

## THE EFFECT OF EARTHQUAKE ON THE SEISMIC STABILITY OF REINFORCED SLOPES USING HORIZONTAL SLICE METHOD

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### ABSTRACT

This paper aims at using Horizontal Slice Method (HSM) for the evaluating the seismic stability of reinforced soil structures employing a limit equilibrium method and pseudo-static analysis. Log-spiral slip surface has been used as the dominant mode of failure in the analysis. In HSM, the sliding wedge is divided into a number of horizontal slices, which do not intersect the reinforcements. A rigorous formulation is conducted by extending the methodology proposed in an earlier paper by the authors using HSM. The paper evaluates the capabilities of the HSM to study the seismic stability of the reinforced soil structures subjected to far field and near field seismic loads. For far field earthquakes the effect of horizontal seismic acceleration is studied. Accordingly the influence of a number of design parameters [coefficient of horizontal seismic acceleration ( $k_h$ )], geometrical parameters [slope inclination angle ( $\beta$ ) and slope height ( $H$ )] and geotechnical parameters [soil density ( $\gamma$ ) and soil internal angle of friction ( $\phi$ )] has been evaluated using the comprehensive formulation of the HSM. In the evaluation of seismic stability of reinforced soil walls and slopes in near field earthquakes the influence of combined horizontal and vertical seismic acceleration is studied. The influence of combined vertical and horizontal earthquake loads on the seismic stability of the reinforced soil structures is presented using two dimensionless parameters introduced in the paper.

Keywords: Horizontal Slice Method, Reinforced soil structures, Pseudo-static, Vertical and horizontal seismic coefficients

### INTRODUCTION

Reinforced soil structures have developed rapidly in the last twenty years in seismically active areas. In spite of excellent performance of such structures during destructive earthquakes, the precise behaviour of these structures under seismic loads is not well defined and fully known. In recent decades, the seismic behaviour of reinforced slopes and walls has been the focus of research (Richardson & Lee, 1975; Ausilio et al., 2000) because reinforced soil structures have performed well during major seismic events (Sandri, 1997). The design of slopes and walls is usually based on limit equilibrium and pseudo-static methods of analysis, which show acceptable agreement with laboratory test results (Zornberg et al., 1998). The development of a new limit equilibrium method of analysis for reinforced soil structures, identified as the Horizontal Slice Method (HSM), is presented in this paper. Shahgholi et al. (2001) employed the method to analyse the seismic stability of reinforced soil walls. The present paper extends the latter work by developing a number of formulations including a fully rigorous method of analysis. The formulations are described and compared with other published methods used for the seismic analysis of reinforced soil structures.

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A number of researchers have considered the vertical component of earthquake acceleration in the analysis of reinforced fill structures. Seed & Whitman (1970) stated that the effects of vertical acceleration are not significant for retaining walls due to the small values of vertical acceleration in comparison with the horizontal component. Nevertheless, some researchers have evaluated the effect of vertical component of seismic acceleration in their study including Ling and Leshchinsky (1998). Mononobe (1924) showed that a combination of vertical and horizontal accelerations led to severe damage of earth structures during the 1923 Kanto earthquake (M=7.9) in Japan. Chopra (1966) has demonstrated the significance of vertical acceleration in the seismic response of earth dams. Therefore, it can be concluded that vertical seismic acceleration could be influential in design. In this study, the rigorous (5N-1) HSM has been used to study the effect of the vertical component of seismic acceleration on the design of slopes. A positive seismic vertical coefficient  $k_v$  was assumed to act upwards at the gravity center of each slice in a pseudo-static approach.

### HORIZONTAL SLICE METHOD (HSM)

In HSM method, the sliding mass is divided into several horizontal slices (Figure 1(a)), which have rigid-plastic behavior and the seismic inertia force is considered as pseudo-static force acting at the center of gravity of each slice. As coarse-grained cohesionless soil is usually used as backfill in reinforced slopes, the effect of pore-water pressure is neglected. In addition, the effect of the facing elements on stability is neglected, which is a common assumption applied in many reinforced soil analyses.

The results of a large number of laboratory shaking table and centrifugal tests on models of reinforced slopes, show that the most frequently observed slip surface occurring during a seismic event Log-spiral failure surface (Zornberg et al. 1998). Therefore, Log-spiral slip surface has been used as the dominant mode of failure in the analysis. In the present research, the base of the slope is assumed to be sufficiently firm, so the failure surface does not pass into the base (Figure 1). It should be noted that Figure 1 also corresponds to the problem considered in this paper.

The basis for the different Horizontal Slice Method formulations is firstly proposed by Shahgholi et al. (2001) and then it was modified and verified by Nouri et al. (2006a; 2006b; 2006c). In the present paper, HSM (Nouri et al., 2006a; 2006c) is employed to perform the seismic stability analysis and parametric study. The equations and unknowns of this formulation are detailed in Table 1. As illustrated in Table 1 HSM formulation satisfies the equilibrium of all vertical and horizontal (internal and external) forces and moment equilibrium for each slice.

In this paper, the soil strength parameter ( $\phi$ ) used is:

$$\phi = \tan^{-1}\left(\frac{\tan(\phi_{Peak})}{F}\right) \leq \phi_{residual} \quad (1)$$

$\phi_{residual}$  and  $\phi_{peak}$  are respectively the residual and peak shear strength parameters.  $F$  is a partial safety factor applied to the strength parameters in order to reduce these parameters to be used in the design procedure and consider the issue of progressive failure to ensure that the design value of  $\phi$  will not be greater than the residual value of the actual angle of internal friction. This safety factor is selected according to the relevant code of practice or engineering judgment.

In this formulation the assumption of Morgenstern and Price (1965) is used:

$$H_i = \lambda \cdot f_i(y) \cdot v_i \quad (2)$$

Where,  $\lambda$  is an unknown constant and  $f_i(y)$  is a function of the depth. Due to the small value of  $\lambda$  ( $0 < \lambda < 1.0$ ) the influence of  $f_i(y)$  on the results is negligible. Therefore,  $f_i(y)$  is considered to be unity in the

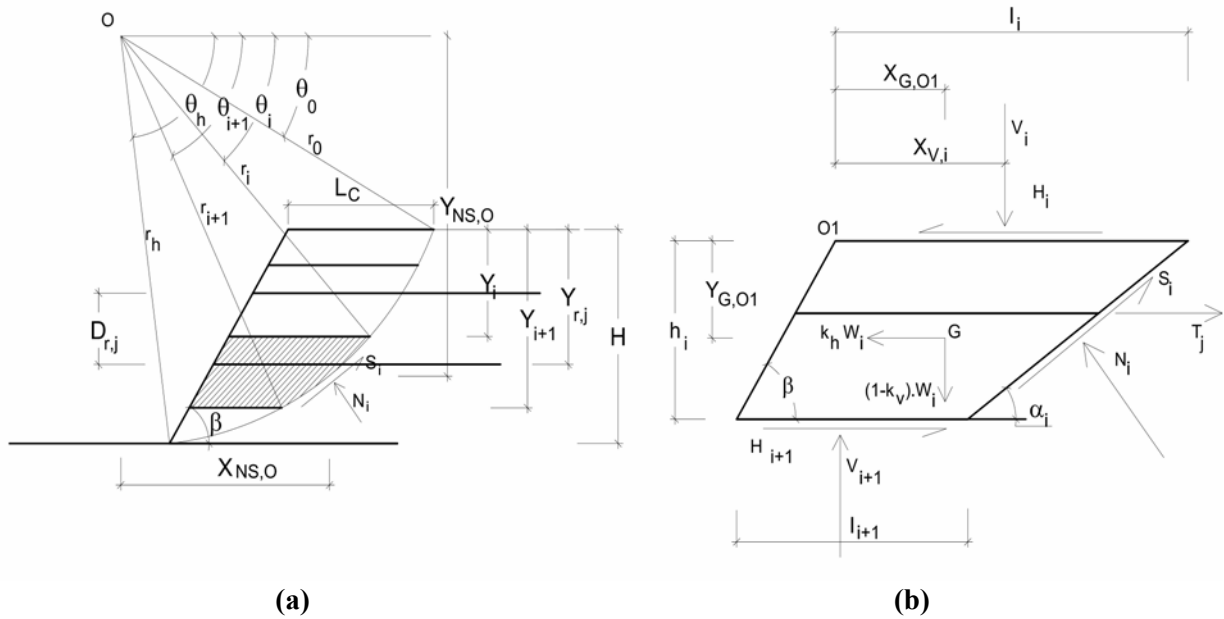
present study according to Lo and Xu (1992). The normal ( $N_i$ ) and shear (tangential) forces ( $S_i$ ) (Figure 1) are assumed to act at the mid-point of base of each slice. As both  $\lambda$  and  $V_i$  in Morgenstern and Price assumption are unknowns, the set of equations in the formulation is non-linear. In the present research, a trial and error procedure is adopted. In such procedure the value assigned to  $\lambda$  (between zero and unity), which produces a redundant equation. Equilibrium of the horizontal forces for slice N is chosen as the verification equation:

$$\sum F_x = 0 \text{ for } n^{\text{th}} \text{ slice} \Rightarrow \varepsilon = T_m + S_n \cos \alpha_n - N_n \sin \alpha_n - k_h w_n - H_n \quad (3)$$

In this equation  $T_m$  is the reinforcement force in the lowest slice, the other parameters are shown in Figures 1(a) and 1(b).

**Table 1: List of unknowns and equations in rigorous (5N-1) formulation**

Unknowns	Number	Equations	Number
Normal force upon each slice ( $N_i$ )	N	$\sum F_x = 0$ (Each slice)	N
Shear force upon each slice ( $S_i$ )	N	$\sum F_y = 0$ (Each slice)	N
Horizontal interslice force ( $H_i$ )	N-1	$\sum M_o = 0$ (Each slice)	N
Vertical interslice force ( $V_i$ )	N-1	$\tau_r = \frac{\tau_f}{F.S.}$ (Each slice)	N
Location of vertical interslice force ( $x_{v,i}$ )	N-1	$H_i = \lambda \cdot f_i(y) \cdot v_i$	N-1
Morgenstern & Price factor ( $\lambda$ )	1	Morgenstern & Price assumption	
Total required force in reinforcements to maintain stability ( $\sum_{j=1}^m T_j$ )	1		
Sum	5N-1	Sum	5N-1



**Figure 1: (a) The Geometry of Log-spiral failure mechanism and horizontal slice method (b) the geometry and acting forces of each slice**

Having established  $\lambda$  as a known value, the remaining (5N-2) equations ( $\sum F_x = 0 : N-1$ ,  $\sum F_y = 0 : N$ ,  $\sum M_o = 0 : N$ ,  $\tau_r = \frac{\tau_f}{F.S.} : N$ ,  $H_i = \lambda \cdot f_i(y) \cdot v_i : N-1$ ) for different Log-spiral slip surfaces can be solved and the maximum value of  $\sum_{j=1}^m T_j$  (the required total force to maintain the stability of the slope) which corresponds to the most critical slip surface is determined. Having obtained all the unknowns the value of  $\varepsilon$  in Equation (3) is calculated. If  $\varepsilon$  is satisfactorily close to zero, the assumed value for  $\lambda$  is acceptable. Otherwise the value of  $\lambda$  is changed and the procedure is continued until  $\varepsilon$  is satisfactorily close to zero. The mobilized force in the  $j^{\text{th}}$  reinforcement layer ( $T_j$ ) can be substituted using an expression suggested by Ling et al. (1997), which represents a linear distribution of forces in the reinforcements. The required total force ( $\sum_{j=1}^m T_j$ ) is normalized to obtain  $K$ , which is analogous to the earth pressure coefficient used in conventional retaining wall design:

$$K = \frac{\sum_{j=1}^m T_j}{\frac{1}{2} \gamma H^2} \quad (4)$$

$$T_j = K \cdot \gamma \cdot Y_{r,j} \cdot D_{r,j} \quad (5)$$

Where  $D_{r,j}$  represents the tributary distance of reinforcement layer  $j$  (the distance between layer  $j$  and  $j+1$ ), (Figure 1(a)); for the first reinforcement,  $D_{r,1}$  is the distance between the first reinforcement and the top of the slope.  $\gamma$  is the soil density and  $H$  is the slope height.

Having determined the critical failure surface, length of  $L_c$  (Figure 1) and following that the maximum required reinforcement lengths could be obtained:

$$L_{\text{reinforcement}} = L_c + L_{a,j} \quad (6)$$

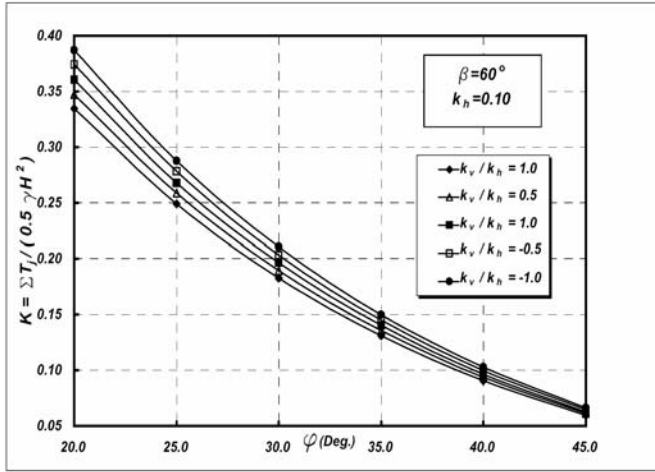
In this equation  $L_{a,j}$  is required anchorage length to ensure the capacity of the reinforcement to develop tensile resistance at the slip surface and depends on the pull-out characteristics of the reinforcement.

## THE EFFECT OF THE COMBINATION OF VERTICAL AND HORIZONTAL SEISMIC ACCELERATION

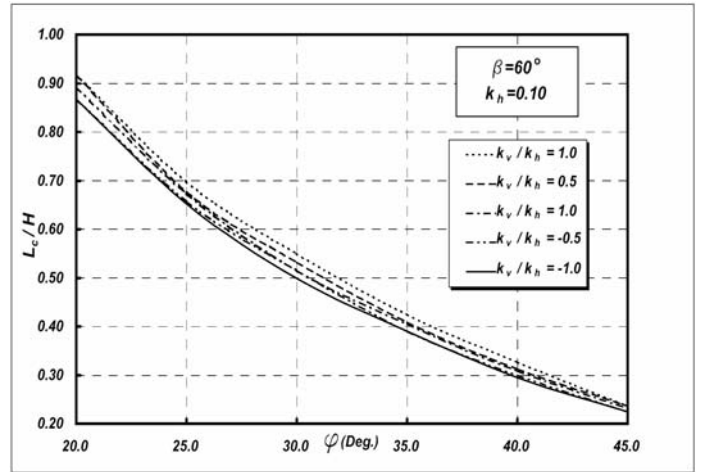
The maximum vertical acceleration recorded in most earthquakes is usually less than 40–50% of their horizontal acceleration (Kavazanjian, 1995). However, near field earthquakes usually creates a considerable vertical acceleration. Recent earthquakes such as Northridge (M= 6.7) recorded significant vertical accelerations at locations close to the epicenter (Stewart et al., 1994).

In the presented research, the influence of vertical seismic acceleration in addition to horizontal seismic acceleration has been studied. On the contrary, no vertical seismic acceleration was considered for far field earthquake. The general geometry of this parametric study is the same as Figure 1.

The parametric study was undertaken for a slope of ( $\beta = 60^\circ$ ) and a vertical wall ( $\beta = 90^\circ$ ). Three coefficients of horizontal seismic accelerations ( $k_h = 0.10, 0.20, 0.25$ ), five different coefficients of vertical seismic accelerations ( $k_v / k_h = 1.0, 0.5, 0.0, -0.5, -1.0$ ) and fill shear strength parameters of  $\phi = 20$  to  $45^\circ$  were assumed. The results of the analyses are presented for two parameters ( $K$  and  $L_c / H$ ) in Figures 2 to 7.

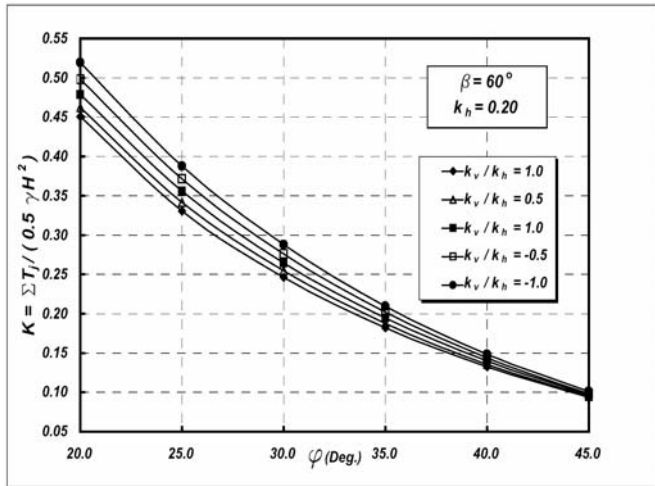


(a)

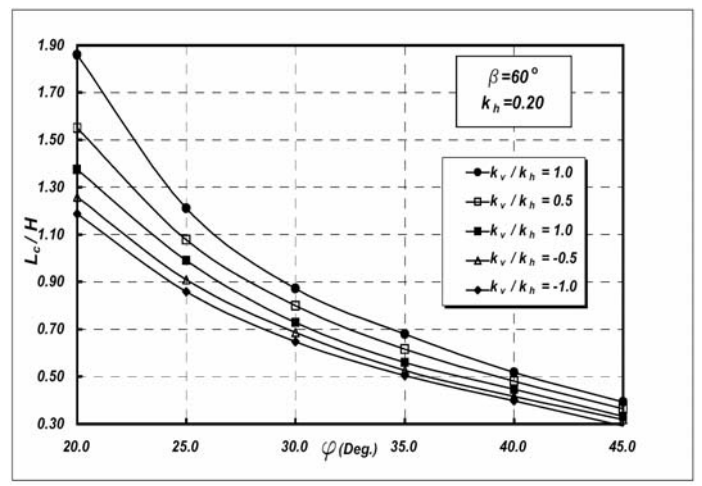


(b)

Figure 2. Results of (a)  $K$  and (b)  $L_c/H$  parameter using rigorous HSM formulation for different values of vertical seismic coefficient, ( $\beta=60^\circ$ ) and ( $k_h=0.10$ )

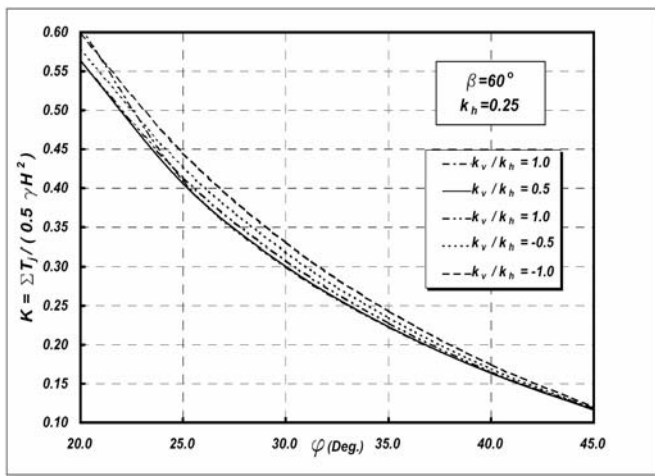


(a)

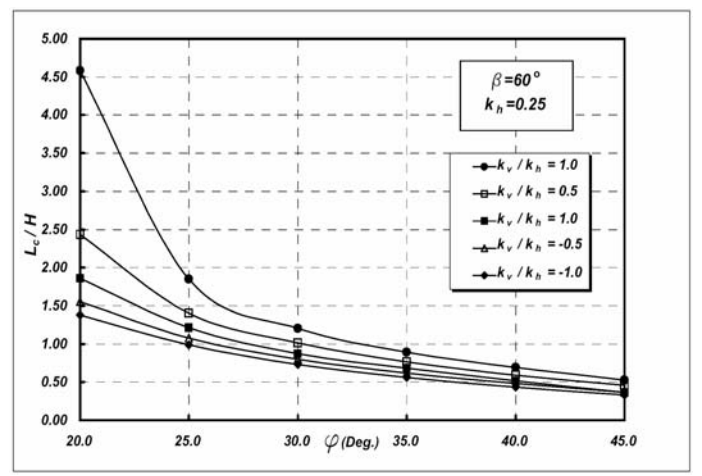


(b)

Figure 3. Results of (a)  $K$  and (b)  $L_c/H$  parameter using rigorous HSM formulation for different values of vertical seismic coefficient, ( $\beta=60^\circ$ ) and ( $k_h=0.20$ )

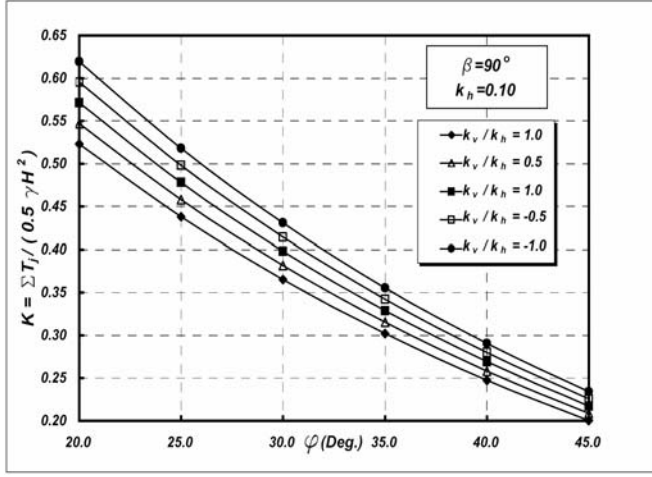


(a)

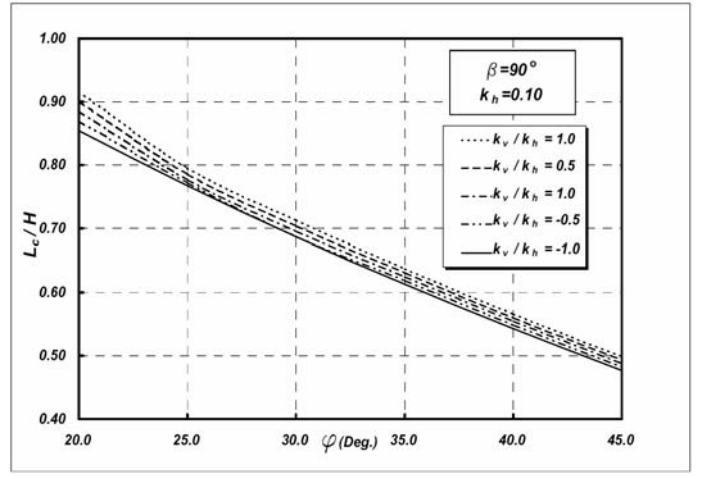


(b)

Figure 4. Results of (a)  $K$  and (b)  $L_c/H$  parameter using rigorous HSM formulation for different values of vertical seismic coefficient, ( $\beta=60^\circ$ ) and ( $k_h=0.25$ )

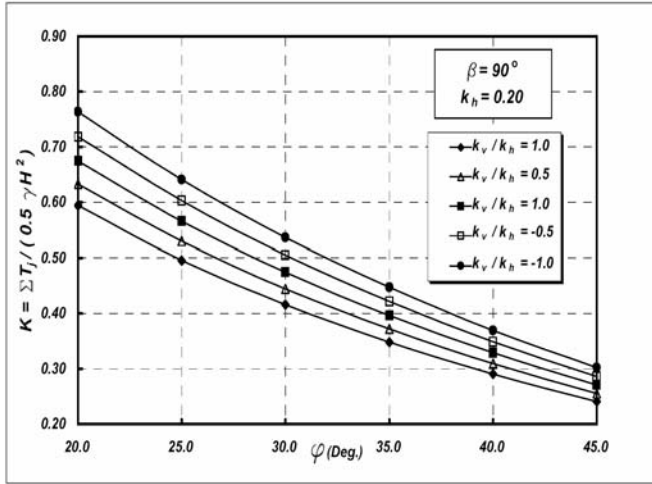


(a)

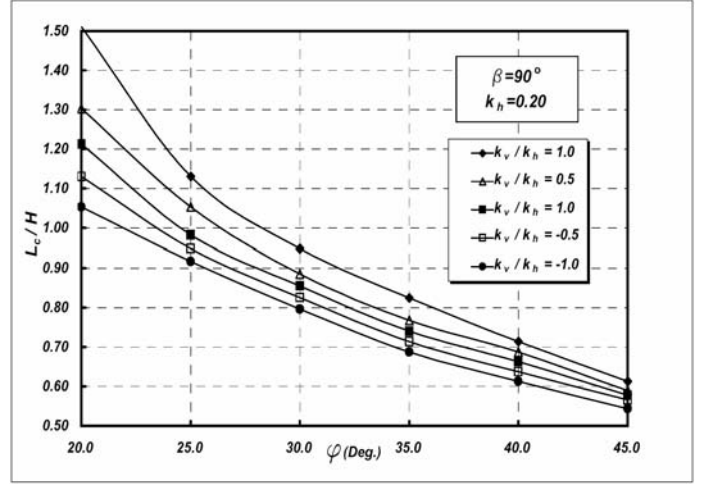


(b)

Figure 5. Results of (a)  $K$  and (b)  $L_c/H$  parameter using rigorous HSM formulation for different values of vertical seismic coefficient, ( $\beta = 90^\circ$ ) and ( $k_h = 0.10$ )

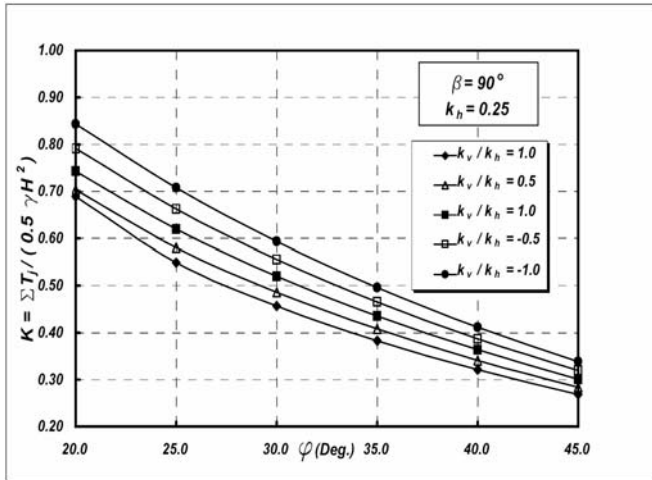


(a)

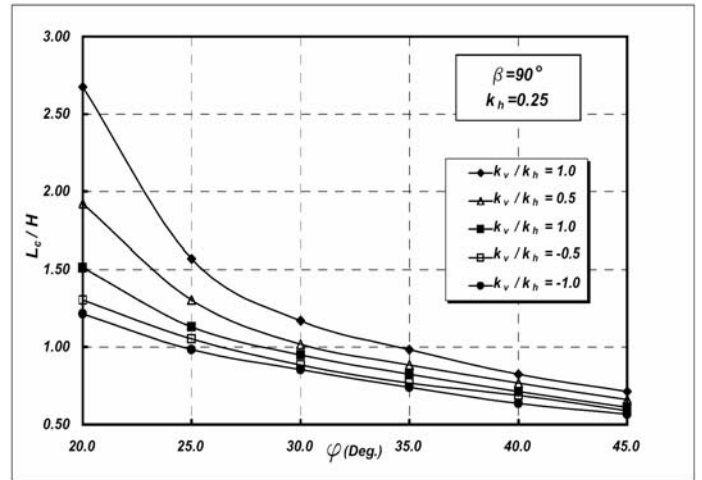


(b)

Figure 6. Results of (a)  $K$  and (b)  $L_c/H$  parameter using rigorous HSM formulation for different values of vertical seismic coefficient, ( $\beta = 90^\circ$ ) and ( $k_h = 0.20$ )



(a)



(b)

Figure 7. Results of (a)  $K$  and (b)  $L_c/H$  parameter using rigorous HSM formulation for different values of vertical seismic coefficient, ( $\beta = 90^\circ$ ) and ( $k_h = 0.25$ )

Regarding the recorded significantly large vertical accelerations at locations close to the epicenter of several earthquakes, the considerable values of vertical in comparison with the horizontal seismic coefficient are likely to happen. However, in most seismic design procedures and codes the vertical seismic coefficient is suggested to be a fraction of horizontal seismic coefficient for evaluating the seismic stability of slopes and walls. For instance, the design recommendation that has been proposed in the tentative Eurocode (CEN, 1994) and PIANC (2001) provides the vertical seismic coefficient as half of the horizontal seismic coefficient. Regardless of the design procedures and codes this paper mainly aims at providing a parametric study on the effect of different values of vertical seismic coefficient in combination with the horizontal values ( $k_v / k_h = 1.0, 0.5, 0.0, -0.5, -1.0$ ).

It can be deduced from Figures 2(a) to 7(a) that the effect of the value of the vertical seismic acceleration,  $k_v$  on the value of required force needed to maintain the stability is negligible especially for shallow slopes ( $\beta$ ). The effect of  $k_v$  is greater for soils of low shear strength ( $\phi < 30^\circ$ ).

The value of  $K$  for vertical slopes ( $\beta = 90^\circ$ ) shows a linear variation of  $K$  with respect to the soil shear strength ( $\phi$ ) and the coefficient of vertical seismic acceleration ( $k_v$ ).

The required length of reinforcement defined by the parameter  $\frac{L_c}{H}$  is more sensitive to the values of  $k_h$  in comparison with  $K$ . However, the effect of  $k_v$  on  $\frac{L_c}{H}$  for low values of horizontal seismic acceleration ( $k_h < 0.20$ ) is negligible; The effects of  $k_v$  on the  $\frac{L_c}{H}$  results are more severe for low values of soil shear strength ( $\phi < 30^\circ$ ) and steep slopes. The vertical component of seismic acceleration acting upwards (positive values of  $k_v$ ) tends to increase the dimension of the sliding wedge and consequently the length of the reinforcement. On the other hand, the force required maintaining the stability of the reinforced slope ( $K$ ) increases for  $k_v$  acting downwards (negative values of  $k_v$ ). These trends are relevant to design, and indicate that the reinforcement length is controlled by  $+k_v$ , while the strength of the reinforcements is controlled by  $-k_v$ .

It can be concluded that it is not necessary to consider the vertical component of seismic acceleration in the analysis for low values of  $k_h$  ( $k_h < 0.20$ ). Conversely the effect of  $k_v$  for higher values of  $k_h$  ( $k_h > 0.20$ ) especially for low values of backfilling soil strength ( $\phi < 30^\circ$ ) and steep slopes is significant. In practice, the use of poor backfilling material ( $\phi < 30^\circ$ ) and also ( $k_h > 0.20$ ) is rare, so the effect of the vertical component of seismic acceleration can probably be neglected in most cases. It should be noted that all the results presented in Figures 2 to 7 correspond to factor of safety value (F.S.) equal 1.

## CONCLUSION

The main object of this paper is to evaluate the effect of vertical and horizontal seismic acceleration using the Horizontal Slices Method of analysis previously described by the authors (Nouri et al., 2006a; 2006c). The study has shown that:

The effect of vertical seismic acceleration on the performance of reinforced slopes is not significant for low values of  $k_h$  ( $k_h < 0.20$ ) and can be ignored in design. On the other hand, higher values of  $k_h$  ( $k_h > 0.20$ ) coupled with the use of poor quality fill ( $\phi < 30^\circ$ ) necessitate the increase of the required resistant forces and especially the length of the reinforcements to maintain the stability of the soil structure. The vertical component of seismic acceleration acting upwards (positive values of  $k_v$ ) tends to increase the dimension of the sliding wedge and as a result the length of reinforcement layers. The reinforcement force required to maintain the stability of a reinforced slope increases for  $k_v$  acting downwards (negative values of  $k_v$ ).

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