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Newmark sliding block model for predicting the seismic performance of vegetated slopes

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ABSTRACT

This paper presents a simplified procedure for predicting the seismic slip of a vegetated slope. This is important for more precise estimation of the hazard associated with seismic landslip of naturally vegetated slopes, and also as a design tool for determining performance improvement when planting is to be used as a protective measure. The analysis procedure consists of two main components. Firstly, Discontinuity Layout Optimisation (DLO) analysis is used to determine the critical seismic slope failure mechanism and estimate the corresponding yield acceleration of a given slope. In DLO analysis, a modified rigid perfectly plastic (Mohr–Coulomb) model is employed to approximate small permanent deformations which may accrue in non-associative materials when subjected to ground motions with relatively low peak ground acceleration. The contribution of the vegetation to enhancing the yield acceleration is obtained via subtraction of the fallow slope yield acceleration. The second stage of the analysis incorporates the vegetation contribution to the slope's yield acceleration from DLO into modified limit equilibrium equations to further account for the geometric hardening of the slope under increasing soil movement. Thereby, the method can predict the permanent settlement at the crest of the slope via a slip-dependent Newmark sliding block approach. This procedure is validated against a series of centrifuge tests to be highly effective for both fallow and vegetated slopes and is subsequently used to provide further insights into the stabilising mechanisms controlling the seismic behaviour of vegetated slopes.

1. Introduction

The use of vegetation to reinforce soil on landslip-prone slopes is an ecologically and economically beneficial sustainable alternative to traditional civil engineering reinforcement techniques [1–3]. The mechanical benefit of roots on slope stability has been commonly accepted. Many analytical models have been developed, based on small site in-situ investigation and laboratory tests, to quantify this benefit and predict its impacts on global slope behaviour [4–6]. However, to the best of authors' knowledge, all of these analytical models have been developed for static/monotonic use. The impacts of vegetation on seismic performance of slopes subjected to earthquake ground motions are generally overlooked in preliminary design. As observed by recent physical modelling studies [7–9], vegetation could highly improve the seismic performance of slopes (in terms of crest settlement) especially for the case of slopes of modest height (e.g. small embankments). As a result, ignoring the benefit of vegetation may lead to a conservative result and the use of more extensive remedial methods (e.g. piling, soil nailing) which may not be necessary. Analytical models which incorporate vegetation are therefore required for use in seismic analysis and design [10].

Eurocode 8 [11], which guides the design and construction of buildings and civil engineering works in seismic regions within Europe, recommends the use of established methods of dynamic analysis, such as Finite Elements (FE) or rigid block models or by simplified pseudo-static methods to determine the response of slopes to a design earthquake. Given the computational expense of the FE method, a complimentary simplified procedure would be highly useful in preliminary design, particularly for identifying key cases for further detailed study via FE. Compared with pseudo-static methods, Newmark sliding block models [12], which as displacement-based methods, are aligned with modern trends in performance-based design and assessment, potentially offer a useful basis for such a method, especially given their popularity. Recently, such methods have been developed to incorporate the large displacement effects of continued sliding in hardening the slope response [13], and also to incorporate the stabilising effects of a row of discretely spaced piles [14].

In this paper, an improved sliding-block procedure is developed to predict the seismic performance of vegetated slopes. The procedure consists of two components. Firstly, an analysis using Discontinuity Layout Optimisation (DLO [15]) is used to detect the critical seismic failure mechanism for slopes incorporating zones of enhanced strength where the roots are present (i.e. the lowest upper-bound mechanism using a virtual work approach and optimisation routine) and predict the

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Nomenclature

A	dimensionless factor to account for strain type
a_{slip}	acceleration of the sliding mass
$a(t)$	shaking induced acceleration
c'	cohesion of soil
c'_{soil}	appear cohesion induced by the soil itself
d_0	initial slip
d_i	an incremental of slip
e	void ratio
$e_{\max}$	maximum void ratio
$e_{\min}$	minimum void ratio
F_s	factor of safety
G_s	specific gravity
$\boldsymbol{g}$	acceleration due to gravity($=$ 9.81 m/s^2)
H	height of slope
H_i	height of slope at step i
h_r	rooting depth
I_D	relative density
I_R	relative dilation index
i	time step
K_O	earth pressure coefficient at rest
k_h	horizontal pseudo-static acceleration coefficients
k_v	vertical pseudo-static acceleration coefficients
k_{hy}	horizontal yield acceleration
$k_{hy(fallow)}$	horizontal yield acceleration of fallow slope
$k_{hy(rooted)}$	horizontal yield acceleration of rooted slope
$k_{hy(fallow)}^{DLO}$	horizontal yield acceleration of fallow slope derived from DLO
$k_{hy(rooted)}^{DLO}$	horizontal yield acceleration of rooted slope derived from DLO
Δk_{hy}	increase of yield acceleration due to the presence of roots
M_s	surface wave magnitude
p'	mean effective confining stress
Q	fitting parameter that depend on the intrinsic sand characteristics
R	fitting parameter that depend on the intrinsic sand characteristics
s	cumulative displacement
t	time
u	pore water pressure
v_i	velocity of slippage at the time step i
z	depth of soil
z_{slip}	slip depth
α_i	horizontal direction cosines of the discontinuity
β	angle to define geometry/slope angel
β_0	initial slope angle
β_{i+1}	instantaneous slope angle
γ	unit weight
ψ'	effective angle of dilation
$\tau_{applied}$	applied down slope shear stress
τ_{ult}	ultimate soil resistance
$\Delta\tau$	additional shear strength provided by roots
σ'_h	horizontal effective stress
σ'	mean effective stress on the slip plane
σ'_v	vertical effective stress
ϕ'	effective angle of friction
ϕ'_{cs}	critical angle of friction
ϕ'_{mob}	the mobilised friction angle
ϕ'_{pk}	(secant) peak angle of friction
ϕ^*	equivalent angle of friction accounting for non-associative flow
χ_i	vertical direction cosines of the discontinuity

contribution to the yield acceleration of a given slope configuration provided by the roots. This derived yield acceleration information is then incorporated into a modified limit equilibrium formulation for a sliding block to further account for the geometric hardening of the slope as it flattens with slip, allowing the permanent settlement at the crest of the slope to be estimated. The procedure is then validated against a database of centrifuge test results reported in [8], and subsequently used to reveal further insights into the seismic behaviour of vegetated slopes.

2. Discontinuity Layout Optimisation

2.1. Fundamental theory

Discontinuity Layout Optimisation [15] is a recently developed numerical limit analysis procedure which can be applied to a wide range of geotechnical stability problems involving cohesive and/or frictional soils. Compared with the more traditional Finite Element Limit Analysis (FELA) technique which requires discretising the problem into solid (finite) elements, DLO employs rigorous mathematical optimisation techniques to identify a critical layout of lines of discontinuity which form a kinematically-admissible collapse mechanism. These lines of discontinuity are typically ‘slip-lines’ in planar geotechnical stability problems and define the boundaries between moving rigid blocks of material which form the mechanism of collapse. Associated with this mechanism is a collapse load factor, determined via the principle of virtual work, which is an upper bound on the ‘exact’ load factor according to formal plasticity theory. The core matrix formulation for seismic problems is given in Appendix A, repeated from [16] for completeness.

2.2. Constitutive modelling of soil

DLO calculations were carried out using the software LimitState: GEO, v.2.0, which involves an adaptive solution procedure described by Gilbert and Tyas [17] to significantly reduce memory requirements and the time (of the order of a few minutes) to reach an optimised solution. The geometry of a vegetated slope problem is shown schematically in Fig. 1. The root-soil matrix is modelled using smeared zones with additional representative shear strength (here incorporated into the soil behaviour as additional cohesion) reflecting the contribution of the roots, which can vary with depth. The maximum rooting depth is denoted as h_r and the lateral spread of the roots by the Critical Rooting

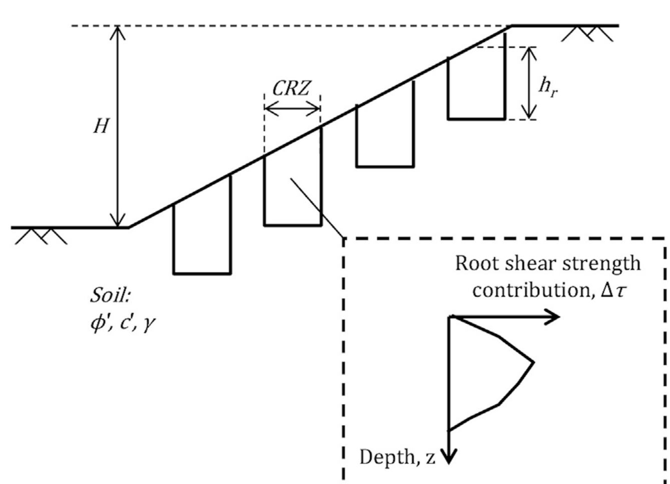

Fig. 1. Schematic of a vegetation reinforced slope.