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Centrifuge Modelling of Vegetated Slopes under Earthquake Loading

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ABSTRACT

The behavior of vegetation-reinforced slopes during a sequence of successive earthquake motions was investigated using centrifuge model tests at 1:10 scale. The model roots used in this study were fabricated using Acrylonitrile Butadiene Styrene (ABS) plastic using 3D printing (rapid prototyping). It is shown that in this case, the presence of root system significantly decreases permanent settlement at the crest of the slope. The majority of the reduction was observed during the first two motions, which was related to the mobilization of the root-soil interaction as the roots bend in response to the soil kinematic loading. After this, less difference was observed because the root shear strength contribution reached a limiting value. Discontinuity Layout Optimisation (DLO) calculation was then employed to better understand the failure mechanism of rooted slope and it was found that the improvement of slope performance is mainly mobilized by the increase of yield acceleration and decrease of acceleration response spectra (ARS).

Introduction

Earthquakes are one of the major triggering causes for landslides (Malamud et al. 2004). Damage from seismically induced landslides and other ground failures sometimes exceeds the damage directly caused by the ground shaking and fault rupture and minimizing this damage has been one of the major concern to geotechnical engineers (Kokusho & Ishizawa 2006). Many types of traditional geotechnical methods have been used to improve the slope stability, such as soil nailing, piles and retaining walls. Vegetation, as an environmental-friendly approach, has been widely used in many natural and man-made slopes in recent years, and it has been generally recognized that this can increase the stability of slopes under static conditions (e.g. Wu 1976; Wu et al. 1979; Mickovski 2010; Sonnenberg et al. 2011). There is anecdotal evidence that vegetated slopes also perform better than fallow slopes during earthquakes. However, little research has yet been reported on the dynamic behavior of slopes planted with vegetation due to the extreme expense and difficulty involved in conducting full scale dynamic testing on shrubs and trees.

Geotechnical centrifuge modelling is an approach which can simulate the global performance of a full-scale soil slope prototype to a high level of fidelity, by achieving similitude of stresses at homologous points within the model and prototype, and offers an effective way to investigate the performance of rooted slopes (e.g. Sonnenberg 2008; Eab et al. 2014). This paper will describe the use of centrifuge modelling to simulate the seismic performance of a slope reinforced with plant root analogues. Compared with the tap root system reported in Liang et.al (2014), heart / plate root system will be modelled here. In addition to the centrifuge tests, Discontinuity Layout Optimisation (DLO) calculations will also be presented to investigate the effects of the roots on yield acceleration to better understand the performance of the slope as observed in the centrifuge.

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Centrifuge Modelling

The dynamic geotechnical centrifuge facility at University of Dundee, UK was used to perform the experimental studies. An Actidyn Q67-2 unidirectional servo-hydraulic earthquake simulator (EQS) was mounted on the centrifuge, which has a radius of 3.5 m and a total payload up to 1500 kg. The EQS was used to simulate a one-dimensional prescribed base input earthquake motion and has a maximum payload of 400 kg, with a maximum table displacement of 2.5mm and a peak operation of 80g. The motion can be exerted to a maximum horizontal acceleration of 40g, over a model scale frequency range of 40 to 400Hz. More details about this equipment can be found in (Brennan et al. 2014). The model was constructed in an equivalent shear beam (ESB) container with internal dimension of 669 mm × 279 mm × 338 mm. The ESB box was constituted of a stack of 6 solid aluminum frames mounted on a rigid, 12 mm thick, aluminum base. The frames are separated by rubber interlayers positioned in between them. The design and construction of this ESB container is described in detail by Bertalot (2013).

Two identical slope models designated as TL03 and TL04 were tested at a scale of 1:10. Among them, the model slope TL03 was reinforced with straight root analogues with a predefined distribution (Figure 1), and was designed to represent a heart / plate root system of tree roots, of which most of the individual roots behave independently. The model TL04, which had identical slope geometry and soil properties but was fallow (unreinforced with roots), was designed as a reference case for the model TL03. The slopes were prepared at a relative density of 55%-60%, had an angle of 27° and a height of 2.4m from toe to crest, with a further 0.8 m underneath. Dry HST 95 silica sand was used to build the models. The characteristics of this sand are shown in Table 1.

During pluviation, the soil was instrumented with 13 type ADXL-78 MEMS accelerometers (ACCs) manufactured by Analog Devices Inc. measuring the horizontal accelerations within the soil specimen. Three external linear variable differential transformers (LVDTs) were also used to measure permanent vertical slope deformations, with one installed at the centre of the crest and the other two placed adjacent to the side walls at different distances along the crest to detect any boundary effects on this.

Table 1. State-independent physical properties of HST95 silica sand (after Al-Defae et al. 2013)

Property	HST 95 silica sand
D_{10}:mm	0.09
D_{50}:mm	0.16
C_u	1.9
C_c	1.06
γ_{max}: kN/m^3	17.6
γ_{min}: kN/m^3	14.3

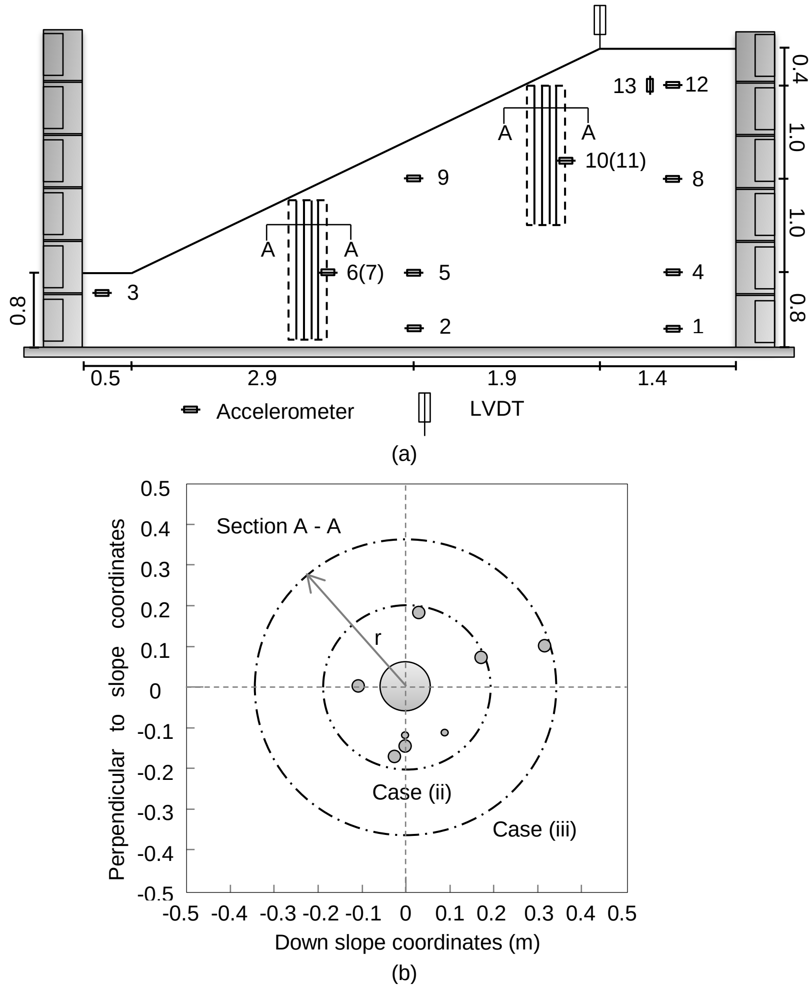

Figure 1. Slope configuration: (a) centrifuge model layout and instrumentation; (b) distribution of root group. All dimensions in m at prototype scale.

The two models were each subjected to eight successive earthquake motions, comprising three different records with distinct peak ground acceleration (PGA), duration and frequency content. The first motion (EQ1) was recorded during the 1995 Aegion earthquake (M_s 6.2) and was predicted to cause only a small amount of slip and predominantly acts to characterize the elastic dynamic behavior of the slope. This initial motion was followed by three nominally identical stronger motions (EQ2 – EQ4) from the 1994 Northridge earthquake (M_s 6.8) and a further three (EQ5 – EQ7) from the 2009 L'Aquila earthquake (M_s 6.3), followed by a final Aegion motion (EQ8). The three motions were downloaded from the PEER (Pacific Earthquake Engineering Research) Next Generation Attenuation model database and are shown as acceleration response spectra (ARS), normalized by the peak acceleration for the case of a system with 5% structural damping, in Figure 3(a). The motions were each band-pass filtered using an eighth-order Butterworth filter to obtain demand motions (Figure 3(b)) which were within the controllable range of the EQS. At 1:10 scale this range is between 4Hz and 30Hz (40-300Hz at model scale). It is also worth mentioning here that at 1:10 scale much of the low frequency content of the original earthquake signal is lost, however, the low scale factor is essential to minimize unwanted grain size effect between root analogues and the soil particles.

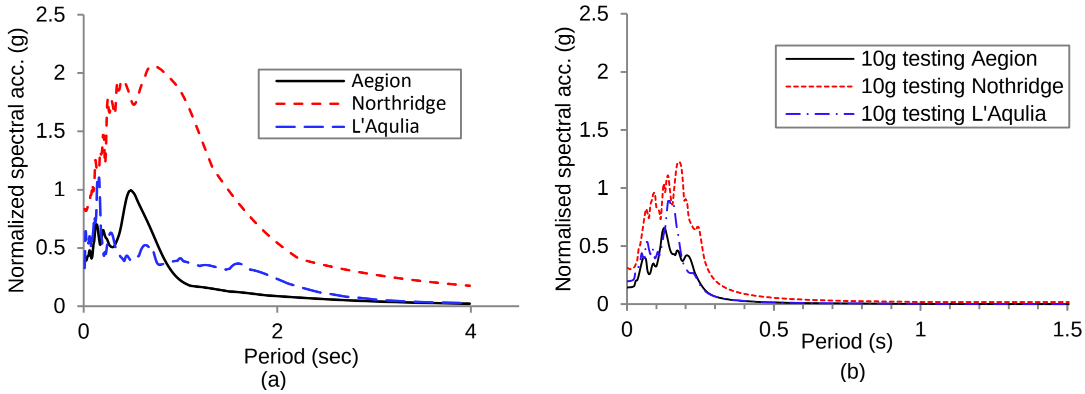

Figure 3 Normalised acceleration response spectra (ARS): (a) initial motion recorded in the field; (b) input motions for centrifuge modelling

Model Root Analogues

The straight root analogues were 150 mm (at model scale) in length and were fabricated using a Stratesys Inc. uPrint SE Acrylonitrile Butadiene Styrene (ABS) prototyper (also known as a 3D printer) at the University of Dundee following the procedure outlined in Liang et al. (2014). The ABS plastic was delivered into the machine in the form of pipe, melted, injected onto the platform and cycled back and forth. When a layer was completed, the injection needle rose and continued with the new cycle. In this way, the model roots could be fabricated to have a similar fibrous-like texture as real roots. The whole printing procedure was controlled by a computer from a digital input file exported directly from the SOLIDWORKS 3-D modelling software. The printed ABS plastic analogues demonstrated very similar material properties to real roots according to uniaxial tensile testing and comparison with real roots data collected from a body of literatures. The tensile strength, T_r (MPa) , and Young's modulus, E (GPa), as a measurement of the root diameter at the point of rupture, D, were found to be:

$$T_r = 57.886 D^{-0.523} \tag{1}$$

$$E = 3.24 D^{-0.55} \tag{2}$$

Full detail of the validation of such root analogue is given by Liang (2015).

Individual straight analogues of varying diameter were arranged in a group with the spatial distribution shown in Figure 1(b) to represent a heart / plate root system, within which individual roots behave independently, as suggested by Wu (1976) and Pollen & Simon (2005). Such a distribution was the same as the middle cross section of the 3-D root cluster (tap root system) designed by Liang et al. (2014) in order to subsequently investigate potential root morphology effect on root soil interaction and global slope performance.

Permanent Seismic Slip of Slopes Reinforced with Roots

Figure 4 shows a comparison of the crest settlement between the root-reinforced slope and the unreinforced slope. The presence of roots highly reduced the permanent settlement (by 61%) compared with the fallow case, especially during the first two earthquake motions. This improvement can be related to a reduction in dynamic ground motion (acceleration) within the sliding mass and an increase in the yield acceleration of the slope – both of these effects will be described in the remainder of this paper. After the first two motions, relatively smaller reductions (in total 14%) were observed, which indicates that the additional resistance provided by the roots is largely constant after the initial rapid increase.

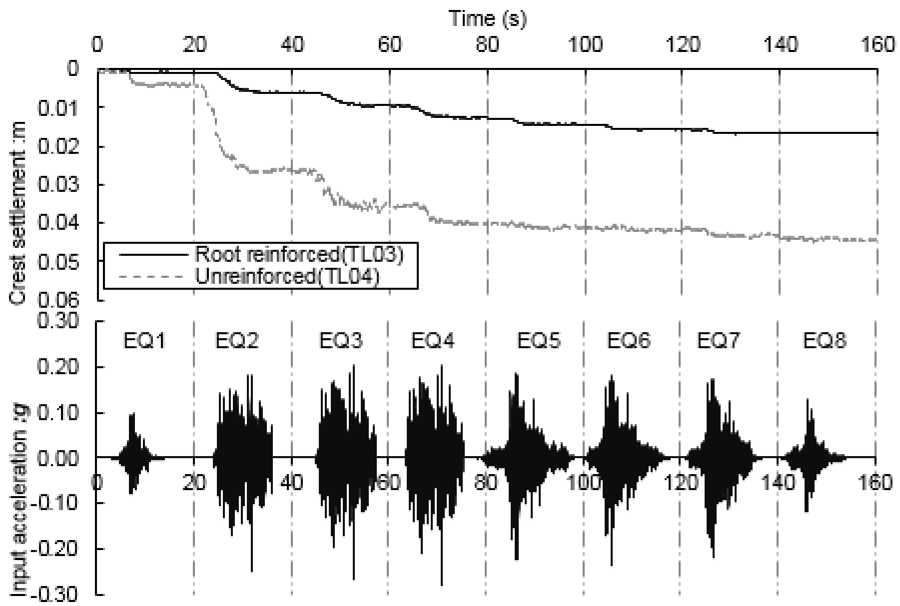

Figure 4. Comparison of permanent crest settlement of fallow and root-reinforced slopes from centrifuge testing

Effect of Roots on Seismic Slope Accelerations

A comparison of acceleration response spectra (ARS) measured at the crest of the slope (instrument 12) and closest to the potential slipping soil mass (instrument 9) are shown in Figure 5 for fallow and rooted cases. Some significant reduction of ARS for EQ1 and EQ2 were observed for the rooted case. This was believed to be one reason behind the reduction of crest settlement shown in Figure 4.

Assessment of Yield Acceleration using Discontinuity Layout Optimisation (DLO)

Visual observation from the centrifuge tests suggested that the slopes modelled in this study failed in a shallow translational mechanism. To further identify this and understand the impact of root soil interaction on the global seismic resistance of the slope, the Discontinuity Layout Optimisation (DLO) technique (Smith & Cubrinovski 2011), specifically developed for seismic stability problems, was employed to determine the least upper-bound collapse mechanism and the associated yield acceleration in both fallow and rooted cases.

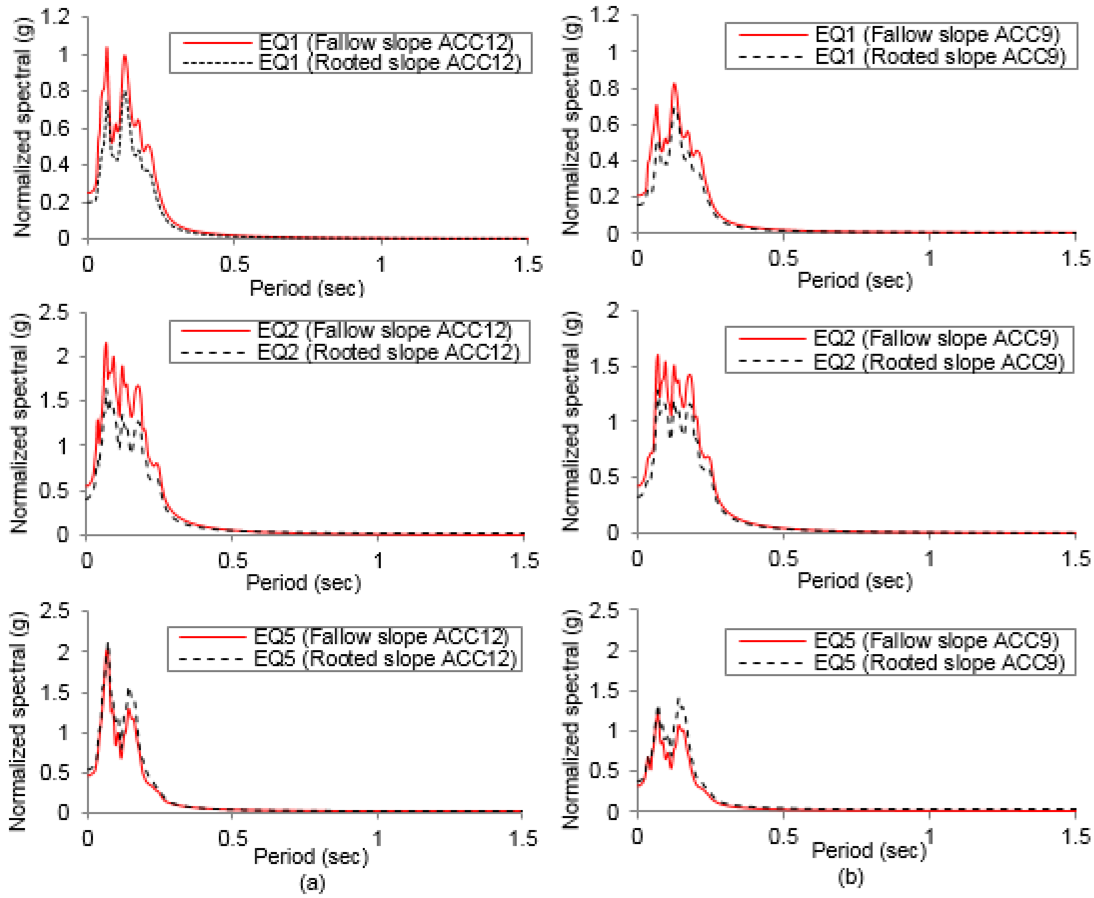

Figure 5. Normalized ARS of three distinct motions between rooted slope and fallow slope: (a) at the crest of the slope; (b) at the location of a root analogue.

DLO calculations were undertaken using the software LimitState:Geo, which involves an adaptive solution procedure described by Gilbert & Tyas (2003) to significantly reduce memory requirements and time required (no more than 5 minutes for one case) for a solution. A typical DLO model used in this study is shown in Figure 6 (fallow case). Compared with the centrifuge model shown in Figure 1, the dimensions of the model domain were extended laterally to represent the semi-infinite soil conditions, though as can be seen from the mechanism in this figure, the container boundaries do not influence the geometry of the mechanism. Fine nodal density (1000 nodes) was used in the calculation to ensure the accuracy of finding the slip plane.

The Mohr–Coulomb model was used in the modelling presented herein, in which 4 input parameters for cohesionless soil were required, namely unit weights under saturated and dry condition (the same in this dry case), and two measurable effective stress strength parameters, ϕ' and c'. As reported by Al-Defae et al. (2013) in their analysis of similar slopes, for large-strain slope deformation problems ,the seismic performance of the slope are governed by the critical state strength. Hence, in modelling the centrifuge tests, $\phi'=\phi'_{cs}$=32° were used.

In terms of c', for the fallow soil beyond the rooted zone, it was set as 0 kPa (cohesionless soil) was used. In the rooted cases, the root-soil matrix was modelled using a smeared zone with additional representative (root) cohesion added to the underlying soil properties. The properties of this smeared zone were determined from a Beam-on-non-linear-Winkler-foundation (BNWF) model reported by Liang et.al (201X).

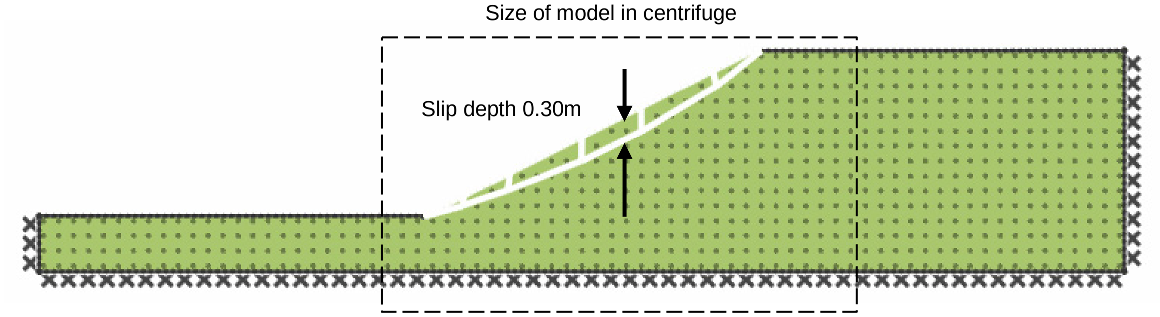

Figure 6. Failure mechanism for the fallow slope from DLO

Table 2 shows a summary of the static factor of safety and the yield acceleration for the two cases calculated by DLO, alongside the values for the yield acceleration of fallow slopes estimated using the modified sliding-block model (Al-Defae et al. 2013). The presence of roots is found to improve slope stability both in the static and dynamic condition. An improvement of about 9.6% is observed on the static safety of factor. As for the dynamic condition, the yield acceleration for slippage is increased by 8%. This increase in yield acceleration, combined with the reduction in accelerations within the slipping soil mass described previously, explain why the crest settlements measured in the centrifuge tests was substantially reduced in the case of the roots.

Table1. Static and dynamic slope stability data

Slope type	ϕ'	F(DLO)	z_{silp}	k_{hy} (DLO)	k_{hy} (Al-Defae et al. 2013)
Fallow	32°	1.359	0.30m	0.0995g	0.087
Rooted	32°	1.489	0.12m	0.1075g	N/A

Conclusions

In this paper, two centrifuge tests are reported, investigating the seismic performance of a slope reinforced with root analogues, and it was found that the presence of roots highly improved the seismic performance of slopes, especially in terms of the permanent crest settlement. A reduction by 61% was observed. This improvement was the result of two factors: (i) an increase of the yield acceleration of the slope and (ii) a reduction of acceleration within the slope. These results suggest that plant roots may be an effective method of improving slope performance in translational slips, in addition to their low cost and excellent sustainability credentials.

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