Experimental and numerical study on soil reinforcement by vetiver grass root system in bioengineering stabilization of soil slopes

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ABSTRACT
In this paper, vetiver grass which has 40cm long and dense 1mm thin root system was implemented in slope vegetation. Laboratory and field compression and shear tests were conducted on soil with and without vetiver grass roots. Test results indicate that vetiver grass root can increase shear strength and improve ductility of soils. Simple soil mechanic model for vegetated soil was proposed for calculation and design. It is suggested that vetiver grass can be utilized in combination with basic soil foundation works such as bottom retaining walls and large-space-distributed short soil nails for bioengineering stabilization of shallow slopes. A simple but important model is suggested for numerical analysis of vegetated soil. Finite element analysis is conducted on a soil slope with and without vetiver grass vegetation.

RÉSUMÉ
Cet article présente l'application d'un système de type herbe vétiver de 1 mm de longueur et ayant de racines de 40 cm pour la végétation des pentes. Des essais de compression et de cisaillement au laboratoire et au terrain ont été réalisés sur le sol avec et sans système de végétation vétiver. Les résultats des essais ont indiqué que la racine de l'herbe de vétiver peut augmenter la résistance au cisaillement et améliorer la ductilité des sols. Un modèle simple de mécanique de sols végétalisés a été proposé pour le calcul et pour la conception. Il est suggéré que l'herbe de vétiver soit utilisée en combinaison avec les travaux de fondation de sols tels que les murs de soutènement et dans la technique des sols cloués pour améliorer la stabilité superficielle des pentes.

1 INTRODUCTION

Due to the high intensities of rainfall, unprotected soil slope can easily be broken down by the energy of rain. Detached soil particles are removed via rill erosion or inter-rill erosion. In addition to soil erosion, landslides usually occur during rainy seasons (Shields and Gray, 1993). Soil and water erosion, instability and failure of deep and shallow seated slopes, and the correspondingly induced environment pollution and disaster, have been becoming key issues between human beings and nature. Shallow-seated slip or shallow mass movement within 1.5 meters depth, comprise the majority of problems faced by people after slope formation, especially in regions with prolonged and high rainfall. To tackle this problem, engineers conventionally rely on the use of 'hard' or 'inert' material such as mortared riprap, shot-concrete or sealing off the slope to prevent water infiltration (Shields, 1991; Shields and Gray, 1993). In slope protection design and construction, retaining wall, anchor and pile are usually the most favourable techniques. Vegetation bioengineering stabilization of slopes is still considered as the routine activities of the landscape engineers mostly for green purpose. However, if some special plants with strong and long root system such as vetiver grass etc., are adopted for slope stabilization from a point view of engineering, and in combination with some necessary geotechnical measures, more and more environmental and economic advantages would play a role in both engineering and garden art application (Zhou, 2008).

People resort to vegetation to help strengthen the surficial 1.5 meters deep layer that is prone to slippage (Gray and Sotir 1992, 1996; Greenway etc., 1984). On the other hand, in order to maintain good geo-environment, protect and recover the polluted eco-system, appropriately maintained and lower-cost vegetation either self-seeded or planted can have the same significant influence to help provide additional stability to soil slopes (Zhuo etc., 2006). Bio-engineering stabilization of slopes had been investigated for several decades due to its economic advantage and green function. Although the benefits and drawbacks associated with vegetation have been the subjects of some debates in recent years, biotechnical stabilization has been used successfully to stabilize and repair steep slopes along highways. One of the earliest applications was reported by means of contour wattling to stabilize steep, fill slopes along the Angeles Crest highway in southern California. Recent examples of soil bioengineering solutions for the stabilization of a highway cut slopes are discussed by Gray and Sotir (1992). Models based on physiology and ecology had been developed to approximate the contribution of tree roots to slope stability (Abe, 1990; Abe and Ziemer 1991; Wu etc., 1988; Wu and Beal 1988; Wu and Watson, 1998).

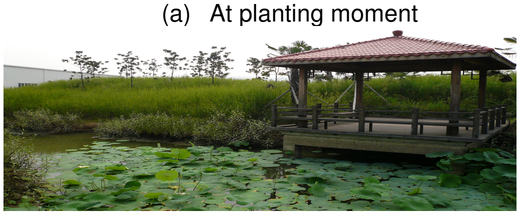
Vetiver, a plant promoted to help conserve soil and water for farmland by the World Bank in the 1980's, has evolved strongly in the late 1990's to become an important soil bioengineering tool ever since the late 1990's (Xu, 2003). However, there are still less researches on slope stabilization with vetiver grass roots, whether in experimental or numerical modeling. Analysing the stability of vetiver grass root reinforced slopes under various conditions is becoming vitally important. The stability analysis of root-reinforced slopes must take account of the properties of roots from laboratory shear tests, as well as their interaction with the surrounding soil. The obtained laboratory modeling results and numerical schemes may be used for the analysis of more complex engineering problems associated with vegetations. In this paper, how vetiver grass roots help in the strengthening soil slope is investigated. Experimental study is performed on soil samples containing different fractions of fiber root of vetiver grass. In situ direct shear test under a normal stress corresponding to the potential shear planes is also conducted. A simple but important model is suggested for numerical analysis of vegetated soil. Finite element analysis is conducted on a soil slope with and without vetiver grass vegetation.

2 TESTS ON VETIVER ROOT STABILIZED SOIL

2.1 Vetiver grass test field and soil behaviour

Vetiver grass was planted to stabilize a shallow slope in Nanjing Hydraulic Research Institute, China (see Figure 1). The strips of vetiver grass were spaced at 1 meter intervals along the contour of the catchment. Within each strip, slips composed of 2 or 3 tillers each were planted at 0.15 meter spacing within the row. The vetiver grass was managed by cutting it back to a height of about 0.4 m twice during each rainy season. This practice helped to promote tillering and thereby form a more solid barrier of grass within the contour strip.

(a) At planting moment



(b) After 1year

Figure 1. Vetiver grass planted before and after 1 year

In laboratory tests, weight ratio between vertiver grass live fibre root and soil was desired as 0.0015 and 0.002. Physical properties of the soil are: w_l = 30.8 %, w_p = 19.2 %, I_p = 11.6 %, G_s = 2.72, w_{op} = 16.0 %, $\gamma_{d,\max} = 1.8$g/cm3.

2.2 Uniaxial compression tests

2.2.1 Oedometer compression test

The properties of soil samples are listed in Table 1.

Table.1 Sample data for oedometer compression test

height/cm	Area/cm^2	Specific gravity	Dry density/(g.cm^{-3})	e_0
2	30	2.72	1.71	0.59

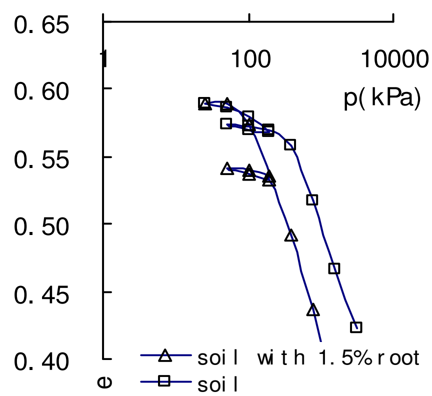


Figure 2. Oedometer compression test result

Oedometer compression test results (Figure 2) indicate that the soil is intermediate compressive, and the soil without grass root is less compressive than that with grass root in compression. This is to say that grass root does not reinforce the soil in oedometer compression tests. Is it true? Actually there are fissures between scattered fibre roots and soil particles during compaction test and thus more compression occurs. Triaxial compression may give a positive answer due to root reinforcement against shear.

2.2.2 Unconfined compression tests

The properties of soil samples are listed in Table 2.

Table.2 Sample data for unconfined compression test

height/cm	diameter/cm	Area/cm^2	Volume/cm^3
8	3.91	12	96

It can be seen from the unconfined compression test result (Figure 3) that the peak strengths are similar between soil sample with root and pure soil sample. However, although root does not increase the unconfined compression strength, it does improve the ductility of soil in shear resistance. This behavior helps to maintain progressive deformation of soil slope by vetiver grass root rather than catastrophic failure of the soil slope.

2.3 Direct shear tests

2.3.1 Laboratory direct shear test

The properties of soil samples are listed in Table 3.

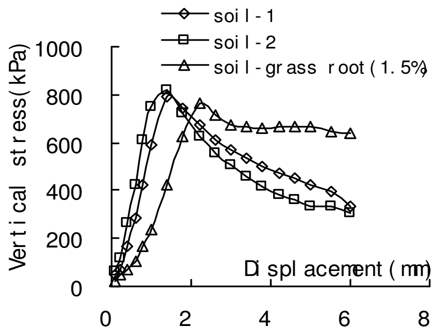


Figure 3. Unconfined compression test result

Table.3 Sample data for direct shear test

height/cm	diameter/cm	Area/cm^2	Volume/cm^3
2	6.18	30	60

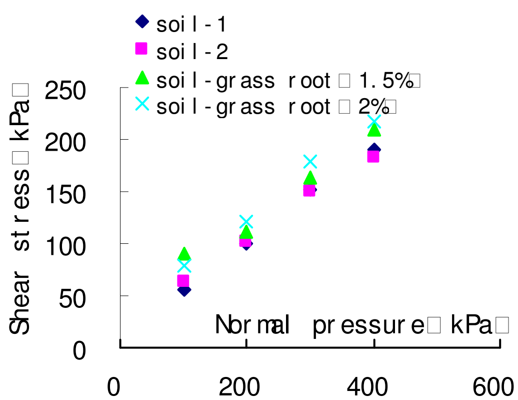


Figure 4. Laboratory direct shear test result

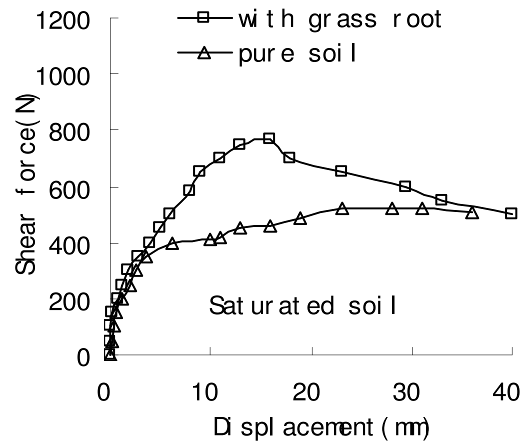
The laboratory direct shear test results (Figure 4) indicate that, grass root increased the cohesion and shear strength of soil obviously, and the higher the addition of fibre root, the larger the increases of strength, however there perhaps is a critical value for the amount of root fractions.

2.3.2 Field direct shear tests

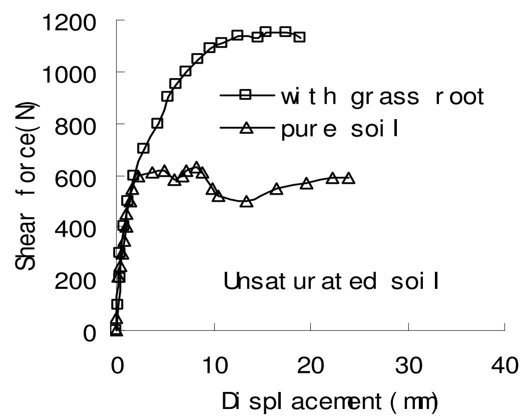
The field direct shear tests were conducted on saturated and unsaturated soils with and without vetiver grass roots, so that effect of suction can be separated from the effect due to root reinforcement.

It can be found from the field direct shear test results (Figure 5) that, grass root increased the shear strength of saturated and unsaturated soils, and the deformation modes for saturated and unsaturated soils with and without roots are different. For saturated soil, root reinforcement effect disappears at large deformation, maybe because root-soil interaction is released at failure state. For unsaturated soil, this phenomenon does not appear in the test, but it could perhaps be observed at larger deformation. Without roots, saturated soil exhibits hardening while unsaturated soil displays softening, and this difference is induced by the apparent over-consolidation due to suction effect. Interestingly with roots, saturated soil exhibits softening while unsaturated soil displays less softening, and this difference has to be interpreted by the combined effect of suction and root reinforcement.

It should be noted that, root reinforcement is permanent with vegetation root alive; however suction effect is temporary due to climate change. When ground water level uplifts, suction decreases and shear strength is reduced. Therefore only root reinforcement effect could be analyzed in practical design for vegetated slope. The combined effect between suction and root reinforcement is worth further investigation, because patterns of soil drying/wetting and moisture state in the vicinity of vegetation on clay soils are very important in unsaturated slope analysis (Biddle, 1983; Zhou, 2008).



(a) Saturated ground with and without grass root



(b)Unsaturated ground with and without grass root

Figure 5. In-situ direct shear test result

3 MODELLING ROOT REINFORCEMENT EFFECT

Groups of vetiver grass roots can be taken as “micro-anchors” in soil. Research on reinforcement effect of vegetation roots can include analysis of the influence of both the spacing and number of the roots as “micro-anchors", on the deformation and failure of the soil slopes (Roering etc. 2003, Watson and Dakessian, 1981; Watson and O'loughlin, 1985). However this method may be difficult to implement, and particularly soil-root interaction is most difficult to assess and calculate.

A simple model has to be developed to interpret the root reinforcement effect. From the above test results we can see root reinforcement increase the apparent cohesion or shear strength. This finding can only be useful if we adopt Duncan's hyperbolic model or Mohr-Coulomb model in numerical analysis, in which cohesion is a basic parameter. However as we know, Duncan's hyperbolic model can not be used for general analysis such as dilation and softening etc, therefore the test-derived apparent cohesion can not be directly utilized in numerical calculation and an alternative model has to be developed based on the test results.

Given fabric yield (GFY) model was proposed by Leroueil and Barbosa (2000) to interpret suction effect or microstructure effect from unsaturated to saturated or from microstructured to reconstituted soils. The key issue in this model is the combination with expansion or contract of cone and cap limit state curves during the corresponding hardening or softening process, by means of a mathematical relationship between anisotropic yield stress and apparent cohesion or shear strength.

When root reinforcement effect is in consideration for increase of shear strength (denoted as $\Delta\tau_f$ with a constant effective frictional angle ϕ') on the side of cone limit state surface (see Figures 4 and 6 from OC to O_1C_1), according to GFY model there should be increases of vertical and lateral yield stresses σ'_{aLb} and σ'_{rLb} of the saturated soil from OABC (pure soil without grass root) to $O_1A_1B_1C_1$ (vegetated soil with grass root) on the side of cap limit state surface.

$$\sigma'_{aL} = \sigma'_{aLb} + \Delta\tau_f \frac{1+\sin\phi'}{\sin\phi'\cos\phi'} \qquad [1]$$

Assuming soil fabric is maintained as the same as in saturated state, and then the anisotropic fabric can be defined by an anisotropic line (AL) with its slope being expressed as

$$K_{AL} = \frac{\sigma'_{rL}}{\sigma'_{aL}} = \frac{\sigma'_{rLb}}{\sigma'_{aLb}} \qquad [2]$$

Combining eqns. [1] and [2], the increase of lateral yield stress due to root reinforcement effect can be expressed as

$$\sigma'_{rL} = \sigma'_{rLb} + K_{AL}\Delta\tau_f \frac{1+\sin\phi'}{\sin\phi'\cos\phi'} \qquad [3]$$

With the same methodology as in GFY model (Leroueil and Barbosa, 2000), cohesion increase due to root reinforcement effect can be linked with preconsolidation pressure, so that extended series of Cam-clay model can be used for vegetated soil slopes. Here only the mathematical relationship between preconsolidation pressure and apparent shear strength are given. Other development is similar to Cam clay model (Zhou, 2008).

When nonlinear release of the soil-root interaction is considered during progressive deformation process of slope, the progressive strength loss from soil-root system failure can be analyzed as

$$\sigma'_{a/rL} = \sigma'_{a/rLb} + \sigma_c \left(\frac{\sigma'_{a/rLb0} + \sigma_c}{\sigma'_{a/rLb}} \right)^{b_\sigma} \qquad [4]$$

Where σ_c is the increased strength due to soil-root interaction, which may be calculated from measured $\Delta\tau_f$, and b_σ is the index for description of this progressive failure.

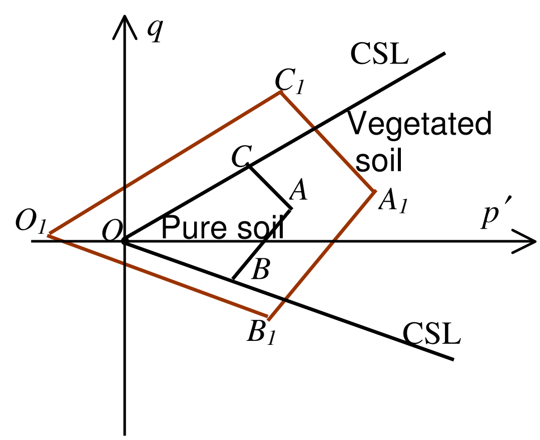


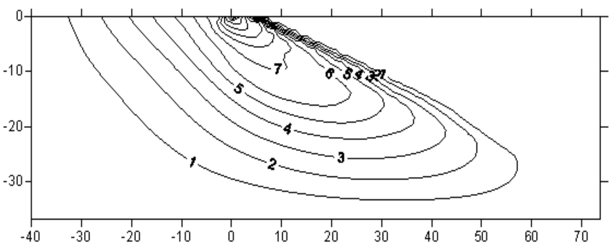
Figure 6. Illustration of GFY model extension for vegetated soil with root reinforcement effect

4 NUMERICAL ANALYSIS OF VEGETATED SLOPE

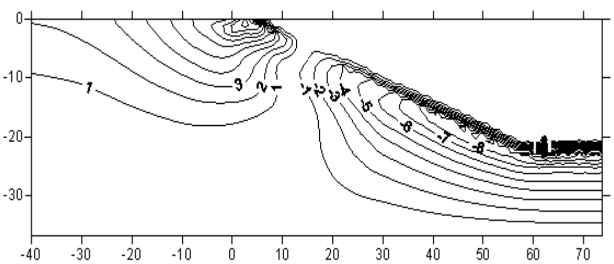
By use of the equilibrium equation, the continuum equations of pore water and pore air, and in consideration of other supplementary equations such as the compatibility equation, the constitutive equation, and the soil-water characteristic curve equation, the finite element equation for saturated and unsaturated soils can be given in a generalized incremental form (Zhou, 2008), whereas the matrices concerning pore water pressure and pore air pressure are different.

$$\begin{bmatrix} [K_{ep}] & \tilde{L} \\ \tilde{L}' & \Delta t\tilde{H} \end{bmatrix} \begin{Bmatrix} \Delta\tilde{U} \\ \Delta U_w \end{Bmatrix} = \begin{Bmatrix} \Delta\tilde{F} \\ \Delta\tilde{Q} - \tilde{H}U_{w,old} \end{Bmatrix} \qquad [5]$$

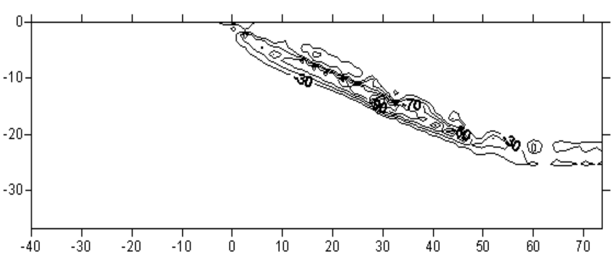
where the matrixes $[K_{ep}]$, $[L]$, $[L']$ and $[H]$ are stiffness matrix for saturated or unsaturated soils, coupling matrices and flow matrix, respectively. $\{\Delta U^n\}$ and $\{\Delta U_w{}^n\}$ are vectors of nodal displacement increments and nodal pore water and pore air pressure increments, respectively. $\{\Delta F^n\}$ and $\{\Delta Q^n\}$ are general load and flow vectors, respectively.



(a) Lateral displacement (mm)



(b) Vertical deformation (mm)

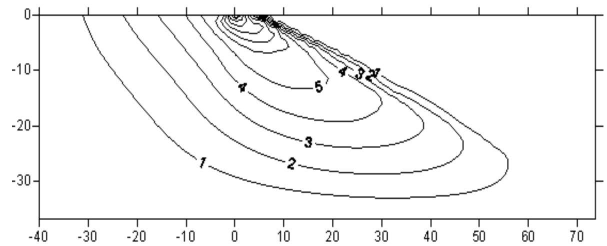


(c) Pore water pressure (kPa)

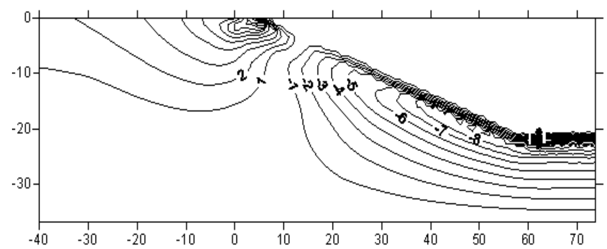
Figure 7 Finite element computed results for naked slope with rainfall infiltration after initial slope excavation

The Newton-Raphson iteration scheme can be used for the solution of the nonlinear finite element equations in Eqn. [5]. Within each increment step, the iteration is continued until the node displacements satisfy the convergence criterion.

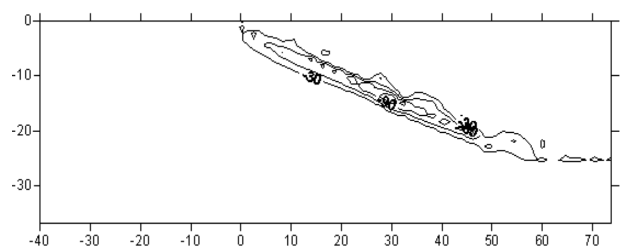
When finite element analysis is performed for naked and vegetated slopes, root reinforcement effect is considered in constitutive equation, as shown in Eqns.[1] to [4]. On the other hand, because roots increase ductility of soil, the air entry value is different for soils with and without roots. For example, in vegetated slope soil is less easy to crack at saturated state. However without vegetation soil slope is easy to crack, and soil has a smaller air entry value than vegetated soil. This means that when rainfall comes, suction loss will be less for vegetated slope than naked slope. By means of constitutive equations [1] to [4] plus air entry suction variation for vegetated slope, finite element analysis gives different results for soil slopes, as shown in Figures 7 and 8. It can be seen that with vegetation protection, soil slope has less deformation and less suction loss during rainfall period than naked slope.



(a) Lateral displacement (mm)



(b) Vertical deformation (mm)



(c) Pore water pressure (kPa)

Figure 8 Finite element computed results for vegetated slope with rainfall infiltration after initial slope excavation

5 CONCLUSIONS

The potential engineering influences of vetiver grass roots and how they can be characterised on site within a geotechnical framework for slope deformation control and stability assessments should be investigated thoroughly via laboratory and theoretical study. The direct reinforcement available from the roots of vetiver grass was identified as providing one of the most significant contributions to slope stability. Studies demonstrated how results from experimental tests and numerical modeling may be used to estimate the potential reinforcement effects available from the vetiver grass roots and the influenced zones within the soil. Some conclusions can be drawn from the preliminary test and numerical analysis:

(1) Soil could be reinforced by vetiver grass root. The reinforcement effect could be described by means of increases of apparent cohesion or shear strength.

(2) A simple model is suggested on the root reinforcement effect that cohesion increase can be interpreted by the corresponding change of preconsolidation pressure, so that Cam-clay type models can be used for vegetated slopes.

(3) Soil reinforced by grass root exhibits progressive deformation behaviour because roots improve both shear strength and ductility of soils. Therefore grass roots can help change the deformation and failure mode of soil slopes from a catastrophic failure case to progressive failure case.

(4) Vegetated soil slope has less downwards deformation and less suction loss during rainfall period than naked slope.

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