Effect of weather conditions on tree stability in Singapore

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**EFFECT OF WEATHER CONDITIONS ON TREE
STABILITY IN SINGAPORE**

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2019

**EFFECT OF WEATHER CONDITIONS ON TREE
STABILITY IN SINGAPORE**

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**Interdisciplinary Graduate School
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A thesis submitted to the Nanyang Technological University in partial
fulfillment of the requirement for the degree of
Doctor of Philosophy

2019

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The first journal paper is Li, Y., Rahardjo, H., Irvine, K. N., & Law, A. W. K. (2018). CFD analyses of the wind drags on Khaya Senegalensis and Eugenia Grandis. *Urban forestry & urban greening*, 34, 29-43.

The contributions of the co-authors are as follows:

- I designed the study and performed all the analyses at the School of Civil and Environmental Engineering. I also analyzed the data.
- Prof Rahardjo provided continuous suggestions during the study.
- I prepared the manuscript drafts. The manuscript was revised by Prof Rahardjo, A/Prof Irvine and A/Prof Law

The second journal paper is Li, Y., Rahardjo, H., & Irvine, K. N. (2019). Effect of Weather Conditions on Leans of One *Eugenia Grandis* Tree in Singapore. *Urban forestry & urban greening*, 43, 126375.

The contributions of the co-authors are as follows:

- Prof Rahardjo suggested the direction
- I performed all the analyses and comparison.
- I wrote the drafts of the manuscript. The manuscript was revised by Prof Rahardjo and A/Prof Irvine.

The conference paper is Li, Y., Rahardjo, H., & Irvine, K. N. (2018). Seepage and Deformation Analyses in Unsaturated Soils Using ANSYS. In *Proceedings of China-Europe Conference on Geotechnical Engineering* (pp. 360-364). Springer, Cham.

The contributions of the co-authors are as follows:

- I came with the idea and performed all the analyses.
- I wrote the drafts of the manuscript. The manuscript was revised by Prof Rahardjo and A/Prof Irvine.

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Abstract

This work presents an integrated approach to modelling the effect of weather conditions on tree stability, including wind, rainfall, temperature, humidity and solar radiation. This approach includes computation of the drag force in computational fluid dynamics (CFD) analyses and evaluation of the behaviour of the trunk-root-soil system under the wind drags applied in deformation analyses. In the deformation analyses, the effects of weather conditions on soil strength and stiffness were incorporated. Soil strength and stiffness are related to the pore-water pressure of soil, which are affected by rainwater infiltration and evapotranspiration related to weather conditions.

The drag coefficients of one mature *Khaya senegalensis* tree and one *Eugenia grandis* tree in Singapore were computed from both CFD analyses and field measurements. The CFD analyses took advantage of the laser scanning approach to generate tree geometries and calculate three-dimensional (3D) leaf area density (LAD) distribution. Multiple porous domains were used to represent the canopy. Within each porous domain, the source and sink terms, as a function of LAD, were used to simulate the turbulent effects of leaves. CFD analyses were performed using ANSYS 17.2 (i.e. the most updated version in 2016). In addition, drag coefficients were calculated from field measurements including wind speeds, tree deflections and the average elastic moduli of the trees. The drag coefficients from the CFD analyses and field measurements were then compared and possible reasons for the difference were discussed.

The deflections of the *Eugenia grandis* tree under wind drag in Singapore during a 20-day monitoring period were analysed in 3D using ANSYS 19.1 (i.e. the most updated version in 2018). The soil strength and modulus were dependent on the pore-water pressure head of soil. To obtain the pore-water pressure head distribution of soil, one-dimensional (1D) analyses were performed using VADOSE modelling in GeoStudio 2012 based on the weather conditions

recorded from the field instrumentations during the 20 days. Using wind drag calculated from the CFD analyses, the lean of the *Eugenia Grandis* tree during the study period was computed by incorporating changes in soil stiffness and soil strength due to changes in pore-water pressure head of the soil.

It was found that the estimated tree lean increased by 16.5% when the change in soil strength and soil modulus as effects of weather conditions were considered, as compared to tree lean calculations without consideration of changes in soil and with the assumption of a constant soil modulus of 20 MPa. These findings highlight the need to consider the effect of weather conditions on soil strength and modulus when analysing tree deflections.

Table of Contents

Acknowledgement	i
Abstract	iii
List of Figures	ix
List of Tables	xiii
List of Symbols	xiv
Chapter 1 Introduction	1
1.1 Research Background.....	1
1.2 Objective	5
1.3 Scope of Work.....	5
Chapter 2 Literature Review	8
2.1 Tree Architecture.....	8
2.2 Tree Failure Mechanics	10
2.3 Unsaturated Soil Mechanics	14
2.3.1 Soil–water Characteristic Curve	14
2.3.2 Permeability Function.....	15
2.3.3 Shear Strength.....	16
2.3.4 Stiffness	17
2.4 Evapotranspiration	19
2.4.1 Potential Evapotranspiration.....	19
2.4.2 Actual Evapotranspiration	20
2.5 Fluid Mechanics and Governing Equations	23
2.5.1 Drag Coefficient	24
2.5.2 Turbulent Flow	24
2.5.2 Computational Fluid Dynamics Modelling	25
2.6 Solid Mechanics and Governing Equations	28

2.6.1 Stress Tensor and Equilibrium Equations	28
2.6.2 Strain Tensor and Strain-Displacement Relationship.....	29
2.6.3 Stress-Strain Relationship.....	29
2.7 Two-Dimensional Analyses and Three-Dimensional Analyses.....	30
Chapter 3 Development of Computational Methods	32
3.1 Additional Coding for the Canopy Consisting of Individual Porous Domains during Computational Fluid Dynamics (CFD) Analyses	32
3.2 Estimation of SWCCs from Field Measurements	35
3.3 Incorporating Unsaturated Soil Mechanics in ANSYS for Deformation Analyses	36
Chapter 4 Research Programme.....	38
4.1 Laser Scanning	40
4.1.1 Geometry Model Construction	40
4.1.2 LAD and LAI Calculation	42
4.2 Field Instrumentations.....	43
4.2.1 Weather Station	44
4.2.2 Piezometer	44
4.2.3 Soil Moisture Sensors	45
4.2.4 Tensiometers.....	46
4.2.5 Linear Variable Differential Transformers.....	46
4.3 Field Infiltration Test	47
4.4 Static Pulling Test	48
4.5 Calculation of Drag Coefficients from Field Measurements	50
4.6 CFD Analyses	54
4.6.1 Airflow through Leafless Models.....	54
4.6.2 Airflow through Leafed Models	56
4.7 Estimation of VWC and Pore-Water Pressure Head.....	57
4.7.1 Estimation of SWCC from Field Measurements	57

4.7.2 Geometry Model and Boundary Conditions.....	58
4.8 Estimation of Tree Leans	59
4.8.1 Wind Drags Calculation	59
4.8.2 Geometry Model.....	60
4.8.3 Incorporation of Unsaturated Soil Mechanics in ANSYS.....	61
4.8.4 Wood and Soil Properties	62
4.8.5 Boundary Conditions, Thermal Condition, and Hydrostatic Pressure Condition ...	64
4.8.6 Grid Independence Study	66
4.8.7 Layer Thickness.....	67
4.8.8 Case Studies.....	68
Chapter 5 Presentation of Results	69
5.1 LAI from Point Cloud Data.....	69
5.2 Meteorological Inputs from Field Instrumentation	69
5.3 Infiltration Test.....	71
5.4 Average Modulus of the Trunk-Root-Soil System from Static Pulling Test.....	71
5.5 Drag Coefficients from Field Measurements	71
5.6 Drag Coefficients from CFD Analyses in ANSYS	73
5.6.1 Airflow through Leafless Models.....	73
5.6.2 Airflow through Leafed Models	78
5.7 Volumetric Water Contents and Pore-Water Pressure Heads from VADOSE/W	82
5.8 Tree Leans from Deformation Analyses in ANSYS	88
Chapter 6 Discussion of Results	95
6.1 Comparison between Leafless Models and Fully Leafed Models	95
6.2 Comparison of Results for <i>Khaya Senegalensis</i> and <i>Eugenia Grandis</i> Trees	96
6.3 Limitation of Range of Wind Velocities in CFD Analyses	97
6.4 The Influence of Flexibility on the Reliability of Numerical Modelling.....	100
6.5 Comparison of Drag Coefficients from Field Measurements and CFD Analyses.....	103

6.6 Comparison of Volumetric Water Contents and Pore-Water Pressure Heads from Field Measurements and Numerical Modelling using VADOSE/W	105
6.7 Effect of Weather Conditions on Tree Lean	106
6.8 Assumptions Used in the Deformation Analyses.....	107
6.9 Application of the Integrated Approach for Monitoring Tree Stability	109
Chapter 7 Conclusions and Recommendations.....	111
7.1 Conclusions	111
7.2 Recommendations	113
7.3 Publications	113
References	115

List of Figures

Figure 1.1. Average monthly wind speed (Meteorological Service Singapore, 2010)	2
Figure 1.2. Monthly rainfall amount (Meteorological Service Singapore, 2010).....	3
Figure 1.3. Number of rainy days per month (Meteorological Service Singapore, 2010).....	3
Figure 1.4. Tree failure after rainfall in Pasir Ris in 2012, Singapore (Rahardjo et al., 2016)...	4
Figure 2.1. Lateral root, sinker root and tap root in the tap root system (Kostler et al., 1968)....	7
Figure 2.2. Heart root system (Crow, 2005).....	8
Figure 2.3. Plate root system (Crow, 2005).....	8
Figure 2.4. Forces acting on the root-soil system (Coutts, 1983).....	9
Figure 2.5. Vertical movement of soil surface under tree winching (Coutts, 1983): (a) profile view; (b) movement on exaggerated vertical scale . RB, position of soil surface when roots are first heard breaking; (c) soil surface at maximum moment in true vertical scale.....	10
Figure 2.6. Components of resistance during uprooting (Blackwell, Rennolls, & Coutts, 1990).....	11
Figure 2.7. Displacement fields of soil under tree pulling in (a) clay-like soil and in (b) sand-like soil (Dupuy et al., 2007).....	12
Figure 2.8. Typical Soil-Water Characteristic Curve (Fredlund & Xing, 1994).	14
Figure 2.9 Extended Mohr-Coulomb Failure Envelope for Unsaturated Soils (Fredlund et al., 1987).....	16
Figure 2.10. Illustration of the flux boundary (NParks & NTU, 2018).	18
Figure 2.11. A typical PML function.....	21
Figure 2.12. Variations between total drag, pressure drag, viscous drag and wind velocity....	22
Figure 2.13. Porous domain around the branches to model the effect of leaves using sink and source terms (Endalew et al., 2009).....	26

Figure 2.14. 2D Geometry model with meshes (Rahardjo et al., 2009).....	29
Figure 2.15. Comparison between 2D analyses and 3D analyses (Li et al., 2018).....	30
Figure 4.1. Locations of the (a) <i>Eugenia Grandis</i> and (b) <i>Khaya Senegalensis</i> trees in the Choa Chu Kang site.....	38
Figure 4.2. The selected (a) <i>Eugenia Grandis</i> tree and (b) <i>Khaya Senegalensis</i> tree.....	38
Figure 4.3. The REIGL VZ-400 terrestrial scanner with the attached top mounted NIKON full frame camera.....	39
Figure 4.4. (a) Scanned <i>Khaya Senegalensis</i> tree point clouds and (b) post-processed 3D model simulated in ANSYS	40
Figure 4.5. (a) Scanned <i>Eugenia Grandis</i> tree point clouds and (b) post-processed 3D model simulated in ANSYS	40
Figure 4.6. Leaf Area Density distribution of (a) <i>Khaya Senegalensis</i> tree and (b) <i>Eugenia Grandis</i> tree in MATLAB.....	41
Figure 4.7. Weather Station installed.....	43
Figure 4.8. Piezometer installed.....	44
Figure 4.9. The (a) CS 616 and (b) Sentek Enviroscan soil moisture sensor.	44
Figure 4.10. The (a) jet-fill tensiometers and (b) installation of the tensiometers.....	45
Figure 4.11. LVDT installed with the rod.....	46
Figure 4.12. (a) Double ring infiltrometer, (b) infiltrometer set up, and (c) infiltration test...47	
Figure 4.13. Diagram of tree pulling test (Wassenaer and Richardson, 2009).....	48
Figure 4.14. . Illustration of (a) one of the anchored trees and (b) one of the testing trees.....	49
Figure 4.15. Velocity inlet profile.	51
Figure 4.16. Illustration of the lever arm used to calculate the bending stress	53
Figure 4.17. Boundary conditions in CFD modelling of leafless trees.....	54
Figure 4.18. Illustration of geometry and boundary conditions in the VADOSE/W modelling.....	58
Figure 4.19. Geometry of trunk, root plate and soil.....	60

Figure 4.20. Cohesion of the two soil layers defined in ANSYS.....	62
Figure 4.21. Temperature condition assigned.	64
Figure 4.22. Hydrostatic pressure boundary condition assigned in ANSYS.....	65
Figure 4.23. Meshed geometry with suitable size from grid independence study.....	66
Figure 5.1. Drag coefficients and best fit of the mean drag coefficients from site instrumented data of (a) the <i>Khaya senegalensis</i> tree and (b) the <i>Eugenia grandis</i> tree.....	71
Figure 5.2. Comparison of best fit of mean drag coefficients with other studies.....	72
Figure 5.3. Pressure contour on (a) the <i>Khaya senegalensis</i> tree and (b) the <i>Eugenia grandis</i> tree.....	76
Figure 5.4. Velocity contour around (a) the <i>Khaya senegalensis</i> tree and (b) the <i>Eugenia grandis</i> tree.....	77
Figure 5.5. Velocity streamline around (a) the <i>Khaya senegalensis</i> tree and (b) the <i>Eugenia grandis</i> tree.....	78
Figure 5.6. Pressure contour on (a) the <i>Khaya senegalensis</i> tree and (b) the <i>Eugenia grandis</i> tree.....	79
Figure 5.7. SWCCs for soils at (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, and (d) 0.8 m.....	82
Figure 5.8. Permeability functions for soils at (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, and (d) 0.8 m.....	84
Figure 5.9. Numerical results and field measurements of volumetric water content at (a) 0.1 m depth soil, (b) 0.2 m depth soil, (c) 0.3 depth soil and (d) 0.8 m depth soil.....	85
Figure 5.10. Numerical results and field measurements of pore-water pressure head at (a) 0.15 m depth soil, (b) 0.3 m depth soil and (c) 0.8 m depth soil.	86
Figure 5.11. Pore-water pressure head vs. depth at noon time from Mar 1, 2017 to Mar 20, 2017.....	87
Figure 5.12. Change in tree lean as meshed number of nodes increases.....	88

Figure 5.13. Change in tree lean as layer thickness decreases.	88
Figure 5.14. Soil modulus as a function of temperature assigned in different soil layers in ANSYS.	89
Figure 5.15. Wind drags at respective wind velocities at noon time during 20 days from Mar 1, 2017 to Mar 20, 2017.....	90
Figure 5.16. Tree leans due to the corresponding wind drags at noon time from Mar 1, 2017 to Mar 20, 2017.....	91
Figure 5.17. Comparison of tree leans in the two cases.	91
Figure 5.18. Differences of tree leans in percentage between applying a soil modulus function or applying a constant soil modulus (i.e. 5 MPa, 10 MPa and 20 MPa) across the 20 days.....	92
Figure 6.1. Point clouds of one <i>Samanea saman</i> tree in the Choa Chu Kang area.	96
Figure 6.2. A proposed relationship between drag coefficient and wind velocity for mature and stiff trees and tree geometries under different wind velocities (after Akagi & Kitajima, 2006).....	97
Figure 6.3. Relationship between Cauchy number and slenderness ratio.....	101
Figure 6.4. Relationship between branch length and branch diameter (Nutto at al., 2006).....	101
Figure 6.5. Deflected tree at different wind velocities.	102
Figure 6.6. Singapore Geological Map (after DSTA, 2009)	104

List of Tables

Table 4.1. Settings in different meshing schemes.	55
Table 4.2. Shear strength parameters of the soils.....	63
Table 4.3. Soil modulus parameters.....	63
Table 5.1. LAI of the <i>Khaya senegalensis</i> tree and the <i>Syzygium grandis</i> tree.....	68
Table 5.2. Climatic data inputs in VADOSE/W from field instrumentations.....	69
Table 5.3. Drag coefficient of the <i>Khaya senegalensis</i> tree.	73
Table 5.4. Drag coefficient of the <i>Eugenia grandis</i> tree.	74
Table 5.5. Summarized results of CFD analyses for the <i>Khaya senegalensis</i> tree.....	80
Table 5.6. Summarized results of CFD analyses for the <i>Eugenia grandis</i> tree.....	80
Table 5.7. SWCC variables for different soil layers.....	83
Table 6.1. Comparison between drag coefficients computed from numerical modelling and site instrumented data.....	103

List of Symbols

u_a	=	pore-air pressure
u_w	=	pore-water pressure
ψ	=	$(u_a - u_w)$ = matric suction
θ_r	=	residual water content
u_w	=	pore-water pressure
θ	=	calculated volumetric water content for a specified matric suction
θ_s	=	saturated volumetric water content
$C(\psi)$	=	correction factor
a	=	empirically derived variable related to the air-entry value of soil
n	=	empirically derived variable related to the maximum slope of the SWCC
m	=	empirically derived variable related to the curvature of the slope of SWCC
b	=	$\ln(100000)$
$k_w(\psi)$	=	calculated unsaturated permeability for a specified matric suction ψ
y	=	a dummy variable of integration representing the logarithm of matric suction
σ	=	total stress
τ	=	shear strength of the soil
σ'	=	$(\sigma - u_w)$ = effective stress
c'	=	effective cohesion
ϕ'	=	effective angle of internal friction
$(\sigma - u_a)$	=	net normal stress
ϕ^b	=	angle indicating the rate of change in shear strength with respect to change in matric suction.

c	=	total cohesion
T	=	temperature
E	=	Young's Modulus
P_a	=	atmospheric pressure
K_L	=	loading modulus number with respect to net normal stress
K_m	=	loading modulus number with respect to matric suction
K_o	=	loading modulus number with respect to both net normal stress and matric suction
$n_{loading}$	=	exponent for loading behaviour associated with net normal stress
$m_{loading}$	=	exponent for loading behaviour associated with matric suction
$l_{loading}$	=	exponent for loading behaviour associated with both net normal stress and matric suction
Γ	=	slope of the saturation vapour pressure versus temperature curve at the mean temperature of the air
Q	=	net radiant energy available at the surface
v	=	psychrometric constant
U_a	=	wind velocity at 2 m height
B	=	inverse of the relative humidity at the mean temperature of the air
A	=	inverse of the relative humidity at the soil surface
R_T	=	total thickness of root zone
R_n	=	depth to the node in question after meshing
A_n	=	nodal contributing area of the node
ρ	=	air density
u	=	wind speed
R_e	=	Reynolds number
D	=	average characteristic width of the body

μ	=	dynamic viscosity of the fluid
M	=	Mach number
u_c	=	velocity of sound
u_i	=	i^{th} component of the velocity; $i = 1,2,3$
x_i	=	Cartesian coordinate
p	=	pressure
u'_i	=	i^{th} component of the fluctuating velocity; $i = 1,2,3$
$\overline{u}_i$	=	i^{th} component of the averaged velocity; $i = 1,2,3$
$\overline{p}$	=	average pressure
p'	=	fluctuating pressure
$\overline{u'_i u'_j}$	=	Reynolds stress tensor
δ_{ij}	=	<i>Kronecker delta</i>
C_d	=	drag coefficient
A_{LAD}	=	average leaf area density of the porous domain in the canopy
k	=	turbulent kinetic energy
ε	=	eddy dissipation rate
$C_{\varepsilon 4}$	=	1.5 is a constant obtained from mixing length anisotropy
T_r	=	taper ratio
P	=	lateral force acting on the attachment
L	=	height of the attachment point
δ	=	displacement of the tree at the attachment point
I	=	second moment of the area of the cross section at the LVDT measuring point
F	=	drag force in the wind direction
C_d	=	drag coefficient
A_{area}	=	projected canopy area perpendicular to the wind direction

H	=	height of the tree
z	=	height coordinate
$u(z)$	=	wind velocity at height z
u_{ABL}^*	=	ABL friction velocity
κ	=	von Karman constant = 0.41
z_0	=	aerodynamic roughness length
u_{ref}	=	wind velocity at the reference height h
$\sigma_{bending}$	=	bending stress at the LVDT measuring point
L_c	=	distance from the centre of pressure on the tree to the LVDT measuring point
y	=	radius of the trunk at the LVDT attachment point
ΔL	=	tree deflections monitored from the two LVDTs
L_0	=	original length of the LVDT combined with the rod
C_μ	=	turbulence model constant = 0.09
C	=	Cauchy number
S	=	slenderness ratio

Chapter 1 Introduction

1.1 Research Background

Trees provide numerous benefits to the environment, such as combating climate change, cleaning the air, cooling our cities, and preventing soil erosion and water pollution. They also provide food and habitats for animals and human beings. Tree failures are thus a significant problem, especially in densely populated urban areas where falling trees may endanger public safety and infrastructure stability (Duryea et al., 2007; Lopes et al., 2009; Schmidlin, 2009). A high number of falling trees may also affect climate by exacerbating the heat island effect and reducing air quality.

Tree failures are usually triggered by high wind velocities, windstorms and snowstorms. Trees with defects may also fail under normal weather conditions. In Singapore, the common reasons for tree failures can be attributed to weather condition, tree architecture (both above-ground and below-ground) and soil condition.

Singapore is as an island city-state with an area of 710 square kilometres located near the equator at the southern tip of the Malaysia Peninsula. It is home to about 5.6 million people (Department of Statistics Singapore, 2018) and has approximately 2 million planted trees along the roadside (The Straits Times, 2018). According to a study of canopy coverage based on the remote sensing technology conducted by MIT Sensaeable City Lab, Singapore was identified as the most treed city in the world (Li et al., 2015; Seiferling et al., 2017; Yuen, 1996).

The tropical and coastal climate of Singapore includes plentiful rainfall with a mean annual precipitation of 2165.9 mm and an average of 167 rainy days (i.e., rainfall above 0.2 mm) per year, according to the records from 1981–2010 (Meteorological Service Singapore, 2010). There is little variation in temperature or relative humidity from month to month or day to day. The daily minimum temperature is about 23–25 °C and the daily maximum temperature is

about 31–33 °C (Meteorological Service Singapore, 2010). The mean annual relative humidity is about 83.9%. Relative humidity in Singapore varies from 90% in the morning to 60% in the mid-afternoon if there is no rain, and frequently reaches 100% during long-lasting rain (Meteorological Service Singapore, 2010).

In Singapore, the average low wind velocity but high precipitation amount can endanger tree stability. Figures 1.1, 1.2 and 1.3 show the average monthly wind velocity, monthly precipitation and number of rainy days per month in Singapore, respectively, based on 1981–2010 records (Meteorological Service Singapore, 2010). The average monthly wind velocity is less than 3.5 m/s, whereas the average monthly rainfall of higher than 100 mm occurring in one to three weeks of the month.

Figure 1.1. Average monthly wind speed (Meteorological Service Singapore, 2010).

Figure 1.2. Monthly rainfall amount (Meteorological Service Singapore, 2010).

Figure 1.3. Number of rainy days per month (Meteorological Service Singapore, 2010).

Tree geometry characteristics also contribute to the tree failures, as trees in Singapore tend to have an extremely large above-ground tree size but a shallow root system. Mature trees in Singapore are typically about 20–30 m in height, but may reach up to 40 m. The weight of mature trees is typically in the thousands of kilograms. The root plate system is shallowly

anchored in the soil because the roots obtain water from the ground surface due to abundant precipitation, instead of extending deeply to reach below-ground water. The heavy weight of large trees coupled with the shallow root system make it easy for trees to fail in Singapore.

A tree may fail by individual branch breakage, trunk breakage or root-soil plate uprooting. Overall instability problems, like trunk breakage or root-soil plate uprooting, are more destructive in urban areas with a very dense population like Singapore, compared to individual branch breakage. In tropical climates, most tree failures occur during thunderstorms—particularly during heavy and prolonged periods of rainfall. Tree failures are easily triggered by rainwater infiltration as soil stiffness and strength are reduced by the additional water, similar to the cause of many slope failures (Au, 1998; Cai & Ugai, 2004). Figure 1.4 shows a tree failure after rainfall, and water ponding can be observed at the root plate. Residual soil is common in Singapore as a result of extensive weathering of rocks in the humid and tropical climate. Residual soil is unsaturated under dry weather conditions, and the negative pore-water

Figure 1.4. Tree failure after rainfall in Pasir Ris in 2012, Singapore (Rahardjo et al., 2016).

pressure in unsaturated soil contributes to its stiffness and shear strength. However, pore-water pressure in soil is highly influenced by the flux boundary conditions due to rainwater infiltration and evapotranspiration. Unsaturated soil loses part of its stiffness and shear strength when the pore-water pressure increases or the soil water content increases, which can lead to

more tree deformations or failure when the soil cannot support the weight of the tree or resist the wind drag.

Studies of the effects of weather conditions on soil-root-trunk systems are lacking, particularly those that consider changes in soil stiffness and strength due to rainwater infiltration and evapotranspiration. However, to further understand tree stability-related problems, it is necessary to incorporate the effects of weather conditions when investigating soil-root-trunk behaviours.

1.2 Objective

The objective of this research is to recommend a validated and integrated approach for estimating the behaviour of the soil-root-tree system under wind drag that incorporates the effect of weather conditions on soil strength and soil stiffness.

1.3 Scope of Work

This research includes both field work and numerical analyses.

For the field work, field instrumentation was installed on one *Khaya senegalensis* tree and one *Eugenia grandis* tree in the Choa Chu Kang area of Singapore to obtain real-time data on weather conditions (wind, rainfall, humidity, temperature and solar radiation), tree deformation, soil water content and pore-water pressure head. The measurements were necessary for weather input and obtaining soil characteristics. The field measurements were also used to validate the numerical results. Laser scanning was conducted in the Choa Chu Kang area of Singapore to obtain the respective geometry, leaf area density and leaf area index of the two trees. These data were used in the numerical analyses when estimating the drag coefficients and evapotranspiration values. Moreover, static pulling tests were carried out in the Changi area of Singapore to obtain the overall stiffness of one *Khaya senegalensis* tree and

one *Eugenia grandis* tree. The overall average stiffness of the two trees was used to calculate the drag coefficients in the field and to validate the numerical results.

In the numerical analyses, the drag coefficients on the *Khaya senegalensis* tree and the *Eugenia grandis* tree were estimated using ANSYS 17.2 through computational fluid dynamics (CFD) analyses and compared with the drag coefficient calculations from the field measurements. Analyses were carried out in VADOSE/W of GeoStudio 2012 to estimate the soil water content and the pore-water pressure head due to evapotranspiration and rainwater infiltration as effects of weather conditions. These results were then compared with the field measurements. Deformation analyses were carried out in ANSYS 19.1 to investigate the behaviours of the soil-root-trunk system under wind drags, with incorporation of changes in soil stiffness and soil shear strength due to changes in the soil water content or pore-water pressure head.

1.4 Significance of Research

The main originalities of this research are as follows:

- An integrated approach was proposed to evaluate the effect of weather conditions on tree stability three dimensionally, including the wind pressure exerted, the effect of wind, rainfall, humidity, temperature and solar radiation on the soil water content, and the influence of water content on soil stiffness and strength.
- The drag coefficients were analysed using CFD modelling through a real above-ground tree architecture generated from laser scanning approach in the field. The leaf area density incorporated was also calculated from the generated point clouds.
- The drag coefficients were calculated based on the instrumented field measurements and static pulling tests. The calculated drag coefficients were used to validate the numerical results from CFD modelling.

- The soil stiffness and strength involved in the analyses are highlighted during tree stability analyses, as they are dependent on the pore-water pressure head computed from the weather conditions. Moreover, the incorporated soil-water characteristic curves (SWCCs) in the evapotranspiration and rainwater infiltration analyses were calculated from instrumented field measurements.

Chapter 2 Literature Review

2.1 Tree Architecture

A tree consists of both its above-ground and below-ground structures. The above-ground structure includes the trunk and crown. The crown is made up of branches and foliage. Different species have different crown shapes, which may be round, cone, umbrella and oblong.

The below-ground structure is the root system, which includes tap roots, lateral roots and sinker roots. Root systems were categorized into three basic groups by Stokes & Mattheck (1996) based on their 3D distribution characteristics: heart root system, plate root system and tap root system. Figure 2.1 shows a tap root system with a large tap root anchored deeply into the soil. Horizontal roots that grow primarily from the bottom of the trunk are called lateral roots. From these lateral roots, sinker roots develop and provide additional anchorage.

Figure 2.1. Lateral root, sinker root and tap root in the tap root system (Kostler et al., 1968).

Figure 2.2 shows a heart root system, in which lateral roots grow in different directions from the base of the stem.

Figure 2.2. Heart root system (Crow, 2005).

Figure 2.3 shows a plate root system in which lateral roots grow only in the horizontal direction from the base of the stem.

Figure 2.3. Plate root system (Crow, 2005).

The shape of the root system is determined by the species as well as site conditions (Stokes & Mattheck, 1996). Thus, a tap root system tree species may develop a plate root system if the ground water table is high and waterlogging prevents potential tap root from growing deeper into the soil. A plate root system may also develop when there is abundant rainwater and roots tend to grow in the surface soils to absorb water.

2.2 Tree Failure Mechanics

Studies of tree stability include aerodynamic effects, mechanical properties and movements of trunk-root-soil system (Coutts, 1983). A tree may fail in its above-ground structure due to trunk and branch breakage or in its below-ground structure in the root-soil plate under wind load. Trunk or branch breakage occurs when the wood yields and the bending stress exceeds its modulus of rupture or flexural strength. According to Blackwell et al. (1990), root anchorage comes from four components: the weight of the root-soil plate, strength of the soil, root tensile strength at the windward side and resistance to bending at the leeward side.

For a plate root system, the windward side and leeward side behave very differently under wind load as shown in Figure 2.4 (Coutts, 1983). Point T is below the centre of the trunk. At the windward side, the root-soil system is subjected to tensile and shear forces and, as a result, it

Figure 2.4. Forces acting on the root-soil system (Coutts, 1983).

is lifted. Point W indicates fracture of the root-soil plate at the windward edge. By contrast, the root-soil plate at the leeward side is subjected to bending and compressive forces against the bearing soil below. Fulcrum Point L, where the root-soil plate is levered out, is at the leeward side (Stokes & Mattheck, 1996). The fulcrum in a heart or tap root system is much closer to the centre of the trunk than that in a plate root system where there is more anchorage near the stem (Stokes & Mattheck, 1996).

Tree winching is used to investigate the effect of wind loading on trees. Coutts (1983) concluded that damage to the root-soil plate was the same whether a tree was uprooted by wind or winching. Figure 2.5 shows the measurements of root-soil plate movement under tree winching (Coutts, 1983). The windward side was lifted, and soil first failed at a strain less than

Figure 2.5. Vertical movement of soil surface under tree winching (Coutts, 1983): (a) profile view; (b) movement on exaggerated vertical scale. RB, position of soil surface when roots are first heard breaking; (c) soil surface at maximum moment in true vertical scale.

0.02, followed by root breakage that occurred at the maximum strain point where the roots were stretched under tension by 10% to 20% of their length (Coutts, 1986).

The total resistance and resistance contributed by different components with respect to displacement were investigated by Blackwell et al. (1990), as shown by the component curves

Figure 2.6. Components of resistance during uprooting (Blackwell, Rennolls, & Coutts, 1990).

in Figure 2.6. The specific values may change with changes in the shape of the root-soil plate or mechanical properties of the soil and wood. Nevertheless, the sequential failure mechanism was highlighted. Windward soil failed first, followed by the windward root failure through uprooting. The total resistance did not meet its maximum when windward soil failed. Root

resistance under tension at the windward side reached its maximum later than the soil because its greater elasticity permitted a larger movement (Coutts, 1983). The leeward roots provided the maximum resistance after windward root breakage; however, the total resistance is no longer sufficient to stabilize the tree.

Previous studies have suggested using the finite element method to calculate movements of the root-soil plate. Dupuy et al. (2007) used simulated root architecture after digitizing to compare the behaviours of root system in cohesive (clay-like) soil and frictional (sand-like) soil, as shown in Figure 2.7. The trunk was assumed rigid and the roots were simulated as beam elements. For the root system in the clayey soil, the soil movements were more symmetrical compared to the movements in sandy soil.

Figure 2.7. Displacement fields of soil under tree pulling in (a) clay-like soil and in (b) sand-like soil (Dupuy et al., 2007).

Moreover, Fourcaud et al. (2008) performed parametric studies to evaluate the importance of each root component in overall stability with different root patterns in a 2D simulation. The trunk and roots were assumed to be rigid in the numerical analyses. Yang et al. (2014) considered the influence of root breakage on the remaining stiffness in their tree stability model. However, very few numerical analyses to date incorporated unsaturated soil mechanics related to the effects of weather conditions.

2.3 Unsaturated Soil Mechanics

In general, soils can be classified as saturated or unsaturated. Saturated soils are naturally found below the ground water table while unsaturated soils exist above the ground water table with the presence of both air and water in the voids.

2.3.1 Soil–water Characteristic Curve

A soil–water characteristic curve (SWCC) describes the relationship between volumetric water content (VWC) and matric suction of soil. Matric suction ψ , which is equal to $(u_a - u_w)$, is the difference between pore-air pressure u_a and pore-water pressure u_w in the soil. VWC changes with matric suction because water storage capacity within the macro- and micro-pores of soil changes with the matric suction value (Fredlund and Rahardjo, 1993). As shown in Figure 2.8, desorption and adsorption curves are different. The adsorption curve is under the desorption curve, meaning that there is a higher water content in desorbing soil than absorbing soil at the same matric suction. When matric suction decreases to 0 kPa, there is residual air content in the soil and the degree of saturation is lower than 1. Several defining parameters of the SWCC including, saturated volumetric water content, air-entry value, and residual volumetric water content are presented in Figure 2.8. The air-entry value (AEV) is defined as the matric suction at which air first enters the pores of the soil and the soil starts to become unsaturated. The AEV corresponds to the matric suction required to replace water with air in the largest pores (Brooks & Corey, 1966). The residual water content (θ_r) is defined as the volumetric water content at which any further increase in matric suction would not significantly remove water from the soil.

Figure 2.8. Typical Soil-Water Characteristic Curve (Fredlund & Xing, 1994).

Fredlund and Xing (1994) proposed a best fit Equation 2.1 to represent SWCC curves, which was found to fit data ranging from 0 to 1,000,000 kPa:

$$\theta = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} \quad \text{Equation 2.1}$$

where θ is the calculated volumetric water content for a specified matric suction; θ_s is the saturated volumetric water content; $C(\psi)$ is the correction factor and was suggested to be equal to 1 by Leong and Rahardjo (1997); ψ is the matric suction; and a , n , and m are empirically-derived variables related to the air-entry value of soil, maximum slope of the SWCC and the curvature of the slope of SWCC, respectively.

2.3.2 Permeability Function

Unlike saturated soils, permeability of unsaturated soils is a function of matric suction and is not a constant value. Unsaturated permeability can be represented by the measured saturated permeability and integrated with the SWCC (Fredlund et al., 1994):

$$k_w(\psi) = \frac{\int_{\ln(\psi)}^b \frac{\theta(e^y) - \theta(\psi)}{e^y} \theta'(e^y) dy}{\int_{\ln(\psi_{aev})}^b \frac{\theta(e^y) - \theta_s}{e^y} \theta'(e^y) dy} \quad \text{Equation 2.2}$$

where b is equal to $\ln(1000000)$; $k_w(\psi)$ is the calculated unsaturated permeability for a specified matric suction ψ (m/s); and y is a dummy variable of integration representing the logarithm of matric suction.

2.3.3 Shear Strength

The shear strength of saturated soils depends on the effective stress $(\sigma - u_w)$, which is the difference between total stress σ and pore-water pressure u_w . Equation 2.3 (Terzaghi, 1943) is commonly used to calculate the shear strength of saturated soils:

$$\tau = c' + (\sigma - u_w)\tan\phi' \quad \text{Equation 2.3}$$

where τ is the shear strength of the soil; $(\sigma - u_w)$ is the effective stress; and c' and ϕ' are the effective cohesion and effective angle of internal friction, respectively.

For unsaturated soils, the shear strength depends on both net normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$. Equation 2.4 shows the shear strength equation for unsaturated soils developed by Fredlund et al. (1978):

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad \text{Equation 2.4}$$

where u_a is the pore-air pressure; $(\sigma - u_a)$ is the net normal stress; $(u_a - u_w)$ is matric suction and ϕ^b is the angle indicating the rate of change in shear strength with respect to change in matric suction.

The shear strength equation of saturated soils can be obtained through a smooth transition from the shear strength equation of unsaturated soils when the matric suction decreases to zero because the pore-water pressure is equal to the pore-air pressure at saturation and, thus, Equation 2.4 becomes the same as Equation 2.3. Figure 2.9 shows the extended Mohr-Coulomb failure envelope for unsaturated soils. The angles ϕ' and ϕ^b are slope angles with respect to the two stress state variables on the two axes, namely net normal stress and matric suction.

Figure 2.9. Extended Mohr-Coulomb Failure Envelope for Unsaturated Soils (Fredlund et al.,1987).

2.3.4 Stiffness

Young's Modulus can be used to measure the stiffness of soils. Rahardjo et al. (2011) proposed Equation 2.5 to estimate the Young's Modulus for saturated soils, as modified from the hyperbolic model proposed by Duncan and Chang (1970). Additionally, Rahardjo et al. (2011) proposed Equation 2.6 to estimate the Young's Modulus for unsaturated soils based on the constitutive equation suggested by Lloret and Alonso (1985).

$$E = K_L P_a \left(\frac{\sigma - u_w}{P_a} \right)^{n_{loading}} \quad \text{Equation 2.5}$$

$$E = K_L P_a \left(\frac{\sigma - u_a}{P_a} \right)^{n_{loading}} + K_m P_a \left(\frac{u_a - u_w}{P_a} \right)^{m_{loading}} + K_o P_a \left(\frac{(\sigma - u_a)(u_a - u_w)}{P_a} \right)^{l_{loading}} \quad \text{Equation 2.6}$$

where E is the Young's Modulus of soil; P_a is the atmospheric pressure; K_L is the loading modulus number with respect to net normal stress; K_m is the loading modulus number with respect to matric suction; K_o is the loading modulus number with respect to both net normal stress and matric suction; $n_{loading}$ is the exponent for loading behaviour associated with net normal stress; $m_{loading}$ is the exponent for loading behaviour associated with matric suction and $l_{loading}$ is the exponent for loading behaviour associated with both net normal stress and matric suction.

Similar to the smooth transition of the shear strength equation for unsaturated soil to saturated soil, Equation 2.5 can be obtained from Equation 2.6 when the matric suction equals zero or pore-water pressure is equal to the pore-air pressure.

Matric suction can contribute additional strength and modulus to unsaturated soil. However, when water infiltrates soil, the soil strength and soil stiffness may significantly decrease as the water content increases and matric suction decreases.

2.4 Evapotranspiration

Evapotranspiration, which is defined as the sum of evaporation and transpiration, influences the water content of soils. As shown in Figure 2.10, weather conditions including rainfall, wind, temperature, humidity and solar radiation can influence evapotranspiration. Evapotranspiration and rainwater infiltration influence the water content of soils and woods.

Figure 2.10. Illustration of the flux boundary (NParks & NTU, 2018).

2.4.1 Potential Evapotranspiration

Potential evapotranspiration includes both potential evaporation and potential transpiration. Traditionally, potential evaporation is calculated based on the Penman method (Penman, 1948) which assumes that the ground surface is always saturated. Other approaches have been suggested for predicting potential evaporation such as the Thornthwaite equation (Thornthwaite, 1948) and the Penman-Monteith equation (Monteith, 1965).

Vegetation plays a significant part in the evapotranspiration process. The amount of energy received by the canopy depends on the surface area covered by leaves. The tree leaf area index (LAI) is a dimensionless value used to describe the ratio of total leaf area and surface land area where vegetation grows. LAI is used to estimate the net radiation intercepting soil surface and, hence, is used to estimate how much energy is available for soil evaporation and how much energy is available for plants to transpire water (Tratch, 1996).

The potential transpiration (PT) value can be estimated by the equation suggested by Ritchie (1972). When LAI is lower than 0.1, PT is equal to 0. When LAI is higher than 2.7, PT is equal to potential evaporation (PE). When PT is between 0.1 and 2.7, Equation 2.7 applies:

$$PT = PE * (-0.21 + 0.7\sqrt{LAI}) \quad \text{Equation 2.7}$$

where PT is the potential transpiration and PE is the potential evaporation.

2.4.2 Actual Evapotranspiration

Actual evapotranspiration is the sum of actual evaporation (AE) and actual transpiration (AT), which depend on both tree and soil characteristics. However, AE is only equal to PE when soil is saturated. For unsaturated soils, AE is less than PE. Wilson (1990) extended the Penman method (1948) and modified the PE equation to include net radiation, wind speed and relative humidity of both the air and soil surface to calculate the actual evaporation from an unsaturated soil surface :

$$AE = \frac{\Gamma Q + v E_a}{v A + \Gamma} \quad \text{Equation 2.8}$$

where AE is the actual vertical evaporative flux (in mm/day); Γ is the slope of the saturation vapour pressure versus temperature curve at the mean temperature of the air (in kPa/°C); Q is the net radiant energy available at the surface (in mm/day); v is the psychrometric constant (in kPa/°C); $E_a = f(u)P_a(B - A)$ (in mm/day), $f(u) = 0.35(1 + 0.15U_a)$, U_a is the wind velocity at 2 m height (in km/hr), P_a is the vapor pressure in the air above the evaporating surface (in kPa),

B is the inverse of the relative humidity at the mean temperature of the air, and A is the inverse of the relative humidity at the soil surface.

When soil becomes saturated and the relative humidity is 100%, the Penman-Wilson formulation becomes the same as the Penman method. The Penman-Wilson (1990) method is applied in VADOSE/W to calculate AE at the soil surface as a function of net solar radiation for all soil moisture conditions, independent of soil type or drying history. The calculated AE value from Equation 2.8 is then modified by Equation 2.9 to account for the portion of energy partitioned to plants:

$$AE_{\text{mod}} = AE * \{1 - (-0.21 + 0.7\sqrt{LAI})\} \quad \text{Equation 2.9}$$

where AE_{mod} is the modified actual evaporation.

Trees draw water from soil because there is higher potential in the soil than the tree. As water moves from soil to tree, there is an increase in the matric suction near the root zone, which makes it more difficult for a tree to draw water from soil. Water movement from soil to tree stops at the wilting point (Tratch, 1996; Nyvall, 2002). Root uptake during transpiration depends on soil suction, root distribution, and potential transpiration (Fatahi, 2007; Fatahi et al, 2010; Rees and Ali, 2006). To calculate AT, VADOSE/W applies Equation 2.10 (Feddes et.al., 1978):

$$AT = PRU * PML \quad \text{Equation 2.10}$$

where PRU is the potential root uptake and PML is the plant moisture limiting factor.

The Plant Moisture Limiting factor (PML) is a function of soil suction and determines the percentage decrease in the ability of plants to draw water from soil as the negative pore-water pressure increases. Under low soil suction, PML is 1. When there is lack of plant water, plants will close stoma and transpiration reduces (Saxton, 1982). PML is 0 when a plant reaches its wilting point and transpiration is 0 when soil suction exceeds the wilting point. A typical PML function suggested by Tratch et al. (1995) is shown in Figure 2.11. When the negative pore-

water pressure is about -100 kPa, the PML, i.e. the ability of a plant to draw water, starts to decrease. When the negative pore-water pressure is about -1500 kPa, the plant is completely unable to draw water and the PML is 0.

Figure 2.11. A typical PML function.

PRU can be calculated as per Fredlund et.al. (2012):

$$\text{PRU} = \frac{2PT}{R_T} \left(1 - \frac{R_n}{R_T} \right) A_n \quad \text{Equation 2.11}$$

where R_T is the total thickness of root zone, R_n is the depth to the node in question after meshing and A_n is the nodal contributing area of the node.

2.5 Fluid Mechanics and Governing Equations

A tree may be deformed or caused to fail by wind. Wind drag is used to describe the net force exerted on a tree in the direction of wind flow. Drag force may include both pressure drag and viscous drag. Pressure drag is caused by the pressure difference between the front and rear surfaces of the tree as air flows through. Pressure drag is related to the flow separations generated as air flow becomes detached from the surfaces of the tree. The generated turbulent wake behind the tree has less pressure than the area in front of the tree, which results in an increase in pressure drag. Viscous drag, also called friction drag, is related to the friction between air and surfaces of the tree. Compared to viscous drag, pressure drag is less sensitive to the Reynolds number. The shape of the body determines whether flow is dominated by viscous drag or pressure drag. For a streamlined body (e.g. a fish), drag is dominated by viscous drag; for a bluff body (e.g. a brick), drag is dominated by pressure drag. For a given frontal area and velocity, the drag force on a streamlined body is smaller than that on a bluff body. However, at low velocities, viscous drag can be dominant even for a bluff body. As illustrated in Figure 2.12, at lower wind velocities, viscous drag is dominant as the friction between the

Figure 2.12. Variations between total drag, pressure drag, viscous drag and wind velocity.

fluid and the body is important; however, as wind velocity increases, pressure drag increases and viscous drag decreases. Laminar viscous drag is only important at very low wind velocities. Therefore, for bluff bodies, viscous drag dominates at lower wind velocities and pressure drag dominates at higher velocities, provided that the shape of the body does not deform much.

2.5.1 Drag Coefficient

The drag coefficient is a dimensionless value used to describe the drag force on a body in a fluid. The drag coefficient of a tree can be measured in the field (Koizumi et al., 2010), through wind tunnel experiments or computed numerically. Endalew et al. (2009) obtained drag coefficients from wind tunnel experiments and numerical analyses. The geometric size of the model in the wind tunnel experiments and numerical analyses was scaled down to 1/10 of the tree size in the field. To keep the Reynolds number and turbulent properties the same, the inlet velocity was accordingly scaled 10-fold. The model in the study of Endalew et al. (2009) was 24 cm high and the tree in the field was 2.4 m high. To obtain the drag coefficient of a mature tree with a height of 20 m, the geometric model should be scaled down to 20 cm for testing in the wind tunnel and the wind velocity should be scaled up to 500 m/s for a wind velocity of 5 m/s in the field. Thus, wind tunnel experiments limit the size of the tree and the high wind velocities required due to scaling make the wind tunnel experiment difficult to conduct.

2.5.2 Turbulent Flow

The Reynolds number, calculated by Equation 2.12, is a dimensionless value used to describe the characteristics of fluid flow. It is also used to differentiate laminar flow and turbulent flow (Reynolds, 1883).

$$R_e = \rho u D / \mu \quad \text{Equation 2.12}$$

Where ρ is the air density, u is the wind speed, R_e is the Reynolds number, D is the average characteristic width of the body and μ is the dynamic viscosity of the fluid.

As observed from Equation 2.12, Reynolds number changes proportionally with the wind velocity. At a wind velocity of 3 m/s, the Reynolds number is calculated at about a magnitude of 10^6 for a tree with a canopy width of 20 m. The airflow through the tree can be thus characterized as turbulent flow, in which the pressure and flow velocity fluctuate chaotically. The flow velocity at solid surfaces, such as the ground, trunk and branch surfaces, is held at zero and assigned a no-slip boundary condition in the numerical analyses. A boundary layer develops when the flow velocity increases from zero at the boundary surfaces to the mainstream wind velocity far from the boundary surfaces. The turbulent boundary layer can be divided into an inner layer and an outer layer. Within the inner layer, the viscous sublayer is the first layer adjacent to the solid surfaces (also called a wall), with a thickness of only a few hundredths of a millimetre (Franzini et al., 1997). In the viscous sublayer, turbulence does not exist and viscous shear force dominates. As mean velocity is linearly proportional to wall distance in the viscous sublayer, wall functions can be used in numerical analyses to represent the effects of near wall turbulence and extremely fine meshes can thus be avoided (Zhang et al., 2017). Further from the wall adjacent to the viscous sublayer is the log-layer, within which the mean velocity is proportional to the logarithm of wall distance. Adjacent to the inner layer further from the solid surface is the outer layer, within which the shear stress distribution is influenced by turbulence.

2.5.3 Computational Fluid Dynamics Modelling

Computational fluid dynamics (CFD) modelling refers to solving fluid flow equations numerically using computers.

The Mach number determines whether a flow is incompressible and can be calculated from:

$$M = u/u_c \quad \text{Equation 2.13}$$

where M is the Mach number, u is the wind speed and u_c is the velocity of sound.

Airflow through trees is typically an incompressible flow with a Mach number less than 0.3 (Franzini et al., 1997). The Navier-Stokes equations, which include one continuity equation and three momentum equations, are derived from the conservation law of mass and momentum (Franzini et al., 1997) and can thus be used for incompressible flow to obtain the drag forces on trees:

$$\partial \mathbf{u}_i / \partial x_i = 0 \quad \text{Equation 2.14}$$

$$\rho \partial (\mathbf{u}_i \mathbf{u}_j) / \partial x_j = -\partial p / \partial x_i + \partial [\mu (\partial \mathbf{u}_i / \partial x_j - \partial \mathbf{u}_j / \partial x_i + 2/3 \delta_{ij} \partial \mathbf{u}_l / \partial x_l)] / \partial x_j \quad \text{Equation 2.15}$$

where $i, j = 1, 2, 3$; $\mathbf{u}_i$ is the i^{th} component of the velocity; x_i is the Cartesian coordinate and p is the pressure.

In turbulent flows, $\mathbf{u}_i$ and p are decomposed into the time-averaged and fluctuating quantities (ANSYS, 2009):

$$\mathbf{u}_i = \overline{\mathbf{u}_i} + \mathbf{u}'_i, \quad p = \overline{p} + p' \quad \text{Equation 2.16}$$

where $\mathbf{u}'_i$ is the i^{th} component of the fluctuating velocity, $\overline{\mathbf{u}_i}$ is the i^{th} component of the averaged velocity, $\overline{p}$ is the average pressure and p' is the fluctuating pressure.

The Reynolds Averaged Navier-Stokes (RANS) equations can be obtained after taking the time average of the Navier-Stokes equations (Fluent, 2011):

$$\partial \overline{\mathbf{u}_i} / \partial x_i = 0 \quad \text{Equation 2.17}$$

$$\rho \partial (\overline{\mathbf{u}_i \mathbf{u}_j}) / \partial x_j = -\partial \overline{p} / \partial x_i + \partial [\mu (\partial \overline{\mathbf{u}_i} / \partial x_j + \partial \overline{\mathbf{u}_j} / \partial x_i - 2/3 \delta_{ij} \partial \overline{\mathbf{u}_l} / \partial x_l)] / \partial x_j + \partial (-\rho \overline{\mathbf{u}'_i \mathbf{u}'_j}) / \partial x_j \quad \text{Equation 2.18}$$

where $\overline{\mathbf{u}'_i \mathbf{u}'_j}$ is the Reynolds stress tensor.

One more unknown term, namely the turbulent Reynolds stress tensor $\overline{\mathbf{u}'_i \mathbf{u}'_j}$, is introduced in the RANS equations and must be solved by a turbulence model, such as the Eddy Viscosity

models or Reynolds Stress Model (RSM). In Eddy Viscosity models, the Boussinesq Hypothesis is used, assuming an isotropic turbulent viscosity, when calculating Reynolds stresses (Fluent, 2011), which is not appropriate if the turbulence is strongly anisotropic. By contrast, the RSM solves the Reynolds stresses directly using six additional equations without any assumptions, but it requires a longer computation time (Fluent, 2011). The Realizable $k-\epsilon$ model and Transition Shear Stress Transport (SST) are two eddy viscosity models that include two additional equations in each model when solving the RANS equations. Gan and Salim (2014) performed numerical simulations of airflow through trees using the RSM method. Five porous cuboids were used to represent the canopy of a tree and a constant pressure loss coefficient was assumed within the porous cuboids to represent the effect of leaves. However, the turbulence created by the leaves was not considered. Endalew et al. (2009) analysed the airflow through a 3D canopy architecture, assuming multiple porous domains around branches with the same diameter, as shown in Figure 2.13. They used source and sink terms in the RANS

Figure 2.13. Porous domain around the branches to model the effect of leaves using sink and source terms (Endalew et al., 2009).

equations in the porous domains to simulate the turbulent effect of leaves. The source and sink terms were functions of the leaf area density (LAD), which is defined as the total leaf area of one side per unit volume with a unit of m^{-1} . However, the LAD distribution used was only dependent on the tree height.

2.6 Solid Mechanics and Governing Equations

Solid mechanics is essential when studying the behaviour of trees and soil under wind forces. Structural analysis can be numerically carried out based on the governing equations in solid mechanics. In these equations, stress, strain and their relationship can be expressed using tensors.

2.6.1 Stress Tensor and Equilibrium Equations

The stress state of a point can be defined by stress tensor τ_{ij} , which consists of nine components (Shames, 1997).

$$\tau_{ij} \equiv \begin{pmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{pmatrix}$$

The principal stresses are calculated from Equation 2.19 (Moaveni, 2003):

$$\begin{vmatrix} \sigma_{xx} - \sigma & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_{yy} - \sigma & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} - \sigma \end{vmatrix} = 0 \quad \text{Equation 2.19}$$

The equivalent stress, also known as *Von Mises* stress, allows a 3D stress state to be represented by a single stress value:

$$\sigma_e = \left\{ \frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \right\}^{\frac{1}{2}} \quad \text{Equation 2.20}$$

where σ_1 , σ_2 and σ_3 are the principal stresses.

From the moment of the momentum equation, $\tau_{ij} = \tau_{ji}$ can be obtained.

Therefore, the differential equations of forces equilibrium for a body can be defined as Equation 2.21 using three equations with six degrees of freedom τ_{ij} .

$$\tau_{ij,j} + B_i = 0 \quad \text{Equation 2.21}$$

2.6.2 Strain Tensor and Strain-Displacement Relationship

Strain is a 2nd order tensor derived from 1st order displacement tensor that measures the deformation of a solid from the original state to the deformed state (Shames, 1997).

$$\epsilon_{ij} = \epsilon_{ji} = \begin{Bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{Bmatrix}$$

The principal strains are calculated from Equation 2.22 (Moaveni, 2003):

$$\begin{vmatrix} \epsilon_{xx} - \epsilon & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{xy} & \epsilon_{yy} - \epsilon & \epsilon_{yz} \\ \epsilon_{xz} & \epsilon_{yz} & \epsilon_{zz} - \epsilon \end{vmatrix} = 0 \quad \text{Equation 2.22}$$

For 2D plane strain modelling, shear strain and normal strain with subscript z becomes 0 and, as a result, the first and third principal strains become Equations 2.23 and 2.24, respectively.

$$\epsilon_1 = \frac{\epsilon_y + \epsilon_x}{2} + \sqrt{\left(\frac{\epsilon_y - \epsilon_x}{2}\right)^2 + (\epsilon_{xy})^2} \quad \text{Equation 2.23}$$

$$\epsilon_3 = \frac{\epsilon_y + \epsilon_x}{2} - \sqrt{\left(\frac{\epsilon_y - \epsilon_x}{2}\right)^2 + (\epsilon_{xy})^2} \quad \text{Equation 2.24}$$

Equation 2.25 between strain and displacement represents the six unknowns ϵ_{ij} with three degrees of freedom u_i .

$$\epsilon_{ij} = \epsilon_{ji} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad \text{Equation 2.25}$$

2.6.3 Stress-Strain Relationship

The stress-strain relationship for linear isotropic, elastic materials is represented by Equation 2.26 (Shames, 1997):

$$\tau_{ij} = \frac{E}{1+\nu} (\epsilon_{ij} + \frac{\nu}{1-2\nu} \epsilon_{kk} \delta_{ij}) \quad \text{Equation 2.26}$$

where δ_{ij} is the *Kronecker delta*:

$$\delta_{ij} = \begin{cases} 1 & \text{when } i = j \\ 0 & \text{when } i \neq j \end{cases}$$

2.7 Two-Dimensional Analyses and Three-Dimensional Analyses

As shown in Figure 2.14, Rahardjo et al. (2009) carried out analyses of tree stability using SIGMA/W (Geo-Slope International Ltd., 2012) with incorporation of unsaturated soil properties. However, the analyses using SIGMA/W assumed a plane strain condition, meaning there was no movement in the direction perpendicular to the 2D plane. The plane strain

Figure 2.14. 2D Geometry model with meshes (Rahardjo et al., 2009).

condition is typically reliable when the thickness of the geometry is much larger than the geometric size in the 2D plane, such that the strain in the direction perpendicular to the plane can be ignored. However, for tree stability analyses, the 2D plane strain assumption may not

be reliable as trees grow in a radial direction. Li et al. (2018) compared differences in tree lean between 2D analyses and 3D analyses. As illustrated in Figure 2.15, they found that 2D analyses underestimated tree leans by 10% compared to 3D analyses, as the restriction in the direction perpendicular to the 2D plane was overestimated in the 2D analyses. Thus, 3D analyses should be used to analyse problems related to trees.

Figure 2.15. Comparison between 2D analyses and 3D analyses (Li et al., 2018).

Chapter 3 Development of Computational Methods

This chapter highlighted the original development of some computational methods in this study, including the additional coding in the numerical analyses to estimate the turbulent effect of leaves, estimating SWCCs based on field instrumentations and the method to incorporate unsaturated soil behaviours in ANSYS during mechanical modelling.

3.1 Additional Coding for the Canopy Consisting of Individual Porous Domains during Computational Fluid Dynamics (CFD) Analyses

In the CFD analyses, additional coding was developed in ANSYS Fluent to represent the momentum sink terms, turbulent kinetic energy sink terms and dissipation rate source terms as the effect of leaves. When wind passes through the tree canopy, a loss in momentum and turbulent kinetic energy, as well as an increase in the eddy dissipation rate, are induced.

When wind increases beyond a threshold, the viscous drag becomes much smaller than the pressure drag and the drag coefficient approaches constant. As a result, viscous drag can be ignored, and the momentum sink terms, turbulent kinetic energy sink terms and dissipation rate source terms can be derived.

The momentum sink term S_u was derived by Sanz (2003) as follows:

$$S_u = -\rho C_d A_{LAD} u^2 \quad \text{Equation 3.1}$$

where ρ is the density of air, C_d is the drag coefficient, A_{LAD} is the average leaf area density of the porous domain in the canopy (m^{-1}) and u is the wind velocity (m/s).

In ANSYS Fluent, the respective coding was developed as:

```
DEFINE_SOURCE(xmom_source,c,t,dS,eqn)
{
```



```

real x[ND_ND];

real con, source;

C_CENTROID(x,c,t);

con = LAD*C_R(c,t)*Cd;

source = -con*fabs(C_U(c, t))*C_U(c,t);

dS[eqn] = -2.*con*fabs(C_U(c,t));

return source;
}

```

The turbulent kinetic energy sink term S_k for dense canopies was modified from Walklate et al. (1996) as follows:

$$S_k = -\rho C_d A_{LAD} k u \quad \text{Equation 3.2}$$

where k is the turbulence kinetic energy.

The respective coding in ANSYS Fluent was developed as:

```

DEFINE_SOURCE(k_source, c, t, dS, eqn)
{

real x[ND_ND];

real con;

real Y_k; // refers to the dissipation of k

C_CENTROID(x, c, t);

con = LAD*C_R(c, t)*Cd;

Y_k = -con*C_K(c, t)*C_U(c, t);

```

```

dS[eqn] = -con*C_K(c, t);

return Y_k;
}

```

The dissipation rate source term S_ε was based on studies by Katul et al. (2004):

$$S_\varepsilon = \rho C_d A_{LAD} C_{\varepsilon 4} \varepsilon u \quad \text{Equation 3.3}$$

where ε is the eddy dissipation rate and $C_{\varepsilon 4} = 1.5$ is a constant obtained from mixing length anisotropy (Sanz, 2003).

The respective coding in ANSYS Fluent was developed as:

```

DEFINE_SOURCE(d_source, c, t, dS, eqn)
{

    real x[ND_ND];
    real con;
    real G_d; // refers to the increase of dissipation rate

    C_CENTROID(x, c, t);
    con = LAD*C_R(c, t)*Cd*Cε4;

    G_d = con*C_D(c, t)*C_U(c, t);
    dS[eqn] = con*C_D(c, t);
    return G_d;
}

```

For each porous domain that is part of the canopy, the codes representing the source and sink terms were written and assigned different leaf area density (LAD) values calculated from the

point cloud data. For different porous domains in the canopy, the respective LADs are different; hence, the corresponding source and sinks values are different.

The file that includes all the codes was imported into the CFD analyses. The drag coefficient was assumed to be 0.5 as the initial drag coefficient value for source and sink value calculations in the first-round analyses. The drag coefficient was computed after the CFD analyses and used as the initial value for the next round of analysis. The drag coefficient continued to converge toward a constant value with more rounds of analyses. The drag coefficient was considered the final value when the difference with the drag coefficient in the previous round of analysis became less than 2%.

3.2 Estimation of SWCCs from Field Measurements

SWCCs are required when computing the soil volumetric water content and pore-water pressure head as a result of rainwater infiltration and evapotranspiration in VADOSE/W.

The SWCC of a soil specimen is usually determined by laboratory tests using equipment such as a Tempe pressure cell, pressure plate cell, centrifuge, WP4 dew point potentiometer and modified triaxial cell. However, the specimens were disturbed during sampling before laboratory tests. Furthermore, sampling of soil around trees is challenging due to the presence of structural and fine roots. SWCCs based on laboratory test results may differ substantially with those from field conditions because the higher or lower number of wooden roots in the specimens will influence the obtained SWCCs. In this study, an alternative method to determine the SWCC was developed based on field instrument data.

In the field, the soil volumetric water contents were measured by the installed soil moisture sensors (EnviroSCAN Probe and CS 616 Time Domain Reflectometry, Campbell Scientific) and the matric suctions were measured by the installed jet fill tensiometers (ICT International).

Real-time measurements of the volumetric water content and matric suction were performed at multiple depths so that SWCCs at varying soil depths could be obtained.

The volumetric water content was plotted against matric suction values. Around 2000 points of measurements within the same month (April 2017) were plotted and best fitted with SWCC equations suggested by Leong and Rahardjo (1997) to obtain the SWCCs at different depths. The resulting SWCCs were used in the numerical analyses of VADOSE/W.

3.3 Incorporating Unsaturated Soil Mechanics in ANSYS for Deformation Analyses

In ANSYS, unsaturated soil properties to be defined are not incorporated in the deformation analyses. In this study, an approach to analyse tree deformation in unsaturated soil is proposed and applied.

The Mohr-Coulomb yield criterion, which was applied in this study, can be defined in ANSYS. However, the criterion in ANSYS is for saturated soil (i.e., $\tau = c' + (\sigma - u_w)\tan\phi'$), and only the effective cohesion c' and effective friction angle ϕ' can be defined. To also incorporate the Extended Mohr-Coulomb yield criterion for unsaturated soil (i.e., $\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$), total cohesion $c = (c' + (u_a - u_w)\tan\phi^b)$ was introduced to substitute effective cohesion c' . Total cohesion c , including effective cohesion c' and additional cohesion from matric suction in unsaturated soil $(u_a - u_w)\tan\phi^b$, was used when defining cohesion in ANSYS. In this case, total cohesion is not a constant value but varies with the matric suction values. With higher or lower matric suction, the additional cohesion from matric suction or total cohesion will be higher or lower.

For saturated soil, matric suction $(u_a - u_w)$ is zero and pore-air pressure u_a is equal to pore-water pressure u_w . For unsaturated soil in the natural field, pore-air pressure u_a is zero. Therefore, shear strength for saturated soils and unsaturated soil can be represented by Equation 3.4 and Equation 3.5, respectively:

$$\tau = c + (\sigma - u_w)\tan\phi' \quad \text{Equation 3.4}$$

$$\tau = c + (\sigma - u_a)\tan\phi' \quad \text{Equation 3.5}$$

Total cohesion c for saturated and unsaturated soil can be represented by Equation 3.6 and 3.7 respectively:

$$c = c' \quad \text{Equation 3.6}$$

$$c = c' - u_w\tan\phi^b \quad \text{Equation 3.7}$$

However, soil strength and soil stiffness in ANSYS can only be defined as a function of temperature T , and not as a function of water content or pore-water pressure. To solve this problem, the pore-water pressure head (u_w/g), where g is the gravitational constant, was substituted by temperature T in ANSYS to define the total cohesion c at different matric suction values. Hence, the defined soil cohesion varied with temperature T in ANSYS, as expressed in Equation 3.8, for unsaturated soil. For saturated soil, the cohesion is a constant and not dependent on temperature T .

$$c = c' - gT\tan\phi^b \quad \text{Equation 3.8}$$

Similarly, the soil modulus can be represented by the function of temperature T in ANSYS as shown in Equation 3.9 for unsaturated soil and Equation 3.10 for saturated soil.

$$E = K_L P_a \left(\frac{\sigma}{P_a}\right)^n + K_m P_a \left(\frac{-gT}{P_a}\right)^m + K_o P_a \left(\frac{-\sigma gT}{P_a}\right)^l \quad \text{Equation 3.9}$$

$$E = K_L P_a \left(\frac{\sigma - gT}{P_a}\right)^n \quad \text{Equation 3.10}$$

As temperature T was used to substitute the pore-water pressure head, the initial condition for the pore-water pressure head profile in the soil was defined as the thermal condition with the temperature profile the same as the pore-water pressure head profile.

Chapter 4 Research Programme

This chapter presents detailed information about the procedures used during field work, including field instrumentation and static pulling tests, and numerical modelling using VODESE/W and ANSYS for analyses of pore-water pressure head, drag coefficient and soil-root-trunk behaviour. The drag coefficient was first computed from the CFD analyses using ANSYS and then compared with the drag coefficient calculated in the field. Due to evapotranspiration and rainwater infiltration resulting from weather conditions, changes in the soil water content and pore-water pressure were investigated using VADOSE/W. By importing the pore-water pressure head profile results, the tree leans could be analysed using ANSYS with the soil modulus and soil strength dependent on the imported pore-water pressure head profile values. The resulting tree leans were also computed under constant soil properties and compared with the computed tree leans considering the effect of weather conditions. Part of the presented content have been published in Li et al. (2018) and Li et al. (2019).

In this study, the Jalan Piring site in the Choa Chu Kang area of Singapore was chosen for installation of field instrumentation and two common tree species in Singapore, namely *Eugenia grandis* and *Khaya senegalensi*, were selected for study after considering availability, access and permits from relevant government agencies. The site location and two trees in this study are shown in Figure 4.1 and Figure 4.2, respectively.

Figure 4.1. Locations of the (a) *Eugenia Grandis* and (b) *Khaya Senegalensis* trees in the Choa Chu Kang site.

Figure 4.2. The selected (a) *Eugenia Grandis* tree and (b) *Khaya Senegalensis* tree.

4.1 Laser Scanning

First, laser scanning was conducted using a V-Line 3D Terrestrial Scanner RIEGL VZ-400 and a Nikon full frame camera (Figure 4.3) to generate point clouds and obtain the geometry of the *Khaya senegalensis* and *Eugenia grandis* trees at the study site. In this study, 28 scanning positions surrounding the canopy and the optimal inclined angles were adopted. The measurements provided accurate 3D point cloud images of the entire canopy. The complete dataset comprised the point cloud data obtained from each measurement position. Using these point cloud data-sets from each position, a single-point cloud data-set could be obtained by registering individual coordinate systems into one common coordinate system by applying the iterative closest point algorithm as suggested by Besl and McKay (1992).

Figure 4.3. The RIEGL VZ-400 terrestrial scanner with the attached top mounted NIKON full frame camera.

4.1.1 Geometry Model Construction

To obtain the geometry model, the leaves and wooden parts in the point clouds were first differentiated using their different reflectance ranges. CANUPO and AutoCAD were used for

post-processing of the point clouds and generation of 3D tree models, which were later used in the ANSYS 17.2 analyses. The point clouds and generated 3D models of the *Khaya senegalensis* and *Eugenia grandis* trees are shown in Figure 4.4 and Figure 4.5, respectively. The *Eugenia grandis* tree was about 25 m in height with a 16 m wide canopy, while the *Khaya senegalensis* tree was about 30 m in height with a 25 m wide canopy.

Figure 4.4. (a) Scanned *Khaya Senegalensis* tree point clouds and (b) post-processed 3D model simulated in ANSYS.

Figure 4.5. (a) Scanned *Eugenia Grandis* tree point clouds and (b) post-processed 3D model simulated in ANSYS.

4.1.2 LAD and LAI Calculation

In addition to generating 3D geometric models, the point cloud dataset of each tree was used to calculate the 3D distributions of leaf area density (LAD) and leaf area index (LAI) per tree, where LAD is defined as the total leaf area of one side per unit volume with a unit of m^{-1} and LAI is defined by dividing the total upper leaf surface of the tree by the surface area of the land. LAD was later used for estimating the drag coefficients in the CFD analyses and LAI was used for estimating the soil water content and pore-water pressure as a result of evapotranspiration and rainfall infiltration in the VADOSE/W analyses.

According to a voxel dimension study carried out by Béland et al. (2014), the optimal voxel cube size is 0.2 m, which was used in this study to obtain the LAD distribution. The LAD profiles of the *Khaya senegalensis* and *Eugenia grandis* trees were plotted in MATLAB as shown in Figure 4.6. The different colours represent the different ranges of each LAD value from the respective 0.2 m voxel cubes. The 3D distributions of LAD reflect the 3D canopy architecture when the scanned geometries and LAD plots are compared.

Figure 4.6. Leaf Area Density distribution of (a) *Khaya Senegalensis* tree and (b) *Eugenia Grandis* tree in MATLAB.

Each tree canopy consists of multiple porous domains, as observed from Figure 4.4(b) and Figure 4.5(b). Equation 4.1 was used to calculate the average LAD for each porous domain by dividing the total leaf area in the domain by the domain volume (Endalew et al., 2009):

$$A_{LAD} = 1/V \sum A_{LAD_i} V_i \quad \text{Equation 4.1}$$

where A_{LAD} is the average leaf area density of the porous domain in the canopy, A_{LAD_i} and V_i are the leaf area density and volume of the voxel, respectively, and V is the volume of the porous domain.

LAI was calculated by dividing the total upper leaf surface of the tree by the surface area of the land. Based on LAI, canopies can be classified as “dense” ($LAI > 4$), “intermediate” (LAI between 3 and 4) or “open” ($LAI < 3$) (Tan & Sia, 2009). A dense canopy describes a close arrangement and multiple stacking of foliage within the canopy; open canopy describes little stacking of foliage within the canopy and intermediate canopy describes a state between dense canopy and open canopy.

4.2 Field Instrumentations

Field instrumentation was installed to acquire weather conditions, the ground water table, soil water content, pore-water pressure head and tree movement during the 20-day period from Mar 1, 2017 to Mar 20, 2017. Weather conditions include wind velocity, air temperature, relative humidity, solar radiation and precipitation. These weather conditions are required input parameters for calculating the soil water content and pore-water pressure head during the evapotranspiration analyses in VADOSE/W. The monitored wind velocity was used when estimating wind drag coefficients in the CFD analyses and estimating drag forces in the deformation analyses using ANSYS. The monitored pore-water pressure head, volumetric water content and tree movements from the field instrumentations were used to validate the numerical model.

4.2.1 Weather Station

A 10 m high weather station was installed as shown in Figure 4.7. Wind velocity, air temperature, relative humidity, solar radiation and precipitation were measured, respectively, using a Campbell Scientific 034B, Campbell Scientific CS215 Temperature and Relative

Figure 4.7. Weather Station installed.

Humidity Probe, Campbell Scientific LI-COR's Solar Radiation Sensors, and rain gauge. Data were recorded every 10 minutes.

4.2.2 Piezometer

A Greenspan PS7000 Pressure sensor piezometer was installed to measure the ground water table, as shown in Figure 4.8. A borehole at a depth of 10 m was made for piezometer

installation. To prevent water penetration, a bentonite seal was placed, and the riser pipe was capped above ground level.

Figure 4.8. Piezometer installed.

4.2.3 Soil Moisture Sensors

Soil moisture sensors (Sentek EnviroSCAN Probe and CS 616 Time Domain Reflectometry from Campbell Scientific) were installed in the soil to measure the soil volumetric water contents (VWC) at varying depths, as shown in Figure 4.9. The measurements were used to validate the numerical results obtained from VADOSE/W. Sentek EnviroSCAN soil moisture

Figure 4.9. The (a) CS 616 and (b) Sentek Enviroscan soil moisture sensor.

sensors were installed at depths of 0.1 m and 0.2 m, while CS 616 soil moisture sensors were installed at depths of 0.3 m and 0.8 m to measure VWC at these depths.

4.2.4 Tensiometers

Tensiometers were also installed in the soil to measure matric suctions, and the obtained data were used to validate the numerical results. In the soil, Jet Fill Tensiometers from ICT International were installed at depths of 0.15 m, 0.3 m and 0.8 m, as shown in Figure 4.10. The Jet Fill Tensiometers were able to measure negative pore-water pressure up to -90 kPa or in other words, matric suction up to 90 kPa considering atmospheric pure-air pressure.

Figure 4.10. The (a) jet-fill tensiometers and (b) installation of the tensiometers.

4.2.5 Linear Variable Differential Transformers

Each tree was equipped with two linear variable differential transformers (LVDTs), as shown in Figure 4.11, to monitor tree movements. Solartron S series AS/5 high performance

displacement sensors were used in this study. They were installed on each tree 1 m above the ground. The two LVDTs measured tree movements in the north-south and east-west directions. Total strain was calculated based on the movements in two perpendicular directions. A 1.2 m long rod was added to the LVDT so that axial displacement was larger with a longer original

Figure 4.11. LVDT installed with the rod. length, resulting in a more accurate reading at larger displacement.

4.3 Field Infiltration Test

Field infiltration tests were performed to determine the actual infiltration rate in the shallow soil layers. The influence of roots near the ground surface was incorporated into the calculations. In line with Parr and Bertrand (1960), a double ring infiltrometer made of hard aluminium sheets was used. The outer ring of the infiltrometer was 52 cm in diameter, while the inner ring was 30 cm in diameter. The outer ring was hammered into the soil to a depth of 5 cm, and the inner ring was then also hammered to a depth of 5 cm.

The constant head method was used. A 5 cm water level was maintained throughout the test in both the outer and inner rings with the height marked by tape. Water was first poured on the soil inside both rings to saturate the soil. Thus, the infiltration rate measured in the next stage

was near the saturated permeability of shallow soils. The infiltration rate was calculated based on how much water infiltrated into the soil within the period. The measured field infiltration rate was applied for the saturated permeability of soil layers between 0.55 m and the ground surface in the subsequent modelling. Figure 4.12 illustrates the double ring infiltrometer used in this study, the set up and the test process.

Figure 4.12. (a) Double ring infiltrometer, (b) infiltrometer set up, and (c) infiltration test.

4.4 Static Pulling Test

Static pulling tests, which involve measuring pulling forces and corresponding tree movements, were conducted to obtain the overall average modulus of elasticity of the tree-root-soil system. Figure 4.13 (Wassenaer and Richardson, 2009) illustrates a typical static pulling test. An anchor is required when pulling a tree, which may be another tree, a truck hitch or a ground anchor. In this study, the anchor was another tree which was connected to the testing tree using a rope. Figure 4.14 shows the pulling set up. A *Khaya senegalensis* tree with a height of 23 m and canopy width of 22 m was pulled to estimate the average stiffness of the instrumented and modelled *Khaya senegalensis* trees in this study. Similarly, one *Eugenia grandis* tree with a height of 23 m and canopy width of 17 m was pulled to estimate the average stiffness of the instrumented and modelled *Eugenia grandis* trees in this study. Each tree was

Figure 4.13. Diagram of tree pulling test (Wassenaer and Richardson, 2009).

pulled for 5 cm of displacement at each step and stopped at a cumulative displacement of 30 cm while still undergoing elastic behaviours. At each step, the resisting force at the corresponding displacement was recorded. A tapered trunk shape was assumed in this study, and the taper ratio of each tree was calculated by dividing the diameter at the trunk bottom by the diameter at the trunk top. The overall stiffness of the tree was then calculated as:

$$E = T_r^3 PL^3 \delta / (3I) \quad \text{Equation 4.2}$$

where E is the average modulus of the respective tree, T_r is the taper ratio, P is the lateral force acting on the attachment, L is the height of the attachment point, δ is the displacement of the tree at the attachment point and I is the second moment of the area of the cross section at the LVDT measuring point.

The calculated average elastic moduli of the two trees were then used to calculate the drag coefficient from the field instrumented data. They were also used in the subsequent deformation analyses.

Figure 4.14. Illustration of (a) one of the anchored trees and (b) one of the testing trees.

4.5 Calculation of Drag Coefficients from Field Measurements

The drag coefficient was calculated as:

$$C_d = 2F/(\rho A_{area} u^2) \quad \text{Equation 4.3}$$

where F is the drag force in the wind direction, C_d is the drag coefficient, ρ is the air density, A_{area} is the projected canopy area perpendicular to the wind direction and u is the mean wind velocity.

In this study, an air density of 1.165 kg/m^3 at a temperature of $30 \text{ }^\circ\text{C}$ was used. The canopy area was calculated from the 3D model generated from the point clouds. The mean velocity u was calculated as:

$$u = \int_0^H u(z)dz / H \quad \text{Equation 4.4}$$

where H is the height of the tree.

To estimate the mean velocity, the vertical wind profile was estimated from the fully developed Atmosphere Boundary Layer (ABL) profile by Richards and Hoxey (1993):

$$u(z) = u_{ABL}^* / \kappa \ln[(z + z_0)/z_0] \quad \text{Equation 4.5}$$

where z is the height coordinate, $u(z)$ is the wind velocity at height z , u_{ABL}^* is the ABL friction velocity, $\kappa = 0.41$ is the von Karman constant and z_0 is the aerodynamic roughness length describing the roughness of the ground surface. In this study, a roughness length of 0.25 m was used since some scattered high obstacles, such as trees, existed in the field (WMO, 2008).

The ABL friction velocity was calculated as per Chiu et al. (2017):

$$u_{ABL}^* = u_{ref} \kappa / \ln[(h + z_0)/z_0] \quad \text{Equation 4.6}$$

where u_{ref} is the wind velocity at the reference height h .

The calculated ABL friction velocity was 0.55 m/s for a wind velocity of 5 m/s at a 10 m reference height.

Thus, the wind velocity inlet profile was calculated from Equation 4.5 and is shown in Figure 4.15.

Figure 4.15. Velocity inlet profile.

Substituting Equation 4.5 and Equation 4.6 into Equation 4.4 gives Equation 4.7 after integration:

$$u = u_{ref}[-H + H\ln(4H + 1) + 0.25\ln(4H + 1)]/\{\ln[(z + z_0)/z_0] H\} \quad \text{Equation 4.7}$$

The mean velocity varies proportionally with the reference velocity u_{ref} , as observed from Equation 4.7. The mean velocity was 5.2 m/s for the 30 m high *Khaya senegalensis* tree and 4.9 m/s for the 25 m high *Eugenia grandis* tree, as calculated from Equation 4.7, based on a reference wind velocity of 5 m/s at a reference height of 5 m.

To calculate the drag coefficient using Equation 4.3, the drag force was estimated from the bending stress, which was calculated from the monitored tree deflections on LVDTs.

Drag force is related to bending stress through:

$$F = \sigma_{bending} I / (L_c y) \quad \text{Equation 4.8}$$

where $\sigma_{bending}$ is the bending stress at the LVDT measuring point, I is the second moment of

the area of the cross section at the LVDT measuring point, L_c (as illustrated in Figure 4.16) is the distance from the centre of pressure on the tree to the LVDT measuring point and y is the radius of the trunk at the LVDT attachment point.

The bending stress in Equation 4.8 is related to the total strain of LVDTs by:

$$\sigma_{bending} = E \sqrt{(\Delta L_1/L_0)^2 + (\Delta L_2/L_0)^2} \quad \text{Equation 4.9}$$

where E is the average modulus of the respective tree, ΔL_1 and ΔL_2 are the tree deflections monitored from the two LVDTs in the two perpendicular directions and L_0 is the original length of the LVDT combined with the rod.

Therefore, drag force is related to LVDT readings, and the drag coefficient can be calculated as follows:

$$F = EI \sqrt{(\Delta L_1/L_0)^2 + (\Delta L_2/L_0)^2} / (L_c y) \quad \text{Equation 4.10}$$

$$C_d = 2EI \sqrt{(\Delta L_1/L_0)^2 + (\Delta L_2/L_0)^2} / (L_c y \rho A u^2) \quad \text{Equation 4.11}$$

Figure 4.16. Illustration of the lever arm used to calculate the bending stress.

4.6 CFD Analyses

CFD analyses were carried out in ANSYS 17.2 to estimate the drag forces on the *Khaya senegalensis* and *Eugenia grandis* trees. CFD analyses of leafless *Khaya senegalensis* and *Eugenia grandis* trees were carried out first to compare the results of different turbulence models. CFD analyses of leafed tree models were also performed to compare the drag coefficients computed by the numerical analyses and field measurements. Moreover, the drag coefficients of the leafless trees and leafed trees, as well as the drag coefficients of the two tree species, were compared.

4.6.1 Airflow through Leafless Models

Before obtaining the drag coefficients of the leafless trees, a grid independence study was carried out to determine the appropriate meshing scheme, which provides the desired accuracy without expensive computing efforts. Multiple meshing schemes, as listed in Table 4.1, were applied during CFD analyses. Meshing Scheme 1 was the coarsest with the lowest number of

meshed nodes, while Meshing Scheme 3 was the finest with the greatest number of meshed nodes.

Table 4.1. Settings in different meshing schemes.

Meshing Scheme	Relevance	Relevance Centre	Smoothing	Span Angle Centre	Growth Rate	Nodes (million)
1	0	Medium	Medium	Medium	1.2	0.8
2	50	Medium	Medium	Medium	1.2	1.9
3	100	Medium	Medium	Medium	1.1	3.5

Figure 4.17 shows the boundary conditions applied in the CFD analyses. A no-slip wall boundary condition was assigned to the ground, the tree trunk and the branches, while a slip symmetry boundary condition was assigned to the top and two side boundaries. The inlet profile was defined by the vertical profile for the fully-developed Atmosphere Boundary Layer

Figure 4.17. Boundary conditions in CFD modelling of leafless trees.

(ABL) profile in Singapore, and the outlet was set to the pressure boundary to enable air to flow out of the domain. The inlet vertical profile comprised three profiles: the velocity profile, turbulent kinetic energy profile and turbulent eddy dissipation rate profile. The velocity profile is presented in Equation 4.5. The kinetic energy profile and turbulent eddy dissipation rate profile are presented in Equation 4.12 and Equation 4.13, respectively (Richards and Hoxey, 1993):

$$k(z) = u_{ABL}^{*2} / \sqrt{C_\mu} \quad \text{Equation 4.12}$$

$$\varepsilon(z) = u_{ABL}^{*3} / \{\kappa \ln[(z + z_0)/z_0]\} \quad \text{Equation 4.13}$$

where C_μ is a turbulence model constant equal to 0.09.

To estimate the drag coefficient using the appropriate turbulence model, separate CFD analyses using three turbulence models (i.e., realizable k - ε model, transition SST model and RSM model) were carried out. The computed drag coefficients using the three turbulence models were compared to investigate the influences of the different turbulence models on the drag coefficient. In the CFD analyses, the Semi-Implicit Method for Pressure-linked Equations (SIMPLE) scheme and the 2nd order upwind scheme were employed as the solution method. The convergence criterion was set as 1×10^{-6} for all parameters. The residual values and drag coefficient were monitored during each CFD analysis. The analysis was terminated only when all values converged and were stable.

4.6.2 Airflow through Leafed Models

CFD analyses of leafed *Khaya senegalensis* and *Eugenia grandis* trees were carried out to obtain their drag coefficients and compared with the drag coefficients calculated from the field measurements. The same boundary conditions used for the leafless trees were applied. To estimate the effect of leaves on airflow through the canopy, the momentum sink term, turbulent kinetic energy sink term and dissipation rate source term were applied to each porous domain

of the canopy, as described in Equations 3.1, 3.2 and 3.3, respectively, in Chapter 3. The realizable k - ε model was used. The solution method and convergence criterion were the same as those used in the analyses of leafless trees.

4.7 Estimation of VWC and Pore-Water Pressure Head

Analyses were carried out in VADOSE/W to estimate the VWC and pore-water pressure head due to evapotranspiration and rainfall infiltration under the weather conditions during the monitoring period of the field instrumentation (i.e., Mar 1 to Mar 20, 2017). The numerical results were then compared with the field measurements. The pore-water pressure head profile results were used in the subsequent deformation analyses when the soil properties were dependent on the pore-water pressure head.

Of note, analyses were only carried out for soil below the *Eugenia grandis* tree. Analyses of soil below the *Khaya senegalensis* tree were not performed as the field data were not continuous or reasonable.

4.7.1 Estimation of SWCC from Field Measurements

The SWCC was required to determine the permeability function and storage capacity of water in the soil before performing the evapotranspiration and infiltration analyses. SWCCs were estimated from the field measurements using the method presented in Chapter 3. More than 2000 sets of field measurements recorded in April 2017 were plotted. Each set contained the VWC and matric suction measurements at different soil depths (i.e., 0.1 m, 0.2 m, 0.3 m and 0.8 m). The SWCCs were obtained after best fitting the data points at the respective depths using the equation suggested by Leong and Rahardjo (1997). The VWCs were measured at depths of 0.1 m, 0.2 m, 0.3 m and 0.8 m, while the matric suctions were measured at depths of 0.15 m, 0.3 m and 0.8 m. Since matric suction was only measured at 0.15 m instead of both 0.1 m and 0.2 m as were done for the VWC measurements, the SWCCs at a soil depths of 0.1 m

and 0.2 m were obtained using the field measured matric suction at 0.15 m with the VWC at the respective depth (i.e., 0.1 m and 0.2 m).

With the estimated SWCCs at various depths, the unsaturated permeability function at the respective depth could then be indirectly estimated from Equation 2.10. The saturated permeability of soil shallower than 0.55 m was estimated from field infiltration tests. A saturated permeability test was conducted in the laboratory for a soil specimen at a depth of 0.8 m to estimate the infiltration rate of deeper soil (i.e. soil from 0.55 m to 4.6 m).

4.7.2 Geometry Model and Boundary Conditions

The geometry model was constructed in VADOSE/W with the assigned boundary conditions as shown in Figure 4.18. At the bottom boundary, a no-flux boundary condition was applied assuming the soil deeper than the bottom boundary has a much lower permeability. The surface evapotranspiration boundary was computed by VADOSE/W using the weather condition inputs (precipitation, wind velocity, air temperature and relative humidity) from the field instrument records and vegetation conditions (i.e., LAI, rectangular root distribution and root depth). The model consisted of four soil layers (i.e., soil depth 0-0.15 m, 0.15 m-0.25 m, 0.25 m–0.55 m and 0.55 m-4.6 m) with the SWCCs and permeability functions at their respective depths. The layer thickness was defined according to the midpoints of the soil depth where instrumented data were recorded (i.e. 0.1 m, 0.2 m, 0.3m and 0.8 m).

VADOSE/W analyses were performed for 20 days (i.e., from Mar 1 to Mar 20, 2017) to estimate the changes in VWC and pore-water pressure head due to evapotranspiration and rainfall infiltration under the weather conditions of the respective day. The numerical results were compared with field measurements at noon on each day.

Figure 4.18. Illustration of geometry and boundary conditions in the VADOSE/W modelling.

4.8 Estimation of Tree Leans

After obtaining the pore-water pressure head, the lean of the same *Eugenia grandis* tree in the Chua Chu Kang area of Singapore under wind drag during the 20-day observation period was computed. During the analyses, unsaturated soil strength and stiffness were incorporated as a function of the imported pore-water pressure head on the respective day.

4.8.1 Wind Drags Calculation

Wind drags calculation was based on Equation 4.3 (i.e., $F = 1/2\rho C_d A u^2$). The drag coefficient was computed from the prior Computational Fluid Dynamics (CFD) analyses using

ANSYS. The air density of 1.165 kg/m^3 was used. The canopy area was calculated from the same 3D model described in Section 4.5. The drag force at noon on each day was computed based on the average wind velocity, which was calculated using Equation 4.7 from the measured wind velocity at the 10-m reference height at noon on the respective day in the field. The drag force was applied to the tree at a height of the centre of pressure.

4.8.2 Geometry Model

For the above-ground structure (trunk), a constant diameter of 0.64 m was assumed, which is the same as the magnitude of the DBH measured in the field. For the below-ground structure, a shallow plate root system was assumed, which is the typical type of root system in Singapore. A shallow root plate system forms when roots easily obtain water from ground level due to abundant rainfall, as occurs in Singapore, instead of extending deep below ground to absorb water. For this study, a plate root system with a depth of 0.3 m and diameter of 10 m was assumed. The boundaries of the supporting soil were defined to have a diameter of 40 m and total depth of 15 m, which should be sufficient to avoid the boundary effect. The soil was defined by two layers from ground level: 0-0.3 m for topsoil and deeper than 0.3 m for deeper soil. The defined geometry in ANSYS 19.1 is shown in Figure 4.19.

Figure 4.19. Geometry of trunk, root plate and soil.

4.8.3 Incorporation of Unsaturated Soil Mechanics in ANSYS

To assess soil shear strength in this study, the Mohr-Coulomb yield criterion was used. However, ANSYS only allows a Mohr-Coulomb yield criterion defined for saturated soil. To determine the Extended Mohr-Coulomb yield criterion for unsaturated soil, the total cohesion c defined as $(c' + (u_a - u_w)\tan\phi^b)$, consisting of effective cohesion and additional cohesion contributed by matric suction in unsaturated soils, was used to replace the cohesion in ANSYS.

In ANSYS, soil shear strength and stiffness can only be defined as a function of the temperature not the water content or pore-water pressure head. To overcome this challenge, temperature T in ANSYS was used to substitute for pore-water pressure head (u_w/g) , where g is the gravitational constant. The details can be found in Section 3.3. The pore-water pressure head

profiles at noon during the 20 days were then exported from VADOSE/W results and imported into the ANSYS Static Structural analyses.

Young's Modulus for unsaturated soil is dependent on both matric suction and net normal stress. However, in ANSYS, the soil modulus can only be defined as a function of temperature, which means that soil modulus can be defined as a function of matric suction if the temperature is used to replace the pore-water pressure head. To define the soil modulus varying with net normal stress, the soils in ANSYS were layered. In each soil layer, the soil modulus only varied with matric suction and the net normal stress was a constant as estimated from the stress level at the mid-depth of the layer.

4.8.4 Wood and Soil Properties

The soil density in the 0-0.3 m layer was 2000 kg/m³ and the soil density in the deeper layer was 2100 kg/m³, as obtained from laboratory tests (NParks & NTU, 2018). The surface infiltration rate of soil at a depth shallower than 0.55 m was obtained from field infiltration test and used as the saturated permeability for the soil shallower than 0.55 m, as presented in Section 4.3. The saturated permeability of the deeper soil (i.e. soil from 0.55 m to 4.6 m) was 5.73E-08 m/s (NParks & NTU, 2018) based on the saturated permeability test conducted in the laboratory for a soil specimen from 0.8 m depth. Soil shear strength parameter values were obtained from the unsaturated shear strength test in the laboratory as reported in Table 4.2 (NParks & NTU, 2018). The total cohesion was then determined for the two soil layers as illustrated in Figure 4.20. Soil modulus parameter values for similar soil specimens reported by Rahadjo et.al (2011) were used in this study, as listed in Table 4.3. The values were obtained from the comparison between results of the numerical simulations and direct shear tests, which were applicable for soils with matric suction of 0–200 kPa and net normal stress of 0–600 kPa (Rahardjo et al., 2011).

The modulus of the above-ground trunk wood was 1.7 GPa, based on the previous CFD analyses and field measurements (Li et al., 2018). The modulus of the below-ground root plate, which is a mixture of wood and soil materials, is less stiff in comparison. It was assumed that 80% of the root plate volume was soil and the remaining 20% was wood. Therefore, the modulus of the root plate was calculated as approximately 1/10 of the modulus of trunk wood, i.e., 170 MPa in this study.

Figure 4.20. Cohesion of the two soil layers defined in ANSYS.

Table 4.2. Shear strength parameters of the soils.

Shear Strength Parameters	c' (kPa)	ϕ' (°)	ϕ^b (°)
Soil Layer 0-0.3 m	9.3	31.3	13.6
Soil Layer below 0.3 m	21.7	31.7	17.2

Table 4.3. Soil modulus parameters.

Soil Modulus Parameters	K_L	K_m	K_o	$n_{loading}$	$m_{loading}$	$l_{loading}$
Both Soil Layers	90.5	92.8	18.9	0.69	0.18	0.99

4.8.5 Boundary Conditions, Thermal Condition, and Hydrostatic Pressure Condition

For the force boundary condition, the wind drag was applied at the centre of pressure on the trunk. For the displacement boundary conditions at the bottom boundary of soil, horizontal and vertical movements were assumed to be 0 as the boundary was deep enough that the effect of wind drags on the bottom boundary was negligible. For the side boundaries, horizontal displacements were assumed to be 0 as the boundaries were far enough that the effect of wind drags on the side boundaries was negligible. Vertical displacements at the side boundaries were allowed, indicating settlements due to gravitational stress.

The temperature profile was defined in the thermal condition, as shown in Figure 4.21, which was the same as the pore-water pressure head profile obtained from VADOSE/W. The unit of the temperature was °C, although the unit of the pore-water pressure head it represented was m. As a result, ANSYS could analyse tree leans using soil moduli and soil strength based on the assigned thermal condition.

Figure 4.21. Temperature condition assigned.

Hydrostatic pressure was assigned as illustrated in Figure 4.22. The hydrostatic pressure profile was assigned based on the pore-water pressure below GWT, as represented by u_w in Equation 3.4 for saturated soils. However, for unsaturated soils above the GWT, the hydrostatic pressure was assigned a value of 0 as the pore-air pressure should be 0 in Equation 3.5. It should be noted that the assigned hydrostatic pressure condition is not equal to the actual pore-water pressure distribution: the hydrostatic pressure assigned is the actual pore-water pressure u_w only for soil below GWT. By contrast, for soil above the GWT, the hydrostatic pressure assigned should be equal to the pore-air pressure u_a , which is 0, so that the soil strength contributed by $(\sigma - u_a)$ is equal to σ and the soil strength contributed by $(u_a - u_w)$ is already incorporated in the total cohesion part. Furthermore, as noted above, the soil modulus function and soil shear strength function are dependent on the assigned temperature profile in the thermal condition rather than the assigned pressure profile in the hydrostatic pressure condition as both functions are dependent on the temperature value.

Figure 4.22. Hydrostatic pressure boundary condition assigned in ANSYS.

4.8.6 Grid Independence Study

A grid independence study was first carried out to obtain a suitable meshing scheme for the subsequent deformation analyses so that the results would be reliable without expensive computing time. The meshed geometry is illustrated in Figure 4.23, with finer mesh for the trunk, root plate, and the soil surrounding the root plate. The mesh far from the root plate was coarser.

Figure 4.23 Meshed geometry with suitable size from grid independence study.

4.8.7 Layer Thickness

To define the soil modulus varying with net normal stress, the soils in ANSYS were layered. In each soil layer, the soil modulus only varied with pore-water pressure head and the net normal stress was a constant estimated from the stress level at the mid-depth of the layer. Thus, to investigate the suitable layer thickness, deformation analyses with different layer thicknesses were carried out so that the resulted tree lean converged as the layer thickness decreased. Analyses with layer thickness of 5 m, 2.5 m, 1.25 m and 0.6 m for soil depths below 0.3 m were carried out and the soil modulus assigned was a function of the pore-water pressure head. A suitable layer thickness was obtained when the difference in the tree lean converged to less than 2%.

After obtaining the approximate meshing scheme and the suitable layer thickness, deformation analyses were performed under wind drag with the pore-water pressure head profile at noon each day during the analysed 20-day period.

4.8.8 Case Studies

To further investigate the effect of weather conditions on tree lean, tree lean was analysed when soil strength and modulus were not related to pore-water pressure head and weather conditions. Hence, in total, two cases were analysed. In Case 1, unsaturated soil properties were incorporated when both the soil modulus and soil shear strength varied with pore-water pressure head imported from the previous VADOSE/W results. In Case 2, unsaturated soil properties were not incorporated when a constant soil modulus was assigned (i.e., 20 MPa, 10 MPa and 5 MPa), and the additional shear strength from matric suction was 0.

Chapter 5 Presentation of Results

This chapter presents the results of field work and numerical analyses carried out in this research. The results from field work, including LAI values from laser scanning, climatic data from field instrumentations, infiltration rate from field infiltration tests and average modulus of the trunk-root-soil system from static pulling tests were presented first. Subsequently, the results from numerical analyses, including the drag coefficients from CFD analyses, pore-water pressure head profile from evapotranspiration analyses and tree leans from deformation analyses were presented. Part of the presented results have been published in Li et al. (2018) and Li et al. (2019).

5.1 LAI from Point Cloud Data

The LAI was obtained from point cloud data, as listed in Table 5.1.

Table 5.1. LAI of the *Khaya senegalensis* tree and the *Syzygium grandis* tree.

Tree Species	Ground Area (m2)	Leafed area	LAI
<i>Khaya senegalensis</i>	554	3871	7
<i>Syzygium grandis</i>	211	1231	6

5.2 Meteorological Inputs from Field Instrumentation

The meteorological data obtained from field instrumentation and used for VADOSE/W analyses are listed in Table 5.2. The precipitation data for the climatic input was calculated as an accumulated amount within the raining period (i.e. from starting time to ending time).

Table 5.2. Climatic data inputs in VADOSE/W from field instrumentation.

Day #	Temperature (°C)		Relative Humidity (%)		Wind (m/s)	Precipitation (mm)	Starting Time	Ending Time
	Max	Min	Max	Min				
1	31.1	24.0	99.9	74.3	0.3	23.6	1.0	16.0
2	28.5	23.3	99.9	61.3	0.3	1.6	7.0	16.0
3	31.8	23.5	99.9	77.8	0.3	37.8	12.0	17.0
4	28.4	23.7	99.9	75.7	0.3	7.6	5.0	17.0
5	29.9	23.4	99.9	55.1	0.1	11.0	14.0	18.0
6	33.3	23.4	99.9	56.9	0.2	13.4	16.0	19.0
7	33.4	23.4	99.9	56.4	0.3	0.8	14.0	20.0
8	33.2	23.4	91.3	52.7	0.3	2.6	17.0	18.0
9	33.8	23.7	87.2	51.8	0.3	0.2	13.0	14.0
10	33.9	23.6	91.1	54.2	0.3	0.0	0.0	24.0
11	32.8	25.5	99.9	52.2	0.4	51.6	15.0	17.0
12	34.0	23.0	99.9	61.1	0.3	20.2	2.0	7.0
13	32.2	23.4	99.9	56.3	0.3	0.0	0.0	24.0
14	34.1	23.8	93.8	73.2	0.4	1.6	10.0	12.0
15	29.4	23.9	95.3	42.0	0.5	0.2	11.0	12.0
16	36.0	24.3	95.6	51.9	0.5	3.6	19.0	21.0
17	34.9	24.0	99.9	54.6	0.4	1.6	14.0	17.0
18	33.3	23.8	99.9	51.5	0.3	67.8	16.0	19.0
19	35.0	23.2	99.9	52.4	0.3	0.2	14.0	15.0
20	34.9	23.3	99.9	63.5	0.4	6.0	8.0	12.0

5.3 Infiltration Test

The infiltration rate was calculated as 2.05×10^{-5} m/s (NParks & NTU, 2018) based on how much water infiltrated into the soil within the given period (i.e. the volume of water poured into the inner ring to maintain the constant head divided by the area of the inner ring and the duration of recorded time). The field infiltration rate was applied for the saturated permeability of soil layers shallower than 0.55 m.

5.4 Average Modulus of the Trunk-Root-Soil System from Static Pulling Test

The average modulus of *Khaya senegalensis* was calculated as 0.9 GPa while the average modulus of *Eugenia grandis* was calculated as 1.23 GPa, based on the static pulling tests of other *Khaya senegalensis* and *Eugenia grandis* trees in Singapore (NParks and NTU, 2018).

5.5 Drag Coefficients from Field Measurements

The drag coefficients of the *Khaya Senegalensis* and the *Eugenia Grandis* trees were calculated from field measurements and plotted against the mean wind velocity, as shown in Figure 5.1. The mean drag coefficients were calculated for each 0.2 m/s velocity interval for the two trees. The best fit of the mean drag coefficients are also plotted in Figure 5.1. According to the specifications of the weather station, the measured wind velocities are only reliable beyond 1 m/s; thus, the starting velocity is 1 m/s in Figure 5.1. The standard deviations of the drag

coefficients were 0.05 and 0.12 for the *Khaya senegalensis* and the *Eugenia grandis* trees, respectively.

(a)

(b)

Figure 5.1. Drag coefficients and best fit of the mean drag coefficients from site instrumented data of (a) the *Khaya Senegalensis* tree and (b) the *Eugenia Grandis* tree.

The mean drag coefficients from field measurements were compared with those of other trees (Koizumi et al., 2010) and plotted together as shown in Figure 5.2. The drag coefficients of all trees followed the same trend, i.e. decreased and converged to a constant value as wind velocity increased.

Figure 5.2. Comparison of best fit of mean drag coefficients with other studies.

5.6 Drag Coefficients from CFD Analyses in ANSYS

5.6.1 Airflow through Leafless Models

Table 4.1 in Chapter 4 lists the details of different meshing schemes for the grid independence study. Computation time of the model was 3 hours using 4 parallel processors if meshed with Meshing Scheme 1, but 4 hours if meshed with Meshing Schemes 2 and 3. Although more meshed nodes and elements are present in the model meshed with Meshing Scheme 3 than

those with Meshing Scheme 2, the computing time was similar. The reason why Meshing Schemes 2 and 3 had similar computing time is because the calculation time per iteration increased with finer meshes, but the number of iterations required to reach the converged solution decreased.

Table 5.3 presents the computed drag results for the *Khaya senegalensis* tree using the realizable $k-\epsilon$ model, transition SST model and RSM model. The drag coefficients using each turbulence model were computed from the model meshed with three different meshing schemes. For all three turbulence models, Meshing Scheme 3 was the most appropriate meshing scheme without expensive computing time to allow for grid independent drag coefficients, and the drag difference was reduced to less than 2% between the successive meshing schemes. As a result, Meshing Scheme 3 was applied during meshing before analysis of the airflow through the *Eugenia grandis* tree. Similarly, Table 5.4 presents the drag results using the realizable $k-\epsilon$ model, transition SST model and RSM model for the *Eugenia grandis* tree.

Table 5.3. Drag coefficient of the *Khaya senegalensis* tree.

Turbulence model	Meshing Scheme	Drag Force (N)	Projected Area (m²)	Drag Coefficient	Change in Drag
Realizable k-epsilon	Meshing Scheme 1	539.9	47.3	0.724	-
	Meshing Scheme 2	473.4	47.3	0.635	14.0%
	Meshing Scheme 3	470.3	47.3	0.631	0.6%

Transition SST	Meshing Scheme 1	527.3	47.3	0.708	-
	Meshing Scheme 2	482.2	47.3	0.647	9.4%
	Meshing Scheme 3	478.2	47.3	0.642	0.8%
RSM	Meshing Scheme 1	520.9	47.3	0.699	-
	Meshing Scheme 2	476.9	47.3	0.640	9.2%
	Meshing Scheme 3	467.7	47.3	0.628	2.0%

Table 5.4. Drag coefficient of the *Eugenia grandis* tree.

Turbulence model	Drag Force (N)	Projected Area (m²)	Drag Coefficient
Realizable k-epsilon	260.2	27	0.689
Transition SST	261.7	27	0.693
RSM	259.1	27	0.686

In the comparison of the drag coefficients among the three turbulence models for the *Khaya Senegalensis* and *Eugenia Grandis* trees (Tables 5.3 and 5.4, respectively), the difference was

less than 2%, which is negligible. As the results of the three turbulence models were similar, only the results using the realizable $k-\varepsilon$ model are presented. Figure 5.3 plots the pressure contours for the *Khaya senegalensis* and *Eugenia grandis* trees. The wind was directly into the page. Therefore, higher pressure was observed at the front of the tree facing the wind and lower pressure was observed at the back of the tree.

As the results were similar for the different turbulence models, when estimating drags on the leafed trees, analyses were performed using only the realizable $k-\varepsilon$ model.

However, the drag coefficient of the *Eugenia grandis* tree was higher than that of the *Khaya senegalensis* tree. One possible reason for this difference is that the larger average wind velocity experienced by the *Khaya senegalensis* tree resulted in a lower drag coefficient, as calculated by Equation 4.3. The *Khaya senegalensis* tree was 5 m taller than the *Eugenia grandis* tree, resulting in a larger average wind velocity experienced by the *Khaya senegalensis* tree because the wind velocity was slower at lower height due to the ABL effect.

(a)

(b)

Figure 5.3. Pressure contours on (a) the *Khaya senegalensis* tree and (b) the *Eugenia grandis* tree.

5.6.2 Airflow through Leafed Models

Figures 5.4 and 5.5 illustrate the velocity contours and the velocity streamlines, respectively, around the *Khaya senegalensis* and *Eugenia grandis* trees on an x-z plane, where the x-

(a)

(b)

Figure 5.4. Velocity contours around (a) the *Khaya senegalensis* tree and (b) the *Eugenia grandis* tree.

direction is the wind direction. As shown, a cavity zone formed at the back of the canopy. Although the canopy was porous, air tended to flow around the canopy because the voids around the canopy provided less resistance and less momentum loss.

(a)

(b)

Figure 5.5. Velocity streamlines around (a) the *Khaya senegalensis* tree and (b) the *Eugenia grandis* tree.

Figure 5.6 plots the pressure contours for the *Khaya senegalensis* and *Eugenia grandis* trees.

The wind was blowing directly into the page. Higher pressure was experienced at the front of the tree facing the wind and lower pressure was experienced at the back of the tree.

(a)

(b)

Figure 5.6. Pressure contours on (a) the *Khaya senegalensis* tree and (b) the *Eugenia grandis* tree.

The gradients from high pressure to low pressure through each porous domain were observed to differ, which could be attributed to the different leaf area densities of different porous domains.

The drag results are summarized in Tables 5.5 and 5.6 for the *Khaya senegalensis* tree and the *Eugenia grandis* tree, respectively.

Table 5.5. Summarized results of CFD analyses for the *Khaya senegalensis* tree.

<i>Khaya Senegalensis</i>	Drag Force (N)	Ratio of the Total Drag	Projected Area (m ²)	Drag Coefficient	Center of Pressure (m)	Ratio of Tree Height (Tree Height = 30 m)
Canopy	3990	0.92	392	0.646	19.0	0.633
Trunk	326	0.08	47.3	0.438	13.4	0.445
Total	4316	1	407	0.673	18.5	0.618

Table 5.6. Summarized results of CFD analyses for the *Eugenia grandis* tree.

<i>Eugenia Grandis</i>	Drag Force (N)	Ratio of the Total Drag	Projected Area (m ²)	Drag Coefficient	Center of Pressure (m)	Ratio of Tree Height (Tree Height = 25 m)
Canopy	1917	0.97	192	0.714	15.1	0.606
Trunk	51	0.03	27	0.135	4.7	0.186
Total	1968	1	196	0.718	14.9	0.595

As shown, the total projected area was less than the summation of the canopy and trunk area—about 8% less for the *Khaya senegalensis* tree and 12% less for the *Eugenia grandis* tree—due to the overlapping projected area between canopy and trunk. The area reduction ratio was higher for the *Eugenia grandis* tree because its ratio of overlapped area was higher than that of the *Khaya senegalensis* tree. The ratio of the drag force on the trunk to the total drag force on the entire tree (i.e., canopy and trunk) was 0.03 for the *Eugenia grandis* tree and 0.08 for the *Khaya senegalensis* tree, since a larger percentage of the trunk area was covered by canopy on the *Eugenia grandis* tree.

It is also noted that the drag force experienced by the *Khaya senegalensis* tree was larger than that experienced by the *Eugenia grandis* tree. This is because the total projected area of the *Khaya senegalensis* tree was larger than that of the *Eugenia grandis* tree.

5.7 Volumetric Water Contents and Pore-Water Pressure Heads from VADOSE/W

The field measurements and the their best fit SWCCs based on Leong and Rahardjo (1997) at soil depths of 0.1m, 0.2 m, 0.3 m and 0.8 m, using the least squares method, are shown in Figure 5.7. The SWCC variables were determined from the best-fit and were therefore assigned for the properties of soils at different layers, as listed in Table 5.7.

Figure 5.7. SWCCs for soils at (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, and (d) 0.8 m.

Table 5.7. SWCC variables for different soil layers.

SWCC	Saturated VWC	a (kPa)	n	m
Soil layer 0-0.15m	0.37	2.80	0.47	0.40
Soil layer 0.15 m- 0.25 m	0.32	1.17	0.54	0.21
Soil layer 0.25 m –0.55 m	0.36	1.60	1.24	0.42
Soil layer 0.55 m- 4.6 m	0.32	3.20	6	0.07

From a laboratory saturated permeability test of a soil specimen from 0.8 m depth, a saturated permeability of $5.73\text{E-}08$ m/s was obtained (NParks & NTU, 2018). This saturated permeability was applied to soil from 0.55 m to 4.6 m. For the soil shallower than 0.55 m, the measured field infiltration rate of $2.05\text{E-}05$ m/s, as presented in Section 5.3, was applied as the soil saturated permeability. From the SWCCs and saturated permeabilities of the soils, the permeability functions at soil depths of 0.1, 0.2, 0.3 and 0.8 m were obtained as shown in Figure 5.8.

Figure 5.8. Permeability functions for soils at (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, and (d) 0.8 m.

Figure 5.9 and 5.10 compare the volumetric water content and pore-water pressure head results of numerical modelling using VADOSE/W and field measurements, respectively, as a result of evapotranspiration and rainwater infiltration. The volumetric water content results at soil depths of 0.1 m, 0.2 m, 0.3 m and 0.8 m, and pore-water pressure head results at soil depths of 0.15 m, 0.3 m and 0.8 m from Mar 1, 2017 to Mar 20, 2017 were plotted at 0.5-day intervals. The precipitation amounts during the 20 days were also plotted to illustrate changes in the volumetric water content and pore-water pressure head due to rainwater infiltration.

Figure 5.9. Numerical results and field measurements of volumetric water content at (a) 0.1 m depth soil, (b) 0.2 m depth soil, (c) 0.3 depth soil and (d) 0.8 m depth soil.

(a)

(b)

(c)

Figure 5.10. Numerical results and field measurements of pore-water pressure head at (a) 0.15 m depth soil, (b) 0.3 m depth soil and (c) 0.8 m depth soil.

Figure 5.11 plots the pore-water pressure head profile at noon (12:00 PM), which was used for the subsequent deformation analyses. The pore-water pressure profile was influenced by the weather conditions. However, the ground water table always fluctuated around 4 m below the ground surface. The pore-water pressure head profile was imported into the subsequent deformation analyses using ANSYS Workbench 19.1 to analyse tree leans at noon time over the 20 days.

Figure 5.11. Pore-water pressure head vs. depth at noon time from Mar 1, 2017 to Mar 20, 2017.

5.8 Tree Leans from Deformation Analyses in ANSYS

First, a grid independence study was conducted to obtain the suitable meshing size. Figure 5.12 plots the difference in resulted lean of the *Eugenia grandis* tree as a percentage when the meshed number of nodes increases. The difference in the tree lean converged and became lower

Figure 5.12. Change in tree lean as meshed number of nodes increases.

than 2% when the meshed number of nodes was 83,439; hence, this meshing scheme was considered suitable for the subsequent analyses.

The suitable layer thickness for the soil region below 0.3 m was then investigated, and the results are plotted in Figure 5.13. A layer thickness of 1.25 m was found to be suitable because the resulted change in tree lean dropped below 2%, as shown in Figure 5.13.

Figure 5.13. Change in tree lean as layer thickness decreases.

Figure 5.14 shows the assigned soil modulus as a function of pore-water pressure head based on Equation 3.9 and 3.10, and the net normal stress was calculated from stress at the centre of the respective layer with a layer thickness of 1.25 m. From Figure 5.14, it can be observed that the soil modulus decreases significantly when the matric suction approaches 0.

Figure 5.14. Soil modulus as a function of temperature assigned in different soil layers in ANSYS.

Using the suitable meshing scheme and layer thickness, deformation analyses were then carried out. The applied wind drags were calculated from the monitored wind velocities at noon from Mar 1, 2017 to Mar 20, 2017. The wind drags and wind velocities are plotted in Figure 5.15. As shown, the drag forces are generally small and below 50 N with wind velocities below 0.8 m/s. The maximum wind drag force was about 155 N with a wind velocity of approximately 1.4 m/s.

Figure 5.15. Wind drags at respective wind speeds at noon time during 20 days from Mar 1, 2017 to Mar 20, 2017.

After obtaining horizontal displacements from the analyses, tree leans were calculated by dividing the horizontal displacements at the point of load application by the height of load application. The calculated tree leans and the respective wind drags at noon from Mar 1, 2017 to Mar 20, 2017 are plotted in Figure 5.16.

Figure 5.16. Tree leans due to the corresponding wind drags at noon time from Mar 1, 2017 to Mar 20, 2017.

Next, the tree leans computed from the analyses with and without incorporation of unsaturated soil behaviours as an effect of weather conditions were compared. Figure 5.17 shows the computed tree leans under the two cases. In Case 1, unsaturated soil properties were incorporated when both the soil modulus and soil shear strength varied with pore-water

Figure 5.17. Comparison of tree leans in the two cases: Case 1. soil modulus changes with pore-water pressure head; Case 2. soil modulus is constant with a magnitude of 20 MPa.

pressure head imported from the previous VADOSE/W results. In Case 2, unsaturated soil properties were not incorporated when a constant soil modulus of 20 MPa was assigned, and the additional shear strength from matric suction was 0.

As the wind drag forces were small with the low wind velocities in the field, soil was always under elastic behaviours as no plastic strain was observed from ANSYS results.

Furthermore, the analyses of lean of the *Eugenia grandis* tree in soil with constant moduli of 20 MPa, 10 MPa and 5 MPa were performed. The differences in tree lean considering the effect of weather conditions are shown in Figure 5.18. As observed, the differences were comparatively large at lower wind forces as the numerical error was significant. The differences converged near a constant value as wind drag increased. The differences converged to 16.5%, 8.3% and 0.7 % when assuming the constant soil modulus of 20, 10 and 5 MPa, respectively. Small turbulences were observed as the differences were affected by slightly different weather conditions across the 20 days. However, the effect of the slightly different weather conditions was small as the turbulences were small, as illustrated in Figure 5.18. The

Figure 5.18. Differences of tree leans in percentage between applying a soil modulus function or applying a constant soil modulus (i.e. 5 MPa, 10 MPa and 20 MPa) across the 20 days.

small differences in pore-water pressure heads, as shown in Figure 5.11, also imply that the effect of different weather conditions across the 20 days was small.

Chapter 6 Discussion of Results

This chapter discusses the results presented in Chapter 5. For CFD analyses, the results between leafless and fully leafed models were compared. The results of CFD analyses between *Khaya senegalensis* and *Eugenia grandis* trees were also compared. Furthermore, the applicable range of wind velocities in the CFD analyses was also discussed. In addition, the influence of tree flexibility in drag coefficient was discussed. Drag coefficients were calculated from field measurements at the same time. Therefore, the drag coefficient from numerical and field works were compared. For evapotranspiration analyses, the volumetric water content and pore-water pressure head from numerical analyses were compared with those from field measurements. For deformation analyses, the tree lean results between whether or not incorporating unsaturated soil mechanics were compared and the effect of weather conditions on tree lean was discussed. Moreover, the uncertainties and assumptions used in this study were discussed. In the end, the application of the integrated approach was discussed. Part of the presented discussions have been published in Li et al. (2018) and Li et al. (2019).

6.1 Comparison between Leafless Models and Fully Leafed Models

The drag coefficients of the leafed models were higher than those of the leafless models. For the *Khaya senegalensis* tree, the drag coefficient of the leafed tree was 0.673 while that of the leafless tree was 0.631, which is a difference of approximately 6.6%. For the *Eugenia grandis* tree, the drag coefficient of the leafed tree was 0.718 while that of the leafless tree was 0.689, which is a difference of approximately 4.2%. These differences exist because the porosity created by the leaves increases the overall drag coefficient of the tree compared to a solid geometry comprising only trunk and branches.

The drag force experienced by the trunk was higher for the leafless models than the leafed models. The reduction of drag force experienced by the trunk of leafed trees can be attributed to the surrounding leaves covering the trunk (Li et al., 2018).

6.2 Comparison of Results for *Khaya Senegalensis* and *Eugenia Grandis* Trees

The drag coefficients of the *Khaya senegalensis* and *Eugenia grandis* trees were comparable at 0.67 and 0.72, respectively. Furthermore, the centres of pressure on the two trees were at a similar height ratio. The centre of pressure for the *Khaya senegalensis* tree was at about 18.54 m, which was a ratio of 0.618 of the tree height, and the centre of pressure for the *Eugenia grandis* tree was 14.87 m, which was a ratio of 0.595 of the tree height. The similar drag coefficients and positions of the centre of pressure as a ratio of total height can be attributed to the similar geometries of the two trees. The drag coefficient of the *Eugenia grandis* tree was slightly larger than that of the *Khaya senegalensis* tree, which may be due to the shorter height and smaller Reynolds number of the former. According to Koizumi et al. (2010) and Mayhead (1973), the drag coefficients of dwarf trees are larger than those of large trees at the same wind velocity. The position of centre of pressure for the *Khaya senegalensis* tree was slightly higher due to the lower centroid of the canopy relative to the *Eugenia grandis* tree.

The lift coefficients of the *Khaya senegalensis* and *Eugenia grandis* trees were calculated and found to be less than 2% of the drag coefficients, which explains the negligible lift force in the deformation analyses. For other tree shapes, like the umbrella-shaped *Samanea saman* tree in Figure 6.1, the lift force is much larger and should not be ignored in tree stability analyses.

Figure 6.1. Point clouds of one *Samanea saman* tree in the Choa Chu Kang area.

6.3 Limitation of Range of Wind Velocities in CFD Analyses

The numerical method to obtain drag coefficients using CFD analyses may not be applied for all wind velocities. Limitations exist for the applicable range of wind velocities. Figure 6.2(a) proposes a change in the drag coefficient when the wind velocity increases. The changes in tree geometry corresponding to different stages are shown in Figure 6.2. Figure 6.2(b) represents a tree under the no wind condition, while Figure 6.2(c) represents a tree experiencing a low wind velocity. When the wind velocity increases from 0 m/s, the drag coefficient decreases because the viscous drag decreases and the pressure drag increases simultaneously, although the overall

drag coefficient decreases because the viscous drag is still dominant. It is assumed that any change in overall projected area due to the fluttering of leaves on mature trees is negligible.

As wind velocity further increases, the viscous drag becomes negligible, the pressure drag becomes dominant, and the drag coefficient converges to a constant and does not change significantly. Figure 6.2(d) represents the drag coefficient and tree geometry at this stage. This is the starting point of the range when the numerical approach presented in this thesis can be applied. The presented numerical method is only applicable when the viscous drag is small and negligible relative to the pressure drag, and so the source and sink terms can be used. In the CFD analyses when applying the source and sink terms, it was assumed that the change in the overall projected area was small and negligible. This implied that the wind forces were not

(a)

(b)

(c)

(d)

(e)

Figure 6.2. Proposed relationship between drag coefficient and wind speed for mature and stiff trees and tree geometries under different wind velocities (after Akagi & Kitajima, 2006).

large, and so reconfiguration of the geometry did not occur. Figure 6.2(e) presents a tree that started to experience streamlining and reconfiguration, resulting in a significant decrease in the drag coefficient (Li et al., 2018). However, the reduction in drag coefficient due to reconfiguration rarely occurs in the field, likely because obvious streamlining only occurs at very high wind velocity for mature trees and the trees typically fail before the wind reaches such velocities.

Mayhead (1973) proposed that wind drag increased linearly, not squared, with wind velocity, as shown in Equation 4.3. In other words, rather than being a constant, the calculated drag coefficient decreases linearly with wind velocity. However, this proposal is only reliable for the range of wind velocities as shown in Figure 6.2 (c). The drag coefficient decreases linearly with wind velocity, approaching a constant beyond a certain wind velocity. In most published studies, the decrease in drag coefficient was attributed to the reconfiguration of trees (Mayhead, 1973; Rudnicki et al., 2004; Koizumi et al., 2010). However, only the decrease in drag coefficient shown in Figure 6.2(e) is due to reconfiguration, not the decrease in drag coefficient shown in Figure 6.2(c). Even for a stiff body that never undergoes reconfiguration when the wind velocity changes, the drag also decreases as the wind velocity increases. This is because the flow is laminar at a low Reynolds number or low wind velocity. Therefore, the decrease in drag coefficient at low wind velocities for mature trees is mainly due to the dominance of the viscous drag, not due to the changes in the projected area or reconfiguration. At high wind velocities, a large decrease in the projected area due to reconfiguration and the streamlining effect can lead to a considerable decrease in drag coefficient. Nevertheless, as shown in both Figure 6.2(c) and Figure 6.2(e), the tree experiences a dominance of the viscous drag over the pressure drag such that the drag coefficient decreases as wind velocity increases.

Thus, the numerical approach should not be applied when the wind velocity is below or beyond this range. Within this range (i.e. as indicated in Figure 6.2(d), viscous drag is negligible

relative to pressure drag, and so the source and sink terms can be used. Moreover, the drag coefficient does not change significantly when the pressure drag is dominant.

Nevertheless, the range of applicable wind velocity can vary from tree to tree because the Reynolds number and slenderness ratio are influenced by geometric size and flexibility is influenced by the average modulus. For slender or flexible trees, the numerical approach may not apply because reconfiguration and streamlining can occur much more easily, resulting in a large decrease in the drag coefficient at a low wind velocity. In this case, the drag force may vary linearly with the wind velocity due to the dominance of viscous drag over pressure drag (Li et al., 2018).

For flexible bodies like grasses, variation in the drag coefficient as wind velocity increases only consists of conditions given in Figure 6.2(c) and 6.2(d) as they are easily deformed by a low wind velocity and the drag coefficient converges to a constant after being almost fully deformed.

6.4 The Influence of Flexibility on the Reliability of Numerical Modelling

As trees are flexible and undergo deflections due to wind drag, the reliability of the CFD analyses may be influenced by the reconfiguration of the tree. If the tree experiences significant deflections, two-way fluid structure interaction (FSI) analysis should be considered, i.e., movements under wind drags should be computed and then the geometry of the tree should be updated accordingly during the CFD analyses.

To explain this, the Cauchy number was introduced and calculated to estimate how much a drag coefficient is influenced by flexibility. The Cauchy number is defined as a dimensionless number describing the relative importance of fluid drag compared to its elastic counterpart, as shown in Equation 6.1. In this study, the Cauchy number was calculated based on Equation 6.2 (Niklas, 1992) to incorporate the effect of slenderness.

$$C = \rho u^2 / E \quad \text{Equation 6.1}$$

where C is the Cauchy number.

$$C_y = \rho u^2 S^3 / E \quad \text{Equation 6.2}$$

where S is the slenderness ratio and defined by the ratio of the length to the width of a body.

According to de Langre (2008), the effect of reconfiguration is negligible if the Cauchy number C_y is less than 1; otherwise, the drag coefficient due to reconfiguration should be considered.

To estimate the Cauchy number in this study, an average modulus of mature trees of 1 GPa was used and a slenderness ratio of 30 was obtained for a tree with a height of 30 m and a diameter of 1 m. The Cauchy number was calculated to be approximately 8×10^{-4} at a wind velocity of 5 m/s by Equation 6.2. Although the Cauchy number tends to increase with wind velocity, it will reach 1 if the wind velocity increases to 173 m/s as calculated by Equation 6.2. Therefore, the effect of reconfiguration was negligible in this study for wind velocities much smaller than 173 m/s.

For an individual branch, Cauchy number is higher due to the higher slenderness ratio. The modulus of branch is similar to the average modulus of the tree, which was about 1 GPa, as measured from three-point bending experiments (NParks & NTU, 2017). Figure 6.3 shows the variation in Cauchy number with slenderness ratio at different wind velocities of 5, 10, 20 and 40 m/s. As observed, the Cauchy number increases with slenderness ratio, reaching 1 when the slenderness ratio reaches 310 at a wind velocity of 5 m/s. In their study on branch diameter and length, as illustrated in Figure 6.4, Nutto et al. (2006) found that the branch length increases linearly with branch diameter, implying that the slenderness ratio of a branch could be a constant. If a branch slenderness ratio of 140 is considered, the Cauchy number of 1 is reached when the wind velocity is around 20 m/s from Figure 6.3. Therefore, in the present study, deflection of an individual branch can be neglected at wind velocities below 2 m/s when

calculating the drag coefficients. However, as wind velocity increases and the Cauchy number exceeds 1, reconfiguration starts to affect the drag coefficients.

Figure 6.3. Relationship between Cauchy number and slenderness ratio(Li et al., 2018).

A canopy with many branches can behave very differently than an individual branch. As

Figure 6.4. Relationship between branch length and branch diameter (Nutto et al., 2006).

illustrated in Figure 6.5(a), as wind velocity gradually increases from 0 m/s, the part of canopy

at the windward side bends first to increase the overall projected area. The deflection of the canopy at the leeward side will be much smaller due to blockage by the part of the canopy at the windward side. As the wind velocity further increases, the canopy at the windward side may be deflected to the leeward side and the overall projected area will decrease, as shown in Figure 6.5 (b). The streamlining effect of the canopy will result in a significant decrease of the drag coefficient as the viscous drag becomes dominant over the pressure drag (Li et al., 2018).

Figure 6.5. Deflected tree at different wind velocities.

6.5 Comparison of Drag Coefficients from Field Measurements and CFD Analyses

As shown in Figure 5.1, most of the monitored wind velocities were small, being below an average of 2.5 m/s. Only when the wind velocity was beyond 2 m/s was the pressure drag dominant for both the *Khaya senegalensis* and *Eugenia grandis* trees, meaning that the source and sink terms could be applied to the porous canopies. Thus, the drag coefficients calculated from the field measurements and CFD analyses were compared to a reference wind velocity of 2 m/s at a reference height of 10 m. It should be noted that the average wind velocity is not equal to the measured wind velocity at the reference height. The average wind velocities were calculated based on Equation 4.7. The drag coefficients from the field measurements were

estimated using the best-fit curve as presented in Figure 5.1. The drag coefficients of the two trees from both the field measurements and numerical modelling are presented in Table 6.1.

Table 6.1. Comparison between computed drag coefficients from the numerical modelling and site instrumented data.

<i>Drag Coefficients from</i>	<i>Khaya Senegalensis</i>	<i>Eugenia Grandis</i>
Numerical Modelling	0.67	0.72
Site Instrumented Data	0.54	0.42

Overall, the values were in the reliable range of drag coefficients for actual trees, i.e. 0.29-0.88 (Koizumi et al., 2010). The drag coefficients calculated from the CFD analyses were higher than those from the field instrumented results.

There were few uncertainties and assumptions during the analyses and calculations, which are discussed in Section 6.8 in detail. However, the main reason for the difference in drag coefficients calculated from the CFD analyses and field instrumented results is because the static pulling tests were conducted on trees that differed from the monitored trees. Error could exist when the moduli of the trees were assumed to be the same. As shown in Figure 6.6, geologically, the monitored trees laid in the Jurong Formation while the trees pulled laid in the Old Alluvium. Although the tree species and geometries were similar, the soil conditions and water content inside the wood could be different (Li et al., 2018). As shown in Equation 4.11, the drag coefficient was linearly proportional to the average modulus of the tree. The drag coefficients calculated from field measurements were lower than those from the numerical modelling, possibly due to underestimation of the average moduli of the two trees. The difference in moduli for the two trees at two locations was considered the main reason for the

difference in drag coefficients between the field calculations and numerical analyses. The drag coefficients from the field calculations and numerical analyses were then compared to estimate the average moduli of the trees for the deformation analyses. It should be noted that the lever arm used to calculate the drag coefficients in the field using Equation 4.11 was assumed to be the same as the lever arm in the numerical analyses. This assumption may lead to errors in the drag coefficients. Therefore, the drag coefficients computed from CFD are more reliable than those calculated from field measurements in this study.

Figure 6.6. Singapore Geological Map (after DSTA, 2009).

6.6 Comparison of Volumetric Water Contents and Pore-Water Pressure Heads from Field Measurements and Numerical Modelling using VADOSE/W

The volumetric water content results from the numerical modelling and field measurements were similar across the 20-day monitoring period. The volumetric water content and precipitation values followed the same trend. In this section, five possible reasons are presented

for the small differences between the observed and modelled volumetric water contents. The first is that wind velocities measured at a 10 m height were used in VADOSE/W, rather than surface wind velocities at 2 m height. As the surface wind velocity at a 2 m height should be lower than the measured wind velocity at a 10 m height due to the boundary effects of the ground, evaporation was slightly overestimated in the numerical model and the analysed volumetric water content was lower than that of the field measurements near the ground surface at soil depths of 0.1, 0.2 and 0.3 m. The second reason is that the SWCCs below a 0.8 m depth and at a 0.8 m depth were assumed to be the same, as there was a lack of data at lower depths. The third reason is that the saturated permeability of soil below a 0.8 m depth was assumed the same as the saturated permeability of soil obtained from the laboratory test for soil at a 0.8 m depth. As a result, the permeability function below 0.8 m was assumed the same as that for soil at a 0.8 m depth, which could lead to the observed larger differences in volumetric water content between the numerical and field values for soil at 0.8 m depth than other depths. Moreover, the specimen tested in the laboratory did not have identical conditions to soil in the field due to sampling disturbance. Lastly, the use of 1D analyses could lead to differences between the numerical results and field measurements because, in the field, measurements may vary with radial distance and the direction of instrumentations from the tree (Li et al., 2019).

6.7 Effect of Weather Conditions on Tree Lean

As shown in Figure 5.18, the differences in tree lean between considering the effect of weather conditions on soil properties and assuming constant soil moduli of 20, 10 and 5 MPa were 16.5%, 8.3% and 0.7 %, respectively. When the constant soil moduli were reduced to 10 MPa and 5 MPa from 20 MPa, the differences in tree lean between considering the effect of weather conditions on soil properties and assuming constant soil moduli also decreased. Thus, a constant soil modulus of 5 MPa can be used across soil regions to simplify the analysis.

However, analyses must first be carried out to determine the suitable constant soil modulus, as this value can vary with different tree species, soils and climates. In the present study, when the soil modulus was 5 MPa, the soil was close to saturated with a matric suction of almost 0 kPa for soil shallower than 1.25 m depth or already saturated for soil below 1.25 m depth, as observed from Figure 5.14.

In this study, none of the soils became plastic and only elastic strains were observed from the ANSYS results; This was because the wind velocities in the field were small, as illustrated in Figure 5.15. In cases when a larger wind force is applied on a tree experiencing a higher wind velocity, part of the soil may yield and show plastic behaviour (Li et al., 2019).

As a result, soil strain and tree deflections could be much more influenced. If changes in soil strength due to changes in weather conditions are not considered, the soil will continue undergoing elastic behaviour when wind drag increases because the shear strength for saturated soil does not decrease with matric suction. At the same time, the critical wind drag that induces tree failure is smaller when considering the effect of weather conditions on soil strength as soil becomes plastic under a smaller force. However, in this study in which small wind forces were monitored and applied, the effect of soil shear strength as a function of matric suction and net normal stress did not influence the final tree lean. In other words, the differences in tree lean between whether or not considering the effect of weather conditions on soil properties were due to the different soil moduli, not the different soil shear strengths, as the soils were all under elastic conditions under small wind forces.

6.8 Uncertainties and Assumptions

In this integrated approach, some uncertainties and assumptions were involved. In the CFD analyses, inaccuracies may stem from the generation of the two geometric models or calculation of the LAD values from the point clouds. The spatial uncertainties existed when an

average value was used as the LAD or LAI input to represent the characteristics of the specific domain. Numerical errors, such as computer round-off error and discretization error, may also be present during the analyses. Moreover, viscous drag was neglected in order to apply the source and sink terms, which may lead to further inaccuracies. During the analyses, the effect of other trees on airflow through the modelled tree was not considered. For field measurements, errors could stem from the instrument inaccuracy, which is 0.3 m/s for the wind velocity measurements and 0.2% linearity for the LVDTs. In addition, limited data at higher wind velocities could result in inaccuracy due to the low wind velocities being monitored. Furthermore, temporal uncertainties could be resulted from the time lag between the time when the wind velocity was registered and the time when the corresponding tree displacement was recorded.

There were some assumptions that influenced the calculated drag coefficients but did not affect the comparison between the field results and numerical results. For both the field calculation and numerical analyses, the mean wind velocity was calculated based on the average of the integration of the wind velocities over 1D height, while the effect of changes in 2D projected area was not incorporated into the calculation of average wind velocity. This may lead to errors in the drag coefficients as the projected area of canopy was larger and experienced a higher wind velocity due to a higher location than the trunk. However, the comparison was not influenced by these assumptions as errors from these assumptions existed in both the field calculations and numerical analyses.

Several assumptions were used in the deformation analyses using ANSYS. First, the root-soil plate was used to simplify the real root architecture and surrounding soil. The root-soil plate strength and modulus were assumed to be constant and did not change with pore-water pressure heads. However, if the real root architecture was incorporated, the weather conditions would also influence the modulus and strength of soil in the root-soil plate region, resulting in a larger

difference in tree lean between the calculation with and without incorporating unsaturated soil mechanics. In unsaturated soil mechanics, instead of constant soil modulus and strength, varied soil modulus and strength dependent on the pore-water pressure head are considered. Secondly, wood strength and wood stiffness were assumed to be constant. Weather conditions affect the water content of soil as well as the water content of wood. Gerhards (2007) reported that the wood modulus and bending strength decreased by 20 % and 30% respectively, when the moisture content increased from 6% to 12% at a constant temperature of 20 °C. Therefore, changes in wood strength and wood stiffness could be incorporated in future studies of tree stability. Thirdly, the lift force was assumed to be negligible in this study because the calculated lift coefficients of the *Khaya senegalensis* and *Eugenia grandis* trees were less than 2% of the drag coefficients. However, for a tree species with an umbrella shape like a *Samanea saman* tree shown in Figure 6.1, the lift force is much larger and should not be ignored in tree stability analyses.

6.9 Application of the Integrated Approach for Monitoring Tree Stability

The integrated approach can be used to estimate the tree lean expected to induce a tree failure. However, the drag force should not be used to evaluate tree failures because the critical force that can cause tree failure is dependent on weather conditions. The force that causes tree failure decreases when there is heavy, prolong rainfall. Thus, the use of tree leans to monitor tree failure is more reliable than drag force or critical wind speed. For example, when the stiffness and strength of the supporting soil decrease due to rainwater infiltration, the tree will fail under a drag force of A at a lean of B. In dry weather conditions, the tree will fail under a drag force of C at a lean of D. As soil strength and stiffness decrease with rainwater infiltration, A will become smaller than C, but tree lean B and D will not differ greatly considering the decrease in soil stiffness and strength due to rainwater infiltration. Therefore, tree lean is more reliable

for predicting tree failure. Given a simplified tree geometry with canopy shape and tree size, as well as soil conditions, the lean of tree at failure can be estimated. By monitoring the leans of trees along roadside, the public can be notified of potential tree failures when the monitored tree leans reach the critical values.

Chapter 7 Conclusions and Recommendations

In this chapter, the conclusions obtained from this study are presented, followed by recommendations for future studies related to tree stability. Lastly, the publications resulting from this research are listed.

7.1 Conclusions

A numerical method of CFD analyses using ANSYS Fluent was performed to estimate the drag coefficients of mature *Khaya senegalensis* and *Eugenia grandis* trees. The numerical approach took advantage of laser scanning to generate the geometry and calculate the leaf area density distribution based on 3D coordinates. Further, CFD simulations were carried out with source and sink terms as a function of the leaf area density to represent the effect of leaves. Conclusions from this study are:

1. The drag coefficients from CFD analyses for the *Khaya senegalensis* and *Eugenia grandis* trees were 0.67 and 0.72, respectively. The similarity in drag coefficients between the two trees may result from the similar overall geometries.
2. The drag coefficients from field measurements were 0.54 for the *Khaya senegalensis* tree and 0.42 for the *Eugenia grandis* tree, which were both smaller than the drag coefficients from the numerical analyses. The differences can be attributed to uncertainties in the numerical modelling and field measurements, estimation of the wind log profile and calculation of the average wind velocity. However, the most likely reason is due to the usage of elastic moduli from different trees of similar species in the numerical analyses as obtained from static pulling tests.
3. The numerical approach is a useful method to obtain the drag coefficient of trees, but it is only applicable when the wind velocity is within a range such that viscous drag can be neglected relative to pressure drag. The wind velocity range when pressure drag is

dominant can be estimated from field measurements but may vary with tree size and flexibility.

4. A numerical approach using GeoStudio and ANSYS Workbench was developed to analyse the effect of weather conditions on 3D tree stability. Weather conditions in this research included wind, rainfall, temperature, humidity and solar radiation, which can affect water content in the soil through infiltration and evapotranspiration. The volumetric water contents analysed using GeoStudio were compared with the field measurements to validate the numerical model. Analyses using ANSYS, with the incorporation of soil stiffness and soil strength dependent on the pore-water pressure results imported from GeoStudio, were conducted to investigate the effect of weather conditions on tree lean. It was found that the computed lean of the *Eugenia Grandis* tree increased by 0.7–16.5% with a soil modulus dependent on the pore-water pressure head compared to the tree lean with a constant soil modulus from 5–20 MPa.
5. However, this range of difference may be larger when the real root architecture and effects of weather conditions on wood modulus and wood strength are incorporated.
6. The wind velocities in the field were small and the soil was under elastic behaviour before the yielding point. The effect of weather conditions on tree lean and tree stability will be larger when wind drag is much higher. Wind drag that triggers tree failure may be smaller when the effect of weather conditions on soil strength is considered, as soil may become plastic under a smaller wind force. Therefore, the effects of weather conditions should be incorporated in tree stability analysis problems to obtain more reliable results.

7.2 Recommendations

For the applications of this integrated approach, it is recommended that the leans of trees along roadside will be monitored and the public can be notified of potential tree failures once the monitored tree leans reach the critical values. This is because using tree lean to monitor tree stability is more reliable than using wind speed due to the incorporation of both the tree geometry and soil condition in the resultant tree lean.

The following recommendations are made for future studies on tree stability:

1. Analyses of tree stability should incorporate the effects of weather conditions on wood properties, as well as the effects of weather conditions on soil properties. However, the effect of water content or pore-water pressure head on wood modulus and strength should be investigated first.
2. The real root architecture should be used to better estimate the behaviours of wood and soil under wind drag, instead of using the root-soil plate for simplification.
3. The low range of measured matric suction due to the local weather conditions is a limitation of this study. As a result, the SWCCs obtained from the field measurements were only reliable for low suctions below 10 kPa. It is recommended that a larger range of SWCCs, including volumetric water content at higher suctions, are included during period of dry weather conditions. This will allow the behaviours of tree and soil to be investigated in both wet and dry climates.

7.3 Publications

Publications resulted from this research are listed:

1. Li, Y., Rahardjo, H., Irvine, K. N., & Law, A. W. K. (2018). CFD analyses of the wind drags on *Khaya Senegalensis* and *Eugenia Grandis*. *Urban forestry & urban greening*, 34, 29-43.

2. Li, Y., Rahardjo, H., & Irvine, K. N. (2018). Seepage and Deformation Analyses in Unsaturated Soils Using ANSYS. In *Proceedings of China-Europe Conference on Geotechnical Engineering* (pp. 360-364). Springer, Cham.
3. Li, Y., Rahardjo, H., & Irvine, K. N. (2019). Effect of Weather Conditions on Leans of One Eugenia Grandis Tree in Singapore. *Urban forestry & urban greening*, 43, 126375.
4. Chan, C., Rahardjo, H., & Li, Y. (2019). Modelling Tree Stability in Unsaturated Soils. *Proceedings of URECA 2017-18*, Nanyang Technological University, Singapore.
5. Bay, P., Rahardjo, H., & Li, Y. (2018). CFD Modelling of Airflow through 3D Canopy Architecture. *Proceedings of URECA 2016-17*, Nanyang Technological University, Singapore.

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