branches and canopy could be visualized in three dimensions when viewed in the computer. However as the laser scanner captures detail within the canopy as a series of scalar points, a surface cannot be generated. Furthermore, a surface cannot differentiate between the woody branches and the leaves. The resulting triangular mesh is not closed and does not define any geometrical properties like volume and area. Future research can be conducted to produce a closed mesh from laser scanning.

7.3.1 Recommendations from the visualization of trees using laser scanning

Laser scanning can provide details of large areas that are not easily captured by other methods. Laser scanning can be the basis of building geometries of structures and providing topographical information in a large area covering many hundreds of square meters. These geometries can then be used for computational fluid dynamics (CFD) modelling.

7.4 Conclusions from the new method used for the structural surveys of trees

The analyses using information from the structural surveys of trees conducted on the five selected trees show that the critical wind speed required to uproot trees could be estimated based on sail area, sail height, location of center of area and root CSA. Therefore to maximize tree resistance against uprooting while preserving reasonably large canopies for trees (large sail area), the canopy height must be minimized and the root CSA increased.

7.4.1 Recommendations from the new method used for the structural surveys of trees (TSSM)

Software tools can be developed to improve the productivity of performing the structural surveys. The software must first capture multiple images of the tree with all the branches and orientations. The laser range finder will capture the Cartesian coordinates of each branch and the software will automatically generate the tree branches in three dimensions for export to a finite element or arboricultural software.

7.5 Conclusions from comparing the wind characteristics of Silat Ave and Telok Blangah Rise

There was a big difference in the measured total wind run between the two instrumented sites which were only about 1 km apart. The wind profile power law could be used to estimate the wind speeds based on elevation above or below a known wind measurement point. The low recorded wind speeds at Telok Blangah and Silat Ave showed that normal wind speeds experienced during tropical thunderstorm events form only a small percentage of the wind loads required for uprooting failures to occur. High factors of safety against trunk snap also showed that wind loads required for snapping healthy tree trunks are far greater than what is normally experienced. However, with the onset of decay and manmade activities affecting rooting extents, trees can uproot and experience trunk snap when enough damage is done to the roots and trunk wood.

7.5.1 Recommendations from comparing the wind characteristics of Silat Ave and Telok Blangah Rise

CFD analysis must be carried out to simulate the urban environment so as to determine how urban structures and topography interact with the wind to greatly amplify wind speeds or create turbulence that can cause trees to fail.

7.6 Conclusions from Numerical modelling on combined effects of canopy geometries, shapes and groundwater table on overturning and resisting moments (EXCEL)

The numerical modelling performed in EXCEL comparing the canopy shapes and dimensions show that cylindrical (rectangular) shaped canopies experience the highest overturning moments compared to the canopies for the same heights and width dimensions of ellipsoid and triangular shapes. This was expected as with larger canopy areas at the same heights, more wind load was applied to the canopy. Using the heart root model to compute soil resistance, the higher strength parameters of the soil found at TBR meant that trees at TBR would fail at higher wind speeds compared to similar trees at SA (all other parameters held the same).

7.6.1 Recommendations from Numerical modelling on combined effects of canopy geometries, shapes and groundwater table on overturning and resisting moments (EXCEL)

Two-way fluid structural interaction (FSI) analysis can be performed on tree geometries to better determine the effects of wind on different species and tree architecture. This analysis can determine more accurately drag forces and this can be transferred to a larger scale analysis. Groundwater table measurements can be made in more low lying locations to determine the areas that have a higher risk of uprooting.

7.7 Conclusions from the effect of groundwater table depth and root plate dimensions on failure mechanisms (SIGMA/W)

As the ground water table depth increases, the soil can become very strong. By estimating the resistive moments of the tree based on the heart root model, large overestimations of the tree's ability to resist lateral loads can occur due to the large slip surfaces used to calculate the resisting moments. The root size, stem (trunk) diameter and wood strength, become more important as these structures (<5% strain) have been shown numerically and experimentally to yield before the soil (>15% strain).

7.7.1 Recommendations from the effect of ground water table depth and root plate dimensions on failure mechanisms (SIGMA/W)

By encouraging deeper and stronger root systems to form, trees can be made stronger against root break. More numbers of larger diameter and deeper lateral roots and sinker roots can mobilize more soil volume and thus shear strength from the larger areas of root/soil slip surfaces. Therefore the ideal rooting structure for a tree would be to have the tree failure criterion defined by the heart root model using a large root plate with a large radius of slip surface originating from the trunk base.

7.8 Conclusions from the effect of flux boundary conditions on soil pore-water pressures and moisture contents (SVFLux)

The results of the tree stability analyses using flux boundary conditions confirmed that rainfall/groundwater table has an effect on tree stability analyses. Rainfall or a shallow ground water table decreases the negative pore-water pressure in the ground and hence decreased the shear strength of the soil. The results also showed that the correct combination of wind, rainfall and groundwater depth can be a triggering factor for tree failure. It is also noted that rainfalls that eradicated the negative pore-water pressures at shallow depths were not very high when the ground water table was near the ground surface.

7.8.1 Recommendations from effect of flux boundary conditions on soil pore-water pressures and moisture contents (SVFLux)

The effect of transpiration or root water uptake from the tree was not observed in this study. This could be due to the shallow ground water table providing a constant source of water to the tree roots. If the ground water table was deeper, root water uptake can cause increased negative pore-water pressure in the soil and in turn adds to the tree stability. This effect can be taken into account in the future. Three-dimensional seepage can also play a part in determining the pore-water pressures in the soil beneath the tree. Seepage analysis can be carried out in the future to characterize this effect.

7.9 Conclusions from numerical modelling on root architecture and soil conditions (ANSYS)

For the shallow root model, the parametric study on number of sinker roots showed that the maximum equivalent stresses and total deformations decreased rapidly for the insertion of the first two numbers of sinker roots. The maximum equivalent stresses and total deformations remained constant with two or more sinker roots. This shows that the effective zone of influence of the sinker roots was a small area around the tree trunk. There was also a limit to the effective depth of sinker roots to significantly reduce the maximum equivalent stresses and total deformations. Larger diameter lateral roots were found to have the biggest impact on reducing maximum equivalent stresses and total deformations. Increasing the soil elastic modulus and compressive yield stress had no impact on reducing maximum equivalent stresses but significantly reduced total deformations from soil compressibility. Trees experiencing failures in the lateral roots (modelled by cutting) experienced higher total deformations when the tension roots were cut. This was followed by the compressive roots and the perpendicular roots in a decreasing order of importance.

7.9.1 Recommendations from numerical modelling on root architecture and soil conditions

Numerical modelling can move from static structural modelling to explicit dynamics and CFD. This is the logical progression of providing advancement in the understanding of the structural engineering of trees as living structures.

The interaction between root architecture, greenwood properties, soil properties, tree health and effects of human activities mean that real time monitoring of these parameters is difficult and not practical. The hidden nature of tree roots mean that non-destructive testing and survey of root architecture is not practical for large scale monitoring of urban trees. Instead, monitoring deformations due to detrimental changes in the tree basal support can be performed by monitoring tree progression of lean angle. Any rapid progression in the lean angle of a tree can be taken as a sign that there is a detrimental change in the tree's rooting and trunk integrity. This monitoring can be accomplished by installing inclinometers on the tree to measure angle of lean.

REFERENCES

- A.L. Little The engineering classification of residual soils Seventh International Conference on Soil Mechanics and Foundation Engineering, vol. 1 ISSMFE, Mexico (1969), pp. 1–10
- Agriculture Dept (U.S.) and Forest Service (U.S.). 1970, How a tree grows. U.S. Government Printing Office
- ANSYS. (2011). 14.0 User's Manual. *ANSYS Inc., Canonsburg, PA*.
- Arthur P. Boresi, Richard J, Schmidt, Advanced Mechanics of Materials, New York: Wiley and Sons Inc, 2002, Print.
- ASTM Standard D143 2009 Standard Test Methods for Small Clear Specimens of Timber. American Society for Testing and Materials.
- Åström, D. O., Forsberg, B., Ebi, K. L., & Rocklöv, J. (2013). Attributing mortality from extreme temperatures to climate change in Stockholm, Sweden. *Nature Climate Change*, 3(12), 1050-1054.
- Bell, H.J., Dawson, A.R., Baker, C.J. and Wright, C.J. 1991. Tree Stability. In: S.J. Hodge (Editor), Research for Practical Arboriculture. HMSO, London, University of York, pp. 94-101.
- Bergeron, C., Ruel, J.-C., J.-G., É. and Mitchell, S.J. 2009. Root anchorage and stem strength of black spruce (*Picea mariana*) trees in regular and irregular stands. *Forestry*, 82(1): 29-41.
- Bertram, J. A. (1989). "Size-dependent differential scaling in branches: the mechanical design of trees revisited." *Trees* 3(4): 241-253.
- Blackwell, P.G., Rennolls, K. and Coutts, M. 1990. A root anchorage model for shallowly rooted Sitka spruce. *Forestry*, 63: 73-91.
- Blight, G. E. (1997). Interactions between the atmosphere and the Earth. *Géotechnique*, 47(4), 715-767.
- Bonser, R. H. C., & Ennos, A. R. (1998). Measurement of prestrain in trees: implications for the determination of safety factors. *Functional Ecology*, 12(6), 971-974.
- Bowles, J.E. 1996. Foundation analysis and design. 5th ed. McGraw-Hill, NewYork.
- Broms, B.B., Design of Laterally Loaded Piles, ASCE Journal of the Soil Mechanics

- and Foundations Division, Vol. 91, 1965, No. SM3, Pages 79-99.
- Broms, B.B., Lateral Resistance of Piles in Cohesive Soils, ASCE Journal of the Soil Mechanics and Foundations Division, Vol. 90, 1964a, No. SM3, Pages 27-63.
- Broms, B.B., Lateral Resistance of Piles in Cohesionless Soils, ASCE Journal of the Soil Mechanics and Foundations Division, Vol. 90, 1964b, No. SM3, Pages 123-156.
- Brooks, R.H., and Corey, A.T. 1964. Hydraulic properties of porous media. Colorado State University (Fort Collins), Hydrology Paper No. 3.
- Brooks, R.H., and Corey, A.T. 1966. Properties of porous media affecting fluid flow. Journal of the Irrigation and Drainage Division, ASCE, 92(IR2): 61–89.
- Brüchert, F., Becker, G. and Speck, T. 2000. The mechanics of Norway spruce [*Picea abies* (L.) Karst]: mechanical properties of standing trees from different thinning regimes. Forest Ecology and Management, 135: 45-62.
- Brudi, E. 2002. Trees and Statics: An introduction. *Arborist News*: 28-33.
- Burgert, I., Okuyama, T. and Yamamoto, H. 2003. Generation of radial growth stresses in the big rays of konara oak trees. J Wood Sci., 49: 131-134.
- Centre for Ecology and Hydrology, Tree roots in the built environment. Research in Amenity Trees series. TSO, London, 2005
- Chapra, S.C. and Canale, R.P. 2002. Numerical Methods for Engineers. 4th Ed. McGraw-Hill, 926 pp.
- Chatterjea, K. (1989). *Observations on the fluvial and slope processes in Singapore and their impact on the urban environment* (Doctoral dissertation, Department of Geography, Faculty of Arts & Social Sciences, National University of Singapore).
- Childs, E. C. and Collis-George, G. N. (1950), “The Permeability of Porous Materials”,
- Proceeding of the Royal Society of London, Series A, 201, pp. 392-405.
- Choi, E. C. C., & Tanurdjaja, A. (2002). Extreme wind studies in Singapore. An area with mixed weather system. Journal of Wind Engineering and Industrial Aerodynamics, 90(12), 1611-1630.
- Coder, K. D. (2009). Root strength & tree anchorage. *University of Georgia Warnell*.
- Coduto, D. P. (2001). *Foundation design: principles and practices*. Prentice Hall.

- Costa, Y. D., Cintra, J. C., & Zornberg, J. G. (2003). Influence of matric suction on the results of plate load tests performed on a lateritic soil deposit. *Geotechnical Testing Journal*, 26(2), 219-227.
- Coutts M. 1986. Components of tree stability in Sitka spruce on peaty grey soil. *Forestry* 59, 173-197.
- Coutts M., Root Architecture and Tree Stability, *Plant and Soil*, 71, 1983, Pages 171-188
- Coutts M.P., Factors Affecting Growth Direction of Tree Roots, *Ann Sci For*, 46, 1989, Pages 277-287
- Coutts M.P., Nielsen C. C. N. and Nicoll B. C., The Development of Symmetry, Rigidity and Anchorage in the Structural Root system of Conifers, *Plant Soil*, 217, 1999, Pages 1-15
- Coutts, M.P. and Nicoll, B.C., Orientation of the lateral roots of trees I. Upward growth of surface roots and deflection near the soil surface, *New Phytologist*, 1991, Pages 119: 227-234.
- Crook, M. J., & Ennos, A. R. (1996). The anchorage mechanics of deep rooted larch, *Larix europea* × *L. japonica*. *Journal of Experimental Botany*, 47(10), 1509-1517.
- Cucchi V & Bert D. 2003. Wind-firmness in *Pinus pinaster* Ait. stands in Southwest France: influence of stand density, fertilisation and breeding in two experimental stands damaged during the 1999 storm. *Annals of Forest Science* 60, 209-226.
- Cucchi V, Meredieu C, Stokes A, Berthier S, Bert D, Najjar M, Denis A & Lastennet R. 2004. Root anchorage of inner edge trees in stands of Maritime pine (*Pinus pinaster* Ait.) growing in different podzolic soil conditions. *Trees* 18, 460-466.
- Cullen, S. 2002a. Trees and Wind: A bibliography for tree care professionals. *Journal of Arboriculture*, 28(1): 41-51.
- Currey, J. D. 2002 *Bones: structure and mechanics*. Princeton, NJ: Princeton University Press
- Danjon, F., Barker, D. H., Drexhage, M., & Stokes, A. (2008). Using three-dimensional plant root architecture in models of shallow-slope stability. *Annals of Botany*, 101(8), 1281-1293.
- Davenport, A.G. 1960. *Wind Loads on Structures*. Technical Paper No. 88 of the Division of Building Research, Natural Resources Council, Canada, 100 pp.

- Dinwoodie, J. M. 1975: Timber - A review of the structure-mechanical property relationship. *J. of Microscopy* 104:3-32
- Dobson, M., Tree root systems. Arboriculture Research and Information Note 130. Arboricultural Advisory and Information Service, Farnham, 1995
- Elie, J. G., & Ruel, J. C. (2005). Windthrow hazard modelling in boreal forests of black spruce and jack pine. *Canadian journal of forest research*, 35(11), 2655-2663.
- England, A.H., Baker, C.J. and Saunderson, S.E.T. 2000. A dynamic analysis of windthrow of trees. *Forestry*, 73(3): 225-237.
- Ennos AR, Fitter AH, Comparative Functional Morphology of the Anchorage Systems of Annual Dicots, *Functional Ecology*, 6, 1992, Pages 71-78.
- Ennos, A. R. (2000). The mechanics of root anchorage. *Advances in Botanical Research*, 33, 133-157.
- Ennos, A. R., & van Casteren, A. (2010). Transverse stresses and modes of failure in tree branches and other beams. *Proceedings of the Royal Society B: Biological Sciences*, 277(1685), 1253-1258.
- ENVAULT. (n.d.). Retrieved January 31, 2012, from <http://www.envault.com.sg>
- F. Ezquerro, L. Gil Wood anatomy and stress distribution in the stem of *Pinus pinaster* Ait Investigación Agraria, *Sistemas y Recursos Forestales*, 10 (1) (2001), pp. 165–209
- Fortunel, C., Ruelle, J., Beauchene, J., Fine, P. V. A., & Baraloto, C. 2014. Wood specific gravity and anatomy of branches and roots in 113 Amazonian rainforest tree species across environmental gradients. *New Phytologist* 202(1): 79-94.
- Fourcaud, T., Ji, J., Zhang, Z. and Stokes, A. 2008. Understanding the impact of root morphology on overturning mechanisms: A modelling approach. *Annals of Botany*, 101: 1267-1280.
- Fraser, A. I. (1962). The soil and roots as factors in tree stability. *Forestry*, 35(2), 117-127.
- Fraser, A.I. and Gardiner, J.B.H. 1967. Rooting and stability in Sitka spruce., *Forestry Commission Bulletin*. No. 40. HMSO, London.
- Frédéric, D., Guillermo, G., Céline, M., Grégoire, L., Jean-Marc, G., Didier, B., ... & Christophe, J. (2009). Phenotypic plasticity of *Pinus pinaster* to water stress: biomass allocation and root architecture. In International Symposium “Root Research and Applications”. Vienna, Austria.

- Fredlund D.G. and Rahardjo H., Soil Mechanics for Unsaturated Soils, New York: Wiley and Sons Inc, 1993, Print.
- Fredlund, D. G. (2006). Unsaturated soil mechanics in engineering practice. *Journal of geotechnical and geoenvironmental engineering*, 132(3), 286-321.
- Fredlund, D. G. Use of soil–water characteristic curves in the implementation of unsaturated soil mechanics J.F.T. Juca, T.M.P. de Campos, F.A.M. Marinho (Eds.), Proceedings of the Third International Conference of Unsaturated Soils, A.A. Balkema Publishers, Recife, Brazil (2002), pp. 887–902
- Fredlund, D. G., Fredlund, M. D. and Zakerzadeh (2001), “Predicting the permeability Function for Unsaturated Soils”, Clay Science for Engineering, Balkema, Rotterdam, pp. 215-222.
- Fredlund, D. G., Morgenstern, N. R., & Widger, R. A. (1978). The shear strength of unsaturated soils. *Canadian Geotechnical Journal*, 15(3), 313-321.
- Fredlund, D. G., Xing, A., & Huang, S. (1994). Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. *Canadian Geotechnical Journal*, 31(4), 533-546.
- Gaffrey, D. and Kniemeyer, O. 2002. The elasto-mechanical behaviour of Douglas fir, its sensitivity to tree-specific properties, wind and snow loads, and implications for stability - a simulation study. *Journal of Forest Science*, 48(2): 49-69.
- Gardiner, B., Byrne, K.E., Hale, S., Kamimura, K., Mitchell, S.J., Peltola, H., and Ruel, J.-C. 2008. A review of mechanistic modelling of wind damage risk to forests. *Forestry*, 81(3), 447-463.
- Gardiner, B., Marshall, B., Achim, A., Belcher, R., and Wood, C. 2005. The stability of different silvicultural systems: A wind-tunnel investigation. *Forestry*, 78, 471-483.
- Gardiner, B.A. 1992. Mathematical Modelling of the static and dynamic characteristics of plantation trees. In: J. Franke and A.E. Roeder (Editors), *Mathematical Modelling of Forest Ecosystems*. Saunders Verlag, Frankfurt, pp. 40-61.
- Gardiner, B.A. 1995. The interactions of wind and tree movement in forest canopies. In: M.P. Coutts and J. Grace (Editors), *Wind and Trees*. Cambridge University Press., pp. 41-59.
- Gardiner, B.A., Stacey, G.R., Belcher, R.E. and Wood, C.J. 1997. Field and wind

- tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry*, 70(3): 234-252.
- Gardiner, B.H. and Quine, C.P. 2000. The mechanical adaption of tree to environmental influences, *Proceeding of 3rd Plant Biomechanics Conference*, Freiberg, pp. 71-82.
- Gasmo, J. (1997). *Stability of unsaturated residual soil slopes as affected by rainfall* (Doctoral dissertation, Nanyang Technological University, School of Civil and Structural Engineering).
- Gasmo, J. M., Rahardjo, H., & Leong, E. C. (2000). Infiltration effects on stability of a residual soil slope. *Computers and Geotechnics*, 26(2), 145-165.
- GeoSlope International Ltd., 2007a. *Seep/W User's Guide for Slope Stability Analysis*. GEO-SLOPE International Ltd, Calgary, Alta.
- Geotechdata.info, Soil Young's modulus, <http://geotechdata.info/parameter/soil-elastic-young-modulus.html> (as of September 17.09.2013).
- Ghani, M. A., Stokes, A., & Fourcaud, T. (2009). The effect of root architecture and root loss through trenching on the anchorage of tropical urban trees (*Eugenia grandis* Wight). *Trees*, 23(2), 197-209.
- Gibson, L. J., & Ashby, M. F. (1999). *Cellular solids: structure and properties*. Cambridge university press.
- Goh, S. G., Rahardjo, H., & Leong, E. C. (2011). Closure to “Shear Strength Equations for Unsaturated Soil under Drying and Wetting” by Goh Shin Guan, Harianto Rahardjo, and Leong Eng Choon. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(12), 1313-1315.
- Goodman A.M., Crook M.J. and Ennos A.R., Anchorage Mechanics of the Tap Root System of Winter Sown Oilseed Rape (*Brassica napus* L.), *Annals of Botany*, 28, 2001, Pages 397-404
- Google Maps. (n.d.). Retrieved January 31, 2012, from <https://www.google.com.sg/maps/@1.3417049,103.676796,15z>
- Gray, D.M., *Handbook on the Principles of Hydrology: with special emphasis directed to Canadian conditions in the discussions, applications and presentation of data*. Secretariat, Canadian National Committee for the International Hydrological Decade, 1970.

- Gromke, C., and Ruck, B. 2008. Aerodynamic modelling of trees for small-scale wind tunnel studies. *Forestry*, 81(3), 243-258.
- Guitard, D.G.E. and Castera, P. 1995. Experimental analysis and mechanical modelling of wind-induced tree sways. In: M.P. Coutts and J. Grace (Editors), *Wind and Trees*. Cambridge University Press., pp. 182-194.
- Hassinen, A., Lemettinen, M., Peltola, H., Kellomaki, D. and Gardiner, B.A. 1998. A prism-based system for monitoring the swaying of trees under wind loading. *Agricultural and Forest Meteorology*, 90(1998): 187-194.
- Hedden, R.L., Fredericksen, T.S. and Williams, S.A. 1995. Modeling the effect of crown shedding and streamlining on the survival of loblolly pine exposed to acute wind. *Canadian Journal of Forest Research*, 25(5): 704-712.
- Herajarvi, H. 2004. Static bending properties of Finnish birch wood. *Wood*
- Holmes, J.D. 2007. Wind Loading on Structures. 2nd Ed.: Taylor and Francis, NY. pp.380.
- Hritzuk, K. J. (1997). The effect of drainage systems in maintaining soil suction. *MEng thesis, School of Civil and Environment Engineering, Nanyang Technological University, Singapore*.
- Ilic, J. 2001. Relationship among the dynamic and static elastic properties of air-dry Eucalyptus delegatensis R. Baker. *Holz als Roh-und Werkstoff*, 59(3): 169-175.
- Indrawan, I. G. B., Rahardjo, H., & Leong, E. C. (2006). Effects of coarse-grained materials on properties of residual soil. *Engineering geology*, 82(3), 154-164.
- International Association Of Wood Anatomists. Committee On Nomenclature. 1957. International glossary of terms used in wood anatomy. *Trop. Woods* 107: 1-36.
- Jeronimidis, G. (1980). The fracture behaviour of wood and the relations between toughness and morphology. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, 447-460.
- K.J. Niklas The influence of gravity and wind on land plant evolution The influence of gravity and wind on land plant evolution Rev. *Palaeobotany Palynology*, 102 (1998), pp. 1–14
- Kamimura, K., Kitagawa, K., Saito, S., & Mizunaga, H. (2012). Root anchorage of hinoki (*Chamaecyparis obtuse* (Sieb. Et Zucc.) Endl.) under the combined loading of wind and rapidly supplied water on soil: analyses based on tree-pulling experiments.

- European Journal of Forest Research*, 131(1), 219-227.
- Keong, L.C., 2004. Wind Effect on Trees and Roof Garden. *Final Year Project Report*. School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.
- Kezdi, A. (1974). Handbook of Soil Mechanics. Elsevier, Amsterdam.
- King D. and Loucks O. L., 1978, The theory of tree bole and branch form. Radiation and Environmental Biophysics 15: 141-165
- Kolitzus H.J., Functional Standards for Playing Surfaces, in Frederick E.C. (ed), Sports Shoes and Playing Surfaces, Champaign IL 1994, Human Kinetics, 1984, Pages 98-118
- Lee, K. W., Zhou, Y. X., Tor, Y. K. and Li, J., Geology of Singapore. Singapore: Defence Science & Technology Agency, 2009. Print
- Leong, E. C., & Rahardjo, H. (1997). Review of soil-water characteristic curve equations. *Journal of geotechnical and geoenvironmental engineering*, 123(12), 1106-1117.
- Leong, E. C., & Rahardjo, H. (1997). Permeability functions for unsaturated soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(12), 1118-1126.
- Leong, E. C., Tripathy, S., & Rahardjo, H. (2003). Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique. *Geotechnique*, 53(2), 173-182.
- Lilly, S. and Davis Sydnor, T. 1995. Comparison of branch failure during static loading of Silver and Norway maples. *Journal of Arboriculture*, 21(6): 302-305.
- Lilly, S. J. (2010). Arborists' certification study guide. D. Neely (Ed.). International Society of Arboriculture.
- Lim T.T., Shear Strength Characteristics and Rainfall-Induced Matric Suction Changes in a Residual Soil Slope, M.Eng Thesis, Nanyang Technological University, Singapore, 1995
- Lim, C.C., Rahardjo, H., Lee, D.T.T., 2013, Effect of tree shape and greenwood properties on tree stability, Proceedings of URECA@NTU 2012-2013 Nanyang Technological University
- Linsley, R. K., Franzini, J. B., Freyberg, D. L., & Tchobanoglous, G. (1992). Water Resources Engineering. MacGraw-Hill. *Inc KNS4673 Integrated Design Project*, 2(2),

3.

Lohmander, P., & Helles, F. (1987). Windthrow probability as a function of stand characteristics and shelter. Scandinavian Journal of Forest Research, 2(1-4), 227-238.

Lundström, T., Jonas, T., & Volkwein, A. (2008). Analysing the mechanical performance and growth adaptation of Norway spruce using a non-linear finite-element model and experimental data. Journal of experimental botany, 59(9), 2513-2528.

M. Budhu, Soil Mechanics and Foundations, New York: Wiley and Sons Inc, 2002, Print

Mattheck C. 1991. Trees: the mechanical design. Berlin: Springer-Verlag.

Mattheck, C. 1990. Why they grow, how they grow: The mechanics of trees. Arboriculture Journal, 14: 1-17.

Mattheck, C. and Bethge, K. 2000. Simple mathematical approaches to tree biomechanics. Arboricultural Journal, 24: 307-326.

Mattheck, C. and Kubler, H. 1995. Wood, The internal optimisation of trees. Springer, 129 pp.

Mattheck, K.; Breloer, H., The body language of trees, a handbook for failure analysis., London, England: Her Majesty's Stationary Office, 1994, Page 240.

Mayhead, G.J. 1973a. Sway periods of forest trees. Scottish Forestry, 27: 19-23.

Mayhead, G.J. 1973b. Some drag coefficients for British trees derived from wind tunnel studies. Agric. Meteorology. 12: 123-130.

McMahon, T. A. and Kronaur, R. E. (1976) Tree structures: deducing the principle of mechanical design. J. Theor. Biol., **59**, 1–24.

Metzger K (1893) Der Wind als massgebender Faktor für das Wachstum der Bäume. Mündener Forstliche Hefte 3:35–86

Meyerhof, G. G. (1955). Influence of roughness of base and ground-water conditions on the ultimate bearing capacity of foundations. Geotechnique, 5(3), 227-242.

Milne, R. and Blackburn, P. 1989. The elasticity and vertical distribution of stress within stems of *Picea sitchensis*. Tree Physiology, 5: 195-205.

M-L. Nykänen, H. Peltola, C. Quine, S. Kellomäki, M. Broadgate Factors affecting snow damage of trees with particular reference to European conditions va Fennica, 31 (2) 7), pp. 193–213

- Moore, J.R. 2000. Differences in maximum resistive bending moments of *Pinus radiata* trees grown on a range of soil types. *Forest Ecology and Management*, 135: 63-71.
- Moore, J.R. and Maguire, D.A. 2004. Natural sway frequencies and damping ratios of trees: concepts, review and synthesis of previous studies. *Trees*, 18(2): 195-203.
- Moore, J.R. and Maguire, D.A. 2005. Natural sway frequencies and damping ratios of trees: influence of crown structure. *Trees*, 19: 363-373.
- Morgan, J. and Cannell, M.G.R. 1987. Structural analysis of tree trunks and branches: tapered cantilever beams subject to large deflections under complex loading. *Tree Physiology*, 3: 365-374.
- Morgan, J., & Cannell, M. G. (1994). Shape of tree stems—a re-examination of the uniform stress hypothesis. *Tree physiology*, 14(1), 49-62.
- Moullia, B., & Fournier-Djimbi, M. (1997). Optimal mechanical design of plant stems: the models behind the allometric power laws. *Proceedings of the Plant Biomechanics, Reading, Centre for Biomimetics, G. Jeronimidis and JFV Vincent*.
- Murthy, V. N. S. (2009). *Geotechnical engineering: principles and practices of soil mechanics*. CRC.
- National Environment Agency (Singapore), 2010. Annual Report.
<http://www.app.nea.gov.sg/cms/htdocs/category_sub.asp?cid=77> (accessed 02.12.14).
- National Environment Agency (Singapore), 2013. Annual Report.
<http://www.app.nea.gov.sg/cms/htdocs/category_sub.asp?cid=77> (accessed 02.12.14).
- Neild, S.A. and Wood, C.J. 1999. Estimating stem and root-anchorage flexibility in trees. *Tree Physiology*, 19: 141-151.
- Ng, C. W., & Menzies, B. (2007). *Advanced unsaturated soil mechanics and engineering*. CRC Press.
- Nicoll, B.C. and Ray, D., Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiology* 16 1996: Pages 899-904.
- Niklas, K. and Spatz, H. (2000). Wind-induced stresses in cherry trees: evidence against the hypothesis of constant stress levels. *Trees*, 14(4), pp.0230-0237.
- NIKLAS, K. J. (2003). Reexamination of a canonical model for

- plant organ biomass partitioning. American Journal of Botany 90, 250–254.
- Niklas, K.J. 1992. Plant Biomechanics. An engineering approach to plant form and function. University of Chicago Press. Uni. Chicago Press., 607 pp.
- Obrzud R. & Truty, A. The hardening soil model - A practical guidebook Z Soil.PC 100701 report, revised 31.01.2012
- Oliver, H. R., & Mayhead, G. J. (1974). Wind measurements in a pine forest during a destructive gale. Forestry, 47(2), 185-194.
- P. Blackburn, J.A. Petty, K.F. Miller An assessment of the static and dynamic factors involved in windthrow Forestry, 61 (1988), pp. 29–43
- Panshin, A. J., & de Zeeuw, C. (1980). Textbook of wood technology. Part 1. Formation, anatomy, and properties of wood.
- Papesch, A.J.G., Moore, J.R. and Hawke, A.E. 1997. Mechanical stability of Pinus radiata trees at Eyrewell Forest investigated using static tests. New Zealand Journal Forest Science, 27: 188-204.
- Peltola, H. 1996a. Model computations on wind flow and turning moment by wind for Scots pines along the margins of clear-cut areas. Forest Ecology and Management, 83(3): 203-215.
- Peltola, H. 1996b. Swaying of trees in response to wind and thinning in a stand of Scots pine. Boundary-Layer Meteorology. 77: 285-304.
- Peltola, H. and Kellomaki, D. 1993. A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. Silva Fennica, 27(2): 99-111.
- Peltola, H., Kellomaki, S., Hassinen, A. and Granander, M. 2000. Mechanical stability of Scots Pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland. Forest Ecology and Management, 135: 143-153.
- Penman, H. L. (1948, April). Natural evaporation from open water, bare soil and grass. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* (Vol. 193, No. 1032, pp. 120-145). The Royal Society.
- Peterson, E.W. and J.P. Hennessey, Jr., 1978, *On the use of power laws for estimates of wind power potential*, J. Appl. Meteorology, Vol. 17, pp. 390-394
- Petty, J.A. and Swain, C. 1985. Factors influencing stress breakage of conifers in high winds. Forestry, 58: 75-84.

- Pham, H. Q., Fredlund, D. G., & Barbour, S. L. (2003). A practical hysteresis model for the soil-water characteristic curve for soils with negligible volume change. *Géotechnique*, 53(2), 293-298.
- Prat, M., Bisch, E., Millard, A., Mestat, P., and Cabot, G. (1995). La modelisation des ouvrages. Hermes, Paris
- Rahardjo, H., Harnas, F. R., Leong, E. C., Tan, P. Y., Fong, Y. K., & Sim, E. K. (2009). Tree stability in an improved soil to withstand wind loading. *Urban Forestry & Urban Greening*, 8(4), 237-247.
- Rahardjo, H., Satyanaga, A., & Leong, E. C. (2013). Effects of flux boundary conditions on pore-water pressure distribution in slope. *Engineering Geology*, 165, 133-142.
- Rasdorsky W.. 1929. Über die Baumechanik der Pflanzen (Teil I–III). *Biologia generalis. Internationales Archiv für allgemeine Fragen der Lebensforschung* 5: 63-94.
- Ray, D., & Nicoll, B. C. (1998). The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry*, 71(2), 169-182.
- Reiterer, A., Sinn, G., & Stanzl-Tschegg, S. E. (2002). Fracture characteristics of different wood species under mode I loading perpendicular to the grain. *Materials Science and Engineering: A*, 332(1), 29-36.
- Rodgers, M., Casey, A., McMenamin, C. and Hendrick, E. 1995. An experimental investigation of the effects of dynamic loading on coniferous trees planted on wet mineral soils. In: M.P. Coutts and J. Grace (Editors), *Wind and Trees*. Cambridge University Press., pp. 204-219.
- Roodbaraky, H.J., Baker, C.J., Dawson, A.R. and Wright, C.J. 1994. Experimental Observations of the Aerodynamic Characteristics of Urban Trees. *Journal of Wind Engineering and Industrial Aerodynamics*, 52(1994): 171-184.
- Ross, R. J. (2010). Wood handbook: wood as an engineering material.
- Rowe, N. P., & Speck, T. (1998). Biomechanics of plant growth forms: the trouble with fossil plants. *Review of Palaeobotany and Palynology*, 102(1-2), 43-62.
- Rudnicki, M.R., Mitchell, S.J. and Novak, M.D. 2004. Wind tunnel measurements of crown streamlining and drag relationships for three conifer species. *Canadian Journal of Forest Research*, 34: 666-676.

- Ruelle, J., M. Yoshida, B. Clair & B. Thibaut. 2007b. Peculiar tension wood 305 structure in *Laetia procera* (Poepp.) Eichl. (Flacourtiaceae). *Trees*, 21(3): 45-355
- Sagar, R.M., and Jull, M.J. 2001. Wind climatology and high wind events in Northeast British Columbia 1995-2000. In *Windthrow assessment and management in British Columbia*. (Mitchell S.J., Ed., Richmond, British Columbia., pp 81-90.
- Samarakoon, M. B., Tanaka, N., & Yagisawa, J. (2013). Effects of local scouring and saturation of soil due to flooding on maximum resistive bending moment for overturning *Robinia pseudoacacia*. *Landscape and ecological engineering*, 9(1), 11-25.
- Schelhaas, M.J. 2008. The wind stability of different silvicultural systems for Douglas-fir in the Netherlands: a model-based approach. *Forestry*, 81(3): 399-414.
- Schniewind, A. P., Quarles, S. L., & Lee, S. H. (1996). Wood fracture, acoustic emission, and the drying process Part 1. Acoustic emission associated with fracture. *Wood science and technology*, 30(4), 273-281.
- Schwendener S.. 1874. Das mechanische Prinzip im anatomischen Bau der Monocotylen mit vergleichenden Ausblicken auf die übrigen Pflanzenklassen Engelmann, Leipzig, Germany.
- Silins, U., Lieffers, V.J. and Bach, L. 2000. The effect of temperature on mechanical properties of standing lodgepole pine trees. *Trees*, 14(8): 424-428.
- Singstat.gov.sg, (2014). *Statistics Singapore - Latest Data*. [online] Available at: http://www.singstat.gov.sg/statistics/latest_data.html#14 [Accessed 9 Dec. 2014].
- Sinn, G., & Wessolly, L. (1989). A contribution to the proper assessment of the strength and stability of trees. *Arboricultural Journal*, 13(1), 45-65.
- Smiley TE (2008b) Root pruning and stability of young willow oak. *Arboric Urban For* 34:123–128
- Smith, V.G., Watts, M. and James, D.F. 1987. Mechanical stability of black spruce in the clay belt region of northern Ontario. *Canadian Journal of Forest Research*, 17: 1081-1091.
- SoilVision System Ltd (2009). SVSlope user's manual. *SoilVision System Ltd., Saskatoon, Sask.*
- Spatz et al., 1998b H.-C.H. Spatz, L. Köhler, T. Speck Biomechanics and functional

- anatomy of hollow-stemmed sphenopsids. I. *Equisetum giganteum* (Equisetaceae) Am. J. Bot., 85 (1998), pp. 305–314
- Spatz, H.-C.H. and Bruechert, F. 2000. Basic biomechanics of self-supporting plants: wind loads and gravitational loads on a Norway spruce tree. Forest Ecology and Management, 135(2000): 33-44.
- Stephens, L.S., Liu, Y., and Meletis, E.I., 2000, "Finite element analysis of the initial yielding behavior of a hard coating/substrate system with functionally graded interface under indentation and friction," Journal of Tribology-Transactions of the ASME, 122(2):381--387.
- Stokes, A., J. Ball, A.H. Fitter, P. Brain, & M.P. Coutts. 1996. An experimental investigation of the resistance of model root systems to uprooting. Annals of Botany 78:415-421.
- Sugden, M.J. 1962. Tree sway period - a possible new parameter for crown classification and stand competition. Forestry Chronicle, 38: 336-344.
- T.S. Frederickson, R.L. Hedden, S.A. Williams Testing loblolly pine wind firmness with a simulated wind stress Can. J. For. Res., 23 (1993), pp. 1760–1765 Testing loblolly pine d firmness with a simulated wind stress Can. J. For. Res., 23 (1993), pp. 1760–1765
- Tee, S.P. et al. (Editors) 2009. *Trees of Our Garden City: A Guide to the Common Trees of Singapore*. National Parks Board,. Singapore. E.J.H Corner.
- Terzaghi, K. 1943, *Theoretical Soil Mechanics*, Wiley, New York.
- Terzaghi, K. P. RB (1948). *Soil mechanics in engineering practice*.
- Tevar Sanz, G., Sanz-Andres, A., Fernandez Canadas, M., and Grande Ortiz, M.A. 2003. Wind effects on *Populus* sp. In *Wind Effects on Trees*, University of Karlsruhe, Germany.
- Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. Geographical review, 55-94.
- Thu, T. M., Rahardjo, H., & Leong, E. C. (2006). Shear strength and pore-water pressure characteristics during constant water content triaxial tests. Journal of Geotechnical and Geoenvironmental Engineering, 132(3), 411-419.
- Timoshenko, S. P., Goodier, J. N., & Abramson, H. N. (1970). *Theory of elasticity*.

- Journal of Applied Mechanics, 37, 888.
- Tree trunks and branches as optimum mechanical supports of the crown: II. The branches The Bulletin of Mathematical Biophysics, 1946, Volume 8, Number 3, Page 95
- Martinus H. M. Esser
- Tresca, H. (1864). Mémoire sur l'écoulement des corps solides soumis à de fortes pressions. C.R. Acad. Sci. Paris, vol. 59, p. 754.
- Van Bavel, C. H. M., & Hillel, D. I. (1976). Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. Agricultural Meteorology, 17(6), 453-476.
- Van Casteren, A., Sellers, W. I., Thorpe, S. K. S., Coward, S., Crompton, R. H., & Ennos, A. R. (2012). Why don't branches snap? The mechanics of bending failure in three temperate angiosperm trees. Trees, 26(3), 789-797.
- Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E., & Clifton, A. W. (1996). Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, 33(3), 379-392.
- Vogel S. 1994. Life in moving fluids, 2nd edn. Princeton, NJ, USA: Princeton University Press.
- Vogel, S. (1989). Drag and reconfiguration of broad leaves in high winds. Journal of Experimental Botany, 40(8), 941-948.
- Vollsinger, S., Mitchell, S.J., Byrne, K.E., Novak, M.D. and Rudnicki, M. 2005. Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. Canadian Journal of Forest Research, 35: 1238-1249.
- von Mises, R. (1913). Mechanik der festen Körper im plastisch deformablen Zustand. Göttingen. Nachr. Math. Phys., vol. 1, pp. 582-592
- Wessolly, L. 1995. Fracture diagnosis of trees, Part 1: Statics-Integrated Methods, measurement with tension test. Stadt und Grün, 6: 416-422.
- Wilson, G.W., 1990 Soil evaporative fluxes for geotechnical engineering problems, PhD Thesis, University of Saskatchewan, Saskatoon, Canada
- Wong, L.C., Sim. A., 2011, New portable four point bending apparatus for flexural testing of greenwood branches, Republic Polytechnic, Singapore.
- Wood, C.J. 1995. Understanding wind forces on trees. In: M.P. Coutts and J. Grace (Editors), Wind and Trees. Cambridge University Press., pp. 133-164.

- Wood, M.J., Scott, R., Volker, P.W. and Mannes, D.J. 2008. Windthrow in Tasmania, Australia: Monitoring, prediction and management. Forestry, 81(3): 415-427.
- Yang, H., Rahardjo, H., Leong, E. C., & Fredlund, D. G. (2004). Factors affecting drying and wetting soil-water characteristic curves of sandy soils. Canadian Geotechnical Journal, 41(5), 908-920.
- Zeng, H., Pukkala, T. and Peltola, H. 2007. The use of heuristic optimization in risk management of wind damage in forest planning. Forest Ecology and Management, 241: 189-199.
- Zhu, J., Matsuzaki, T. and Sakioka, K. 2000. Wind speed within a single crown of Japanese black pine (*Pinus thunbergii* Parl.). Forest Ecology and Management, 135: 19-31.

APPENDIX I

The following are the static structural runs described in Section 5.6.6

Figure 1 to Figure 3 show the ANSYS analysis on variation of number of sinker roots.

Figure 1 Model with 12 sinker roots showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

a)

b)

Figure 2 Model with 16 sinker roots showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

a)

b)

Figure 3 Model with 20 sinker roots showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

Figure 4 to Figure 6 show the ANSYS analysis on variation of depth of sinker roots.

Figure 4 Model with 8 sinker roots at 1.0 m depth showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

a)

b)

Figure 5 Model with 8 sinker roots at 3.0 m depth showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

Figure 6 Model with 8 sinker roots at 4.0 m depth showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

Figure 7 to Figure 9 show the ANSYS analysis on variation of diameter of lateral roots.

a)

b)

Figure 7 Model with 8 sinker roots at 3.0 m depth with lateral roots of 0.6 m showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the tip of the trunk.

a)

b)

Figure 8 Model with 8 sinker roots at 3.0 m depth with lateral roots of 0.8 m showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole model.

a)

b)

Figure 9 Model with 8 sinker roots at 3.0 m depth with lateral roots of 1.0 m showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole model.

Figure 10 to Figure 13 show the ANSYS analysis on variation of soil elastic moduli and compressive yield stress

Figure 10 Model with 8 sinker roots at 3.0 m depth with soil modulus of 12.6 MPa and compressive yield stress of 301 KPa showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole model.

a)

b)

Figure 11 Model with 8 sinker roots at 3.0 m depth with soil modulus of 14.2 MPa and compressive yield stress of 338 KPa showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole model.

a)

b)

Figure 12 Model with 8 sinker roots at 3.0 m depth with soil modulus of 17.4 MPa and compressive yield stress of 414 KPa showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole model.

a)

b)

Figure 13 Model with 8 sinker roots at 3.0 m depth with soil modulus of 19.0 MPa and compressive yield stress of 451 KPa showing restraint by the sinker roots (soil hidden). a) Maximum equivalent von-Mises stress experienced in windward and perpendicular sinker roots. b) Maximum total deformation experienced by the whole model.

APPENDIX II

Figure 14 Point cloud of the two *Syzygium grande* at Silat Ave.

Figure 15 Point cloud of the scene at Silat Ave.

Figure 16 Point cloud of the scene at Telok Blangah Rise