Influence of tree type to suction development and the stability of slope

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Abstract. The overall aim of this research is to provide an assessment of suction development in a typical soil slope embankment. In particular, it demonstrated how different type of trees via their water-uptake demands enhances the stability of soil slope cutting, within a London clay formation. A total of 7 analyses were performed. The first analysis was performed to determine the saturated undrained Factor of Safety of the un-vegetated case study slope. A mature Oak tree was then superimposed on both the slope toe and its crest, and it was discovered that the presence of the tree at such locations increased the slope Factor of Safety by 2.15% and 2.00% respectively. A mature Horse Chestnut tree was then considered on the slope, and the tree enhanced the slope Factor of Safety by 2.01% and 1.94% on the toe and the crest respectively. The next analysis considered the effect of mature Poplar tree with a root zone deeper than both the Oak and the Chestnut; the Poplar tree increased the slope Factor of Safety by 12.65% and 2.77% at the toe and the crest respectively, indicating tree species with deeper root zone produced greater impacts than those with shallow root zone. Although 2% increase in Factor of Safety is not overlay significant but 12.7% is, therefore the findings indicate the magnitude at which trees with deep root zone enhanced the slope factor of safety albeit more on the slope toe.

Keywords: Factor of Safety, Slope, Oak, Chestnut, Poplar, Crest, Toe

1. Introduction

Over a long period of time, failures of natural and man-made slope presents a major challenge to geotechnical engineers, and whenever it occurs, depending upon its nature, it usually causes significant damage to lives and properties and often, obstruction of various human activities. Slopes stability causes significant problem in many countries, as such, capability to understand and/or predict slope behavior under different field conditions and producing a safe designs are becoming a priority [1]. This is a problem that is worsened by a climate change and increasingly intense rainfall [2].

According to Griffith and Lu (2005)[3] soil suction plays a significant role in stabilizing geotechnical structures, although these suction are largely dependent on soil type and its infiltration conditions. It is indeed a well known phenomenon that the variation of pore-water pressure stands to be the major factor affecting the slopes performances. The magnitude of pore water pressure determines the effective stresses in a soil slope which in turn controls its volumetric behavior and the soil strength [4].
Slopes are often covered by various types of vegetation ranging from grass cover to more established shrubs and trees; therefore understanding their various effects on pore-water pressure is of paramount importance[5]. In temperate climates like The United Kingdom (U.K), Suctions (i.e. negative pore-water pressure) generally occurs after a dry periods, especially in the summer, when soil water is been removed due to evaporation and transpiration. Positive pore water pressures occur following wet periods as water infiltrates the soil, and are typically highest at the end of spring between March and May in the northern hemisphere as there is little evapotranspiration during the winter months [5], [6]. In reality soils often exhibit both saturated and unsaturated zones through much of the year – and this transition is governed by the position of the water table.

Smethurst et al., (2006)[5] noted that various studies of suctions in vegetated slopes were carried out. An example of such studies includes a recent field investigations by Greenwood, (2011) [7] to quantify the impact of different vegetation types on slope stability. However, little effort has been made to link those identified suction changes to an assessment based on properties of a particular vegetation type obtained through real-life available data as recommended by Blight, (1992). This indeed is very important, as different type of vegetation always exhibits a different behavior with regards to suction generation due to their varying water uptake demands.

Therefore, this work utilized the opportunity provided by a real life data obtained by Biddle, (1998) [8]and Smmethurst et al., (2006) [5] to investigate the contribution of different types of trees on the soil suction development and the stability of embankment slope in general.

2. Theoretical background and solution procedure

The term slope describes a portion or part of natural inclined surface and the resolution of its stability problem requires taking into account field equations and constitutive laws [9]. An example of these slopes includes transportation slopes, canals and dyke and earth dams. It is always paramount to check a stability of a proposed slope, as its failure usually attracts a huge loss of properties and at times human lives, therefore a certified and precise analysis need to be done to avert slope failure occurrence [10].

A slope failure usually occurs along a curved surface when a huge mass of soil slides with respect to the remaining mass. In general, there is a downward or outward movement of the soil mass, and as forces initiating failure overcome the soil shear strength, the slope failure occurs. The factors leading to the slope failure may be classified as either those that increase shear stress or factors that reduces the soil shear strength. The former may be due to water causing saturation of soils, seepage pressure, slope steepening by erosion or excavation and additional surcharge load; the latter may be due to increase in pore water pressure or water content, cyclic load and weathering [10],[11].

This work adopt a slice method of slope stability analysis according to [12], the potential failure surface is assumed to be circular arc with centre (O) and radius (r). The soil mass (ABCD) above a trial failure surface (AC) is divided by vertical planes into a series of slices of width (b), as shown in figure 1 below.
The base of each slice is assumed to be a straight line. For any slice, an inclination of the base to the horizontal is ($\beta$) and the height measured on the centre line is (h). The analysis is based on the use of lumped factor of safety ($F$), defined as the ratio of available shear strength ($\tau_f$) to the shear strength ($\tau_m$) which must be mobilized to maintain a condition of limiting equilibrium after Lambe and Whitman, (1969).

Hence the factor of safety in terms of effective stress is given by Lambe and Whitman (1969) as:

$$F = \frac{\Sigma(W \cos \beta - u_a) \tan \theta' + C L_a}{\Sigma W r \sin \beta}$$

(Aitchison and Richards (1965) [14] provided an accepted definition of soil moisture suction as the difference between soil pore water pressure and the ambient air pressure. A simple framework that will allow assessing the influence of suction changes on soil shear strength has been sought and used. For this purpose, Fredlund et al., (1978) [15] provided a relationship to express suction influences on soil shear strength and incorporating the effects of suction due to vegetation water uptake as reproduced here as equation (2).

$$\tau = c' + (\sigma - u_a) \tan \theta' + (u_a - u_w) \tan \theta_b$$

Where ($u_a - u_w$) is the matric suction and can simply be donated as $S$ and $\theta_b$ is an angle indicating the rate of increase in shear strength relative to matric suction, cohesion $c'$ and the slope angle $\theta'$ are the shear strength parameters (Fredlund et al., 1978). In this relationship, atmospheric pressure $U_a$ is assumed zero and two stress variables, the matric suction and the net normal stress are used to describe unsaturated shear strength of soil while only effective normal stress is used for saturated soil [16].

3. Methodology

This work utilized the opportunity provided by a real life data obtained by [8] and [5]. The data in both works were mapped together in order to investigate the contribution of different types of trees on the soil suction development and the stability of embankment slope.

The slope chosen for this study is a cutting along the A34 Newbury bypass in England (OS grid reference SU455652). This was chosen as the data was accessible and the study was for a uniform soil conditions and vegetation characteristics (mainly grass) as provided by [5] while the work of the [8] provided the moisture content deficit based on the different trees water uptake demands. The slope is assumed to be fully saturated with a saturated unit weight of 19.21 kN/m$^3$ for London Clay adopted from [17]. A number of trial slips were considered and the critical slip with the minimum Factor of
Safety was obtained. The slip circle obtained has the maximum depth of 7.7m with an arc length of 37.89m, these might be due to the values of shear strength parameters adopted and the nature of the slope geometry. As such the factor of safety for the fully saturated slope in an undrained condition incorporating the effect of suction as given by Rees and Ali (2012) [16] will be,

\[ F_{oS} = \frac{\Sigma C_m + \text{Stand}^b}{\Sigma Wm^b} \]  

(3)

First, the slope critical failure plane was determined using Fellenius method, and the lowest Factor of Safety so obtained was adopted as the benchmark for the succeeding analyses. Biddle, (1998) [8] indicated that for all the chosen trees, moisture contents at their proximity is at field capacity during the spring, and in the mid to late September becomes driest. As such these ranges (difference between full capacity moisture and entirely dry soil) were used in this work to quantify the variation of the moisture content. The data is then used to calculate the suction generation, and employed in all the subsequent stability analyses. The moisture content data at proximity of a particular tree is first studied from the work of Biddle, (1998) [8] and the corresponding moisture contents at particular depths are traced as in figure 2.

![Figure 2. Moisture content profile tracing.](image)

The water content data provided by Biddle, (1998)[8] is largely spaced, usually at 4m apart due to the locations of the Neutron Probe used in determining the field moisture content, a linear interpolation is carried out to find the corresponding moisture between known reading and beyond. A grid system of 300mm x 300mm is used for that purpose as presented in figure 3.

![Figure 3. Moisture content variation beneath a slope at the proximity of mature tree.](image)
Suctions are generally quantified in terms of water potential ($\psi$), which stands to be the difference between pure water that is freely available in the system to the chemical potential of free water at same temperature and atmospheric pressure. It simply quantifies the ability of the water to do work compared to the work done by an equal mass of pure water. Water will always move from the region of high potential to low potential. The water potential is measured in energy per unit volume referred to as Pascal (Pa) in Standardized system of measurement (SI), but as this is very small unit, it is more usual to refer to kilo Pascal (kPa) [8].

The moisture content at the base of each slice corresponding to its enclosed square grid is converted first into capillary potential ($\psi$), using soil water characteristic curve in figure 4 and then to suction ($S$), by applying equation (4), with the unit weight of water ($\gamma_w$) taken as 9.807 kN/m$^3$. The model ($S \tan \phi^b$) representing the overall influence of suction to the shear strength of soil, given after[15], is then added to the resisting part of the factor of safety equation as in Equation 3.

![Figure 4. Soil water retention curve for London clay redrawn after Croney, (1977)[17].](image)

\[
S = \psi \gamma_w
\]  
(4)

A spreadsheet formula is created based on Equation (3), incorporating the influence of suction generation due to the action of the superimposed tree within the proximity of the slope, and the changes of Factor of Safety being identified and recoded.

**Table 1.** Material parameter of London Clay at the case study slope [5], [17].

| Soil type          | London Clay |
|--------------------|-------------|
| Slope angle ($\beta$) | 16°         |
| Slope height       | 8m          |
| Slope width        | 28m         |
| Effective cohesion ($c'$) | 15 kN/m$^2$ |
| Undrained Cohesion $C_u$ (kPa) | 67.5         |
| Angle of shearing resistance | 20°         |
| Dry unit weight $\gamma_d$ | 14.6 kN/m$^3$ |
| Saturated unit weight $\gamma_s$ | 19.21 kN/m$^3$ |
| Void ratio         | 0.89        |
| Specific Gravity   | 2.73        |
| $\phi^b$           | 16°         |
3.1 Determination of Critical Failure Plane

The factor of safety can be correctly obtained only if the critical failure surface for a given slope is accurately identified. Fellenius has shown that the centre of the most critical circle lies on what he refers to as “line AB”. To draw line (AB), the point (B) is located at a depth H and at a distance 4.5H from point (P) at the toe of the slope, where (H) is the height of the slope as in figure 5.

Figure 5. Newbury slope showing position of critical plane.

Figure 6. Fellenius Line (AB) method of determining CSS.

The point (A) is located by drawing two lines (PA) and (QA), where (PA) makes angle (α) with the slope line (PQ) and (QA) makes angle (β) with the horizontal (Q). The angles (α) and (β) are obtained from the Table (2), and they depend upon the slope geometry. The centre of the most critical circle may lie anywhere on the line (AB) or its extension. The centre of trial circles are taken on this line shown as O’’, O and O’. The factor of safety obtained with these trial centres are generally plotted as normals to the line (AB) to obtain a curve of FOS. The centre corresponding to the minimum factor of safety indicates the most critical circle.
Table 2. Fellenius Method slope angles adopted from Arora, (2011).

| Slope Geometry | alpha  | beta  |
|----------------|--------|-------|
| 1:1            | 28°    | 37°   |
| 1:1.5          | 26°    | 35°   |
| 1:2            | 25°    | 35°   |
| 1:3            | 25°    | 35°   |
| 1:5            | 25°    | 37°   |

The critical failure slip of the Newbury slope was determined manually using Fellenius Line AB method as explain above, and the data obtained fed into a spreadsheet software (SLIP4EX) provided by [18] for quick analysis and the factor of safety results to be obtained through different methods such as Swedish, Bishop and Greenwood, the results are presented in Table 3.

The Factor of Safety obtained by critical slip plane analysis is fixed as control for all subsequent analyses. It could be noticed that the depth of the critical slip is 7.70m (table 3), deeper than the root zone of the selected tree chosen for the case study if situated near the slope centre, hence the decision to locates the trees near the slope toe and its crest throughout the work.

Table 3. Trial circles geometry and Factor of Safety by different method.

| Max. Depth (m) | Arc Length (m) | Saturated | Swedish | Greenwood Simple | Simple Bishop |
|----------------|----------------|-----------|---------|-----------------|--------------|
| 12.00          | 44.69          | 1.55      | 1.80    | 1.95            |
| 10.80          | 42.87          | 1.46      | 1.68    | 1.79            |
| 10.05          | 41.85          | 1.45      | 1.66    | 1.75            |
| 9.20           | 40.49          | 1.70      | 1.90    | 1.96            |
| 8.30           | 38.77          | 1.56      | 1.74    | 1.79            |
| 7.70           | 37.89 1.32     | 1.42      | 1.58    | 1.60            |
| 6.35           | 34.81          | 1.59      | 1.71    | 1.70            |
| 5.80           | 34.04          | 1.76      | 1.89    | 1.86            |
| 5.20           | 32.39          | 1.87      | 1.98    | 1.93            |

4. Tree Induced Suction
Soil suction is an important mechanism within the hydrological factors that controls the stability of slope, and is heavily influenced by the presence of vegetation through their water uptake demand. Smethurst et al. (2006) [5] noted that, in a conventional static slope stability analysis in which worst-case pore pressure conditions are considered, suction generated by vegetation will only have a beneficial effect to a slope if they are carried through into winter and early spring. Mature trees growing in a low permeability clays have been shown to generates adequately large suctions in the summer to prevent full re-wetting of the soil in winter and early spring [19]. However, suctions generated by light shrubs and grass cover are seldom held on through winter period [7]. Knowledge of the effect of various vegetation on pore water pressure is very important, and more so the effect of particular species. This reason herald the idea behind this research in which the effect of three different tree species, Oak, Chestnut and Poplar were investigated and quantified.
The original plan was to include the mid-slope in the analysis. But this proved impractical, as none of the trees chosen for the study has a root zone extending to the depth that will incur any effect to the stability if placed on the mid-slope. This is based on the information of tree root zone obtained from [20], [21] and [22].

4.1 Oak Tree on London Clay Slope
This research was performed to determine a soil drying pattern (Figure 7) within a proximity of a white mature Oak tree (*Quercus alba L.*), situated on a London Clay at Roxeth Recreation Ground London, and its influence on slope stability. The tree chosen was 16m long, with 89cm breast height diameter (b.h.d) based on Biddle, (1998)[8]. Its drying pattern data is mapped onto London Clay slope provided by (Smethurst et al., 2006)[5]. A heart root form of root-architecture is considered based on the measured information of Oak tree located on a sloping ground as provided by [21]. The root zone for the heart-root architecture is assumed to extend to a depth of 3m as in Hinckley et al., (1981)[20] and a radial distance of 5m from both centre line of the tree system as adopted by Urban, (2010) [22].

4.1.1 Oak Tree on Slope Toe. Table (4) shows the spacial distribution of moisture content at the proximity of mature Oak tree. Taking the tree elliptical root zone into consideration in Figure (8), the centre of slice 1 is exactly 4.3m away from the tree (corresponding to the first neutron probe position on Biddle, (1998)[8] work. And within a depth of 1.1m, this gives the moisture content of 39.6% and converted to the suction value of 70kPa. Slice 2 centre line is situated 6.7m away from the tree with the elliptical root zone cutting its base (at critical slip) at the depth of 2.85m, which gave the moisture content of 46.74% and converted to a suction of 1.08kPa. These suction values were then imployed into stability analysis in Table 5.

![Figure 7. Soil drying profile on London Clay 4m and 8m away from mature Oak tree, figure redrawn after Biddle, (1998)[8].](image-url)
Table 4. Moisture Content (%) variation away from mature Oak tree (Biddle, 1998)[8].

| DEPT | 2.5 | 2.8 | 3.1 | 3.4 | 3.7 | 4.0 | 4.3 | 4.6 | 4.9 | 5.2 | 5.5 | 5.8 | 6.1 | 6.4 | 6.7 | 7.0 | 7.3 | 7.6 | 7.9 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.30 | 15.54 | 16.41 | 15.06 | 20.9 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 | 21.06 |
| 0.80 | 25.58 | 30.02 | 30.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 | 31.06 |
| 1.30 | 25.58 | 28.11 | 28.57 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 |
| 1.80 | 25.58 | 28.58 | 27.50 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 | 28.54 |
| 2.30 | 25.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 |
| 2.80 | 25.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 |
| 3.30 | 25.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 |
| 3.80 | 25.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 | 28.58 |

Figure 8. Mature Oak tree near the toe of slope showing the moisture content (%) at the bases of the slices.
Figure 9. Mature Oak tree near the toe of slope showing the suction generated at the bases of the affected slices.

The existing slope parameters (Table 1) are maintained, and with the benchmark factor of safety of 1.32, the influence of matric suction caused by the tree (Stanφb) will simply be added to total resisting forces, and then the factor of safety recalculated. Biddle, (1998) indicated a soil moisture content variation at the proximity of mature Oak tree only to the limit of 3.5m depth as in figure 7 of which beyond that depth the moisture content basically remain the same irrespective of the time of the year.

Therefore, the Saturated Undrained Factor of Safety with the influence of mature Oak tree near the slope toe is given by

$$F_{OS} = \frac{\sum C_s + Stanφ^b}{\sum W_{inj}} = \frac{945 + 20.4}{715.87} = 1.35$$

The Factor of Safety increased by 2.2% from 1.32 (The saturated undrained FOS bench mark) to 1.35. It could be noticed that at this location, the tree suction affects only slices 1 and 2, whose slip line passes through the root zone. Although this value seems a little bit smaller compared to 7.7% obtained

| Slice No. | Height (m) | Unit wt (kN/m^3) | Breadth (m) | Alpha Deg | Matric Suction (kPa) | Gb | Stanφb |
|-----------|------------|------------------|-------------|-----------|----------------------|----|--------|
| 1.00      | 1.10       | 19.21            | 2.40        | 25.00     | 70.0                 | 16.0 | 20.1  |
| 2.00      | 2.85       | 19.21            | 2.40        | 21.00     | 1.1                  | 16.0 | 0.3   |
| 3.00      | 4.15       | 19.21            | 2.40        | 16.00     | 0.0                  | 16.0 | 0.0   |
| 4.00      | 5.85       | 19.21            | 2.40        | 11.00     | 0.0                  | 16.0 | 0.0   |
| 5.00      | 6.35       | 19.21            | 2.40        | 4.00      | 0.0                  | 16.0 | 0.0   |
| 6.00      | 7.05       | 19.21            | 2.40        | 2.00      | 0.0                  | 16.0 | 0.0   |
| 7.00      | 7.60       | 19.21            | 2.40        | 8.00      | 0.0                  | 16.0 | 0.0   |
| 8.00      | 7.60       | 19.21            | 2.40        | 12.00     | 0.0                  | 16.0 | 0.0   |
| 9.00      | 7.70       | 19.21            | 2.40        | 19.50     | 0.0                  | 16.0 | 0.0   |
| 10.00     | 7.50       | 19.21            | 2.40        | 25.50     | 0.0                  | 16.0 | 0.0   |
| 11.00     | 7.00       | 19.21            | 2.40        | 30.00     | 0.0                  | 16.0 | 0.0   |
| 12.00     | 5.95       | 19.21            | 2.40        | 37.00     | 0.0                  | 16.0 | 0.0   |
| 13.00     | 4.10       | 19.21            | 2.40        | 45.00     | 0.0                  | 16.0 | 0.0   |
| 14.00     | 1.45       | 19.21            | 2.40        | 52.00     | 0.0                  | 16.0 | 0.0   |

$$\Sigma = 20.4$$
by [16], with the same Oak tree at the slope toe. This may be as a results of different slope geometry used by former, as the tree root zone affects more slice in Rees and Ali, (2012) than in this work, considering this work used a slope within a London Clay formation whose nature of the water retention curve quite differed with the Boulder clay used by Rees and Ali, (2012). There are many factors that may likely affects this result as well, position of the tree with respect to the slope toe, nature of the tree root zone, slope geometry, shear strength parameters and time of the year when the moisture content data is collected.

4.1.2 Oak Tree on London Clay Slope Crest. The second case considered the effect of the same mature Oak tree on the Newbury slope crest at figure 10. All the properties of the tree and the slope mentioned in previous case remain the same. Due to the nature of the slope gradient and the chosen tree root architecture, only slice 14 is within the depth to be affected by suction generation.

The tree is situated 4.0m away from the centre line of slice 14, cutting the critical slip plane (CSP) of the slice at 1.45m depth. Having obtained the moisture content of 39.83% and converting it to capillary potential of -677.36cm using SWCC shown in figure 4, the suction obtained was 66.41kPa. And its value was then employed into the stability analysis as in the previous case.

![Figure 10. Mature Oak tree near the crest of the slope showing the suction at the base of the affected slice.](image)

The Saturated Undrained Factor of Safety with the influence of mature Oak tree near the slope crest is obtained and is increased by 2.00% from 1.32 to 1.34.

4.2 Horse Chestnuts on London Clay Slope
A mature Chestnut tree (*Aesculus Hippocastanum*) situated on a London Clay at King Edward VIII Park, Wembley London is chosen for this purpose, the tree based on Biddle, (1998)[8] was 15m high, with 67cm b.h.d and its drying pattern data is mapped onto a London Clay slope provided by (Smethurst et al., 2006)[5].

The root zone architecture is assumed to extend to a depth of 2.5m as in Hinckley et al., (1981)[20] and a radial distance of 5m from both centre line of the tree system [22]. As in previous case, the moisture variation of London Clay due to the proximity of mature Horse chestnut tree was traced from the work of Biddle, (1998)[5], and the data is then mapped on the Newbury slope, thereby determining the suction generated on the slope due to variation of the moisture content.
4.2.1 Mature Horse Chestnut on Slope Toe. The tree here is situated on the slope toe as in the previous analysis. The tree root zone crossed the CSP at the depth of 1.1m. The corresponding moisture content at its base is 39.87%, converting the moisture content into capillary potential and then to suction at the base of the affected slice gives -677.36cm and 66.41kPa respectively. The suction value is then employed into the stability calculation.

The Factor of Safety increased by 2.01% from 1.32 to 1.34

4.2.2 Mature Horse Chestnut on Slope Crest. The tree is situated 1.4m away from slice 14, with its root zone cutting the slice base at CSP at the depth of 1.45m. The corresponding moisture content is 40%, converting the moisture content into capillary potential of -653.58cm using SWCC yields a suction of 64.01kPa. The suction value is then employed into the stability analysis.

Again, due to the nature of the slope gradient, only slice 14 on the up-slope was affected when the tree is situated on the slope crest. The tree generated 64.01kPa of suction at the affected slope base, which in turn increases the Factor of Safety of the slope by 1.94% at 1.34.

4.3 Poplar Tree on London Clay Slope
A mature Poplar tree (Populus Salicaceae) situated on a London Clay at Woodcock Park, London is chosen for this purpose, the tree based on Biddle, (1998)[8] was 24m long, with 61cm b.h.d and its drying pattern data (Figure 12) is mapped onto London Clay slope as provided by (Smethurst et al., 2006)[5]. The root zone architecture is assumed to extend to a depth of 6.5m as in Dickmann et al., (1996) and a radial distance of 5m from both centre line of the tree system based on Urban, (2010)[22].

The moisture variation of London Clay due to the proximity of the mature Poplar tree was traced from the work of[19], and the data is then mapped on the Newbury slope thereby determining the suction generated on the slope due to variation of the moisture content.
Figure 12. Soil drying profile on London Clay 4m away from mature Poplar tree, figure redrawn after Biddle, (1998)[8].

4.3.1 Mature Poplar on Slope Toe

![Image](image-url)

Figure 13. Mature Poplar near the slope toe showing the spacial distribution of moisture content.

The moisture content at the base of slice 1 is 34.49% in figure 13 generating a suction of 364kPa. And slice 2 at the depth of 2.85m has the moisture content 46.01% yielding a suction of 53.1kPa. The suction values are then employed into stability calculation. A total of 417kPa of suction was generated due to the variation of moisture as a result of the tree being in the proximity of the slope, increasing the Factor of Safety of the slope by 12.65%.

4.3.2 Mature Poplar on Slope Crest. This case considers the effect of the same mature Poplar tree on the Newbury slope crest, all the properties of the tree and the slope mentioned in earlier remain the
same. The tree is situated at 3.3 m away from slice 14 centre lines, and due to the nature of the slope gradient and the chosen tree root architecture, only slice 14 is within the depth to be affected by suction generation. The suction generated at the base of slice 14 on the slope crest is calculated to be 91 kPa and same value is employed into stability analysis.

These results indicate that, the Poplar tree influences the slope stability more than both the other two trees (i.e. Oak and Horse Chestnut), this is largely due to the nature of its roots zone architecture extending deeper than the others. The result also indicated that trees with deeper and wider root zone significantly enhance the stability of slope as in Osman and Barakbah, (2006)[25] and Fatahi et al., (2010)[26], whose both indicated that the nature of tree root zone architecture have more influence on slope stability although with a much larger amount.

The general findings of all the analyses are summarily tabulated in the Table (6).

### Table 6. Factor Safety Summary table.

| S/N | Type of Analysis        | Factor of Safety | % Difference |
|-----|-------------------------|------------------|--------------|
| 1   | Saturated Undrained     | 1.32             | 0            |
| 2   | Oak tree at toe         | 1.34             | +2.15        |
| 3   | Oak Tree at crest       | 1.34             | +2.00        |
| 4   | Horse Chestnut tree at toe | 1.34           | +2.00        |
| 5   | Horse Chestnut tree at crest | 1.33      | +1.94        |
| 6   | Poplar tree at toe      | 1.49             | +12.65       |
| 7   | Poplar tree at crest    | 1.36             | +2.77        |

### 5. Conclusion

It can be clearly seen from Table (6) that, irrespective of their type, trees enhances the stability of embankment slope mostly when they are situated near the slope toe. Although 2% increase in Factor of Safety obtained from trees with shallow root zone is not overlay significant but 12.7% obtained from deep root zone tree is, therefore the findings indicate the magnitude at which trees with deep root zone enhanced the slope factor of safety albeit more on the slope toe. The work shaded more light as to importance of tree characteristics, on how it affects stability of slopes. Properties such as root zone, age, distance from the slope and water uptake are shown to have a significant role when it come to influence of tree on the slope stability. And all these are in one way or the other inter-dependent on the particular soil type and its conditions. This work considered influence of vegetation on slope stability on London clay based on the data provided by two different works. Various limitations and factors might have affect the findings of the work, as such the recommendations for further studies such as carrying out similar study on different type on soil such as boulder clay or considering different types of trees with different nature of the root zones and water uptake demands may be considered.

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