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Increase in shear modulus of soil due to tree root permeation and soil matric suction

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ABSTRACT

The tree root permeated ground improvement methods are now being widely used around the world. Tree roots increase the stiffness of the soil by root reinforcement effect and soil suction effect. Shear modulus of soil is an important parameter in assessing the increase of shear strength of soil due to tree root permeation. Therefore, in this study the variation of shear modulus with respect to the variation of matric suction has been assessed and its trends has been identified according to the variation of the shear displacement. The shear modulus can be defined as how the material responds to shear stress and it is usually symbolized as `G`. Shear modulus (G), is directly proportional to the Young's modulus (E) and inversely proportional to the Poisson's ratio (V). Young's modulus (E) and Possion's ratio (V) are directly influenced by root permeated effect. Shear modulus was calculated using the results obtained during the direct shear test carried out for soil only specimens and root permeated specimens. Direct shear tests were carried out under three different normal stresses and five different matric suction levels. Shear modulus increases with the increase in matric suction for both reinforced and unreinforced specimens. Further, the shear modulus of the reinforced sample is higher than the identical un-reinforced specimen. It can be observed that root permeated samples show more ductile behaviour than soil only specimens due to reinforcing effect of the roots in root permeated soil, from the plotted results between shear modulus over the shear displacement. This behaviour is important in Finite Element Modeling of the root permeated soil as the settlement evaluations are carried out using the stiffness of the materials. In this paper the variation of the shear modulus with matric suction in root permeated soil and its uses FEM modeling will be discussed.

Keywords: Ground Improvement, Root permeated soil, Shear modulus.

1 INTRODUCTION

The vast increase in population and the high demand for infrastructure facilities in metropolitan areas has led to the construction of large number of massive earth structures, including major highways and railways. Therefore, new trends of ground improvements have been searched by the Engineers and ground improvement techniques using Vegetation have been emerged. Tree roots are the main component, when the effect of vegetation on ground improvement is considered because tree roots, reinforce the soil through their mechanical properties, increase suction through the root water uptake induced by evapotranspiration, and dissipate excess pore water along the shorter paths. A mature tree can provide 30kPa suction at the wilting point, and a well spread out woody root system can apply a good resistance to the shear displacement.

1.1 Root reinforcement effect

Tree roots can increase the shear strength of soil by mechanical means. Over the past few decades the increase in the shear strength of soil with tree roots has been discussed and examined in

numerous different ways by various research groups. Docker and Hubble (2001) suggested that tree roots can provide mechanical strength to soil in two main ways:

1. Increase the shear strength due to the anchoring effect of larger, stiffer roots
2. An increase in shear strength due to the apparent cohesion provided by smaller roots.

Docker & Hubble (2009) carried out in-situ shear tests on blocks of soil containing the roots of four riparian tree species. Figure 1 shows the plots of average shear stress against the displacement of the tested species. Accordingly, the greatest shear resistance is provided by A. floribunda, followed by the other species (E. elata, E. amplifolia, and then C. glauca) with only a small discernible difference between them. Therefore, Docker & Hubble (2009) suggest that A. floribunda roots provide a much higher tensile strength.

With the results from these experiments, Docker and Hubble (2009) describe two types of root failures;

Type 1: Failure occurs after reaching the maxi-mum shear resistance before testing has been com-pleted. This type of failure exhibits a definite de-crease in resistance as the displacement increases.

Type 2: Failure occurs before reaching maxi-mum resistance or with continuously increasing shear resistance throughout the test, or with no rec-orded reduction from the original state.

Further, this study concluded that the two different root shapes show the two different failure patterns.

Pallewattha et al. (2019) study shows that the in-crease of shear strength due to root permeation is influenced by the matric suction of the adjacent soil.

2 TESTING PROCEDURE

In this study a direct shear test was carried out using the large shear box which is shown Figures 2. A root permeated soil specimen was used and five different suction values were selected, e.g. 0kPa, 50kPa, 100kPa, 150kPa, and 200kPa. This suction range was selected based on laboratory visible wilting point, i.e. 200kPa. Three tests were carried out for each suction value and three different normal stresses were considered, i.e., 10kPa, 20kPa and 30kPa. Furthermore, 15 additional tests were carried out on unreinforced direct shear specimens for comparison. The wooden boxes with internal dimensions 300mm(W) x 300mm(L) x 200mm(H) were used to plant the trees. Polyurethane

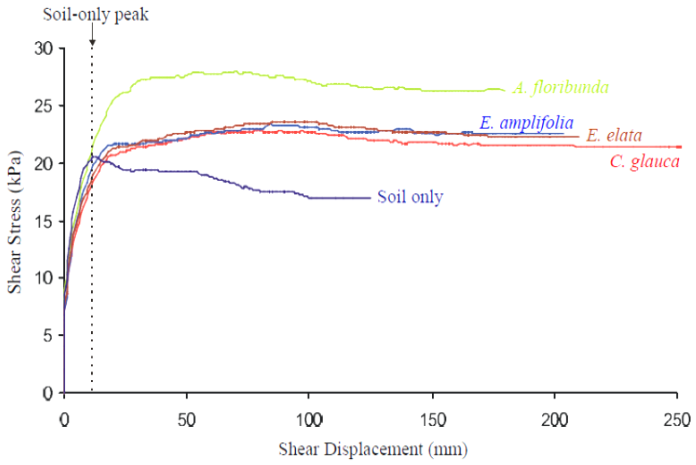

Figure 1: Average shear stress versus displacement plots for the four tree species and the soil-only tests. (Modified after Docker & Hubble2009)

sealer was applied inside the boxes to prevent deterioration due to water absorption; if the wood deteriorates the texture of the soil becomes contaminated, making it difficult to obtain an equivalent root system. The soil was initially compacted inside the wooden boxes using the steel plate and

wooden collar to obtain a dry density of 1350kgm-3. Every sample was prepared using an equivalent compacting method, such as 18% gravimetric moisture content, and two layers with the same height and the same weight.

All the boxes were scanned with CT scanning to check the uniformity of the compacted soil and then recently germinated plants (15-20mm tall) with undistorted root systems were planted in the boxes. The plants were selected to obtain the same possible growth rate and ensure an equal and undistorted final root system, thus making it easier to make a direct comparison between the samples. These plants grew under the same environmental conditions for a period of 12 months. The tree used in this study was an '*Euculyptus botryoides',* a species of eucalyptus with a good spreading root system, evergreen, and which is commonly available in NSW.

The large 300mm x 300mm x 200mm shear box was used to carry out the test. The soil specimen with the tree was transferred from the wooden box to the brass shear box with minimal disturbance to the specimen; this was only possible by performing a large number of trails. A suction sensor was installed inside the shear box close to the shear zone of the soil. The specimens were allowed to reach the required level of suction for several days. A 15mm diameter vertical sand pile was installed inside the shear box to check the width of the shear zone.

Subsequently, the direct shear tests were carried out at three different normal stress values (10kPa, 20kPa, 30kPa) at each level of suction; the specimen was sheared at a rate of 2.5mm/min.

3 RESULTS AND DISCUSSION

3.1 Shear modulus of the soil sample

The shear modulus can be defined as how the material responds to shear stress, it is usually symbolised as `G`. Figure 3 shows a schematic diagram which represents the stress strain curve for an elasto-plastic material where the shear modulus is obtained by the first derivative of shear stress over the shear strain. Therefore, the increment of shear stress over the strain with respect to displacement is an important parameter. The shear modulus was used to compare the stiffness variations of the root permeated soil since the shear strength is the dominant property of the soil.

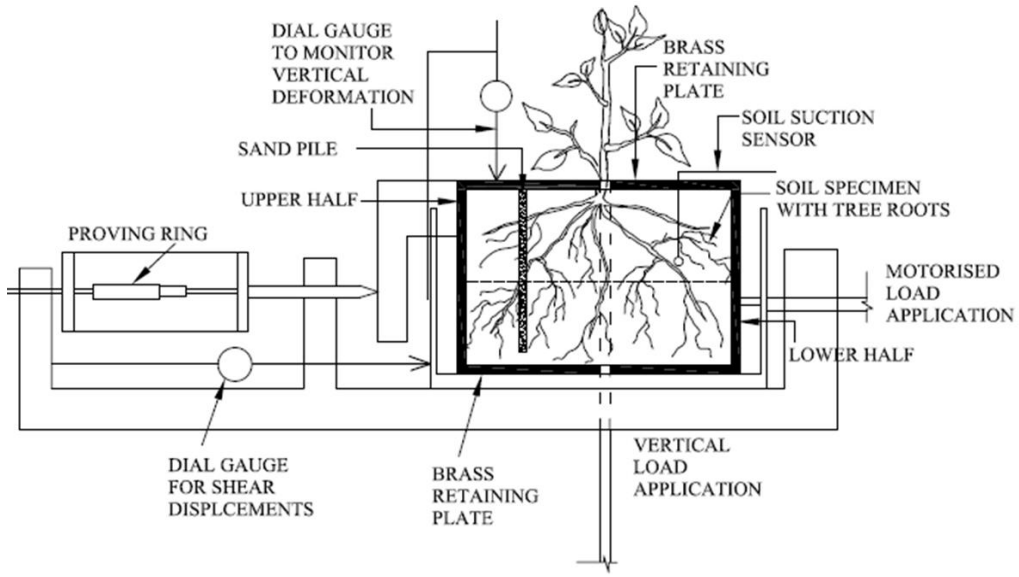

Figure 2: Schematic Diagram of direct shear test for root permeated soil – 300mm x 300mm sample

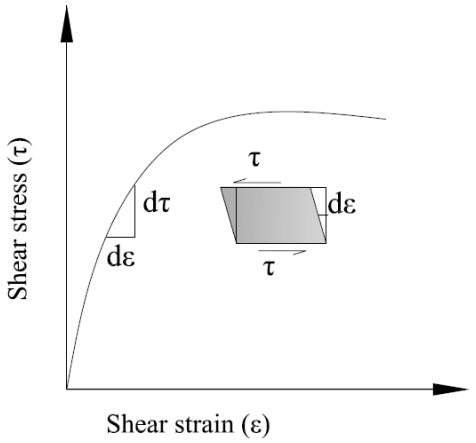

Figure 3: Stress strain curve for an elasto-plastic material

This study clearly showed that the shear strength of the root permeated soil increases compared to the non-permeated soil sample with the same laboratory condition. Further the aforementioned increment increases with the increase of soil suction. This occurs due to the variation of the soil stiffness and the ductility in the root permeated soil.

Increment of shear stress with respect to displacement was plotted for saturated soil condition and shown in figure 4 to obtain the variation of shear modulus of soil. The increment of shear stress over strain (dτ/dε) of the unreinforced specimens tested at 0kPa suction, lagged behind from root permeated specimens which began from a displacement of 2.2mm to 6mm, and which can be identified as the displacement zone where the peak shear values occur.

The initial dτ/dε of the root permeated sample is also higher than the unreinforced specimen, while the unreinforced specimens show a steadier variation of dτ/dε and the root permeated specimens have more scattered variations. It can be observed that root permeated samples show more ductile behaviour than soil only specimens' reinforcing effect.

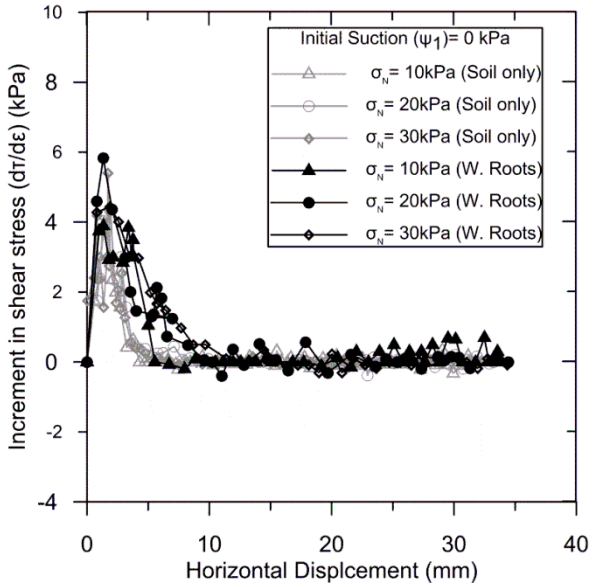

Figure 4: The increment of shear stress over strain (dτ/dε) with respect to displacement (0 kPa suction))

Figure 5 represents the variation of dτ/dε over the displacement of specimens tested under four different suction levels (i.e. 50kPa,100kPa, 150kPa and 200kPa).The variation of dτ/dε values for the root pemeated samples tend to increse with the high suction values, while all the root permeated

specimens were more ductile than the unreinforced specimens; this leads to an increase in the peak shear value of the root permeated specimens. However, this increase in dτ/dε with the suction is high at 50kPa and low at 200kPa. This is due to the soil suction is a dominanat parameter rather than the root permeation of the soil speciman. Further it shows that the normal stress does not have any influence over the dτ/dε value after 10mm shear displacement and this is due to the loss of contact between soil particles over large displacements.

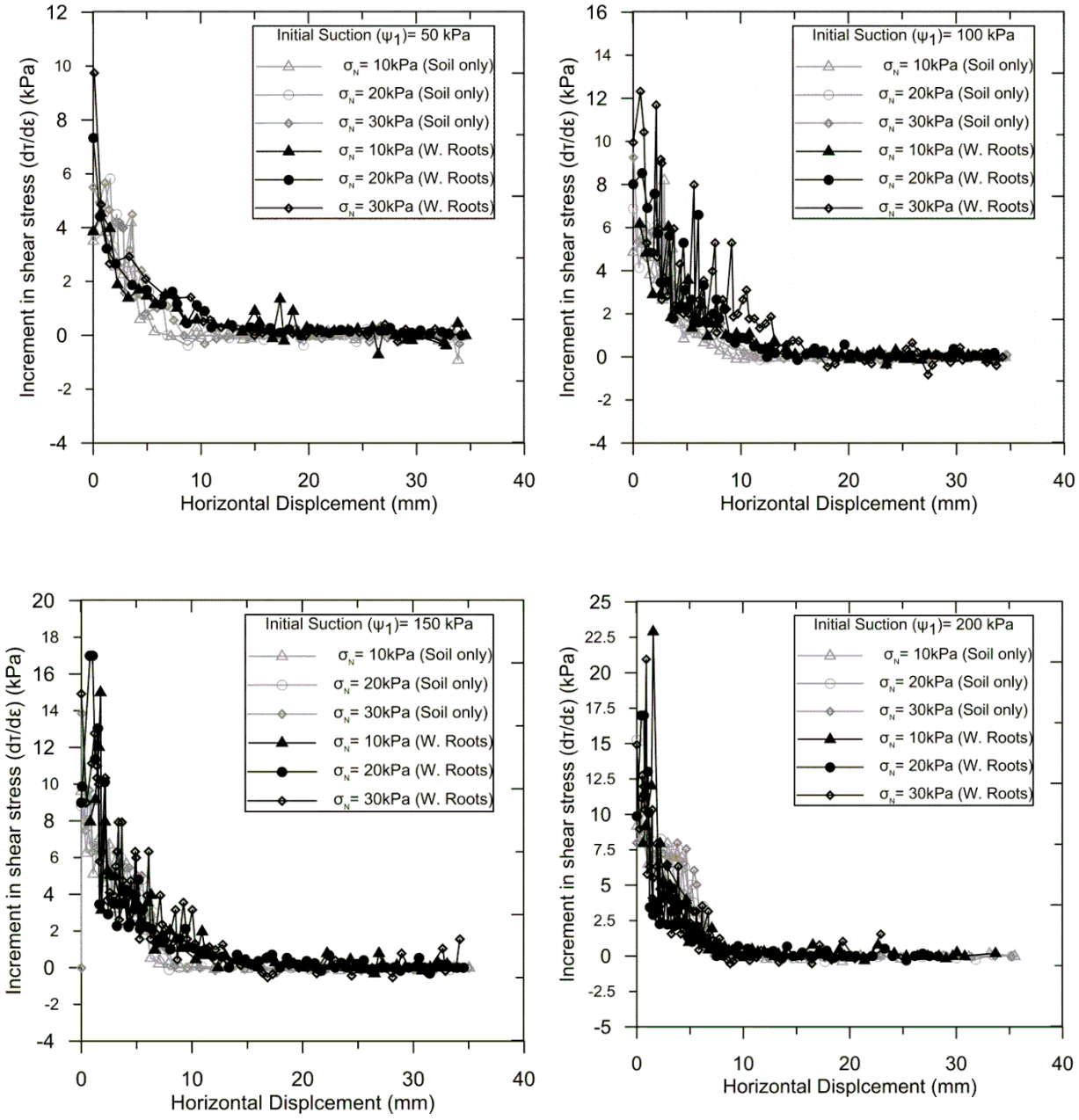

Figure 5: The increment of shear modulus with respect to displacement dτ/dε

4 FEM MODELLING

PLAXIS 2D 2015 (VIP) was used in this study because it is a widely used finite element program which can be utilised in geotechnical engineering designs. The material model used in PLAXIS is based on the stress strain relationship of the input material, and it is defined by the set of mathematical equations related to the stress strain rates.

Plane strain analysis was used in this study considering the strain can only takes place in x-y direction. Root system was reduced to 2 dimensional system considering the stiffness variation along the tree line, because the analysis time increases considerably in 3 dimensional system than 2dimensional system. The output 2D system was checked over the 3D system and there were no any noticeable variation.

The Model results from the Pallewattha et al (2019) was used in Numerical Simulations along with the shear modulus values since the shear modulus can be easily used as an input to the PLAXIS 2D. Settlement was compared at the most critical point where the middle of the ballast layer sits between the vegetated and non- vegetated sections at different suction values; (Pallewattha (2017)) the results are then used to predict the effectiveness of trees planted alongside railway ballast. Furthermore, the method outlined in this chapter can be used to determine the distance from the tree to the toe of railway ballast needed to achieve the settlement values desired for future designs. The layers of soil in unreinforced analysis were defined using only one bore hole, but three holes were used to define the triangular root zone.

The mathematical model in Pallewattha et al (2019) can predict the increase in shear strength due to native vegetation, which is relevant to the properties of the root system and soil, as well as the hydraulic properties of the system. Therefore if those properties for any railway system are known, then the predictions can be made using FEM analysis with PLAXIS 2D. Furthermore, to design a railway system with a green corridor, this model and the FEM analysis can be used effectively, as described in next section. The data obtained from Potter (2006) and Fatahi's (2007) publications for the green corridor along railway line in Miram Australia, have been used in this FEM analysis.

4.1 FEM results and discussion

Figure 6a, 6b show the settlement results obtained at the Miram site in the vegetated and non-vegetated sections. Maximum settlement occurs at the centre of the ballast, which is marked as X'; settlement at X in non- vegetated ground is 36 mm and 23mm in vegetated ground. Both settlements are acceptable with regards to the serviceability of the rail track, and since this reduction is more than 50%, it is a considerable reduction in the settlement due to the presence of tree roots. A simple direct shear test was simulated to verify the usability of the material model chosen for the root permeated section and input parameters.

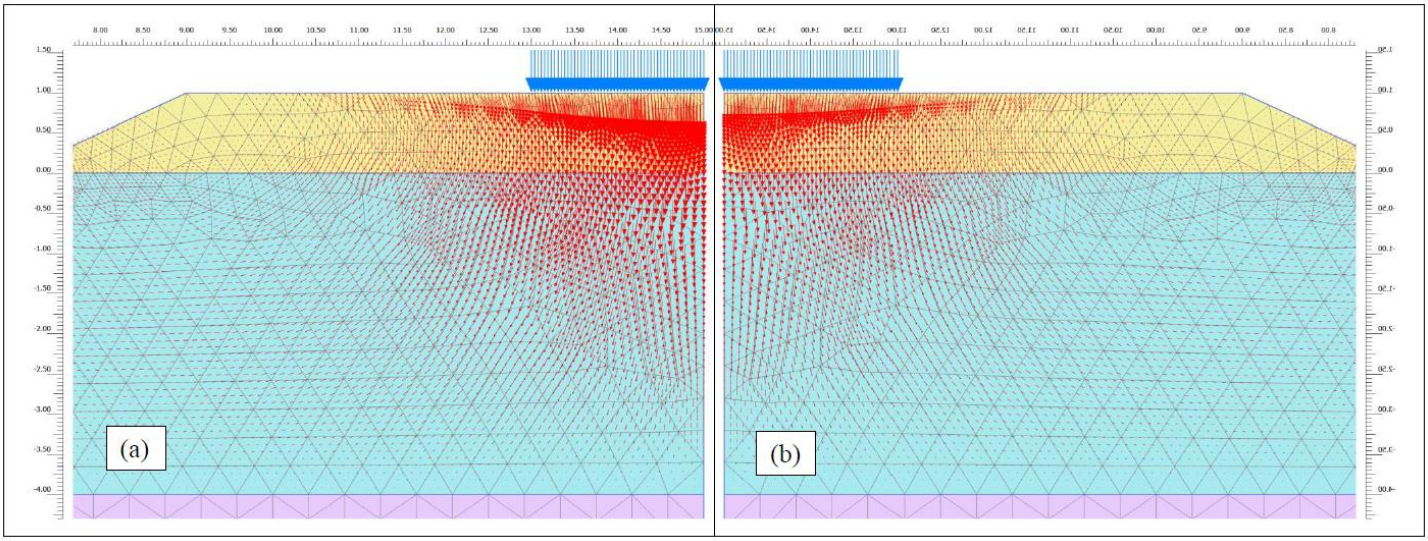

Figure 6a, 6b: Displacement vector (a) non-vegetated ground (b) vegetated ground (shows less displacement)

5 CONCLUSIONS

Shear modulus of the root permeated soil increases with suction to a certain level of soil suction and it shows scattered behavior due to the root failures. This increase of shear modulus with suction is not prominent at large horizontal displacement. Shear modulus can be used as a direct input for Finite Element Analysis to simplify model development without compromising the results.

6 ACKNOWLEDGEMENTS

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