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2019

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.
<https://dx.doi.org/10.1016/j.ufug.2019.126375>

<https://hdl.handle.net/10356/151522>

<https://doi.org/10.1016/j.ufug.2019.126375>

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Downloaded on 26 Apr 2023 20:24:49 SGT

Effect of Weather Conditions on Leans of One *Eugenia Grandis* Tree in Singapore

Abstract

An approach to model the effect of weather conditions on tree stability is presented, where the weather conditions include wind, rainfall, temperature, humidity and solar radiation. The weather conditions could affect the rainwater infiltration and evapotranspiration, hence change the water content in the soil and influence the soil properties such as stiffness and strength when resisting the wind drags on the tree. One-dimensional (1D) modelling in GeoStudio 2012 was used to analyse the pore-water pressure head distribution in soil under the recorded weather conditions for 20 days. Three-dimensional (3D) modelling in ANSYS 19.1 was then used to analyse the leans of one *Eugenia Grandis* tree deformed by wind drags in Singapore during the 20 days. The soil modulus and soil strength were considered as functions of the water content in the soil, which were computed from VADOSE modelling in GeoStudio 2012 under the real time weather conditions measured from the field instrumentations. Moreover, the wind drags were calculated from a previous study that analysed the drag coefficient on the same *Eugenia Grandis* tree. The leans of the *Eugenia Grandis* tree under wind drags during the studied period were computed by incorporating the change in soil stiffness and soil strength due to the change in water content of the soil. The computed tree leans from the analyses increased by 16.5% when the soil strength and soil modulus changed with water content of the soil as compared to the computed tree leans without the incorporation of the changes in soil strength as an effect of weather conditions and assuming a constant soil modulus of 20 MPa. It is suggested that effect of weather conditions on soil should be considered in the analyses related to tree deformations.

Keywords: Tree Leans, Weather conditions, Soil Strength, Soil stiffness, Unsaturated Soil

1. Introduction

1.1 Windstorms and Tree Failures

Mechanical failures of a tree involve individual branch failure, trunk failure or root-soil plate failure. Among all the failure modes, overall instability problems such as trunk failures or root-soil plate failures are more destructive and pose greater threats to public safety compared to the individual branch failures, especial in urban areas with a dense population like Singapore. In cold climates, snowfall can be important because snow adds to the weight of the branches with resulting failure. However, in tropical climates, most tree failures occur during windstorms, particularly when wind and rainfall occur together, because rainwater infiltration can significantly reduce soil stiffness and soil strength. Many studies on slope stability (Au, 1998; Cai & Ugai, 2004) have highlighted the effect of rainwater infiltration on reducing soil strength and inducing slope failures.

Figure 1 shows the average monthly wind speeds in Singapore for the period from 1981 to 2010 (Climate in Singapore, 2010). Although the average wind speeds are small, less than 3.5 m/s, the average monthly rainfall can be higher than 100 mm, with one to three weeks in a month exhibiting measurable rainfall for the same period of record (i.e. from 1981 to 2010), as shown in Figures 2 and 3 (Climate in Singapore, 2010).

Tree failures occur even under small wind speeds in Singapore, probably due to the high amount of precipitation. Water ponding can be observed sometimes in the soil after a tree failure under rainfall (e.g. Figure 4). In this case, soil strength and soil modulus were significantly reduced as water infiltrated into the soil. However, very few studies have incorporated the change in soil strength and soil modulus related to changes of water content in the soil when considering tree failures. Therefore, this study aims to investigate the effect of

weather conditions on tree leans by incorporating the change in soil strength and soil modulus due to soil moisture change.

1.2 Soil-Water Characteristic Curve (SWCC), Soil Strength and Soil Stiffness

In general, soils can be classified into saturated soils and unsaturated soils. Saturated soils can be naturally found below the ground water table while unsaturated soils commonly exist above the ground water table with the presence of both air and water in the voids. The unsaturated condition could help in building additional strength or stiffness of soils observed in association with steep slopes, for example, and as explained in the following discussion.

A soil–water characteristic curve (SWCC) describes the relationship between volumetric water content (VWC) and matric suction of a soil. Matric suction ψ , 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 in the soil changes with matric suction because water storage capacity within the macro and micro pores of a soil change with respect to various matric suction values (Fredlund and Rahardjo, 1993).

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

$$\theta = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} \quad \text{Equation 1}$$

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 suggested equal to 1 by Leong and Rahardjo (1997), ψ is the matric suction, a , n , and m are empirically-derived variables related to the air-entry value of soil, inflection point of the SWCC and the slope of the SWCC, respectively.

Unlike saturated soils, the permeability of unsaturated soils is a function of the matric suction instead of a constant value. Unsaturated permeability can be represented by measured saturated permeability and integrating along the SWCC (Fredlund et al., 1994):

$$k_w(\psi) = \frac{\int_{\ln(\psi)}^b \frac{\theta(e^y) - \theta(\psi)}{e^y} \theta'(e^y) dy}{\int_{\ln(\psi_{aev})}^b \frac{\theta(e^y) - \theta_s}{e^y} \theta'(e^y) dy} \quad \text{Equation 2}$$

where b is equal to $\ln(100000)$, $k_w(\psi)$ 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.

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 3 (Terzaghi, 1943) is commonly used to calculate the shear strength of saturated soils:

$$\tau = c' + (\sigma - u_w) \tan \phi' \quad \text{Equation 3}$$

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

Different from saturated soils, the shear strength of unsaturated soils depends on both net normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$. Equation 4 shows the shear strength equation for unsaturated soils developed by Fredlund et al. (1978):

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad \text{Equation 4}$$

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 a 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 matric suction decreases to zero, pore-

water pressure is equal to pore-air pressure and Equation 4 becomes the same as Equation 3.

The angles, ϕ' and ϕ^b are slope angles with respect to the two stress state variables in two axes, net normal stress and matric suction.

Young's Modulus can be used to measure the stiffness of a soil. Rahardjo et al. (2011) have suggested Equation 5 to estimate the Young's Modulus for saturated soils modified from the hyperbolic model proposed by Duncan and Chang (1970). Additionally, Rahardjo et al. (2011) proposed Equation 6 to estimate the Young's Modulus for unsaturated soils based on a constitutive equation suggested by Lloret and Alonso (1985). Equation 6 is applicable for a soil with a matric suction between 0 and 200 kPa and a net normal stress between 0 and 600 kPa based on numerical simulations and direct shear strength tests (Rahardjo et al., 2011).

$$E = K_L P_a \left(\frac{\sigma - u_w}{P_a} \right)^n \quad \text{Equation 5}$$

$$E = K_L P_a \left(\frac{\sigma - u_a}{P_a} \right)^n + K_m P_a \left(\frac{u_a - u_w}{P_a} \right)^m + K_o P_a \left(\frac{(\sigma - u_a)(u_a - u_w)}{P_a} \right)^l \quad \text{Equation 6}$$

where E is Young's Modulus of soil, P_a is atmospheric pressure, K_L is loading modulus number with respect to net normal stress, K_m is loading modulus number with respect to matric suction, K_o is loading modulus number with respect to both net normal stress and matric suction, n is the exponent for loading behaviour associated with net normal stress, m is the exponent for loading behaviour associated with matric suction and l is the exponent for loading behaviour associated with both net normal stress and matric suction.

Similar with the smooth transition of the shear strength equation for unsaturated soil to saturated soil, Equation 5 can also be obtained from Equation 6 when matric suction equals zero or pore-water pressure equals pore-air pressure.

Matric suction could contribute additional strength and modulus to the unsaturated soil. However, as water infiltrates into the soil, soil strength and soil stiffness could be significantly reduced as water content increases and matric suction decreases.

1.3 Evapotranspiration

Evapotranspiration, defined as the sum of evaporation and transpiration, influence the water content in the soil. Vegetation plays a significant part in the evapotranspiration process. 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. The LAI is used in VADOSE/W (Geo-Slope International., 2012) to estimate the net radiation intercepting soil surface, and hence to estimate how much energy is available for soil evaporation and how much energy is available for plants to transpire water. The potential transpiration (PT) value can be estimated based on 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 7 applies:

$$PT = PE * (-0.21 + 0.7\sqrt{LAI}) \quad \text{Equation 7}$$

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

Actual evapotranspiration is the sum of actual evaporation (AE) and actual transpiration (AT), which depend on both tree and soil characteristics.

AE is equal to PE when soil is saturated. Some approaches have been suggested to estimate PE such as Thornthwaite equation (Thornthwaite, 1948), Penman method (Penman, 1948) and Penman-Monteith equation (Monteith, 1965). However, AE starts to decrease and become less than PE when soil becomes unsaturated. Wilson (1990) extended the method of actual evaporation calculation suggested by Penman (1948) as:

$$AE = \frac{\Gamma Q + v E_a}{v A + \Gamma} \quad \text{Equation 8}$$

where AE is the actual vertical evaporative flux (in mm/day), Γ is the slope of the saturation vapor pressure versus temperature curve at the mean temperature of the air (in $kPa/^{\circ}C$), Q is the net radiant energy available at the surface (in mm/day), v is the psychrometric constant (in $kPa/^{\circ}C$), $E_a = f(u)P_a(B - A)$ (in mm/day), $f(u) = 0.35(1 + 0.15U_a)$, U_a is the wind speed 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 equal to 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 8 is then modified by Equation 9 to account for a portion of energy partitioned to the plants:

$$AE_{mod} = AE * \{1 - (-0.21 + 0.7\sqrt{LAI})\} \quad \text{Equation 9}$$

where AE_{mod} is the modified actual evaporation.

To calculate AT , VADOSE/W applies the equation (Feddes et.al., 1978):

$$AT = PRU * PML \quad \text{Equation 10}$$

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 the soil as the negative pore-water pressure increases. With low soil suction, the PML is 1. When there is lack of plant water, plants will close stoma and reduce transpiration (Saxton, 1982). The PML is 0 when the plant reaches its wilting point and transpiration will be 0 when soil suction exceeds the wilting point. A typical PML function suggested by Tratch et al. (1995) is shown in Figure 5. When the negative pore-water pressure is about -100 kPa, PML , 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.

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

$$PRU = \frac{2PT}{R_T} \left(1 - \frac{R_n}{R_t}\right) A_n \quad \text{Equation 11}$$

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.

1.4 Two-Dimensional (2D) Analyses and Three-Dimensional (3D) Analyses

Rahardjo et al. (2009) carried out analyses on tree stability using SIGMA/W (Geo-Slope international Ltd., 2012) and incorporated unsaturated soil properties. However, SIGMA/W can only analyse tree stability problems in two dimensions as illustrated in Figure 6 and plane strain condition is commonly assumed as zero in the direction perpendicular to the 2D plane. Nevertheless, this assumption requires that the thickness of soil and tree in the direction perpendicular to the 2D plane are comparatively much larger than the geometry size on the 2D plane so that the strain in that direction can be ignored. Given these assumptions, it seems that 3D analysis is more appropriate for a tree stability problem. Li et al. (2018) conducted analyses comparing the difference in the induced tree leans between 2D analyses and 3D analyses. As illustrated in Figure 7, they found that 3D analyses produced a larger tree lean estimate, around 10% difference, as compared to 2D analyses. 2D modelling underestimates the tree deformations as there is overestimated restriction in the direction perpendicular to the 2D plane. Therefore, both 3D modelling and incorporating unsaturated soil properties should be used when analysing problems related to trees under windstorms.

2 Material and Methods

One *Eugenia Grandis* tree located in the Chua Chu Kang area of Singapore was studied in this research as *Eugenia Grandis* is one of those tree species commonly planted in Singapore. The height of the studied *Eugenia Grandis* tree is about 25 m and the width of the canopy is about 16 m. The change in the soil water content and pore-water pressure due to evapotranspiration and rainwater infiltration dynamics were investigated as a function of weather conditions. The tree leans were then analysed considering the change in soil modulus and soil strength due to the change in pore-water pressure in the soil.

2.1 Effect of Weather conditions on the Water Content in the Soil

Analyses were conducted using VADOSE/W to investigate the effect of rainwater infiltration and evapotranspiration on the soil. The results were validated using the field measurements on the soil water content and pore-water pressure head.

2.1.1 Field instrumentations

Climatic data during 20-day period from Mar 1, 2017 to Mar 20, 2017 as collected from automated field instrumentation were used as the inputs to compute the transient water content and the transient pore-water pressure head in the soil using VADOSE/W. To obtain the climatic inputs, a 10-m high weather station was installed in the field. The wind speed, temperature, relative humidity and solar radiation were measured using Campbell scientific 034B, Campbell scientific CS215 Temperature and Relative Humidity Probe, Campbell scientific LI-COR's Solar Radiation Sensors, respectively. The readings were recorded every 10 minutes.

Instrumentation was also installed in the soil to measure the volumetric water content and the pore-water pressure heads. The measurements were used to compare with the numerical results using VADOSE/W. In the soil, jet fill tensiometers (ICT International) were installed at depths

of 0.15 m, 0.3 m and 0.8 m below the *Eugenia Grandis* tree to measure the pore-water pressure head. Meanwhile, soil moisture sensors (EnviroSCAN Probe and CS 616 Time Domain Reflectometry from Campbell Scientific) were installed at depths of 0.1 m, 0.2 m, 0.3 m and 0.8 m below the *Eugenia Grandis* tree to measure the volumetric water content (VWC) in the soil. Moreover, a piezometer was installed to measure the ground water table at about 10 m from the tree.

2.1.2 Numerical modelling using VADOSE/W

VADOSE/W was used to compute the volumetric water content and the pore-water pressure head in the soil as the effects of weather conditions. The modelled soil geometry with the boundary conditions are shown in Figure 8. The no-flux boundary condition was applied at the bottom boundary with the assumption of low permeability for the deeper soil. The surface flux boundary was computed by VADOSE/W with the inputs of climatic conditions and vegetation conditions. The model consists of four soil layers (0-0.15 m, 0.15 m-0.25 m, 0.25 m–0.55 m and 0.55 m-4.6 m) with different SWCCs and permeability functions derived from the field measurements. The respective 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). To obtain the SWCCs, matric suction values were calculated first from pore-water pressure head measurements in the field. More than two thousand recorded VWC and matric suction data points from field instrumented measurements in April 2017 were plotted at different soil depths (0.1 m, 0.2 m, 0.3 m and 0.8 m). Therefore, SWCCs could be obtained after best fitting the data points. Since pore-water pressure heads were only measured at 0.15 m instead of 0.1 m and 0.2 m as with the VWC measurements, SWCC at a soil depth of 0.1 m was obtained from the field measured VWC at 0.1 m and matric suction values at 0.15 m while SWCC at a soil depth of 0.2 m was obtained from the field measured VWC at 0.2 m and matric suction values at 0.15 m. The field measurements and the best fit SWCCs at 0.1m, 0.2 m, 0.3 m and

0.8 m using the least squares method are shown in Figure 9. SWCC variables for soils from different depths are listed in Table 1.

The unsaturated permeability functions could indirectly be estimated from SWCC and saturated permeability data based on Equation 2. Field infiltration tests were carried out to estimate the saturated permeability of the soil shallower than 0.55 m and laboratory tests were carried out to estimate the saturated permeability of the soil in the layer from 0.55 m to 4.6 m. Field infiltration tests using a double ring infiltrometer according to Parr and Bertrand (1960) were carried out in the field to determine the actual infiltration rate nearby the *Eugenia Grandis* tree. The infiltration rate obtained from the field measurements incorporated the influences of roots near ground surface on the soil permeability. Water was poured on the soil inside both rings to saturate the soil so that the infiltration rate measured in the next stage was close to saturated permeability. A constant head of 5 cm water level was maintained throughout the test. The infiltration rate was calculated to be $2.05\text{E-}05$ m/s based on how much water infiltrated into the soil within the period. The field infiltration rate was applied for the saturated permeability of soil layers shallower than 0.55 m. To measure the infiltration rate of the deeper soil (i.e. soil from 0.55 m to 4.6 m), a saturated permeability test was conducted in the laboratory for a soil specimen from 0.8 m depth, with a saturated permeability of $5.73\text{E-}08$ m/s being obtained (NParks & NTU, 2018).

For the evapotranspiration boundary condition, climatic data (precipitation, wind speed, air temperature and relative humidity) from the field instrument records were used as the inputs. LAI in this research was obtained by point clouds after scanning the *Eugenia Grandis* tree using the V-Line 3D Terrestrial Scanner RIEGL VZ-400. Point clouds for the *Eugenia Grandis* tree are shown in Figure 10. More details about this scanning procedure have been presented earlier (Li et al., 2018). The LAI was calculated to be 6, which is reasonable for a dense canopy as observed with close arrangement and multiple stacking of foliage (Gower & Norman, 1991).

2.2 Deformation analyses in ANSYS

2.2.1 Geometry

In this study, one *Eugenia Grandis* tree in the Chua Chu Kang area of Singapore with a height of about 25 m and diameter at breast height (DBH) of about 0.64 m was chosen for the analyses.

A shallow plate root system commonly exists for trees in Singapore since the roots can absorb water at the ground level due to the abundant rainfall in Singapore, instead of extending deep to obtain water. Therefore, a plate root system with a depth of 0.3 m and diameter of 10 m was assumed in this study.

The above-ground structure was assumed to have a constant diameter of 0.64 m based on the measured DBH in the field. In the analyses, the diameter of the soil is 40 m and the total depth of the soil is 15 m, which are large enough to avoid the boundary effect. The defined geometry in ANSYS 19.1 is shown in Figure 11.

2.2.2 Soil Properties and Wood Properties

The volumetric water content and the corresponding matric suction or pore-water pressure at noon time (12 p.m.) during the 20 days were exported from VADOSE/W and imported into ANSYS Static Structural analyses. The soil was defined with two layers from ground level: 0-0.3 m for top soil and below 0.3 m for deeper soil as illustrated in Figure 11. Table 2 lists the soil shear strength parameters from unsaturated triaxial shear strength tests in the laboratory (NParks & NTU, 2018) and Table 3 lists the soil modulus parameters from a previous study on similar soil specimens (Rahardjo et al., 2011). The density of the soil from 0-0.3 m was 2000 kg/m³ and the density of the soil below 0.3 m was 2100 kg/m³ as obtained from laboratory tests.

Mohr-Coulomb yield criterion in ANSYS was used in this study. However, ANSYS only has the criterion for saturated soil as: $\tau = c + \sigma \tan \phi$. To incorporate the effective shear strength for both saturated soils and unsaturated soils, the cohesion c in ANSYS can be defined as the total cohesion C equal to $(c' + (u_a - u_w) \tan \phi^b)$, including both the effective cohesion and the additional cohesion from matric suction in unsaturated soils. The value for ϕ in ANSYS can be the same as ϕ' . Therefore, Equation 3 and Equation 4 can be represented by:

$$\tau = C + (\sigma - u_w) \tan \phi' \quad \text{Equation 12}$$

$$\tau = C + (\sigma - u_a) \tan \phi' \quad \text{Equation 13}$$

For saturated soils, matric suction $(u_a - u_w)$ is zero and $u_a = u_w$. For unsaturated soils, u_a is zero. Therefore, Equations 14 and 15 could be used to represent total cohesion in ANSYS for saturated soils and unsaturated soils, respectively. Figure 12 illustrates the relationship between the total cohesion and the pore-water pressure head for the two layers.

$$C = c' \quad \text{Equation 14}$$

$$C = c' - u_w \tan \phi^b \quad \text{Equation 15}$$

ANSYS allows soil strength and soil stiffness to be defined as only a function of temperature instead of water content or pore-water pressure. To overcome this challenge, the approach used in this study was to use temperature T in ANSYS to substitute for pore-water pressure head (u_w/g) , where g is the gravitational constant.

As Young's Modulus for unsaturated soils varies with both matric suction and net normal stress, the soil region in ANSYS needs to be separated into different layers. Each soil layer can be assigned with a soil modulus which only varies with matric suction, as σ could be estimated from the stress level at the mid-depth of the layer. Therefore, deformation analyses with different layer thicknesses were carried out and a suitable layer thickness was found when the resultant tree lean converged and the difference in the tree lean become less than 2%. A grid

independent study was carried out first, to obtain suitable meshing scheme for the subsequent deformation analyses.

The modulus of trunk wood used in the model was 1.7 GPa, based on a previous study that applied CFD analyses and field measurements (Li et al., 2018). The modulus of the root plate was assumed as a tenth of the modulus of the trunk wood since the root plate includes both soil and wood. The modulus of the root plate was calculated based on the assumption that the root plate consists of 80% soil volume and 20% wood volume.

2.2.3 Wind Drags Calculation

Wind drags on the *Eugenia Grandis* tree were calculated from:

$$F = 1/2\rho C_d A u^2 \quad \text{Equation 16}$$

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

The drag coefficient is 0.69 and the centre of pressure is at 14.9 m, which were computed from Computational Fluid Dynamics (CFD) analyses on the same *Eugenia Grandis* tree (Li et al., 2018). The CFD analyses included the effect of leaves by applying a momentum loss term, turbulent kinetic energy loss term, and eddy dissipation rate source term in the canopy as functions of leaf area density calculated from point cloud data using the laser scanning approach. Therefore, drag forces could be computed based on the wind speed measurements in the field and applied at the height of centre of pressure of the tree.

2.2.4 Boundary Conditions and Cases Analysed

The wind drag was applied at the centre of pressure on the trunk. For the soil bottom boundary, the horizontal and vertical movements were assumed zero as the boundary was deep enough and the effect on the bottom soil was negligible due to wind drags. For the side boundaries, no horizontal displacements were allowed as the boundaries were far enough from the tree under wind drags. Settlements due to gravitational stress were allowed at the side boundaries. The thermal condition was applied based on the results of the pore-water pressure head distribution from VADOSE/W as shown in Figure 13. Therefore, the unit is °C when assigning the thermal condition but it is representing the imported pore-water pressure head distribution with a unit of meter. As a result, ANSYS could compute soil modulus and soil strength based on the temperature values during analyses. Moreover, hydrostatic pressure boundary condition was also assigned based on the GWT values for the 20-day study period from VADOSE/W as illustrated in Figure 14. The hydrostatic pressures were necessary for u_w in Equation 12 for saturated soils below the GWT. For unsaturated soils above the GWT, the hydrostatic pressure was assigned 0. It needs to be noted that the assigned hydrostatic pressure condition is not equivalent to the actual pore-water pressure distribution. From Equation 12 representing the soil below the GWT, the hydrostatic pressure assigned is the actual pore-water pressure u_w . However, from Equation 13 representing the soil above the GWT, the hydrostatic pressure assigned should be equal to the pore-air pressure u_a , which is 0. Furthermore, as noted above, the soil modulus function and the soil shear strength function are dependent on the assigned thermal condition instead of the assigned hydrostatic pressure condition.

Two cases were analysed and compared to investigate the effect of weather conditions on tree leans. Case 1 and Case 2 were carried out to compute tree leans with soil properties varying by soil water content related to weather conditions and soil properties not considering the change in the soil water content respectively.

In Case 1, unsaturated soil properties were considered when both soil modulus and soil shear strength varied with pore-water pressure heads as imported from the previous VADOSE/W results. In Case 2, unsaturated soil properties were not considered when a constant soil modulus was assigned (i.e. 20 MPa, 10 MPa and 5 MPa) and additional cohesion from matric suction was 0.

3 Results and Discussion

3.1 Change in Volumetric Water Content and Pore-Water Pressure Head as an Effect of Weather Conditions

Figure 15 (a), (b), (c) and (d) compares the volumetric water content from Mar 1, 2017 to Mar 20, 2017 for the numerical modelling by VADOSE/W and field measurements at 0.1 m, 0.2 m, 0.3 m and 0.8 m soil depth, respectively. Values at noon time were chosen to represent the respective day and to make the comparison between numerical and field results. Moreover, the results at noon time were used as the inputs for the subsequent deformation analyses under the wind drags at noon time. The precipitation values during the 20 days were also plotted to illustrate the temporal relationship with volumetric water content.

Numerical modelling and field measurements generally show similar volumetric water content and follow the same trend as precipitation changes. There are four possibilities to help explain the small differences between the observed and the modelled volumetric water content. The first reason is that the wind speeds used as inputs were measured at a 10 m height. However, the surface wind speed at a 2 m height should be lower due to the boundary effects of the ground. Therefore, the evaporation is slightly overestimated in the numerical modelling and the resultant volumetric water content is lower than the field measurements near the ground surface at the 0.1m, 0.2m and 0.3 m soil depths. The second reason results from the assumption of the SWCC below 0.8 m due to lack of data at a lower depth. The SWCC at a depth below

0.8 m was assumed to have the same SWCC as 0.8 m. Another possible reason is related to the estimated saturated permeability from the laboratory test for the deeper soil at 0.8 m. The specimen in the laboratory did not have identical conditions to the field due to sampling disturbance. It was also assumed the saturated permeability of soil below 0.8 m was the same as the saturated permeability at 0.8 m. As a result, the permeability function at a soil depth below 0.8 m was assumed the same as the soil properties at 0.8 m, which could lead to the observed differences of results between numerical and field values for soil at 0.8 m depth. In addition, the use of 1D analyses could lead to the differences between numerical results and field measurements. In the field, the measurements may vary with radial distance and the direction of the instrumentations from the tree.

Figures 16 (a), (b) and (c) show the comparison of pore-water pressure head from Mar 1, 2017 to Mar 20, 2017 at noon time between numerical modelling by VADOSE/W and field measurements at the 0.15 m, 0.3 m and 0.8 m soil depths respectively. Numerical modelling and field measurements result in very similar pore-water pressure heads.

The pore-water pressure heads versus depth from Mar 1, 2017 to Mar 20, 2017 at noon time are plotted every five days in Figure 17. Changes in pore-water pressure head can be observed as an effect of weather conditions. Ground water level also fluctuated around 4 m below ground. The pore-water pressure head distributions with soil depth during the 20 days at noon time were then imported into deformation analyses in ANSYS Workbench 19.1. Tree leans at noon time during the 20 days were then computed under the wind drags calculated from the corresponding weather condition.

3.2 Tree Leans from Deformation Analyses

3.2.1 Grid Independence Study

Meshes were refined in the preliminary analyses to obtain a suitable meshing size with acceptable accuracy. The change in the resultant lean was calculated as a percentage and illustrated in Figure 18 with different meshed number of nodes. The most suitable meshing scheme was found to be 83439 nodes as change in the resultant lean was lower than 2% when the meshed nodes almost doubled. The meshed geometry is shown in Figure 19.

3.2.2 Layer Thickness

The soil region below 0.3 m was layered to assign the different soil moduli as a function of pore-water pressure head based on the net normal stress at the central depth of the respective soil layer. Analyses with layer thickness of 5 m, 2.5 m, 1.25 m and 0.6 m for soil depths from 0.3 m to 5 m were carried out and it was found that 1.25 m was the suitable thickness when the resultant change in tree lean decreased below 2%, as shown in Figure 20.

Figure 21 shows the assigned soil modulus as a function of pore-water pressure head based on Equation 5 and Equation 6. It can be observed that the soil modulus drops significantly when matric suction approaches 0.

3.2.3 Tree Leans Analysed from the Two Cases

The wind drags calculated from wind speed monitoring, Mar 1, 2017 to Mar 20, 2017 at noon time, are plotted in Figure 22. The wind drags are small with a maximum wind drag force of about 155 N, when the maximum wind speed is about 1.4 m/s. Most wind drags are below 50 N at respective wind speeds below 0.8 m/s.

Tree leans were calculated by dividing the horizontal displacements at the point of load application with the height of load application. Tree leans computed from the deformation analyses from Mar 1, 2017 to Mar 20, 2017 are plotted in Figure 23, together with the wind drags.

Figure 24 illustrates the comparison of the resultant tree leans in the two cases: considering the effect of weather conditions on soil and tree leans not considering the climatic effect with an assumption of a constant soil modulus equal to 20 MPa. In this study, none of the soils became plastic and only elastic strains were observed from ANSYS results. This is because wind speeds in the field were small as illustrated in Figure 22. In the case when wind force becomes larger with a higher wind speed, part of the soil could yield and undergo plastic behaviour. Hence the effect of weather conditions on soil deformation and tree leans could become much larger. Moreover, the wind drags that induce a tree failure will decrease as soil becomes plastic under a smaller force with a higher water content in the soil. However, in this study with small wind forces, the effect of soil shear strength as a function of matric suction and net normal stress does not have an influence on the final tree leans. In other words, the difference in tree leans between the two cases in Figure 24 is due to the different soil moduli instead of different soil shear strength as the soils were all under elastic conditions with small wind forces.

The differences of tree lean in percentage between Case 1 (considering the effect of weather conditions) and Case 2 (not considering the effect of weather conditions on soil with an assumption of constant soil modulus equal to 20 MPa, 10 MPa and 5 MPa), were calculated and are illustrated in Figure 25. It was found that the differences converged as force increased. The differences are comparatively large due to numerical error at smaller wind forces. Small turbulences could be observed because of the weather conditions in the field across the 20 days. However, the effect of weather conditions is small in terms of the turbulence, as the weather conditions did not produce a large effect on the pore-water pressure heads (Figure 17). As climate changes and when drastic changes in pore-water pressure heads occur, the turbulences in the leans could be larger between applying the soil modulus as a function of pore-water pressure heads and assuming constant soil modulus.

From Figure 25, it is observed that when the constant soil modulus is 20 MPa, the difference of tree leans converges to 16.5% as force increases. When the constant soil modulus is reduced to 10 MPa and 5 MPa, the difference of tree leans also decreases to 8.3% and 0.7 % respectively. Therefore, a 5 MPa soil modulus can be used to represent the average soil modulus across the soil region and simplify the analysis. However, analyses need to be carried out first to find the most suitable constant soil modulus to be used as this value could vary with tree species, soils and climates. It is difficult to estimate the suitable constant soil modulus to be used without analyses. From the soil modulus function graph in Figure 21, it is observed that when soil modulus is 5 MPa, the soil is close to saturated as matric suction is almost 0 kPa for soil at shallow depth (0-1.25 m) or already saturated for deeper soil below 1.25 m.

3.3 Limitations in the Current Study

Some limitations still exist in this study. Firstly, the root-soil plate was used in this study instead of the real root architecture and the surrounding soil. This assumption could lead to inaccurate estimation on the strength and the stiffness of the root-soil plate. Moreover, the root-soil plate strength and modulus were assumed constant in this study and did not change with pore-water pressure heads as in the pure soil region. However, with a real root architecture incorporated, the effect of weather conditions will also influence the soil modulus and soil strength surrounding roots in the root-soil plate in addition to the pure soil region and a larger difference will be observed in the tree leans between the two cases (i.e. considering the effect of weather conditions or not on soil modulus and soil strength).

Secondly, the wood strength and wood stiffness were assumed constant in this study. Weather conditions could affect not only the water content in the soil, but also the water content in the wood. Gerhards (2007) has found that the wood modulus and bending strength generally decreased by 20 % and 30% respectively when the moisture content increased from 6% to 12%

at a constant temperature of 20 °C. Therefore, the change in wood strength and wood stiffness could be incorporated in future studies of tree stability.

Thirdly, the low range of measured matric suctions due to the local weather conditions is another limitation in this study. The SWCC was obtained from the best fit of the field measurements, which were low suctions below 10 kPa. Therefore, the obtained SWCC may not be applicable at higher suctions under dry weather conditions, although the results showed a limited range of suctions during the modelled 20 days. Nevertheless, during a much drier period when the suctions can increase to a high value like 100 kPa, the results could be affected. In that case, it is recommended to record the measurements during the dry period at high suctions as well and to obtain the SWCC again.

4 Conclusion

The effect of weather conditions on tree stability in Singapore was analysed in this study with an innovative approach using GeoStudio 2012 and ANSYS 19.1. The approach presented in this study could be applied in other cases when analysing 3D tree stability as well. Weather conditions in this research included wind, rainfall, temperature, humidity and solar radiation, which could affect the water content in the soil through infiltration and evapotranspiration. When considering the effect of weather conditions on soil stiffness and soil strength, the computed leans of *Eugenia Grandis* tree under wind drags could increase by 0.7 % to 16.5% compared to the tree leans with a constant soil modulus from 5 MPa to 20 MPa. However, this range of difference could be larger when the real root architecture is considered and the effect of weather conditions on wood modulus and wood strength is incorporated. In this study, the wind speeds in the field were small and the effect of weather conditions on soil strength did not take effect when soil was still under elastic behaviour before yielding point. Nevertheless, the wind force that triggers a tree failure could be smaller when the effect of weather conditions

487 on soil strength is considered as soil would become plastic under a smaller wind force.
488 Therefore, it is suggested the effect of weather conditions be incorporated in tree stability
489 analysis problems to obtain more reliable results.

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491 **Acknowledgement**

492 This study was supported by Nanyang Environment and Water Research Institute (NEWRI),
493 Interdisciplinary Graduate School, Nanyang Technological University, as well as National
494 Parks Board, Singapore.

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Figures

Figure 1. Average monthly wind speed (Climate in Singapore, 2010).

Figure 2. Monthly rainfall amount (Climate in Singapore, 2010).

Figure 3. Number of rainy days per month (Climate in Singapore, 2010).

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Figure 4. Tree failure after rainfall in Pasir Ris in 2012, Singapore (Rahadjo et al., 2016).

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Figure 5. A typical PML function (after Fredlund et.al, 2012).

Figure 6. Geometry in 2D modelling (Rahardjo et al., 2009).

Figure 7. Comparison between 2D analyses and 3D analyses (Li et al., 2018).

Figure 8. Illustration of geometry and boundary conditions in the VADOSE/W modelling.

Figure 9. SWCCs for soils at 0.1 m, 0.2 m, 0.3 m, and 0.8 m.

Figure 10. Scanned *Eugenia Grandis* tree point clouds (Li et al., 2018).

Figure 11. Geometry of trunk, root plate and soil.

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Figure 12. Cohesion of the two soil layers defined in ANSYS.

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Figure 13. Temperature condition assigned.

Figure 14. Hydrostatic pressure boundary condition assigned in ANSYS.

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(c)

(d)

Figure 15. 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.

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(a)

(b)

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Figure 16. 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 17. Pore-water pressure head vs. depth at noon time every five days from Mar 1, 2017 to Mar 20, 2017.

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Figure 18. Change in tree lean as meshed number of nodes increases.

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Figure 19. Meshed geometry with suitable size from grid independence study.

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Figure 20. Change in tree lean as layer thickness decreases.

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Figure 21. Soil modulus as a function of temperature assigned in different soil layers in ANSYS.

Figure 22. Wind drags at respective wind speeds at noon time during 20 days from Mar 1, 2017 to Mar 20, 2017.

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Figure 23. Tree leans due to the corresponding wind drags at noon time from Mar 1, 2017 to Mar 20, 2017.

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Figure 24. Comparison of tree leans in the two cases.

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Figure 25. 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.

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Tables

Table 1. 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

Table 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 3. Soil modulus parameters.

Soil Modulus Parameters	K_L	K_m	K_o	n	m	l
Soil Layer 0-0.3 m	90.5	92.8	18.9	0.69	0.18	0.99