

# Understanding the stability of Samanea saman trees through tree pulling, analytical calculations and numerical models

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1 *Understanding the stability of Samanea saman trees through tree pulling, analytical*  
2 *calculations and numerical models*

3

4 **Abstract**

5 There have been several cases of tree failure in Singapore. Many studies have shown that  
6 soil properties and root architecture of trees are important factors that govern tree stability.  
7 Twenty *Samanea saman* trees were planted in different soil media, which were original in-  
8 situ soil, top soil, mixture of 50% granite chips and 50% top soil, and mixture of 80%  
9 granite chips and 20% top soil. The objectives of this study were to investigate tree  
10 overturning processes and also to compare the results of tree pulling tests with results from  
11 an analytical calculation and numerical modeling for different soil types. The results  
12 showed that stability of the trees were not governed by the shear strength of the soil.  
13 Factors that affected tree stability included cross-sectional area of the roots and root plate  
14 area. Tree pulling test and numerical modeling results showed that there were two modes of  
15 failure which occurred when a tree was overturned. The first mode was the shear failure of  
16 soil and the second was a combination of shear failure of soil and root breakage. The  
17 maximum overturning force obtained from the tree pulling test was in the same order of  
18 magnitude as the maximum overturning forces obtained from the analytical calculation and  
19 numerical modeling.

20

21 **Keywords:** Tree stability, soil mixtures, *Samanea saman*, tree pulling test, finite element  
22 modeling.

23

## 24 **1. Introduction**

25 Trees are an important component of the urban environment and provide numerous  
26 advantages to humans. However, tree failure can cause damage to property and  
27 infrastructures and may also cause injury or loss of life. There have been several cases of  
28 tree failures associated with low soil strength in Singapore. In order to enhance tree  
29 stability, methods to improve the engineering properties of soil for developing a better tree  
30 root and soil system need to be investigated.

31

32 Fine-grained soils have been commonly used as tree growing media. A mixture of fine-  
33 grained soil and coarse-grained soil has been used to overcome the challenges associated  
34 with urban trees in relation to tree stability (Grabosky and Bassuk, 1995). As compared to  
35 a fine-grained soil, the soil mixture has higher shear strength due to an increase in contact  
36 pressure between the coarse-grained particles. In addition, the resulting macro pores allow  
37 for tree roots to penetrate, down to a maximum depth and this will enhance the stability of  
38 the tree and soil system. Rahardjo et al. (2008) found that shear strength of a soil  
39 increased significantly after mixing the soil with more than 50% of granite chips.

40

41 Previous studies of tree root systems showed that the strength of tree root anchorage is  
42 governed by several factors, such as root architecture (Dupuy et al., 2005; Fourcaud et al.,  
43 2008), soil physical and analytical properties (Dupuy et al., 2005), depth, shape and

44 weight of soil root plate (Coutts, 1986), and the location of the rotational axis during  
45 overturning (Mickovski and Ennos, 2002, Fourcaud et al., 2008). Root architecture is an  
46 important component of tree stability. However, natural biological variability makes it  
47 difficult to model the effect of branching and mechanical properties of the root accurately  
48 (Mickovski et al., 2007).

49

50 Tree pulling tests had been conducted on trees to study the mechanism associated with tree  
51 failures (Peltola, 2006). These tests involved pulling the tree sideways until failure or till a  
52 pre-determined displacement occurred. The force required to bring about failure was  
53 recorded. Tree failure could occur due to either stem failure or the whole tree overturning  
54 (Crook and Ennos, 1996). However, tree pulling is costly and destructive. Therefore, the  
55 number of tree that can be pulled to study the mechanism of tree failure is often limited.  
56 These limitations make modeling through the use of analytical calculations and numerical  
57 methods a more feasible option (Dupuy et al., 2007). Several studies such as those  
58 conducted by Dupuy et al. (2005), Fourcaud et al. (2008) and Rahardjo et al. (2009)  
59 showed that numerical modeling is a very useful tool in studying the behavior of soil-root  
60 interaction.

61

62 Rahardjo et al. (2009) proposed two failure modes associated with the overturning of a  
63 tree: shear failure of soil and root failure. Shear failure of soil (SFS) occurs along a slip  
64 surface without having any additional resistance from the roots. Root failure mode occurs  
65 when the resistance of the root system in withstanding the load is exceeded. These root

66 resistances are shear resistance in the transverse plane, slippage resistance and tensile  
67 resistance. When the applied force exceeds these resisting forces, there will be three  
68 possible modes of root failure: (i) shear failure of root system (SFRS), (ii) slippage of root  
69 system (SRS), and (iii) tensile failure of root system (TFRS). Shear failure of root system  
70 occurs if the shear stresses imposed to the roots are higher than the shear strength of the  
71 roots. Slippage of root system occurs when the slippage force exceeds the adhesion  
72 between the root and the soil. Tensile failure occurs when the tensile stress acting on the  
73 roots exceeds the tensile strength of the roots. The forces involved in the analytical  
74 calculation are illustrated in Figure 1.

75

76 *Samanea saman* or commonly known as rain tree is easily recognized by its characteristic  
77 umbrella-shaped canopy. The tree usually reaches 15 to 25 m in height with a canopy  
78 diameter often being wider than the height of the tree. This species is commonly found  
79 along the streets, car parks and open park lands in Singapore. *Samanea saman* was used in  
80 this study because it tends to develop a shallow root plate in the urban landscape and  
81 possesses a high growth rate as compared to other tree species. It is well known that a  
82 plate root possesses the least effective resistance to withstand wind load as compared to  
83 other types of root architecture such as heart and tap root (e.g. Coutts, 1983).

84

85 The objective of this study was to investigate the overturning processes and also to study  
86 the results obtained from the tree pulling test which was subsequently compared with the  
87 results generated from analytical calculations and numerical models for the different soil

88 types. For this purpose, pulling/overturning experiments involving twenty trees grown in  
89 four different soil mixtures were carried out in the field. The data obtained from the tree  
90 pulling tests were then numerically modeled and analyzed using analytical calculations  
91 and a numerical method.

92

## 93 **2. Material and Methods**

### 94 *2.1 Study site and soil engineering properties*

95 The experiment was conducted on an open land in the western end of Singapore. A total  
96 of 20 rain trees had been planted for three years in a tree pit of 2.5 m x 2.5 m and 1.0 m  
97 depth. The ages of the trees when planted were approximately three years old with heights  
98 of around three meters. There were four soil mixtures used in the experiment namely top  
99 soil (TIF), original in-situ soil (IIF), 50% Granite chips and 50% Top Soil (50GC-50TS)  
100 and 80% Granite chips and 20% Top Soil (80GC-20TS). Details of the soil mixtures are  
101 given in Rahardjo et al. (2008). There were five trees planted in each soil mixture. The trees  
102 were planted in a random arrangement as illustrated in Figure 2.

103

104 TIF used in this research was brown in color and consisted of loamy soil, organic matter  
105 (compost), and sand on a volume basis ratio of 3:2:1, respectively. Percentages of granite  
106 chips used in the mixture for improving the soil shear strength in this study were 50% and  
107 80% on dry mass basis. To compare the performance of soil improvement, trees were also  
108 planted in the original in-situ soil (IIF). Soil testing was conducted in accordance with  
109 ASTM standards. Soil moisture content was determined by drying soil samples at a

110 predetermined temperature in accordance with ASTM D-2216 (1998), while the field  
111 density test was conducted following the sand replacement method using sand cone  
112 apparatus in accordance with ASTM D-1556 (2003). The particle size determination was  
113 conducted using a sieve analyses in accordance with ASTM D-422 (1998). Shear strength  
114 measurement for the TIF (top soil) and IIF (original in-situ soil) was carried out using  
115 consolidated-undrained triaxial tests with pore pressure measurement in accordance with  
116 ASTM D-4767 (1995). The shear strength data for the 50GC-50TS and 80GC-20TS were  
117 already reported in Rahardjo et al. (2008). The shear strength of a soil can be represented  
118 by the Mohr-Coulomb failure criterion as follows:

$$119 \quad \tau_{ff} = c' + (\sigma_f - u_w)_f \tan \phi' \quad (1)$$

120 where  $\tau_{ff}$  is the shear stress on the failure plane at failure (kPa),  $c'$  is the effective  
121 cohesion, which is the shear strength intercept when the effective normal stress is equal to  
122 zero, (kPa).  $(\sigma_f - u_w)_f$  is the effective normal stress on the failure plane at failure (kPa),  
123  $\sigma_{ff}$  is the total normal stress on the failure plane at failure (kPa),  $u_{wf}$  is the pore-water  
124 pressure at failure (kPa) and  $\phi'$  is the effective angle of internal friction ( $^\circ$ ). The grain size  
125 distributions of the soil mixtures used in this study are shown in Figure 2. The mixing of  
126 granite chips and top soil resulted in a very compact soil structure that had a high shear  
127 strength as shown in the summary of soil engineering properties presented in Table 1.

128

129

130

131 2.2 *Tree pulling test*

132 Before conducting the tree pulling test, several tree characteristics such as girth  
133 circumference, tree height, stem volume and crown width were recorded. The tree pulling  
134 test was conducted using an automated winch (Ingersoll Rand-FA7) which was capable of  
135 providing a maximum load of seven (7) metric tonnes. When the tree was pulled sideways,  
136 the crown has a higher lateral displacement as compared to the stem of the tree. Therefore,  
137 the crown can exert additional overturning moment to the root system. This additional  
138 moment is a function of the crown volume. The trees in the tree pulling test had different  
139 crown volumes. Therefore, the crowns of the trees were pruned to remove all lateral  
140 branches in order reduce the effect of crown weight on the overturning force during the tree  
141 pulling test. The winch was positioned on a fix platform that had been customized to the  
142 general height of the trees and an attachment was placed on the tree at a height of 1.3 m  
143 from the ground . The winch was then connected to a dynamometer (Dillon Edxtreme-Edx-  
144 2T) by a sling which was capable of recording forces up to 200 kN and then connected to  
145 the tree. The dynamometer was connected to a wireless device that transmitted the data to a  
146 personal computer. A distometer was used to measure the deflection of the tree and it was  
147 positioned at the opposite side of the winch. A high resolution digital camera and a video  
148 camera were used to record the overturning process. The tree was pulled at a constant rate  
149 of 6 cm per second. The resistance force and the corresponding displacement were  
150 measured in intervals of one second. The test was terminated when the force registered was  
151 constant or declined from the peak force. After failure, the root-soil plate depth and  
152 diameter of the slip surface were measured and recorded. The set-up of the tree pulling test

153 is presented in Figure 3. After conducting the tree pulling test, the soil and the roots were  
154 air-spaded and the tree was removed for further measurements. The total cross-sectional  
155 area of the roots (CSA) was measured following a technique proposed by Nicoll and Ray  
156 (1996). The diameter of each lateral root larger than 1 cm was recorded at 50 cm distance  
157 from the centre of the tree and the CSA was calculated using the following equation:

158

$$159 \quad CSA = \pi \left( \frac{d_h + d_v}{4} \right)^2 \quad (2)$$

160

161 where  $d_h$  is the horizontal diameter of the roots and  $d_v$  is the vertical diameter of the roots.

162

163 One-way analysis of variance (ANOVA) is a statistical method that is commonly used to  
164 compare more than two population means. One-way ANOVA was performed using SPSS  
165 software to investigate the effect of different soil conditions on the measured tree  
166 characteristics and the effect of different soil conditions on the pulling force. The null  
167 hypothesis was that the means of each dependant variables were equal or there was no  
168 significant difference in the variables. An  $\alpha$  value of 0.05 was used in the one-way ANOVA  
169 statistical analyses.

170

171

172

173 2.3 *Analytical calculation*

174 Analytical calculation was performed to determine the forces required to overturn the tree.  
175 There were two steps involved in the analytical calculation. The first step was to analyze  
176 the resisting shear force generated by the soil using the ordinary method of slices  
177 (Fellenius, 1936) that is commonly used for slope stability analysis. Root-soil plate depth  
178 and diameter of the slip surface were determined based on the pulling test measurements.  
179 The second step was to analyze the resistance of the root system as suggested by Rahardjo  
180 et al. (2009) using the following equations. In this study, the shear strength of the wood  
181 was assumed to be 0.5 MPa and the tensile strength of the root was assumed as 4.3 MPa  
182 (Ziemer, 1978).

183

184 The resisting shear force ( $F_{shear}$ ) provided by the roots is determined as:

185 
$$F_{shear} = \sum_{i=1}^N A \tau_{shear} \quad (3)$$

186 where N is the number of roots, A is the surface area of the root ( $m^2$ ) and  $\tau_{shear}$  is the shear  
187 strength of root (kPa)

188

189 The resisting slippage force ( $F_{slip}$ ) provided by the roots is expressed as:

190 
$$F_{slip} = \sum_{i=1}^N KL_{slip} \tau_{slip} \quad (4)$$

191 where N is the number of roots, K is the circumference of each root (m),  $\tau_{slip}$  is the  
 192 slippage strength between soil and root and  $L_{slip}$  is the length of horizontal root providing  
 193 the slippage resistance.

194

195 The resisting tensile force ( $F_{tensile}$ ) provided by the roots is calculated as follows:

196 
$$F_{tensile} = \sum_{i=1}^N A \tau_{tensile} \quad (5)$$

197 where  $\tau_{tensile}$  is the tensile strength of root (kPa)

198

#### 199 2.4. Numerical Modeling

200 The numerical modeling of tree stability during the pull out test was performed using  
 201 SIGMA/W (Geo-Slope International Ltd) software. The problem was modeled as a plane  
 202 strain, two-dimensional stress-strain finite element model as shown in Figure 4. The model  
 203 consisted of three main parts. The first part was the surrounding in-situ soil of 20 m width  
 204 and 8 m depth. The second part was the soil inside the tree pit of 2.5 m width and 2.0 m  
 205 depth. The third part was the root model using the diameter taken as an equivalent  
 206 diameter calculated from the sum of individual root cross section area (CSA) measured at  
 207 50 cm from the stem of the tree. The last part was the stem whose dimensions were also  
 208 obtained from the field measurement. The finite element mesh of the model consisted of  
 209 triangular elements. The adhesion between soil and root was ignored in the numerical

210 modeling. The boundary conditions of the surrounding soil were taken as zero horizontal  
211 displacement on both vertical sides and zero displacement in both directions at the bottom  
212 of the model as shown in Figure 4.

213

214 For the numerical modeling, the soil was modeled as an elastic-perfectly plastic material.  
215 The elastic part was governed by the modulus of elasticity (E) and Poisson's ratio ( $\nu$ ) of  
216 the soil. The modulus of elasticity of the soil was taken from the initial tangent of stress-  
217 strain curve as obtained from the shear strength test on a saturated soil sample. The yield  
218 point was defined in accordance with the Mohr-Coulomb failure criterion. If the stress  
219 exceeds the yield point, the stress-strain curve will be a horizontal line, representing the  
220 plastic condition of soil. Root material was considered as an elastic-perfectly plastic  
221 material with a modulus of elasticity of  $5 \times 10^6$  kPa and a Poisson's ratio of 0.3 and a  
222 maximum yield stress of  $10^3$  kPa (Carmichael, 1984).

223

224 An incremental force of 0.1 kN was applied in 100 time steps on the tree stem at 1.3 m  
225 from the ground surface. Displacement, shear stress and strain were computed at every  
226 time step. The force-displacement curve was generated to represent the behavior of the  
227 tree-root system by plotting the incremental force against the displacement at the point  
228 where the force was applied.

229

230

231

232 **3. Results**

233 *3.1. Tree pulling test results*

234 Trees planted at the study site were six years old at the time of the pull-out tests. The  
235 average height and girth circumference of the trees were  $6.58 \pm 0.25$  m and  $50.6 \pm 8.6$  cm,  
236 respectively. The average crown diameter of the trees was  $6.2 \pm 1.9$  m. Statistical analyses  
237 using one-way ANOVA test showed that the average height and diameter, and the crown  
238 diameter were not affected by different soil conditions as shown by the summary on tree  
239 characteristics detailed in Table 2.

240

241 As the tree overturned, the soil in the windward side of the tree experienced tension,  
242 whereas the soil in the leeward side of the tree experienced compression. Two typical  
243 force-displacement curves from the tree pulling test are shown in Figure 5. The failure  
244 force was defined as the force at which the tree started to experience excessive stem  
245 displacements without any increase in the measured force. The failure force was reached  
246 when the root strength was exceeded or the soil-root plate overturned. Curve for Tree#19  
247 (Figure 5) represents a tree with root failure and curve Tree#3 represents a tree with soil  
248 plate overturning or soil failure. The force-displacement curve of root failure showed a  
249 high overturning force that could be sustained for some time after root failure had occurred  
250 and until the tree was completely overturned. The force-displacement curve of soil usually  
251 showed a low overturning force that dropped suddenly when soil failure occurred.

252

253 Results of one-way ANOVA for the maximum pulling force required to uproot the trees  
254 planted in different soils are also summarized in Table 2. While a significant difference was  
255 not identified ( $p=0.493$ ), it was shown that trees planted in IIF (original in-situ soil) had the  
256 highest mean maximum pulling force, while the trees planted in 50GC-50TS had the lowest  
257 mean maximum pulling force.

258

259 The maximum overturning force required to overturn each tree in the tree pulling test is  
260 summarized in Appendix 1 along with the different soil types, cross-sectional area of the  
261 root, root plate depth and root plate radius. The highest maximum overturning force  
262 occurred in Tree#19 planted in IIF (original in-situ soil) with a maximum overturning force  
263 of 20.8 kN while the lowest maximum overturning force occurred in Tree#17 planted in  
264 80GC-20TS soil with a maximum overturning force of 0.6 kN. There were variations in the  
265 maximum overturning force for trees planted in the same soil. These variations showed that  
266 the maximum overturning force was not dependent on the soil type. Figure 6a and Figure  
267 6b shows the relationship between maximum overturning forces for the trees planted in IIF,  
268 TIF, 50GC-50TS, and 80GC-20TS against root plate radius and cross-sectional area and  
269 root plate depth, respectively. There were relatively strong relationships between the  
270 maximum overturning force and root plate radius ( $R^2=0.56$ ) and also between the  
271 maximum overturning force and root cross-sectional area ( $R^2=0.61$ ) as compared to the  
272 relationship between the maximum overturning force and the root plate depth ( $R^2=0.21$ ).

273

274

275 3.2. *Analytical calculation*

276 The input data for analytical calculations were taken from the tree pulling test. The  
277 formulas used were similar to the formulas used by Rahardjo et al. (2009) and are presented  
278 in Section 2.4 of this paper. The results of the analytical modeling for different failure  
279 modes are shown in Figure 7. The results show that the highest maximum overturning force  
280 to overturn a tree is associated with the tensile failure of the root system (TFRS), while the  
281 lowest maximum overturning force to overturn a tree is associated with the slippage of root  
282 system (SRS). The highest maximum overturning force occurred in Tree#20 planted in  
283 80GC-20TS soil for all failure modes, whereas the lowest maximum overturning force  
284 occurred in Tree#17 planted in 80GC-20TS for SFRS and TFRS failure modes and Tree#18  
285 planted in TIF for SRS and SFS failure modes. Tree#20 has the highest maximum  
286 overturning force due to its high CSA and its widest radius of root plate among the other  
287 trees. Tree#17 has the lowest CSA among all trees which resulted in a lower shear and  
288 tensile capacity of the roots. However, the root plate of Tree#17 was deeper than the root  
289 plate of Tree#18 which resulted in a higher soil shear and root slippage resistance for  
290 Tree#17.

291

292 3.3. *Numerical modeling*

293 The force-displacement curves obtained from the numerical modeling show two typical  
294 patterns as shown in Figure 8a. The first pattern with a lower overturning force at failure  
295 represents a typical curve for the mode of shear failure of soil (SFS). The SFS failure mode  
296 occurred when the root length was shorter than the radius of the slip surface of soil. The

297 second pattern with a higher failure force represents a typical curve for a combination of  
298 SFS and shear failure of root system (SFRS) which usually occurred in trees with roots that  
299 intersected the slip surface of soil. An illustration of these failure modes is shown in Figure  
300 8b and Figure 8c. The SFS failure mode usually developed at the edges of the root zone,  
301 whereas the combination of SFS and SFRS usually developed at the root zone resulting in  
302 almost a similar size of the failure root plate. The maximum forces required to overturn the  
303 trees and the failure modes obtained from the numerical modeling are presented in Figure  
304 9. The failure modes obtained from the numerical modeling (SFS and combination of SFS  
305 and SFRS) were generally similar to the failure modes obtained from the tree pulling tests  
306 (soil failure and combination of soil failure and root breaking). The highest maximum  
307 overturning force observed in the numerical modeling was associated with Tree#20 which  
308 was similar to the analytical calculation result whereas the field tree pulling tests showed  
309 that Tree#19 has the highest maximum overturning force. The lowest maximum  
310 overturning force observed in the numerical modeling was associated with Tree#3 whereas  
311 the analytical calculation and the field tree pulling tests showed that Tree#17 has the lowest  
312 maximum overturning force.

313

314 For SFS failure mode, the numerical modeling and analytical calculation over-predict the  
315 maximum overturning forces obtained from the field overturning experiment as shown in  
316 Figure 10a. For the combination of SFS and SFRS failure mode, the maximum overturning  
317 forces obtained from the numerical modeling were in the same order as compared to the  
318 maximum overturning forces obtained from the tree pulling test whereas the maximum

319 overturning forces from the analytical calculation over-predicted the maximum overturning  
320 forces obtained from the field overturning experiment as shown in Figure 10b.

321

#### 322 **4. Discussion**

323 Mixing top soil with granite chips increased the shear strength parameters of the soil  
324 (Rahardjo et al., 2008). However, the increased shear strength of the soil did not guarantee  
325 a larger resistance to overturning for trees as shown in the field test results. This was  
326 shown by the results of the statistical analysis of overturning forces for different soil  
327 conditions. The statistical analyses showed that the difference in the mean overturning  
328 force was statistically insignificant. The statistical analyses in tree characteristics for  
329 different soil conditions also showed that the difference in mean tree characteristics was  
330 statistically insignificant. The statistically insignificant difference in the tree characteristics  
331 planted in different soil conditions may have led to the statistically insignificant difference  
332 in the overturning force for trees planted in different soil conditions.

333

334 Although, it was found that different soil conditions yielded a statistically insignificant  
335 difference in the overturning force, the tree pulling test result showed that there were linear  
336 relationships between root cross-sectional area (CSA) and root plate radius with the forces  
337 needed to overturn the tree. This was similar to reports by Nicoll and Duncan (1996),  
338 Crook and Ennos (1998) and Mickovski and Ennos (2002). This shows that the root  
339 properties such as the root cross-section area (CSA) and root plate radius were in fact very  
340 crucial in tree stability. In addition, the root CSA and root plate radius values were not

341 affected by the soil medium as shown by the statistical analysis. Therefore, further studies  
342 on methods to increase root CSA and root plate radius are necessary in order to enhance  
343 our understanding of tree stability. It was also found that the root plate depth did not  
344 greatly affect the maximum overturning force of *Samanea saman* unlike the results found  
345 by Moore (2000) on *Pinus Radiata* or Abd. Ghani et al. (2009) on *Eugenia grandis*. This  
346 might be caused by the fact that the depth of the root plate in *Samanea saman* was  
347 generally shallow as compared to the depth of root plate in these other species. Thus, the  
348 limited range of root plate depth created a statistically insignificant difference in the  
349 overturning force.

350

351 Based on soil shear strength tests results, IIF (original in-situ soil) was one of the weakest  
352 soils; however, the highest maximum overturning force recorded from the tree pulling test  
353 was the force required to overturn Tree #19 that was planted in IIF soil. The force required  
354 to overturn Tree#19 was higher than the force required to overturn Tree #20 which was  
355 considered to have the highest overturning force based on the analytical calculation and  
356 numerical modeling. Several factors might have contributed to this difference such as the  
357 root orientation and the variation of the root strength in the field. The effect of root  
358 orientation and clustering might affect the maximum overturning force as suggested by  
359 Abd. Ghani et al. (2009). The roots that were found in the windward direction of a tree  
360 with a plate root tended to have a higher overturning force as reported by Ennos (2000).  
361 The shear and tensile strengths of the root vary between tree to tree and also vary for the  
362 same tree as it moves further away from the tree's stem as suggested by Bischetti et al.  
363 (2005) and Genet et al. (2008).

364

365 Field overturning experiments showed that there were two governing failure modes which  
366 were visually determined by the condition of the roots. If the root was not broken, the  
367 failure mode would be attributed to the shear failure of the soil (SFS). The second failure  
368 mode was associated with root breakage. However, the mechanism of root failure is  
369 unknown (i.e shear failure or tensile failure). The numerical modeling performed in this  
370 study suggested that two failure modes could have occurred during the field  
371 overturning/pulling experiment, These were shear failure of soil (SFS) and a combination  
372 of shear failure of soil (SFS) and shear failure of root (SFRS). The maximum overturning  
373 forces obtained from the numerical model were comparable to those obtained from the  
374 field overturning/pulling experiment. As a result, root breakage observed in the tree  
375 pulling test could be attributed to the shear failure of roots (SFRS) as simulated in the  
376 numerical model.

377

378 In general, the maximum overturning forces obtained from the numerical model  
379 overestimated the maximum overturning forces measured in the tree pulling test up to  
380 between 15 to 25%. This may have been the result of the variability of shear strength  
381 parameters and root properties that was not accounted for in the finite element modeling.  
382 The shear strength parameters in the finite element model were obtained from laboratory  
383 shear strength tests. The shear strength near the ground surface might vary significantly  
384 due to the development of roots during the period of tree growth (Tengbeh, 1993). The  
385 root properties might also not be uniform for the entire tree root system (Stokes and  
386 Mattheck, 1996). The model also assumes that the root diameter is constant to be equal to

387 the equivalent CSA of the roots. This assumption may have a weakness because the root  
388 diameter can be highly variable compared to the root diameter at 50 cm from the trunk  
389 used for the CSA calculations. However, similar trends on the factors affecting the  
390 maximum overturning force were observed in the numerical model as in the tree pulling  
391 test as shown in Figure 11a and Figure 11b.

392

393 The analytical calculation results overestimated the maximum overturning forces for the  
394 combination between SFS and SFRS modes. This could be due to the fact that the  
395 assumption that all roots failed at the same time when the maximum overturning force  
396 reached the failure force might not be the actual case. In reality, failure might have  
397 occurred progressively (O'Sullivan and Ritchie, 1993). The selection of values of  
398 parameters used in the analytical calculation especially for tensile and shear strength  
399 parameters of root was critical because it could greatly affect the maximum overturning  
400 force calculation using the analytical solutions and should be investigated further in order  
401 to enhance the accuracy of the results obtained.

402

403 The analytical calculation and numerical modeling used in this study required the cross-  
404 sectional area of the roots and the root plate depth. These parameters are not easily  
405 obtained without an invasive method. Therefore, further improvements of the analytical  
406 calculation and numerical models for the prediction of tree stability are required so that  
407 these models can eventually have the ability to effectively predict the stability of tree.

408

409 The study reported in this paper was conducted on twenty trees of one species of the same  
410 age. This condition limited the study to one root type which was a plate root. Plate root is  
411 the weakest root architecture in withstanding overturning (Coutts, 1983) and therefore, it  
412 represented the most critical root architecture for tree stability. Oliver and Mayhead (1974)  
413 reported that the wind speed that uprooted trees were actually lower than the measured  
414 forces used in the tree pulling test. This might be due to the nature of wind loading that  
415 was a continuous and dynamic loading for a long period of time, whereas the field tree  
416 pulling test experiment was a static and quick loading test. Therefore, it is appropriate to  
417 consider a variety of species, other root architectures and dynamic loading in future studies  
418 of similar nature.

419

## 420 **5. Conclusions**

421 Shear strength of soil increased when it was mixed with granite chips. However, the  
422 increase in soil shear strength alone may not increase the stability of the tree because many  
423 factors come into play when considering tree stability. Cross-sectional area of the root and  
424 the root plate area were found to be parameters that increase the stability of the tree as  
425 observed in the field experiment and numerical analyses. Shear failure of soil and a  
426 combination of soil shear failure and root breakage were found to be the prevalent failure  
427 modes during tree overturning. The maximum overturning force to reach failure as  
428 measured in the field experiment was of the same order of magnitude as the maximum  
429 overturning forces obtained from the numerical modeling and analytical calculation.

430

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433 and National Parks Boards Singapore. The authors wish to thank Mr. Andhika Sahadewa  
434 and other colleagues for their assistance during the tree pulling test.

435

436 **References**

437 Abd. Ghani, M., Stokes, A., Fourcaud, T., 2009. The effect of root architecture and root  
438 loss through trenching on the anchorage of tropical urban trees (*Eugenia grandis*  
439 *wright*). *Trees-Structure and Function* 23, 197-209

440 ASTM, D-2216, 1998. Standard Test Method for Laboratory Determination of Water  
441 (Moisture) Content of Soil and Rock by Mass.

442 ASTM, D-1556, 2003. Standard Test Method for Density and Unit Weight of Soil in Place  
443 by the Sand-Cone Method.

444 ASTM, D-422, 1998. Standard Test Method for Particle-Size Analysis of Soils.

445 ASTM, D-4767, 1995. Consolidated Undrained Triaxial Test for Cohesive Soils.

446 Bischetti, G.B., Chiaradia, E.A., Simonato, T., Speziali, B., Vitali, B., Vullo, P., Zocco, A.,  
447 2005. Root strength and root area ratio of forest species in Lombardy (Northern Italy).  
448 *Plant and Soil* 278, 11-22

449 Carmichael, E.M., 1984. *Timber Engineering Practical Design Studies*. E&F. N. Spon,  
450 London.

451 Coutts, M.P., 1983. Root architecture and tree stability. *Plant and Soil* 71, 171-188.

452 Coutts, M.P., 1986. Components of tree stability in Sitka spruce on peaty gley soil.  
453 *Forestry* 59, 173-197.

454 Crook, M.J., Ennos, A.R., 1996. The anchorage mechanics of deep rooted larch *Larix*  
455 *europaea x japonica*. *Journal of Experimental Botany* 47, 1509-1517.

456 Crook, M.J., Ennos, A.R., 1998. The increase in anchorage with tree size of the tropical  
457 tap rooted tree *Mallotus wrayi*, King (Euphorbiaceae). *Annals of Botany* 82, 291-296.

458 Dupuy, L., Fourcaud, T., Stokes, A., 2005. A numerical investigation into the influence of  
459 soil type and root architecture on tree anchorage. *Plant and Soil* 278, 119-134.

460 Dupuy, L., Fourcaud, T., Lac, P., Stokes, A., 2007. A generic 3D finite element model of  
461 tree anchorage integrating soil mechanics and real root system architecture. *American*  
462 *Journal of Botany* 94, 1506-1514.

463 Ennos, A.R., 2000. The mechanics of root anchorage. *Advance botanical research* 33, 133-  
464 157.

465 Fellenius, W., 1936. Calculation of the Stability of Earth Dams. In: *Transaction of the*  
466 *Second Congress on Large Dams, Washington, D.C., Vol. 4. United States*  
467 *Government Printing Office, Washington D.C., pp. 445-463.*

468 Fourcaud, T., Ji J-N., Zhang, Z. Q., Stokes, A., 2008. Understanding the impact of root  
469 morphology on overturning mechanism: A modeling approach. *Annals of Botany* 101,  
470 1267-1280.

471 Genet, M., Kokutse, N., Stokes, A., Fourcaud, T., Cai, X.H., J-N, J., 2008. Root  
472 reinforcement in plantations of *cryptomeria japonica* D. Don: effect of tree age and  
473 stand structure on slope stability. *Forest Ecology and Management* 256, 1517-1572.

474 Grabosky, J. & Bassuk, N., 1995. A new urban tree soil to safely increase rooting volumes  
475 under sidewalks. *Journal of Arboriculture* 21, 187-201.

476 Holtz, R.D., & Kovacs, W.D., 1981. *An introduction to geotechnical engineering*, Prentice  
477 Hall Inc, New Jersey USA, pp. 719.

478 Mickovski, S.B., Bengough, A.G., Bransby, M.F., Davies, M.C.R., Hallet, P.D.,  
479 Sonnenberg, R., 2007. Material stiffness, branching pattern and soil matric potential  
480 affect the pullout resistance of model root systems. *European Journal of Soil Science*  
481 58, 1471-1481.

482 Mickovski, S.B. & Ennos, A.R., 2002. A morphological and mechanical study of the root  
483 systems of suppressed crown Scots pine *Pinus sylvestris*. *Trees - Structure and Function*  
484 16, 274-280.

485 Moore, J.R., 2000. Differences in maximum resistive bending moments of *Pinus radiata*  
486 trees grown on a range of soil types. *Forest Ecology and Management* 135, 63-71.

487 Nicoll, B.C & Duncan, R., 1996. Adaptive growth of tree root systems in response to wind  
488 action and site conditions. *Tree Physiology* 16, 891-898.

489 O'Sullivan, M.F & Ritchie, R.M., 1993. Tree stability in relation to cyclic loading.  
490 *Forestry* 66, 69-82.

- 491 Oliver, H.R., & Mayhead, G.J., 1974. Wind measurements in a pine forest during a  
492 destructive gale. *Forestry* 47, 185-194.
- 493 Peltola, H.M., 2006. Mechanical stability of tree under static loads. *American Journal of*  
494 *Botany* 93, 1501-1511.
- 495 Rahardjo, H, Harnas, F.R., Leong, E.C., Tan, P.Y., Fong, Y.K., Sim, E.K., 2009, Tree  
496 stability in improved soil to withstand wind loading. *Urban Forestry and Urban*  
497 *Greening* 8, 237-247.
- 498 Rahardjo, H, Indrawan, I.G.B., Leong, E.C., Yong, W.K., 2008. Effects of coarse-grained  
499 materials on hydraulic properties and shear strength of soil. *Journal of Engineering*  
500 *Geology* 101, 165-173.
- 501 Stokes, A., & Mattheck, C., 1996. Variation of wood strength in roots of forest trees.  
502 *Journal of Experimental Botany* 47, 693-699.
- 503 Tengbeh, G.T., 1993. Effect of grass roots on shear strength variations with moisture  
504 content. *Soil Technology* 6, 287-295.
- 505 Ziemer, R.R., 1978. An apparatus to measure the cross cut shearing strength of roots.  
506 *Canadian Journal of Forest Research* 8, 142-144.

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Table 1 Soil engineering properties

Soil type/ (USCS classification symbol)	Effective cohesion $c'$ (kPa)	Effective angle of internal friction $\phi'$ (°)
TIF (SC)	2	25
IIF (CL)	5	24
50GC-50TS (SC)	5	44
80GC-20TS (GP)	25	48

Table 2. Summary of statistical analyses result of tree characteristic for different soil condition

Characteristic/Soil	IIF	TIF	50GC-50TS	80GC-20TS	P values
Height (m)	6.58±0.15 a	6.50±0.10 a	6.60±0.14 a	6.62±0.15 a	0.932
Girth circumference (m)	0.46±0.01 a	0.50±0.01 a	0.51±0.02 a	0.56±0.01 a	0.424
Crown width (m)	5.57±0.24 a	6.10±1.15 a	6.81±1.34 a	6.47±0.56 a	0.811
Overturning force (kN)	12.19±2.66 a	7.96±1.18 a	6.98±2.74 a	9.85±3.53 a	0.493
Root depth (m)	0.93±0.07 a	1.05±0.2 a	0.68±0.13 a	0.75±0.08 a	0.218
Cross sectional area (CSA) (cm <sup>2</sup> )	179.17±49.23 a	118.97±40.16 a	111±37.27 a	231.86±120.29 a	0.598

Mean±standard error. Pairs of values in a column followed by the same letter are not significantly different at the  $\alpha=0.05$  level.

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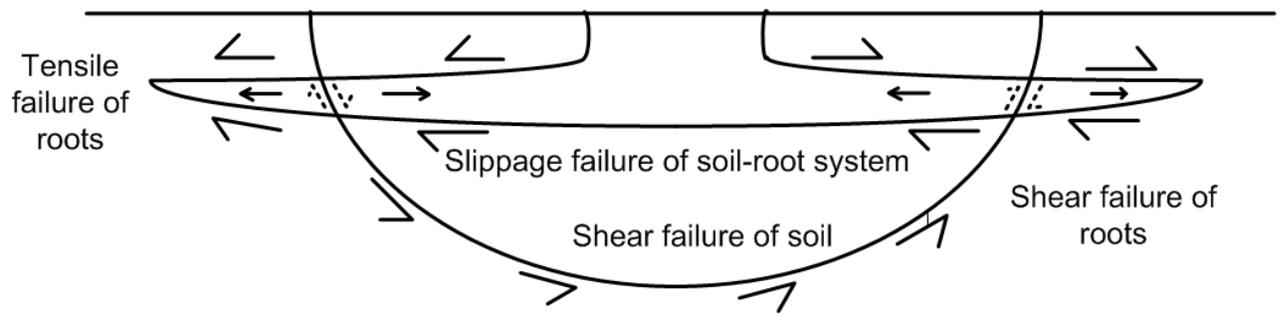
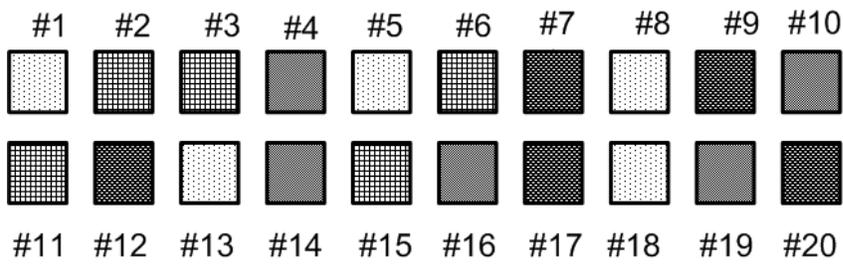


Figure 12 Soil-root interactions (from Rahardjo et al., 2009)



Legend:



: TIF



: 50GC-50TS



: IIF



: 80GC-20TS

N

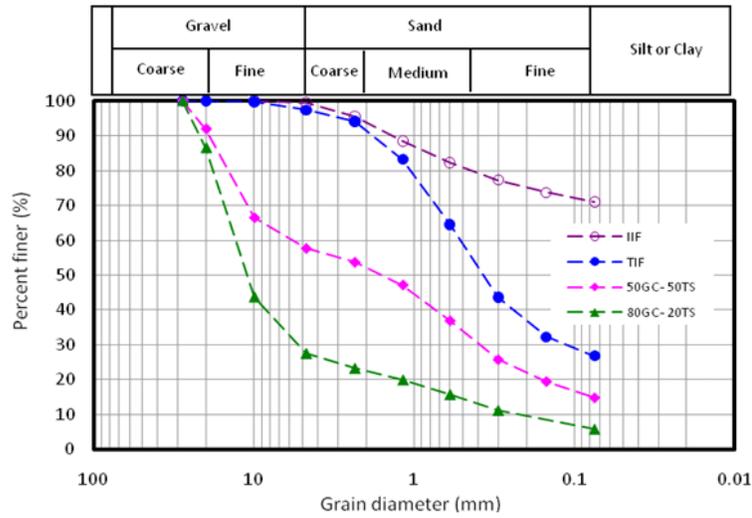


Figure 13 Soil type arrangement for tree planting and grain size distributions of soils used in the study

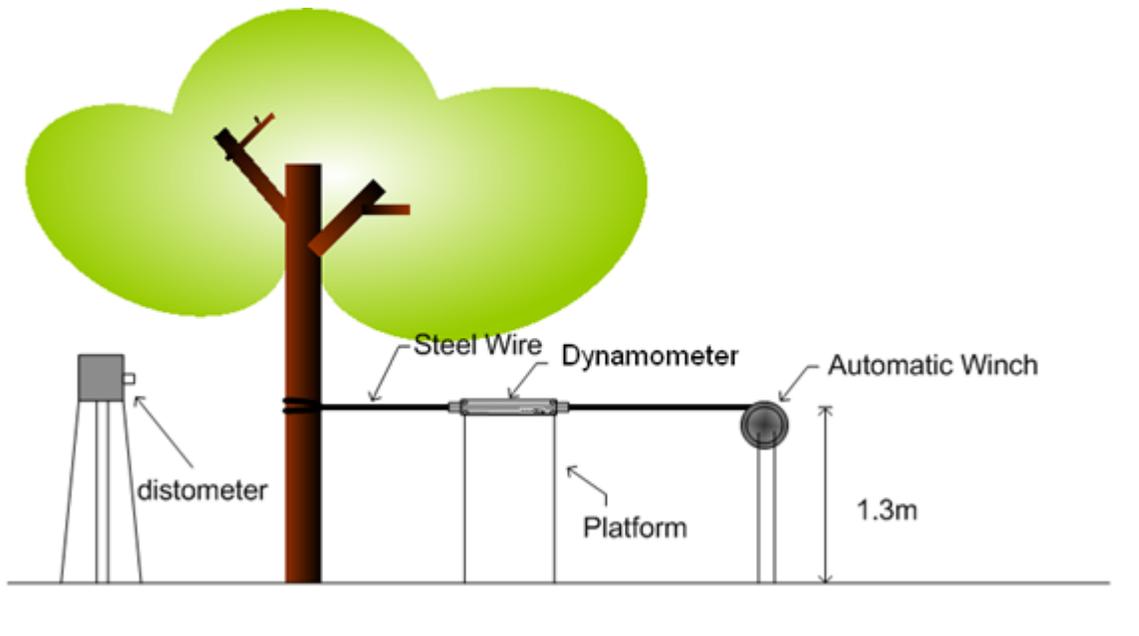


Figure 14 Tree pulling test set-up for tree pulling test (not to scale)

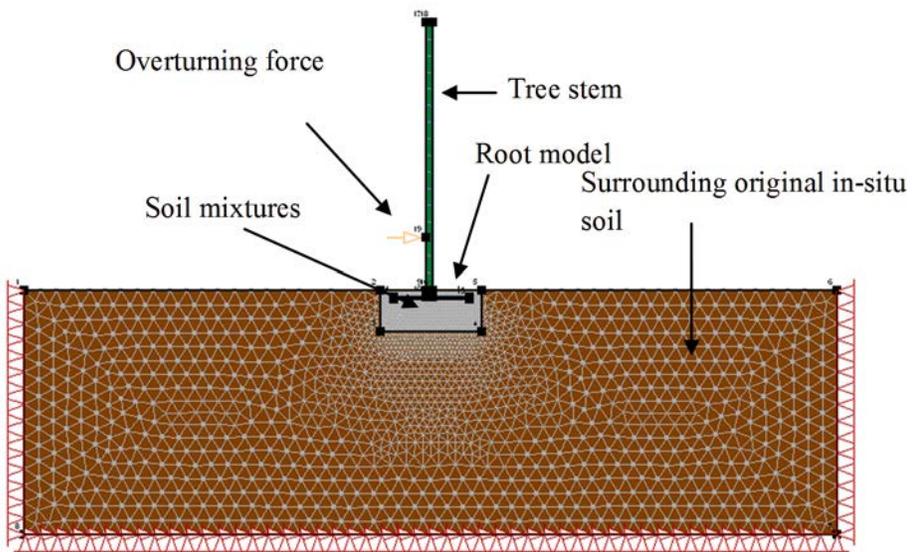


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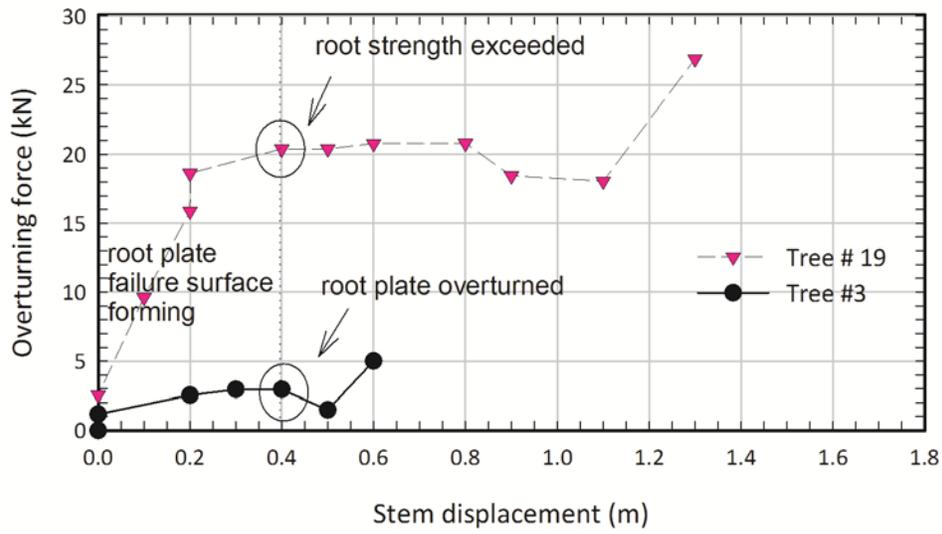


Figure 16 Typical force-displacement curve obtained from tree pulling test

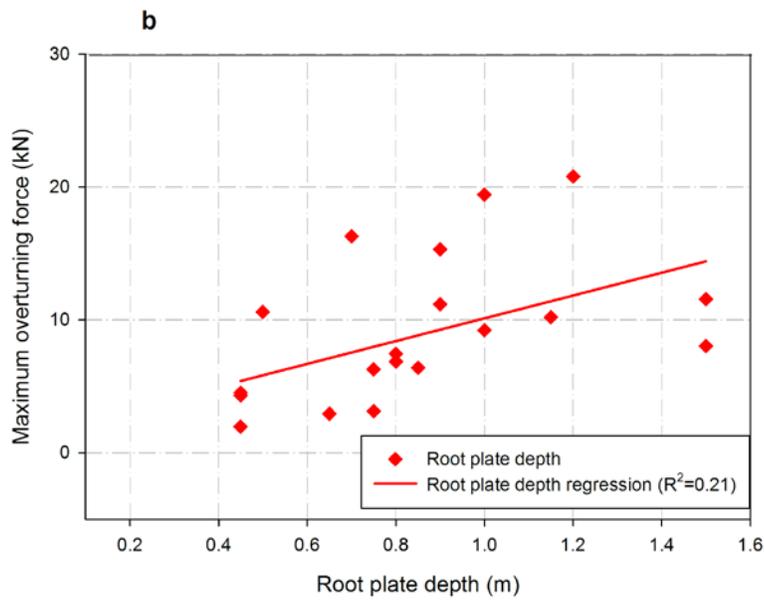
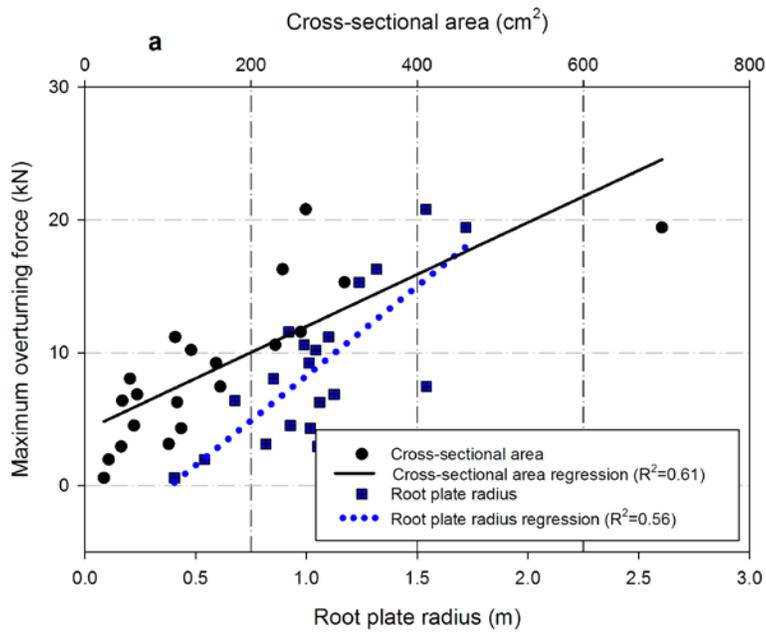


Figure 17 Correlations between maximum overturning force with a. root plate radius and cross-sectional area and b. root plate depth

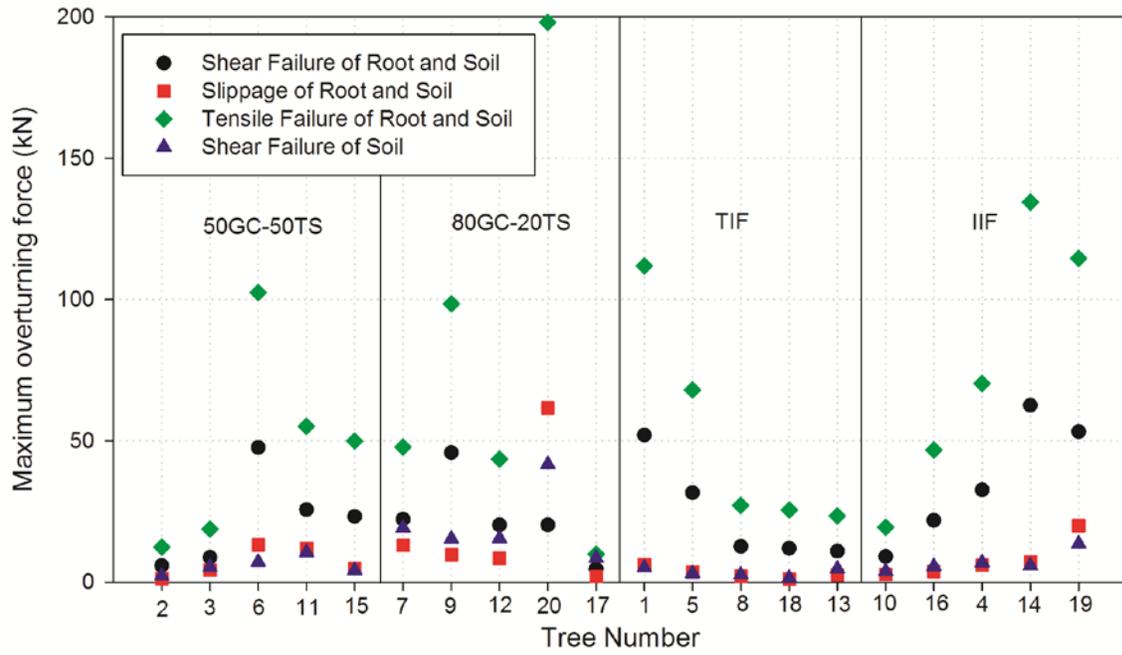


Figure 18 Analytical calculation results for different failure modes

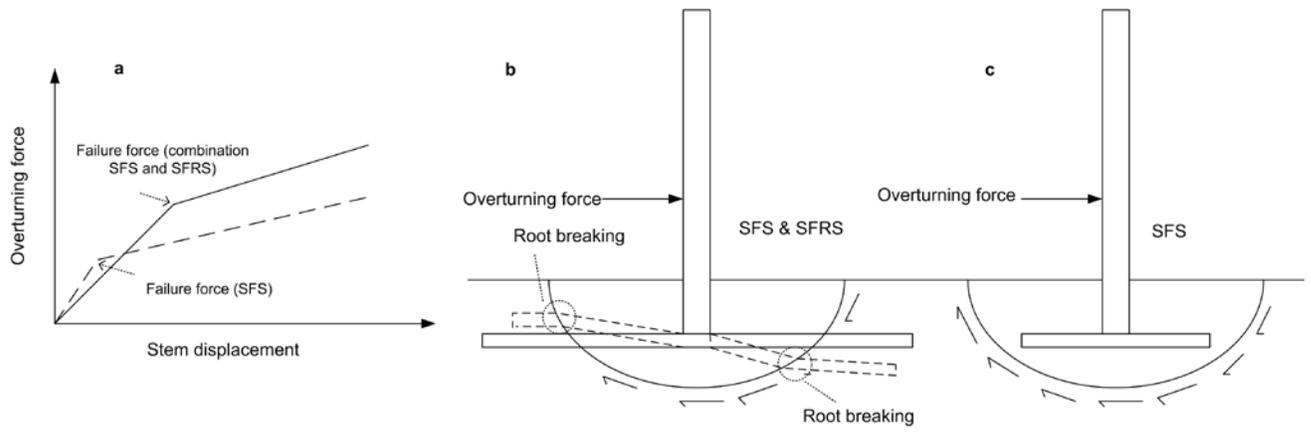


Figure 19 a. Typical force-displacement curve pattern obtained from numerical analyses.  
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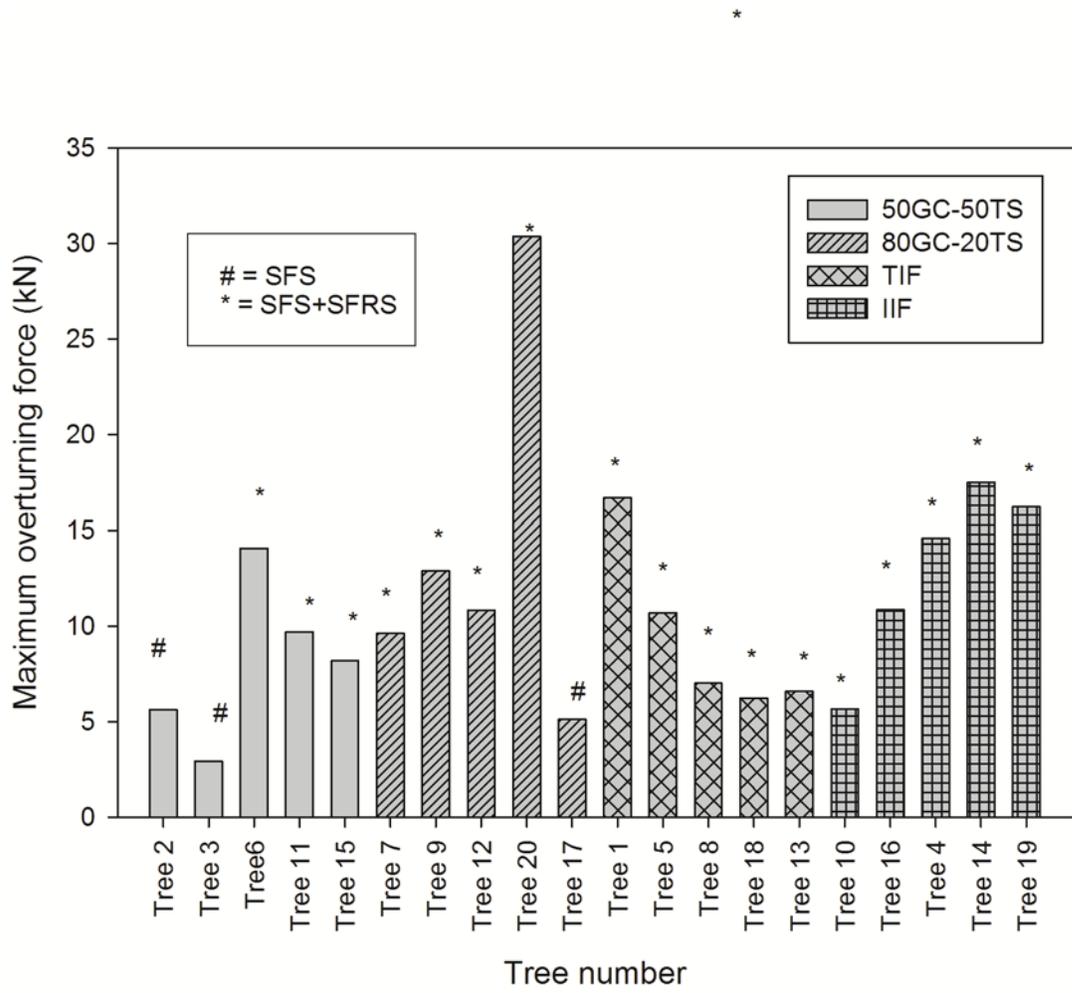


Figure 20 Maximum overturning force and failure mode obtained from numerical modeling

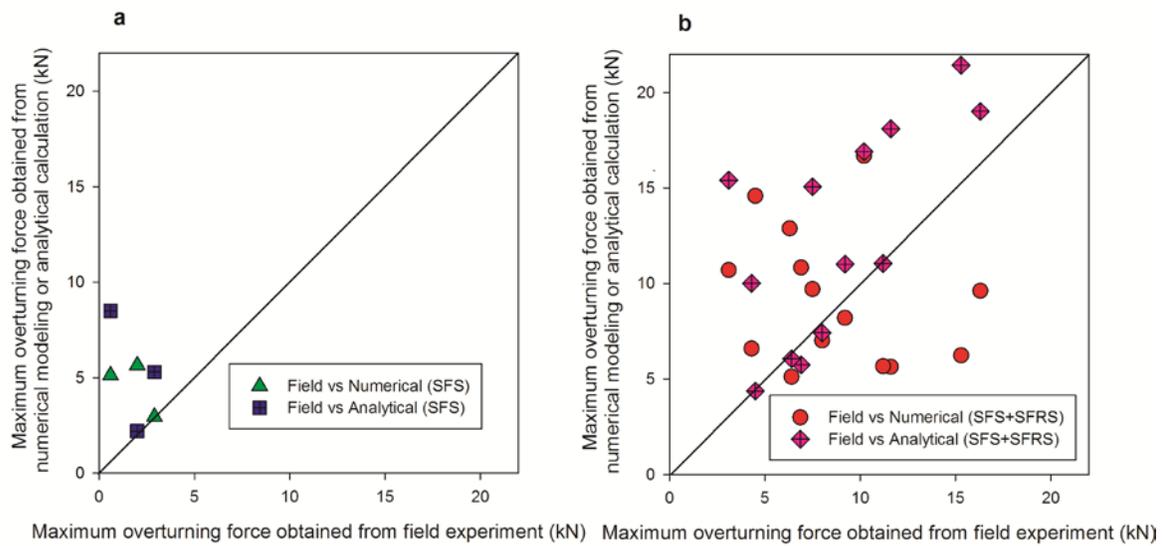


Figure 21 Comparison of overturning force obtained from tree pulling test and numerical modeling for a. SFS failure mode b. SFS+SFRS failure mode

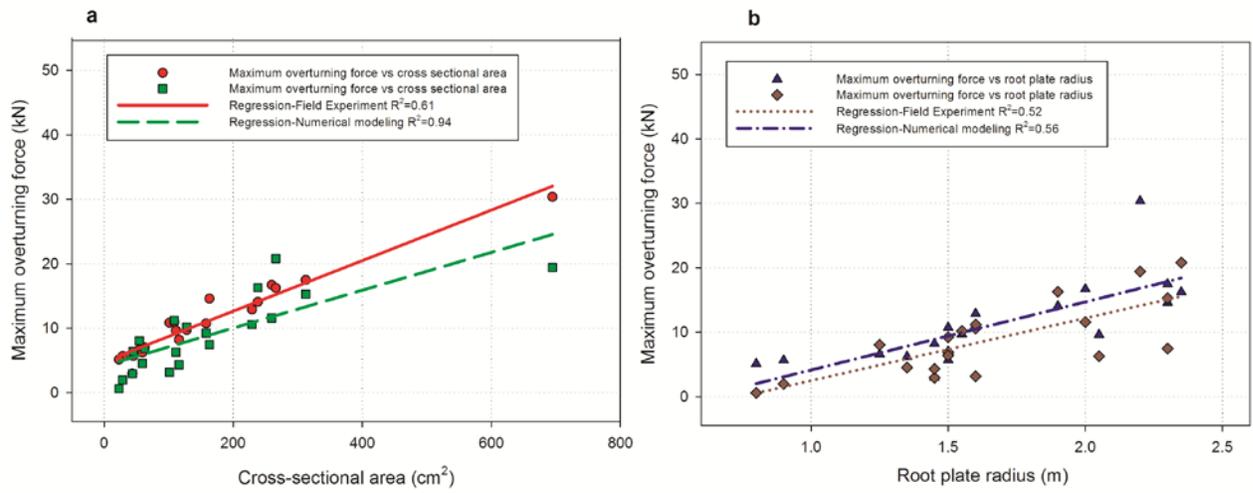


Figure 22 Relationship between the maximum overturning force and a. cross-sectional area, b root plate radius obtained from tree pulling test and numerical modeling

## APPENDIX

Appendix 1 Tree characteristics recorded in the tree pulling test

Tree no	1	2	3	4	5	6	7	8	9	10
Soil type	TIF	50GC- 50TS	50GC- 50TS	IIF	TIF	50GC- 50TS	80GC- 20TS	TIF	80GC- 20TS	IIF
CSA (cm <sup>2</sup> )	259.9	28.8	43.7	163.2	158.2	238.2	111.2	62.9	229.2	45.2
Root depth (m)	1.5	0.5	0.7	0.8	1.0	0.7	0.8	0.8	0.5	0.9
radius of root plate (m)	0.9	0.5	1.1	1.5	1.0	1.3	1.1	1.1	1.0	0.7
Maximum Overturning force (kN)	11.6	2.0	2.9	7.5	9.2	16.3	6.3	6.9	10.6	6.4
Height (m)	6.6	6.6	6.6	6.6	6.6	7	6.8	6.5	6.5	6.5
Girth circumference (m)	0.55	0.4	0.4	0.55	0.58	0.63	0.54	0.45	0.53	0.42
Crown width (m)	9.5	2.8	5.2	5.8	7.8	7.88	7.05	3.2	4.6	5.3
Tree no	11	12	13	14	15	16	17	18	19	20
Soil type	50GC- 50TS	80GC- 20TS	TIF	IIF	50GC- 50TS	IIF	80GC- 20TS	TIF	IIF	80GC- 20TS
CSA (cm <sup>2</sup> )	128.07	101.23	54.47	312.53	116.16	108.93	23.09	59.32	266.06	694.64
root depth (m)	1.2	0.8	1.5	0.9	0.5	0.9	0.8	0.5	1.2	1.0
radius of root plate (m)	1.0	0.8	0.9	1.2	1.0	1.1	0.4	0.9	1.5	1.7
Maximum Overturning force (kN)	10.2	3.1	8.0	15.3	4.3	11.2	0.6	4.5	20.8	19.4
Height (m)	6.7	6.7	6.7	6.7	6.1	6.1	6.1	6.1	7	7
Girth circumference(m)	0.68	0.63	0.45	0.39	0.42	0.49	0.59	0.48	0.44	0.5
Crown width (m)	10.8	7.3	4.2	5.6	7.35	6.3	5.78	5.8	4.85	7.6