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STABILIZATION OF SEISMICALLY UNSTABLE SLOPES USING PILES: PARAMETRIC ANALYSIS

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ABSTRACT

A recently developed and validated simplified numerical model for the investigation of the response of slope stabilizing piles is utilized to explore the parameters determining the effectiveness of such systems. Pile diameter and spacing, depth of pile embedment, soil strength and stiffness are the key problem parameters investigated. It is shown that a pile spacing of 4 diameters is the most cost-effective being able to generate soil arching between the piles. For relatively small pile embedment, pile response is dominated by rigid-body rotation, without substantial flexural distortion: The critical embedment depth to achieve fixity conditions at the base of the pile is found to range depending on the relative strength of the unstable ground compared to that of the stable ground (i.e. the soil below the sliding plane)

Keywords: Slope Stabilization, Piles, finite elements

INTRODUCTION

Slope stabilization using piles constitutes a widely accepted and successfully applied method [e.g. Heyman & Boersma, 1961; Kitazima & Kishi, 1967; Leussink & Wenz, 1969; Nicu et al., 1971; De Beer & Walleys, 1972; Ito & Matsui, 1975; D' Appolonia et al., 1977]. Existing design methods are either *pressure* or *displacement-based* [e.g. De Beer et al., 1972; Ito & Matsui, 1975; Poulos, 1995] or *numerical* methods [e.g. Oakland & Chameau, 1984; Poulos & Chen, 1997]. Although the latter are in principle the most rigorous since they can provide fully coupled solutions to the problem, their 3D application is computationally expensive and time consuming.

The methodology employed herein for the design of slope stabilization piles is formulated on the basis of the decoupled approach [Viggiani, 1981; Hull, 1993; Poulos, 1995; 1999], and combines the simplicity of widely accepted analytical techniques with the advantages of 3D FE modeling. The method entails two steps:

*Step 1 : C*onventional slope stability analysis to compute the required lateral resisting force *RF* needed to increase the safety factor of the slope to the desired value, and

Step 2 : Selection of a pile configuration capable of offering the required *RF* (to increase the safety factor of the slope to the desired level) for a prescribed deformation level.

Recently, Kourkoulis et al (2010) developed and validated a new approach for the calculation of RF (second step), which is based on the decoupling of slope geometry from the computation of pile lateral capacity, thus allowing numerical simulation of only a limited region of soil around the piles. The present paper utilizes this decoupled analysis method to derive insights on the factors affecting the response of piles and pile groups. The approach of Kourkoulis et al., 2010 is briefly described in the ensuing.

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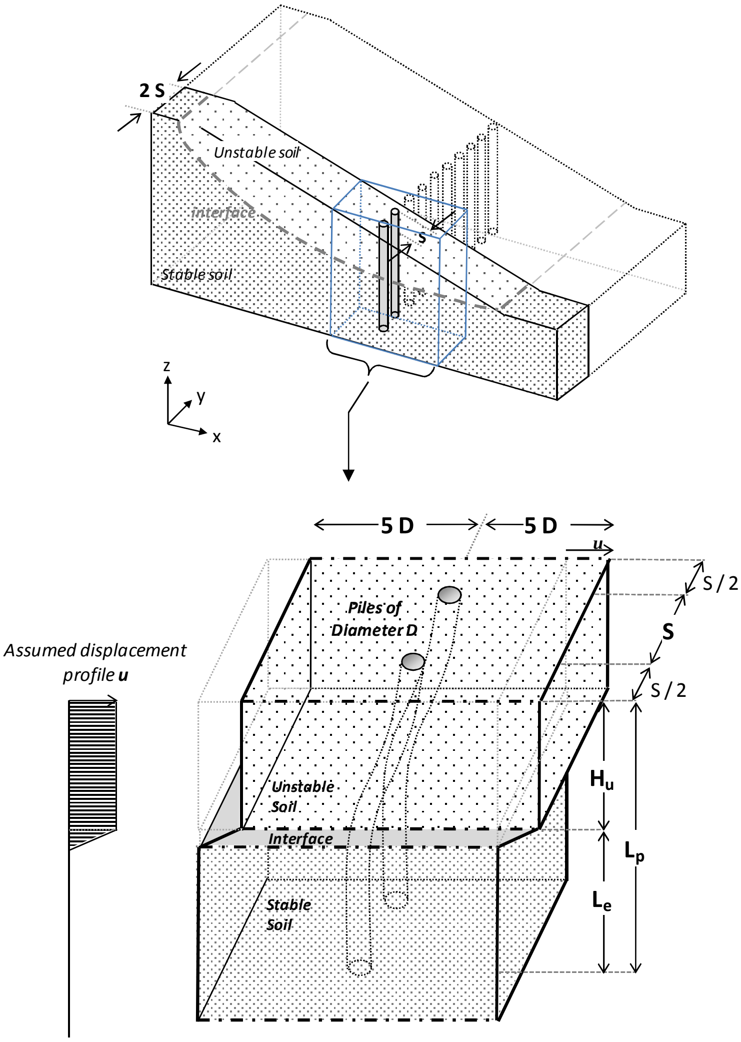

Figure 1: Schematic illustration of the simplified decoupled methodology for estimation of pile ultimate resistance. Instead of modeling the whole slope-soil-pile system (top sketch), we focus on the pile(s) and a representative region of soil at its immediate vicinity (blue box). The geometry and key parameters of the simplified model are shown at the bottom sketch.

DECOUPLED METHODOLOGY FOR ASSESSING PILE LATERAL CAPACITY

As schematically illustrated in **Figure 1**, in *Step 2,* instead of modeling the whole slope−soil−pile system, we focus on a representative region of soil around the pile. The ultimate resistance is computed by imposing a uniform displacement profile onto the model lateral boundary. This simplification has been justified as reasonable by Poulos, 1999; and Kourkoulis et al., 2010, among others. Having eliminated the detailed slope geometry, a sliding interface at depth H_u is pre-specified in the simplified FE model; where the piles, of diameter D and length L_p at spacing S, are embedded into the stable soil layer for a length L_E. Since the zone of influence of each pile does not exceed 5D (Reese & Van Impe, 2001), the length of the

model can be limited to 10*D*. In order to model a representative soil slice, the width of the model has been taken equal to 2*S*.
An elastoplastic constitutive model with Mohr-Coulomb failure criterion is used for the soil, while the pile is modeled with 3D beam elements, circumscribed by 8-noded hexahedral continuum elements of nearly zero stiffness. As discussed in detail in Kourkoulis et al. [2010], the nodes of the beam are rigidly connected with the circumferential solid element nodes of the same elevation. Hence, each pile section represents a rigid disc. The beam elements provide the pile strength and stiffness characteristics while the circumferential solid elements are able to capture the 3D geometry effects. Analyses are conducted assuming linear or nonlinear pile response.

PARAMETRIC ANALYSES

A plethora of parametric analyses have been performed in order to examine the behaviour of slope stabilizing piles nailing unstable cohesionless soil layers of various depths and material properties. The interface depth from the surface (H_u), is varied parametrically, covering the range from a shallow (H_u = 4m) to a quite deep (H_u = 12 m) landslide. The factors examined are:

(a) *Effect of Pile Spacing*
(b) *Stable Soil Layer Strength*
(c). *Depth of Pile Embedment depth into the Stable Layer*
(d). *Pile Non-linearity*

Effect of Pile Spacing

This section investigates the effect of pile-to-pile spacing on the effectiveness of the latter in nailing soil slopes. It is widely accepted that the pile spacing must ensure sufficient arching effect between the piles in a row. In general, arching stems from the stress transfer through the mobilization of shear strength (i.e. the transfer of stress from “yielding” parts of a soil mass to adjoining non-yielding or less compliant parts). *Wang and Yen (1974)* studied analytically the behavior of piles in a rigid-plastic infinite soil slope with emphasis on arching effects, and concluded that a critical pile spacing exists in both sandy and clayey slopes, beyond which practically no arching develops. A number of pile spacings have been investigated in order to determine the dependence of arching mechanism on pile distance by means of the proposed simplified approach. Our analyses assumed that loading is imposed on the free field (i.e. far enough from the piles region) on the soil nodes. After application of the load, the pile displacement has a value of u_p, while the soil between the piles displaces u_{ip} . Soil arching is assumed to be accomplished if the ratio of u_{ip} / u_p, ranges between 1 and 2, i.e. the pile and neighboring soil displace almost equally. For higher u_{ip} / u_p ratios arching cannot be claimed achieved.
Figure 2 displays two characteristic snapshots of the FE analyses, comparing a dense (s=2D) to a loose pile arrangement (s=7D). The unstable soil layer is considered to be a sand with $\varphi = 28^o$, $\psi = 2$, and $c = 3\ kPa$. The bottom soil layer is assumed to be very hard soil with $S_u = 600\ kPa$. The interface properties are $\varphi = 16^o$, $c = 3\ kPa$, and $\psi = 1$ and its location is assumed at 4m depth from the soil free surface. **Figure 2a** plots the displacements contours on the model surface for the case of piles of diameter $D = 1.2\ m$ spaced at 2 *D*, i.e , 2.4 m. From the displacements contours distribution it is evident that the soil between the piles has been restricted by the presence of the piles hence displacing almost equally with them—a clear manifestation of arching. On the contrary, in the case of piles spaced at 7 *D* (**Fig. 2b**), the intermediate soil has not been confined by the piles and flows between them. 3 *D* numerical parametric analyses have been performed to define the maximum pile spacing that ensures sufficient degree of arching as a function of their diameter. The results are summarized in the plot of **Figure 3**. It is apparent that spacings of 2, 3 and 4 times the pile diameter are able to provide soil arching. For spacings greater than 5 diameters soil flows between the piles; such arrangements are therefore not applicable to slope

stabilization and will not be examined. Evidently, the most economical pile arrangement in terms of arching is the spacing of 4 diameters. However, both the cases of *2 D* and *3 D* will be examined since these correspond to the most common arrangements of single piles used for slope stabilization purposes. As expected, increasing the pile spacing improves each pile's effectiveness but reduces the total resistance force offered per unit width. **Figures 4a and b** indicate the effect of pile spacing on the produced pile lateral resistance for the case of a shallow landslide of H_u = *4m* and for a relative deep landslide of H_u = *8m* respectively. It is observed that in the shallow landslide case (the behaviour of all arrangements is similar and almost independent of pile spacing. Yet the *2 D* spacing ensures slightly higher RF values for the same pile head displacement compared to that achieved by the *4 D* configuration. In the deep landslide case of H_u =*8m* (**Fig. 4b**), the discrepancies among the different pile spacings are more obvious. The increased flexibility of the soil-pile system requires substantially increased pile deformation for the same Resistance Force (RF) to be developed, which in turn amplifies the differences between the alternative arrangements. For instance, a *2 D* configuration may offer almost double pile resistance (≈ 1000 kN/m) compared to that offered by a *4 D* system (≈ 500 kN/m) when the pile is deformed 5 cm at its top. It is worth noting that these results refer to elastic piles of diameter *D* = *1.2m*. In case of the non-linear pile, the maximum realistic moment that may be developed must not exceed the actual structural strength of the pile. Hence, it must be pointed out that although the maximum value of the resistance force developed (elastically) is independent of pile spacing for all landslide depths, the only acceptable ultimate RF values are those which are achieved at acceptable levels of the bending moment.

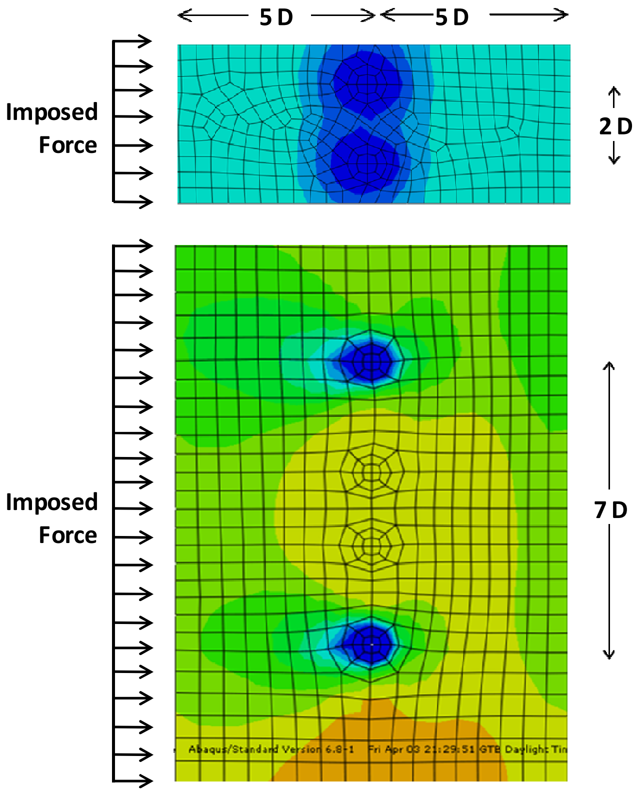

Figure 2: **Contours of horizontal displacements (a) of a dense pile configuration (distance between piles 2D) and (b) of a sparse pile configuration (pile distance 7D).**

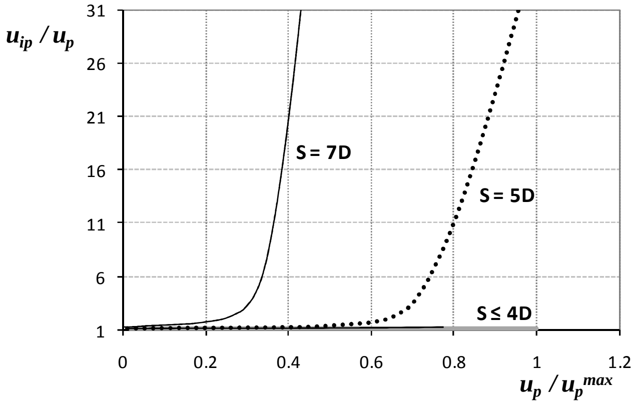

Figure 3: Comparison of the interpile displacements calculated for different pile spacings in sandy soil. It is obvious that for spacings S > 5D, soil flows between the piles.

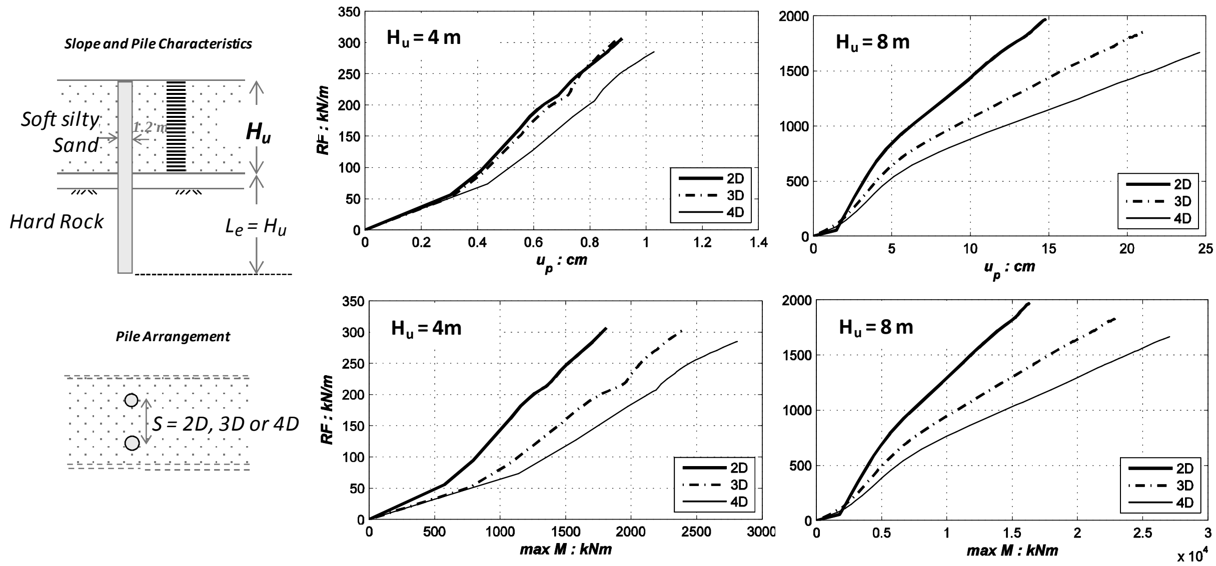

Figure 4: (a) Resistance Force offered by the pile vs Pile head displacement diagrams and RF vs maximum Bending Moment Diagrams for various pile spacings for a shallow landslide (H_u = 4m) (b) Resistance Force offered by the pile vs Pile head displacement diagrams and RF vs maximum Bending Moment Diagrams for various pile spacings for a deep landslide of H_u = 8m

Effect of Stable Ground Strength

The strength and stiffness of the stable ground were investigated parametrically to model materials ranging from relatively loose sand to a rock-type material. The idealized soils of the stable ground layer are as follows :

i. *loose silty sand* : $\varphi = 28^o$, $\psi = 2$, $c = 3$ *Kpa*, $G = 16$ *Mpa*
ii. *dense sand* : $\varphi = 38^o$, $\psi = 2$, $G = 32$ *Mpa*
iii. *soft rock* : $\varphi = 45^o$, $\psi = 5$, $c = 50$ *Kpa*, $G = 1.2$ *Gpa*
iv. *rock* : $\varphi = 45^o$, $\psi = 5$, $c = 100$ *Kpa*, $G = 4.0$ *Gpa*

The strength parameters of the *stable soil layer* were chosen so that the ultimate passive soil pressure provided by the *stable* soil layer $(P_u)_{stable}$ is greater or equal to the ultimate passive soil pressure $(P_u)_{unstable}$ developing in the *unstable* layer. For cohesionless soil, the latter is given by [Broms, 1964] :

$$(P_u)_{unstable} = a\, K_p\, \sigma'_{vo} \qquad (1)$$

where α is a parameter ranging between 3 and 5, K_p the passive earth pressures coefficient, and σ_{vo} the overburden stress. And for cohesive soil of undrained shear strength S_u :

$$(P_u)_{unstable} = N_p\, S_u \qquad (2)$$

where N_p a parameter ranging between 9 and 12.

Thus, the strength parameters of the four idealized stable ground soils yield the following ratios of $(P_u)_{stable}$ to $(P_u)_{unstable}$ [Kourkoulis, 2009] :

(a) $(P_u)_{stable} = (P_u)_{unstable}$ for *loose silty sand*
(b) $(P_u)_{stable} = 1.6\ (P_u)_{unstable}$ for *dense sand*
(c) $(P_u)_{stable} = 3.0\ (P_u)_{unstable}$ for *soft rock*
(d) $(P_u)_{stable} = 6.0\ (P_u)_{unstable}$ for *rock*

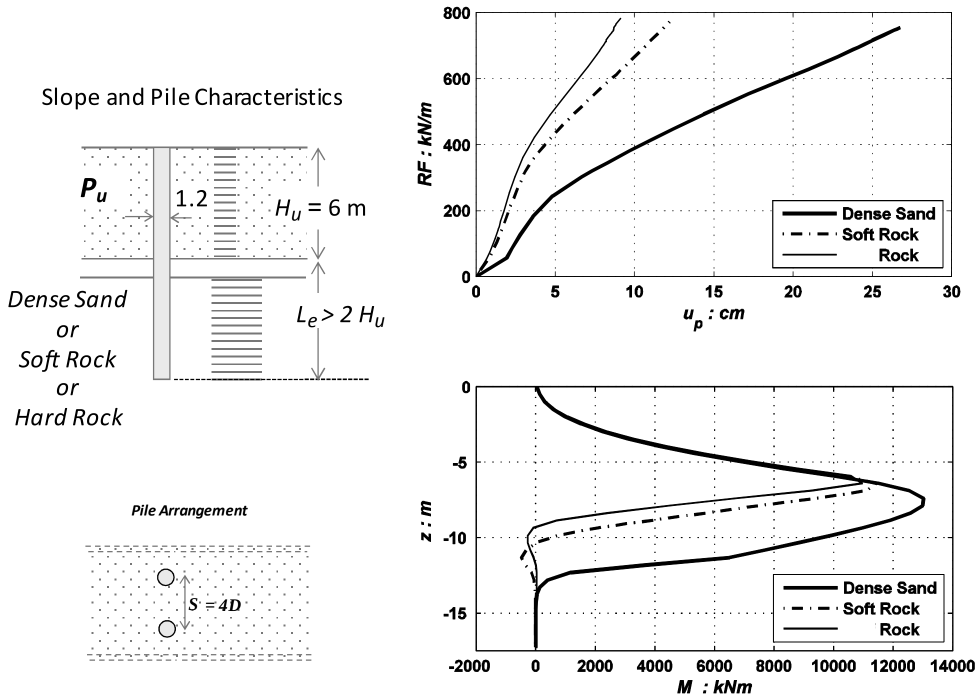

Figure 5 : Effect of the Stable Ground stiffness f or Unstable Ground. with: G=16 MPa, φ=28^o, c=1 kPa, H_u= 6m, and elastic pile with: D=1.2m, L_e=H_u , S=4D

In all cases examined, the embedment depth L_e of the pile into the stable layer was assumed equal to $2H_u$, so that full fixity conditions could be guaranteed (although for the rock cases such an embedment will not be necessary). The stable layer strength determines the fixity conditions of the pile below the interface. As expected, the analysis reveals that the very soft stable layer is unable to provide adequate fixity conditions thus enabling the rotation of the pile as a rigid body. Conversely, in case of the stiff stable layer, the pile displacement is mainly attributed to its deformation and subsequently leads in the development of substantial bending moments. Hence the same pile embedded length in a low strength substratum may not provide the same level of ultimate resistance force with that in a stiff stratum unless it is extensively displaced **(Figure 5).** Given that the pile displacements may be of vital importance for the design, it is crucial that soil properties be seriously examined when designing slope "nailing" with piles.

Effect of the Depth of Pile Embedment (L_e)

The embedment depth of the pile into the stable ground has been varied parametrically as it is expected to influence the pile behavior, depending on the strength of the soil and the thickness of the sliding soil which must be stabilized. The embedment depth L_e is expressed as a function of the height H_u of the unstable block. The values examined are: $L_e = 0.7\ H_u$, $L_e = H_u$, $L_e = 1.2\ H_u$, $L_e = 1.5\ H_u$
The optimum pile embedment depth will be this which ensures adequate pile fixity while remaining economical. To further elucidate this behavior two extreme example cases are compared: (a) the nailing of an unstable soft silty sand layer of thickness H_u=6m through a row of piles with pile to pile distance of $4\ D$, embedded in the underlying stable layer of the same properties **(Figure 6)** and (b) the nailing of the same layer through the same pile configuration but now embedded into a much stiffer stable ground of $(P_u)_{stable} = 3.0\ (P_u)_{unstable}$ **(Figure 7).** Assume that the conventional slope stability analysis (Step 1) has produced a required RF of the piles so as to ensure stability of the slope equal to *RF= 280 kN/m*. As evidenced by **Figure 6**, in case of the soft stable layer only embedment depths greater than H_u may provide the adequate force while maintaining the pile displacements under reasonable limits. On the contrary, when the strength of the stable ground is sufficiently high, economic pile design may dictate pile embedment even less that $0.7\ H_u$ (**Fig. 7**).

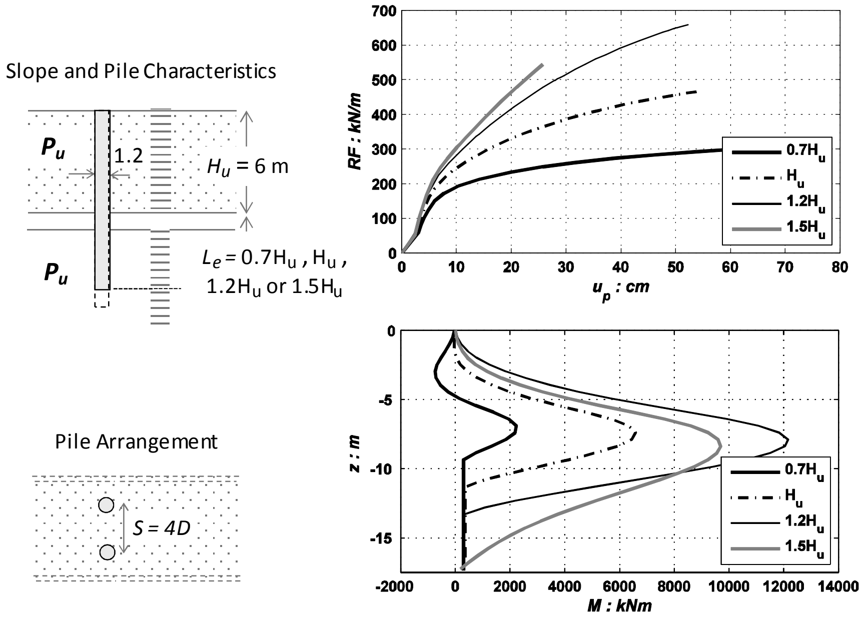

Figure 6: Effect of Pile Embedment Length. Case study of Unstable Ground with: E=40 MPa, φ=28°, c=1 kPa, H_u= 6m. and Stable Ground with: E=40 MPa, φ=28°, c=1 kPa. Elastic Piles of D=1.2m, at S=4D

Insufficient embedment depth results in rigid body-type rotation **(Fig. 8**), a finding consistent with Poulos' [1999] description of the "*short pile*" mode of failure which involves mobilization of the stable soil strength. This means that the pile structural capacity is not adequately exploited ; hence such a design would not be economical. To utilize the full pile structural capacity, a larger embedment depth is required (as L_e increases, so does the ability of the stable stratum to provide fixity conditions). As evidenced by

Figures 6 and 7, when the stable soil strength increases, the discrepancies among different embedment depths become less pronounced. This implies the existence of a critical embedment depth L_e, which is of the order of 1.2H_u in this case. This result is in accord with the suggestion of Poulos (1999) that the "*critical*" or "*effective*" length of the pile in the stable soil layer should be at least equal to H_u (for a pile embedded into a stable soil of ultimate resistance $2P_u$, i.e. 2 times the resistance of the unstable soil). This means that, for economical design, the pile length in the stable layer should not exceed the elastic critical length of the pile in that layer as calculated by Poulos & Hull (1989), Gazetas & Dobry (1984), Randolph (1981).

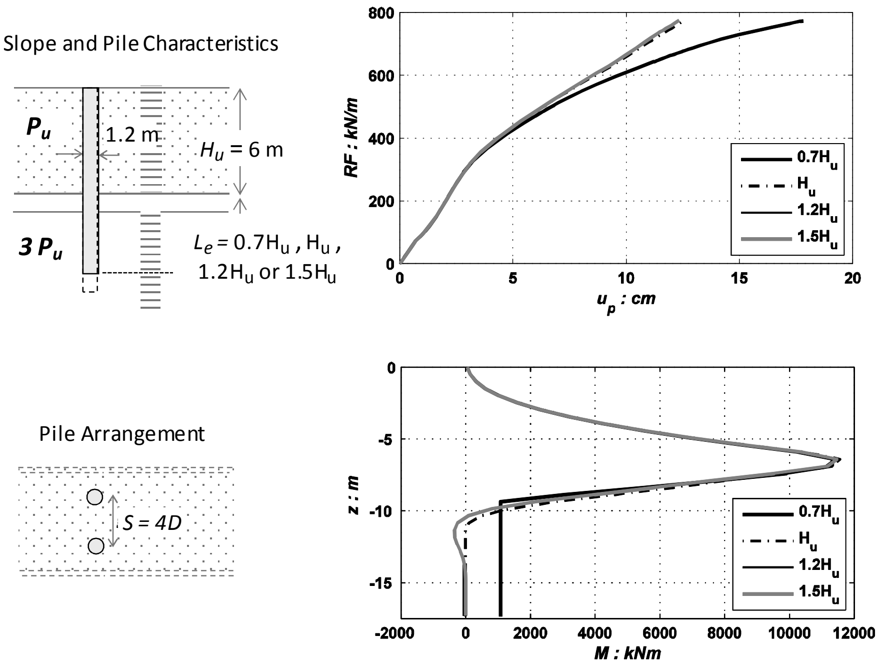

Figure 7: Parametric Analysis Results investigating the effect of Pile Embedment Length. Unstable Ground Characteristics: E=40 MPa, φ=28^o, c=1 kPa, H_u= 6m. Stable Ground Characteristics: E=3 GPa, φ=45^o, c=50 kPa. Pile Characteristics: D=1.2m, S=4D, Elastic pile.

CONCLUSIONS

This paper has exploited a "*hybrid*" methodology for design of slope stabilizing piles [presented and thoroughly validated in Kourkoulis et al., 2010] to derive insights on the factors affecting the response, and to produce dimensionless "design charts" useful in practice. The key conclusions are:

(1) A pile spacing $S \leq 4D$ is required to generate soil arching between the piles. For $S > 5D$ the piles will behave as single piles, and the soil may "flow" between them. Hence, such an arrangement cannot be applied for slope stabilization. $S = 4D$ is considered to provide the most cost-effective solution : it is the largest spacing (i.e. with the least amount of piles) required to produce soil arching between the piles, so that the inter-pile soil will be adequately retained. This conclusion is in accord with practice, where spacings between 3*D* and 5*D* are typically implemented.

(2) When the piles are embedded in a substratum of relatively low strength, a large pile deflection is required to reach the same level of ultimate resistance *RF* as when embedded in a stiff substratum.

(3) For a small pile embedment, the response of the pile is dominated by rigid-body rotation, without substantial flexural distortion. This finding is consistent with Poulos [1999] description of the "*short pile*" mode of failure, which involves mobilization of the stable soil strength and failure of the soil underneath the pile. This means that the pile structural capacity is not adequately exploited, and hence such design will not be economical. It is noted, however, that if the stable stratum is of high strength, the increase of embedment length will unavoidably be associated with an increased installation cost. Such cost implications have not been examined herein.

(4) The critical embedment depth L_e to achieve fixity conditions at the base of the pile depends on the relative strength of the stable ground $(P_u)_{stable}$ compared to that of the unstable ground $(P_u)_{unstable}$. It is found to range from $1.5H_u$ for $(P_u)_{stable} = (P_u)_{unstable}$ to $0.7H_u$ for $(P_u)_{stable} = 3(P_u)_{unstable}$ (where H_u is the thickness of the unstable soil).

(5) Single piles may be inadequate for stabilization of deep landslides. In such cases, pile groups may be the most efficient solution.

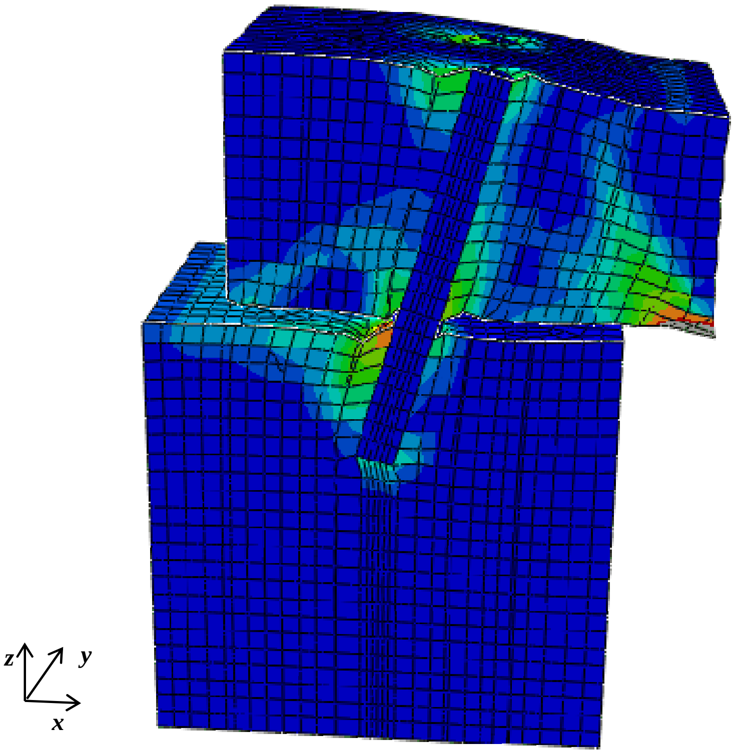

Figure 8: Snapshot of the FE analysis of pile subjected to lateral soil movement. The insufficient embedment depth of the pile leads to its rigid-body-type rotation.

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