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ENHANCING SLOPE STABILITY WITH VEGETATION

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ABSTRACT: Landslides can have serious impact on natural and human environment and their prevention and mitigation is of global concern. The ability of a slope to resist a landslide depends on the materials and the properties of which it is composed. This project focuses on the increased landslide resistance of a slope due to vegetation. The properties of the soil-root composite were measured in laboratory and, from these results, calculation and graphically based evaluation was used to determine their qualities for resisting landslide. The results show that vegetation roots had a stabilising effect on the slope, limited to the rooting depth. Knowing the rooting depth (generally between 0.5 and 1.5 m) and dependent on the species, a correlation between the ratio of root weight to soil weight and the slope ability to resist landslide was implied from experimental results and a hypothetical design chart and equation were derived.

Keywords: Geotechnical Engineering, Slope Stability, Root Weight Ratio, Root Reinforcement, Ecological Engineering

1. INTRODUCTION

Slope stability is an important aspect of the built and natural environment. Slope failures and landslides can have a significant human and monetary cost. Understanding and preventing these failures is an important facet of environmental civil engineering and the contribution of vegetation towards increasing slope stability.

The use of vegetation to stabilise slopes is a practice which has been used throughout the world. This form of slope stabilisation has been described as 'Ecological Engineering' and defined as 'the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both' [1]. It is seen as a 'soft' engineering approach when compared to traditional, 'hard', methods of slope stabilisation, for example; soil nails, anchors, meshes, retaining walls, slope geometry modification etc. This, 'soft', approach offers many benefits such as increasing biodiversity, self-sustainability, cost effectiveness and visual aesthetics while being environmentally friendly [1].

There are two types of slope, natural and artificial [2]. Natural slopes are formed over time through geological and geomorphic processes, for example; mountain forming, river activity, glacial and tidal activity. These slopes are only stable if the soil of which they are constructed has sufficient stress to resist the gravitational forces exerted on the potential sliding mass.

Artificial slopes or earthworks are either cut into the ground (soil or rock) or built up as in spoil heaps, waste tips or embankments. Cut slopes and cuttings are made to provide access for infrastructure such as train tracks, roads, canals, etc .

Translational failure is defined as 'linear movement along a bedding plane or a soil layer lying near to the (sloping) surface' [3]. Such movements are 'normally fairly shallow and parallel to the surface' [3].

It is important to understand the ways in which soil and vegetation interact in order to be able to assess the safety of a slope to prevent human casualties and economic losses.

2. VEGETATION BENEFITS FOR A SLOPE

Reference [4] states that '…the most important and general problem is a shallow seated instability of a slope'. They also state that this is at a depth of around 0.5-2m below the ground surface and that this is in fact the most widespread form of slope failure particularly in cuttings and embankments. It can also be seen that vegetation roots anchor the vegetation and provide reinforcement of soil.

2.1 Factor of safety of unrooted and rooted soils

Reference [5] studied the effect on slope stability of two White Oak (*Quercus alba*) trees. The findings of their research say that depending on the potential slip surface, the factor of safety (FOS) varied from 2.8-3.7 and 1.8-2.0 for unrooted soil. When the mean value of the FOS increased significantly for surface depths of 0.3m, however as distance progresses to a depth of 1.2m these benefits diminish.

The F.O.S. for a slope may be calculated using the 'infinite slope model' [3]. This formula is shown below.

$$F = \frac{c' + (\gamma z - \gamma_w h)cos^2 \beta \; tan\varphi'}{\gamma z \; sin\beta \; cos\beta} \quad (1)$$

Where: c'- apparent cohesion of the soil (kN/m^2); z – depth to shear plane (m); H – height of ground water level above shear plane (m); γ – density of soil (kg/m^3); γ_w – density of water (kg/m^3); β – slope angle (^{0}); φ' – angle of friction (^{0})

The modified formula for translational failure on an infinite slope when including the effects of vegetation [6] is shown below.

$$F.O.S = \frac{(c' + c'R) + \{[(\gamma_Z - \gamma_W h) + W]cos^2\beta + \mathrm{T}sin\Theta\}tan\varphi' + \mathrm{T}cos\Theta\}}{[(\gamma_Z + W)sin\beta + \mathrm{D}]cos\beta} \quad (2)$$

The above formula, Eq. 2, incorporates four additional variables to the F.O.S formula for soil alone. These are; c'R – the enhanced shear stress due to roots (kN/m^2 or kPa), T- tensile root force acting at the base of the shear plane (kN/m), W – surcharge of the vegetation (kN/m^2) and D – wind loading parallel to the slope (kN/m). By adding these factors into the formula a F.O.S for soil including roots can be found. The authors comment that the most important variables in improving slope F.O.S. are the enhanced shear stress and the tensile root force.

3. EXPERIMENTAL WORK

It was decided that the direct shear test would be the most appropriate testing equipment to evaluate an improvement in resistance to translational failure due to root (vegetation) presence. Soil samples were cut/ extracted using a core cutter and placed inside the box (60x60x25mm) and tested as per BS 1377, 1990.

In order to ascertain the cohesion (c') of soil alone and the pseudo-cohesion (c'R) added by roots, incremental values of normal stress of 25.89, 39.51 and 53.14 kPa were applied to the samples. By comparison of these normal stress values against the values of shear stress obtained from the tests, graphs which showed the cohesive stress, c', and the angle of friction, φ, of the soil could be produced. Shear tests for each value of normal stress were carried out. The author was determined to evaluate whether the mass of vegetation within a sample would correlate to the increase in shear stress (ΔS) observed (if any) within the same sample. This root weight to soil ratio, 'root weight ratio' (RWR), is not strictly the same as the 'root area ratio' (RAR), the RAR is calculated by taking the diameter of all roots (generally larger roots, such as tree/ shrub roots) and finding the ratio of root area to soil area. In the case of grass it was decided that this would be extremely time consuming/ difficult to record accurate measurements. Instead, the RWR (the weight of the vegetation mass within the sample against the weight of the sample as a whole) would be measured in an effort to see if this is an adequate substitute for RAR in the instance of grass.

The soil was determined by inspection to be 'topsoil'/ 'organic' and by sieve test to be a 'well graded sandy soil'. The moisture content was also assessed. After each sample of rooted soil had been tested in the shear box, the superficial vegetation was removed and it was washed in a 1.18mm sieve from the sieve test rig. This particular sieve size was selected in order to allow finer soil material to pass through its apertures retaining any organic material. The remaining vegetation was allowed to dry in the laboratory. By comparing the weight of the dried roots against the original weight of the sample, the RWR was found and this could be compared against the shear stress found for that sample.

4. RESULTS AND ANALYSIS

4.1 Direct shear testing of the soil only

By plotting the results of the shear test (Fig.3), shear stress over normal stress, the apparent cohesion of the soil was found to be, c' = 10kN/m^2 and the peak angle of friction, φ' = 16^0.

4. 2 Slope F.O.S. for unrooted soil

The F.O.S. for the soil was calculated as [3]:

$$\text{F.O.S} = \frac{c' + (\gamma z - \gamma_w \, h)cos^2\beta tan\varphi'}{\gamma z \sin\beta \cos\beta} \quad (3)$$

Apparent cohesion, c' = 10kN/m^2 – Experimental result; Peak angle of friction, φ' =16^0 - Experimental result; Density of soil, γ= 10.6kN/m^3 – Experimental result; Depth to shear plane, z= 0.1 – 0.5m. This range of depths was chosen according to [7] as, 'maximum depth of roots of grass and forbs in temperate zones is usually no greater than 0.5'. Therefore below this depth any slip plane will be subject to the shear apparent cohesion and peak angle of friction of the soil alone; Density of water, γ_w = 9.81kN/m^3; Height of water table, h = 0.5m – This was chosen as a worst case scenario to give the lowest F.O.S. possible for completely saturated conditions.

Angle of slope, β = 45^0 was chosen as it is the upper limit of slope angle for the equation. Additionally, any slopes built of greater angles would likely use other technologies, for example geotextiles [6].

4.3 Direct shear testing

These tests (Fig. 3) showed that the apparent cohesion due to roots, calculated as c′R = c′ (roots and soil) – c′ (soil alone), was 10 kN/m^2.

In the case of vegetated soil, a modified version of the "drained infinite slope model" formula was used [6].

Assumptions: Depth to shear plane, z = 0.5m ; Density of water, γ_w = 9.81kN/m^3; Depth of water table, h_v = 0.5m. Surcharge of vegetation, W = 0 kN/m^2; Angle of slope, β = 45^0 - Chosen to keep consistency with calculation; Tensile root force, T = 9.34x10-3kN ; Angle between roots and slip plane, θ = 45^0; Wind loading force, D = 0 k N/m.

Assumptions: The weight of the surface vegetation and its subsequent normal force on the soil are quantified as 'W', the surcharge. This surcharge is included in the calculation primarily due to the plausibly high force exerted on soils by trees, in this instance 'W' has been assumed to be zero as the surcharge exerted by grass is likely to be very small and of little consequence.

The tensile root force for the grass used experimentally was not tested. This testing would require specialized equipment that was unavailable. As a substitute for this, a value for tensile root force from a similar grass [8] was used as 5 kN/m.

The wind loading force, 'D', is chiefly concerned with the effect of 'wind throw'. In the case of grass, the surface area upon which wind can act is small in comparison to trees, additionally grasses tend to be flexible and unlikely to transfer a great deal of force to the roots. The angle between roots and slip plane, θ, has been taken to be equal to that of the slope angle, β, as it was assumed that roots had grown in a gravitropic manner.

4.4 Root area ratio (RAR) modification

RAR is not uniform throughout its depth and it decreases non-linearly to zero between the surface and its lowest depth.

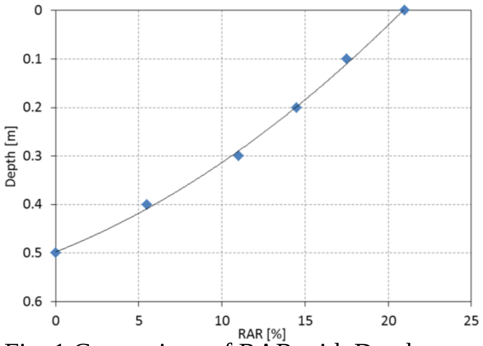

Fig. 1 Comparison of RAR with Depth

In order to account for this transition between soil with additional root cohesion, c′R, and soil with soil cohesion alone, c′, the c′R value has been factored down with depth according to a chart of RAR. Based on Fig. 1, an average line was calculated and drawn in order to find suitable reduction factors to take depth into account. Fig. 1 was created by averaging RAR values over depth from a graph of similar grasses [9].

4.5 Root Weight Ratio (RWR)

After testing, the rooted soil samples were washed clean of soil and the remaining roots dried and weighed. The ratio of the weight of the dry roots to the weight of the initial soil mass was calculated this was compared with the shear stress (equal to peak shear stress) found by testing for each sample. The results of this test are shown in Table 1.

Sample	Total Weight (g)	Root Weight (g)	Ratio (%)	Shear Stress (kN/m^2)
1	65.1	13.7	21.04	30.83
2	64.1	13.2	20.59	27.50
3	68	14.4	21.17	31.94
4	104	9.6	9.23	35.83
5	121	11.8	9.75	35.28
6	61.6	12.4	20.13	29.44
7	83.5	11.2	13.41	42.78
8	60	12.1	20.17	39.17
9	60	11.7	19.50	41.11

Table 1 RWR Results

5. DISCUSSION

5.1 Soil properties

The in-situ soil was determined to have a density of 1106.25kg/m^3 and a moisture content of 33%. The soil was classified as 'well graded sandy soil' in accordance with the British Classification System for Engineering Purposes and visually identified as 'topsoil' / 'organics'. All results and findings are only valid for these soil parameters pending further research.

5.2 Shear stress and angle of friction

It can be seen from the shear test results of both unrooted and rooted soils that the individual samples yielded varying results. This variation in results could be attributed to the non-uniform nature of different samples in terms of soil composition and in the case of rooted soils, root mass. When the results for each value of normal stress were averaged they produced values which gave linear lines with upward trends when graphed. This would be expected from soil samples subjected to increasing values of normal stress as increased loading would create greater compaction of the sample and therefore greater friction between particles/ roots and soil across the imposed shear plane.

The unrooted soil reached its max. shear stress 18.33, 24.72 and 27.59kN/m^2 for normal stresses of 25.89, 39.51 and 53.14kN/m^2 respectively. The rooted soil produced shear stress values of 30.09, 34.81 and 41.02kN/m^2 for normal stress values of 25.89, 39.51 and 53.14kN/m^2 respectively. When graphed, this showed that the apparent cohesion, c’, of unrooted soil was 10kN/m^2 and of rooted soil, 20kN/m^2, this apparent cohesion occurs under a normal stress value of 0kN/m^2 and is indicative of the stress of an unloaded soil. This indicates that the apparent cohesion due to roots, c′R, for this particular grass is equal to 10kN/m^2, at least for the root mass found at 0.125mm below the surface. From these results we see that the apparent cohesion of the soil has doubled due to the presence of roots.

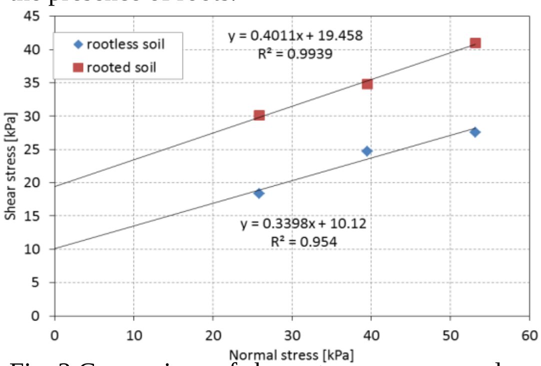

Fig. 2 Comparison of shear stress over normal stress for unrooted and rooted soils.

Fig. 2 demonstrates the comparison of rooted and unrooted soils, it can be seen that shear stress over normal stress rises linearly with what would appear to be a constant difference in shear stress of 10kN/m^2. This can be attributed to the presence of roots in the rooted soil samples.

5.3 Slope F.O.S.

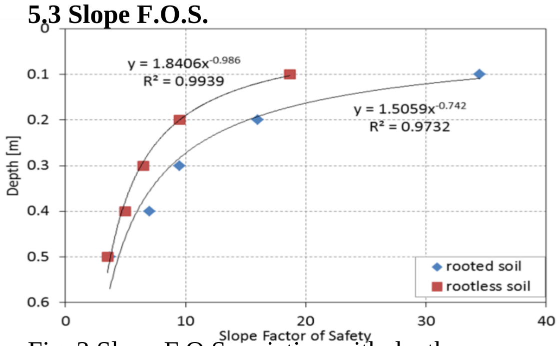

Fig. 3 Slope F.O.S variation with depth.

Since a vegetated slope would require to be unobstructed on its surface so that sunlight may reach the vegetation, the only normal stress which should be applied to the slope would be that of gravity and so the c′ and c′ + c′R values of unrooted and rooted soils are the most important values in this graph.

In Fig. 3, a comparison of F.O.S has been created for unrooted and rooted soil. We can see that the F.O.S for both soils decreases with depth, this would be expected as with additional depth, the horizontal force of a soil mass due to increasing area will increase, lowering its stability. We also see that with increasing depth the F.O.S of rooted soil reduces until at 0.5m it reaches the same value as rooted soil. This would be expected as due to the RAR modification applied to the rooted soil F.O.S. formula, c′R decreases from 0.84 to 0 between 0.1m and 0.5m depth. This shows that any increased F.O.S due to roots can only exist where roots are present in the soil and is dependent on their density at that depth.

Since the soil type used in the experiment has yielded apparent cohesion values c′ and c′R, of 10kN/m^2 and 10kN/m^2 respectively and given that calculated factors of safety have been high, a graph has been produced in which the apparent cohesion, c′, of the soil has been reduced from 10 to 0 kN/m^2 whilst keeping the apparent cohesion due to roots at 10kN/m^2. An assumption has been made in maintaining the c′R value at 10kN/m^2, this assumes that the vegetation will grow in a similar manner and to a similar density with depth as that of the soil used experimentally. The object of this comparison is to find the properties of a soil that may be improved to a useable standard by the vegetation used in this experiment. The slope angle used in this comparison will be 45^0 with a depth of 0.3m.

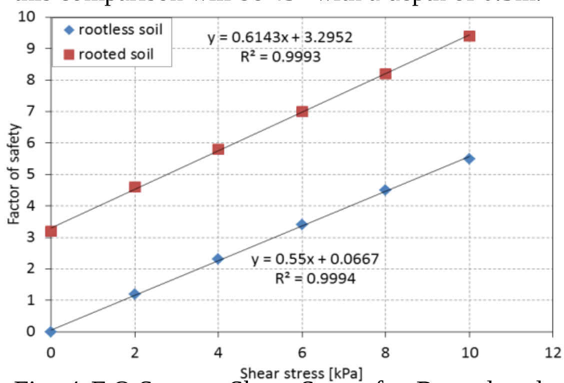

Fig. 4 F.O.S. over Shear Stress for Rooted and Rootless soil.

In Fig. 4, a comparison of the F.O.S. for unrooted and rooted soil whilst lowering the apparent cohesion, c′, of the soil and keeping the apparent cohesion due to roots, c'R, constant is presented. In this diagram we see that in order to keep a F.O.S. for slope stability above 1.5, a value of apparent cohesion, c', of around 2.2kN/m^2 is required for unrooted soil. The F.O.S. at this point for a soil rooted with the same vegetation used in the previous experiments was around 5.

5.4 Root weight ratio (RWR)

From laboratory experimentation, a positive correlation between RWR and shear stress was found and shown on Fig. 5. Sample 1 had a RWR of 21.045% and a shear stress value of 30.83kN/m^2, Sample 2 had a RWR of 20.593% and a Cu of 27.5kN/m^2 and Sample 3 had a RWR of 21.176% and a Cu of 31.94kN/m^2. Other samples exhibited this relationship however due to the problem of weight variance, the set of results for normal testing of 25.89kN/m^2 have been selected for further discussion as these results used samples with the smallest weight variance. To investigate this further, the relationship between RWR and Shear Stress was plotted along with the average shear stress of soil for the same normal stress, 18.33kN/m^2.

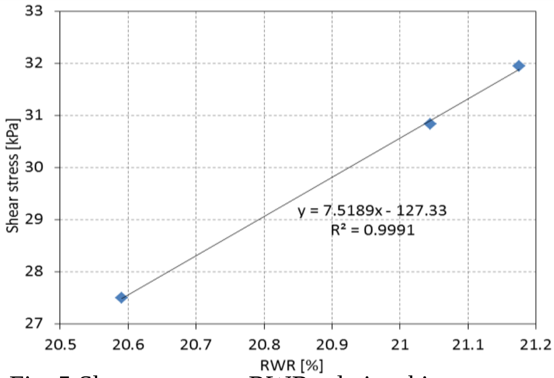

Fig. 5 Shear stress vs RWR relationship

Fig. 6 shows the increase in shear stress from the first point, unrooted soil (e.g. 0% RWR) to the later three rooted soil points. The black line indicates the trend of the rooted soil points, this trend appears to be linear and as no greater values of RWR were found during the experiments, only assumptions can be made. An assumption would be that the RWR (%) in a soil must tend to an upper limit. The samples of rooted grass were from a mature lawn which has had over ten years of growing time, perhaps for this grass type and possibly the soil conditions present, values of RWR(%) will not exceed approximately 23-25% as this may be a limit.

Since there appears to be a correlation between RWR and shear stress, an assumption would be that between values of RWR of 0 and 21.176% (the highest value), shear stress must rise in a polynomial curve, the data points of which are plotted in Fig. 6. The reasoning behind this assumption is based on two main facts evidenced by the experimental results:

A RWR of 0% must be equal to 18.33kN/m^2 as this is the shear stress of the soil itself under a normal load of 26.89kN/m^2. The trend line in Fig. 6 cannot continue linearly as it would cross the RWR axis at roughly 16-17(%). This would indicate that when RWR is equal to 16-17%, shear stress is zero. This cannot be true as the shear stress of the soil alone is 18.33kN/m^2 under a normal load of 26.89kN/m^2.

5. 5 Assumed polynomial curve

In Fig. 6 an assumed curve has been plotted based on the assumptions. This curve increases linearly before tending to a limit. In an attempt to describe/plot the hypothetical curve shown in Fig. 6, a polynomial equation was used.

Unfortunately due to the lack of data for samples with RWR greater than 1 and less than 20.593% this produced an unsatisfactory curve with negative values. In order to produce a satisfactory curve, three additional points were plotted on the hypothetical curve and these were used to create a formula which accurately described the hypothetical curve. The points were applied at RWR's of 5, 10, 15% and yielded approximate shear stress values of 19.5, 21 and 22.5kN/m^2 respectively. Once applied to the graph, a polynomial curve was drawn and an equation describing the curve derived, Eq. 4.

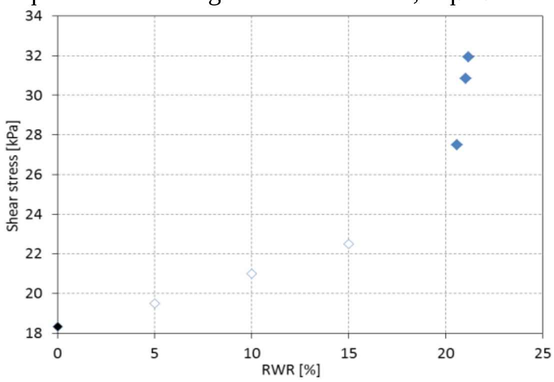

Fig. 6 Modified c'R +c' over RWR graph.

The derived equation:

$$\boldsymbol{y = 0.0003x^4 - 0.0107x^3 + 0.1072x^2 - 0.0777x + 18.331} \quad (4)$$

When modified to replace the axis denotations we arrive at a hypothetical formula to obtain shear stress from root weight ratio, Eq. 5.

$$c'R + c' = 0.0003RWR^4 - 0.0107RWR^3 + 0.1072RWR^2 - 0.0777RWR + 18.331 \quad (5)$$

"Total apparent cohesion ($c'R$ + c') over root weight ratio (RWR) equation."

For values of $c'R+c'$ in kN/m^2, RWR in percent (%) and where $c' = 18.331\ kN/m^2$.

6. CONCLUSIONS

The aim of this project was to investigate the relationship between vegetation and slope stability in order to assess its benefits and to investigate whether a relationship between RWR and shear stress existed. The key findings of the project are discussed in the following sections.

Laboratory experiments have confirmed that vegetation roots increase the shear resistance, angle of friction and therefore the F.O.S of a soil however this increase is not uniform with depth. For the soil used in the experiments, vegetation was shown to improve the F.O.S by 75% at a depth of 0.1m however this diminished to 0% by 0.5m. It has been seen that, depending on the species of vegetation, roots may not grow to a depth below the shear plane, rendering them ineffective in slope stabilisation. Due to this, shear plane depth and root growth depth should be a major consideration when using vegetation to stabilise a slope. The grass tested in this project, could not be used to stabilise any slopes with shear planes deeper than 0.4m but could perhaps be useful if used in conjunction with other vegetation.

Reference [5] discussed how areas of reduced ΔS, increased shear stress due to roots, could occur between trees stabilising a slope. Perhaps the grass used in this dissertation or a similar variety could be used to improve ΔS between trees to stop localised failures. References [10] and [11] discussed how artificially planting 'live stakes' on a slope at depths of up to two meters has been shown to be an effective form of stabilisation. This method is particularly attractive as it provides immediate stabilisation and can be planted at a depth of up to 2m which is greater than most vegetation roots can grow. This method is also easier to understand and model when compared to a root mass as the 'live stakes' act in a similar manner to soil nails.

Root weight ratio (RWR)

The RAR of roots in a soil mass was found to be of great importance as this diminished with depth and correlated with $c'R$. The RAR with depth varied between vegetation species and this would have to be considered in order to create an effective 'Ecological Engineering' slope stability solution. The difficulty of measuring RAR for grasses was discussed as being difficult due to the small nature of grass root diameter (centipede grass roots averaged 0.66mm in diameter). For this reason, it was decided to see whether the RWR would be an adequate substitute.

When using samples of a similar weight, the results strongly suggested a correlation between RWR and $c'R$. Criticisms that could be made of the hypothetical formula include the fact that only one soil type/ grass type was tested, low amount of data used to plot graphs and the assumptions made. Further research would be required to validate the results found in this research.

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