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A new analytical approach to estimate the seismic tensile force of geosynthetic reinforcement respect to the uniform surcharge of slopes

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Abstract. This paper investigates the pseudo-static analysis of reinforced slopes with geosynthetics under the influence of the uniform surcharge to evaluate the maximum tensile force of reinforcements. The analytical approach has basically been used to develop the new practical procedure to estimate both tensile force and its distribution in the height of the slope. The base of developed relationships has been adapted from the conventional horizontal slice method. The limit equilibrium framework and the assumptions of log-spiral failure surface have directly been used for proposed analytical approach. A new analytical approach considering a single layer of non-cohesion soil and the influence of uniform surcharge has been extracted from the 5n equation and 5n unknown parameters. Results of the proposed method illustrated that the location of the surcharge, amount of internal friction and the seismic coefficient have the remarkable effect on the tensile force of reinforcement and might be 2 times increasing on it. Furthermore, outcomes show that the amount of tensile force has directly until 2 times related to the amount of slope angle and its height range. Likewise, it is observed that the highest value of the tensile force in case of slope degree more than 60-degree is observed on the lower layers. While in case of less degree the highest amount of tensile force has been reported on the middle layers and extremely depended to the seismic coefficient. Hence, it has been shown that the tensile force has increased more than 6 times compared with the static condition. The obtained results of the developed procedure were compared with the outcomes of the previous research. A good agreement has been illustrated between the amount results of developed relationships and outcomes of previous research. Maximum 20 and 25 percent difference have been reported in cases of static and seismic condition respectively.

Keywords: analytical method; geosynthetics; tensile force; slope; seismic

1. Introduction

The investigation into the stability of reinforced slopes with the geosynthetics reinforcement under the static and seismic loads has widely been considered as the main research topic in the field of geotechnical engineering. The considerable number of previous research has reported the significant result of this issue (Prader *et al*. 2005, Tang *et al*. 2009). The practical experiences and previous studies have proved that using the geosynthetic reinforcements such as geotextile or geogrid have the significant effects on the bearing capacity and the dynamic responses of the slopes (Sandri 1998, Tatsuoka *et al*. 1998, Koseki *et al*. 2006, Jones and Clarke 2007, Moghaddas Tafreshi *et al*. 2015, Tavakoli Mehrjardi *et al*. 2016). A number of the mentioned studies have methodically concentrated on the surcharge and load impacts on the slopes and retaining walls stability (Tavakoli Mehrjardi *et al*. 2016). Moreover, the considerable number of the physical models regarding the real scale slope under a point load (Gerber 1929, Spangler 1938, Moghaddas Tafreshi *et al*. 2015), applying elasticity theory with an emphasis on the linear surcharge (Mishra 1980, Tavakoli Mehrjardi *et al*. 2016), and the strip surcharge (Jarquio 1981) have completely been evaluated to develop a conventional method for estimating the influence factors on the slope stability (Coulomb 1776, Rankine 1857, Borthakur *et al*., 1988, Javankhoshdel and Bathurst 2016).

Analytical method has extensively been used in the previous studies to appraised the retaining walls and slopes deformation (Hausmann and Lee 1978, Lareal *et al*. 1992, Saran *et al*. 1992, Ling *et al*. 1997, Bathurst and Hatami 1998, Michalowski 1998, Ausilio *et al*. 2000, Allen *et al*. 2003, Huang *et al*. 2006, El-Emam and Bathurst 2007, Huang and Wang 2005, Huang and Wu 2006, 2007, Choudhury *et al*. 2007, Shekarian and Ghanbari 2008, Reddy *et al*. 2009, Leshchinsky *et al*. 2009, Mojallal and Ghanbari 2012, Aminpoor and Ghanbari 2014, Mojallal *et al*. 2012). In addition, different types of the experimental and numerical studies have also been carried out to verify the analytical research's achievement (Koseki *et al*. 1998, El-Emam and Bathurst 2005, Huang and Wu 2009, Huang and Luo 2010, Rowe and Skinner 2001, Skinner and Rowe 2005, Tavakoli Mehrjardi *et al*. 2017, Tavakoli Mehrjardi and Motarjemi 2018). Moreover, the effect of uniform surcharge on the active earth pressure (Motta 1994, Ahmadabadi and Ghanbari 2009) and its reliability to the type of surcharge was done by using distinctive technics (Georgiadis and Anagnostopoulos 1998). The substantial number of the seismic analysis on the stability of retaining walls and other structures have widely been addressed in

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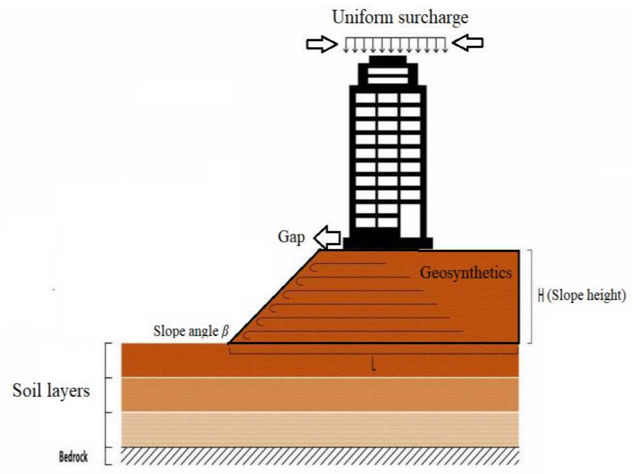


Fig. 1 A schematic of reinforced slopes problem that affect by uniform surcharge

the literature (Cascone and Caltabiano 2000, Caltabiano *et al*. 2011, Greco 1999, 2003, 2005, 2006, Basha and Basudhar 2010, Basha and Babu 2011, Abbasi Maedeh *et al*. 2017). Likewise, the reliable international codes and guidelines have widely referred to the analytical relationships that have been suggested in the literature (Jewell 1991, Wihelm Ernest and Sohn 2002, AASHTO 2007).

To consider the seismic stabilization of slopes the pseudo-static method has been known as the major conventional technic for evaluating the slope and walls. The method has the easy application and satisfactory result that has completely proved by both limit equilibrium analysis and experimental tests (Zornberg *et al*. 1998a, Giri 2011). Besides, the vertical and horizontal slice methods are known as the particular and practical analytical approaches that basically have been extracted from the limit equilibrium. They have basically different assumptions of mechanisms to estimate the failure surfaces (Janbu 1957, Morgenstern and Price 1965, Spencer 1967).

The vertical slices method has been defined as a solution for the reinforced soil problems. It has different bugs to solve the passive cases and it would make equation solutions difficult by the increase of the unknowns. Hence, the use of no-vertical methods has strongly been recommended (Juran *et al*. 1990, Yamagami *et al*. 1999). Lo and Xu (1992) used the horizontal slices method for analyzing the static stabilization and solving the reinforced slopes problem. The horizontal slices method has deeply improved by other previous researchers (Nouri *et al*. 2006, 2008, Azad *et al*. 2008, Shekarian and Ghanbari 2008, Shekarian *et al*. 2008, Ahmadabadi and Ghanbari 2009, Ghanbari and Ahmadabadi 2010a, Ghanbari and Ahmadabadi 2010b, Ghanbari and Ahmadabadi 2010c, Ghanbari and Taheri 2012). Furthermore, the method has been suggested for the seismic stability of slopes in case of no-surcharge slopes by Shahgholi *et al*. (2001). The gap of mentioned literature is that there is no a direct analytical procedure to estimate the tensile force of reinforcement considering the effect of slope height, inclination and the surcharge effect in both cases of the static and seismic condition. A schematic of the explained gap has been shown in Fig. 1.

Literature reviewing shows that there is no a direct method and procedure to evaluate and estimate the amount of tensile force in the length of slope height and considering both seismic and surcharge effect. In this study, the main propose is to develop a new analytical procedure to evaluate the surcharge load effects on the slope stability and estimate the reinforcement's tensile forces with an emphasis on both seismic and static conditions. To consider the critical and close to reality condition for slope sliding the log-spiral failure surface mechanism and rigid-plastic behavior have been assumed to develop the relationships. Moreover, a non-cohesion soil has been considered to assessment. The tensile force estimation in the height of the slope and its reinforcement and its related graphs would be shown as the final results of the proposed analytical procedure.

2. Basic concept, assumptions and equations

The following assumptions have been considered to develop the new relationships for estimating the internal tensile forces of reinforcements as the simplification. Based on the results of many centrifuges and shaking table tests on the scaled geotechnical structure models, it has extremely been proved that the most of failure surface during the earthquake is observed as the log-spiral form (Sawada *et al*. 1993, Zornberg *et al*. 1998b, Michalowski 1997, Leshchinsky 2001). Hence the log-spiral sliding form has been considered for the current study analytical procedure to use in the basic equations. Furthermore, the limit equilibrium theory for estimating the failure surface has been applied to create the proposed analytical relationships (Fig. 1). Where H is the slope height, φ is the internal friction angle of the soil, r_0 is the failure surface radius at slope crown equal with θ_0 angle and the r_h failure surface radius at slope claw equal with θ_h angle. To estimate the radius of the log-spiral failure surface following relationships (Eq. (1) and Eq. (2)) have extremely been suggested where r_0 is the depended radius as a function of the arbitrary angle θ_0.

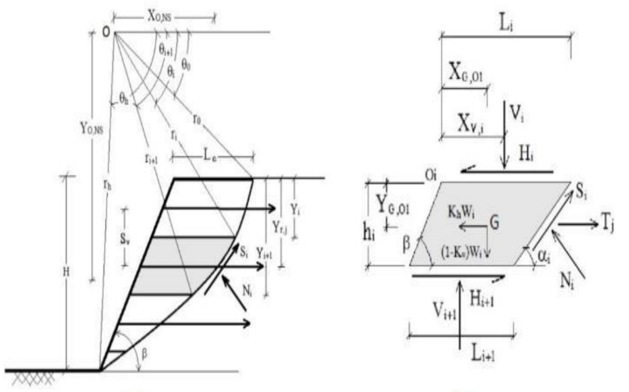
$$r_i = r_0 \exp^{[(\theta_i - \theta_0)\tan\varphi]} \tag{1}$$

$$r_0 = \frac{H}{\sin\theta_h \exp^{[(\theta_h - \theta_0)\tan\varphi]} - \sin\theta_0} \tag{2}$$

To estimate the maximum distance of the failure surface the Eq. (3) has shown the believable amounts. Limitations of changes for both parameters θ_0 and θ_h have been assumed according to a recommended rate by Nouri *et al*. (2006). The mentioned relationship is largely powerful to quantify the distance between the slope edge and the failure surface at the top of the slope's crown (L_c).

$$L_c = \left(\frac{r_0}{\sin\theta_h}\right) \times \left[\sin(\theta_h - \theta_0) - \frac{H}{r_0} \times \frac{\sin(\beta + \theta_h)}{\sin\beta}\right] \tag{3}$$

Where β is the slope angle and L_c is the maximum distance of the failure surface up to the surface of the slope.



(a) (b)

Fig. 2 A schematic view of the no-surcharge reinforced slope and its affected forces

Table 1 Equations and unknowns for formulating horizontal slices method to calculate the tensile force of reinforcements in case of no-surcharge slope

Equations	Numbers	Unknowns	Numbers
$\sum F_x = 0$ For each slice	*n*	S_i Shear forces at base of each slice	*n*
$\sum F_y = 0$ For each slice	*n*	N_i Normal forces at base of each slice	*n*
$\sum M_o = 0$ For each slice	*n*	T_i Tensile forces of each slice	*n*
$S_i = N_i \tan\varphi + C$ For each slice	*n*	H_i Inter-slice shear forces	*n*
Summation	4*n*	Summation	4*n*

The schematic view of the no-surcharge reinforced slope and its affected forces on each horizontal slice has been illustrated in Fig. 2.

Current work assumes that the embankment has consisted of the homogeneous granular (sand or gravel) and dry soil without adhesive features. Also, it has been considered that the failure surface passes through slope claw and the effect of T_i will occur in the middle of the height for each horizontal slice. While the action point of N_i is located in the middle of the base for each slice. Then, the effect of facing elements on the slope stability has been completely neglected. Besides active pressure effect has applied to the tensile force of the reinforcement. In the case of the no-surcharge slopes, the relationships have been offered with 4n equation and 4n unknown according to Table 1.

The optimal slices number has been considered in this study. However, the number of horizontal slices can be changed regarding other proposed conditions. The height of horizontal slice has been achieved by $h_t=H/n$. Where n is the number of horizontal slice and h_i is the height of each slice. N_i and S_i forces have been applied on the center of the floor level for slices and their horizontal and vertical distance from the point O have been calculated by Eqs. (4) and (5).

$$X_{O,NS} = r_i \cos\theta_i - \frac{h_i}{2\tan\alpha_i} \tag{4}$$

$$Y_{O,NS} = r_i \sin\theta_i + \frac{h_i}{2} \tag{5}$$

The equations that presented in Table 1 are offered by Eqs. (6) to (8).

$$\begin{gathered}\sum F_x = 0 \ \ (for\ each\ slice) \\ S_i \cos\alpha_i - N_i \sin\alpha_i + T_i - H_i + H_{i+1} - k_h W_i = 0\end{gathered} \tag{6}$$

$$\begin{gathered}\sum F_y = 0 \ \ (for\ each\ slice) \\ S_i \sin\alpha_i + N_i \cos\alpha_i - V_i + V_{i+1} - (1-k_v) W_i = 0\end{gathered} \tag{7}$$

$$\begin{aligned}&\sum M_o = 0 \ \ (for\ each\ slice) \\ &(S_i \sin\alpha_i + N_i \cos\alpha_i)(X_{O,NS}) + (S_i \cos\alpha_i - N_i \sin\alpha_i)(Y_{O,NS}) + \\ &T_j(Y_{r,j} + r_0 \sin\theta_0) - H_i(r_i \sin\theta_i) + H_{i+1}(r_{i+1} \sin\theta_{i+1}) - \\ &V_i(r_i \cos\theta_i - L_i + X_{v,i}) + V_{i+1}(r_{i+1}\cos\theta_{i+1} - L_{i+1} + X_{v,i+1}) - \\ &(1-k_v) W_i (r_i \cos\theta_i - L_i + X_{G,O_1}) - k_h W_i (r_i \sin\theta_i + Y_{G,O_1}) = 0\end{aligned} \tag{8}$$

Where αi is the failure surface angle of each slice in the ratio with the horizon, k_h and k_v are the vertical and horizontal seismic coefficients. Also, W_i is the weight of i^{th} block which has been estimated by Eq. (9).

$$W_i = A_i \times \gamma \times 1 \quad (for\ each\ slice) \tag{9}$$

The Mohr-Coulomb yield criterion has also been considered for the fourth suggested equation in Table 1 (Eq. (10)).

$$S_i = N_i \tan\varphi + C \quad (for\ each\ slice) \tag{10}$$

The vertical stress on horizontal slices is estimated due to following relationships (Eqs. (11) to (13)) Segrestin *et al*. (1992).

$$\sigma_v = \gamma \times z \times \tanh(au + b), \quad u = \frac{x}{z} \tag{11}$$

$$a = 2 \times \tan\alpha \times Log\left(\frac{2 \times K_a}{K_a + K_\alpha}\right) \tag{12}$$

$$b = 0.5 \times \left(Log \frac{K_a + K_\alpha}{K_a - K_\alpha}\right) \tag{13}$$

Where x and z are the direct distance from origin and depth of the intended point respectively. In addition, the active lateral Rankine pressure (K_α) has been computed by Eq. (14).

$$K_\alpha = \left[\frac{\sin(\alpha - \varphi)}{\sin\alpha + \sqrt{\sin\alpha \times \cos(\alpha - \varphi) \times \sin\varphi}}\right]^2 \tag{14}$$

3. Results of the no-surcharge reinforced slope

The explained relationships have completely used to

Table 2 Geometrical and geotechnical characteristics of studied slopes

Item	Value
Inclination angle of the slope β (°)	45 to 90
Internal friction angle of the soil φ (°)	20 to 40
Horizontal seismic coefficient k_h	0.0 to 0.2
vertical seismic coefficient k_v	0.0
unit weight of the soil γ (kN/m^3)	20
cohesion of soil c (kN/m^2)	0.0

evaluate the maximum effective force for reinforcements in case of the no-surcharge slope. Two innovated no-dimension parameters have been made to help for generating the proposed analytical procedure. The first new no-dimension parameter "K" is a representative to the total force of reinforcements that achieve by Eq. (15).

$$K = \frac{\sum_{j=1}^{m} T}{0.5 \times \gamma \times H^2} \tag{15}$$

The second no-dimensional developed parameter is the ratio L_c/H that is the agent of the least required length for the reinforcement. As a template case to control the result of the mentioned no-dimension parameters the geometrical and geotechnical properties of the regular and common slopes have been explained in Table 2 and the outcomes have been shown in Fig. 2.

The previous research has implicitly suggested to neglect the vertical seismic coefficient in case of $k_h \leq 0.2$ while in case of more values it is extremely suggested to consider the effect of the vertical seismic coefficient as well (Nouri *et al*. 2006). More importantly, the location of vertical seismic effect has exactly been considered on the gravity center for each horizontal slice (Nouri *et al*. 2008). The result of estimation from the parameters "K" shows in Fig. 3. Achieved outcomes show that the effect of K_h on the total force of reinforcements in case of 90-degree slopes is approximately two times greater than the 60-degree slopes. Other achievements show that the friction angle has the remarkable effect to increase the reinforcement forces in case of higher inclination slopes. Obtained results show that the factor "K" would be capable to increase up to 3 times in the limited range of friction angle, K_h=0 and the slope inclination in the range of 45 to 90 degree. While graphs show that in the similar condition and change the K_h=0.2 the factor "K" would be illustrated maximum 2 times increase.

To estimate the radius of slope failure with an emphasis on the regular type of slope, soil properties and seismic condition the result of slope radius in four different cases of slope conditions have been illustrated in Fig. 4. It is observed that the plain failure has the maximum estimation of sliding radius. While both the log-spiral and circular sliding have had approximately the same results to estimate

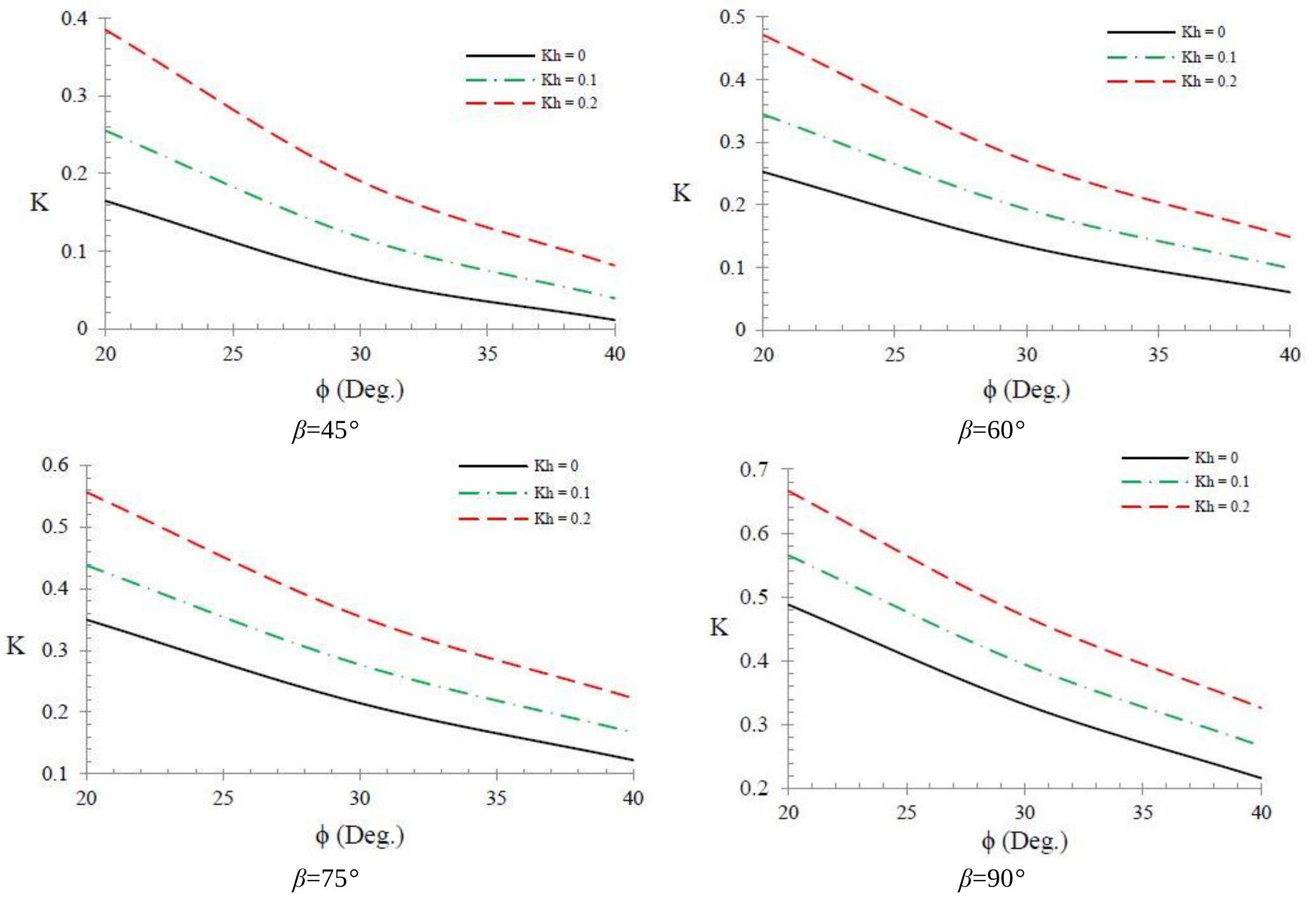


Fig. 3 Results of the no-dimension parameter "K" vs internal friction

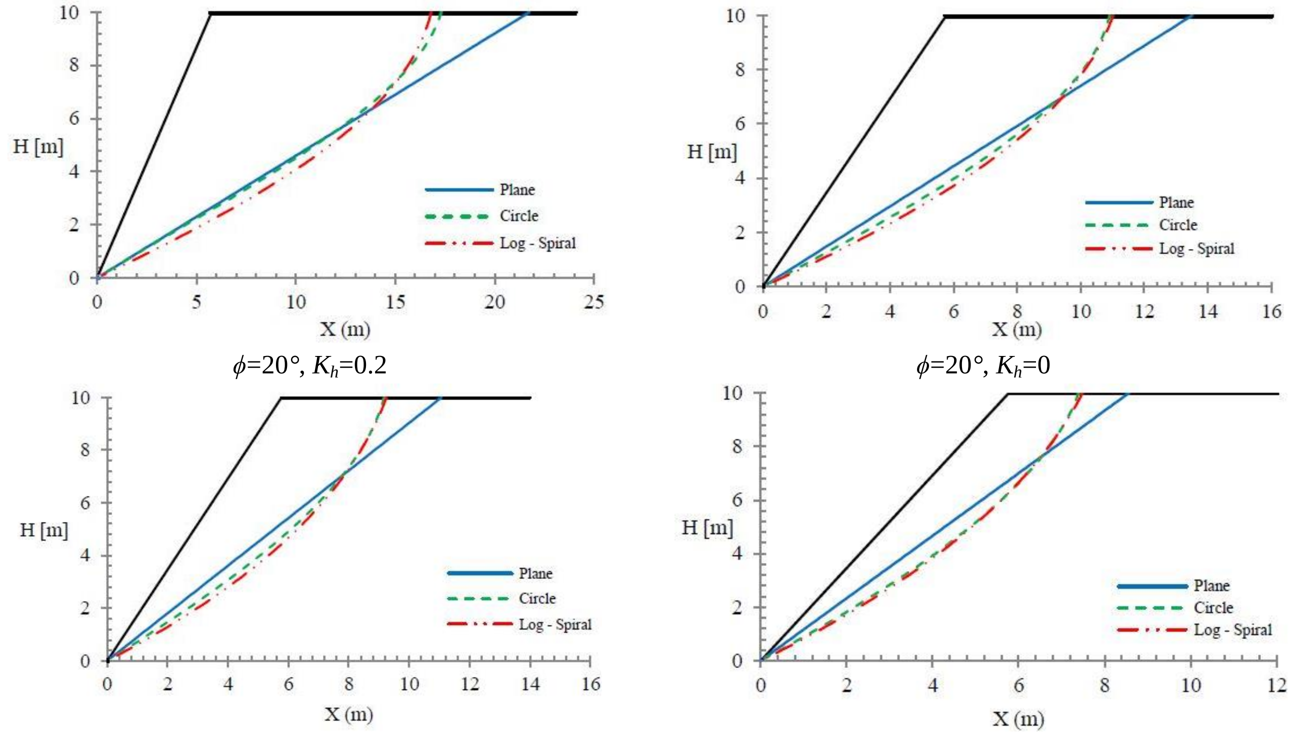


Fig. 4 Results of the sliding radius with an emphasis on sliding type (β=60°, H=10 m, γ=20 kN/m^3)

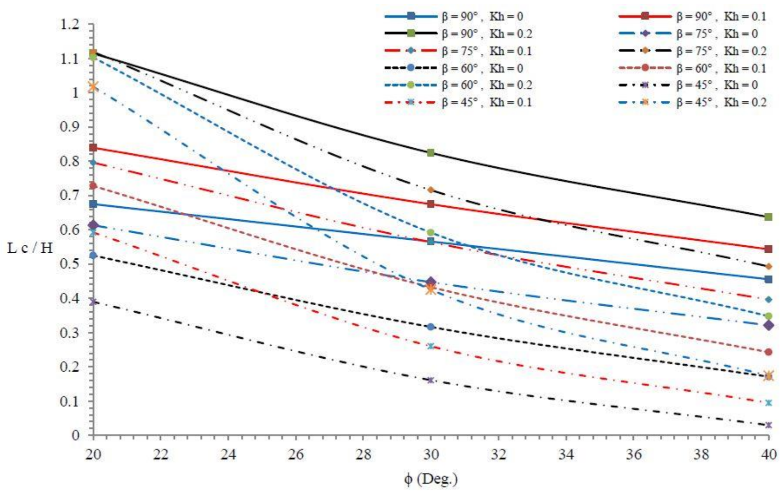
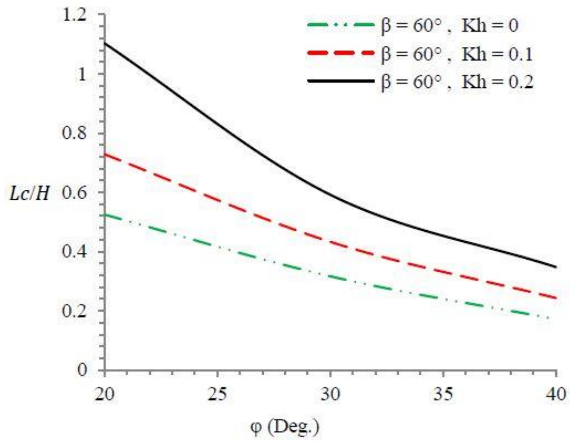


Fig. 5 Results of the no-dimonsial parametr L_c/H Vs. internal friction

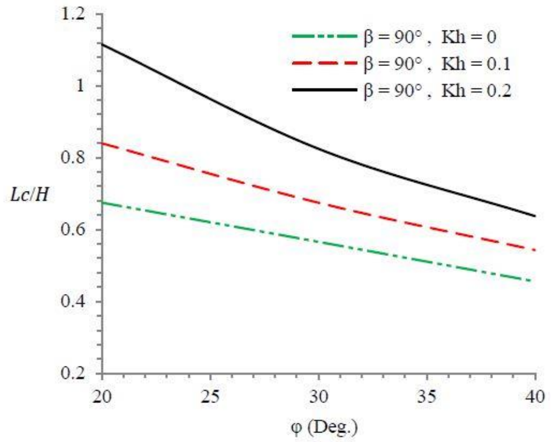
the failure radius. Subsequently, results show that due to a similar geometry and seismic ratio and friction angle 20 and 40-degree the sliding radius would be changed 1.5 and 1.2 times increase respectively.

To consider a closer look to the achieved results show that the total required force of the reinforcement and the least required length of the reinforcement (L_c) have directly depended to internal friction. Hence both mentioned factors would be increased with an emphasis on decrease the internal friction (φ). Assuming the static slope stability condition and fine sand and slope inclination 45-degree (φ=30) the primary estimation of reinforcement length has been calculated about 0.16H but in case of 90-degree the primary estimation has been reported "0.6H". A comparison of seismic condition for the slopes 90 and 60 it is observed that considering similar seismic condition the 2 time higher length would be estimated for the slope reinforcement in case of 90 degrees slope. Results of the second no-dimensional developed factor related to different inclination, seismic ration, and internal friction have been shown in Figs. 5 and 6.

To validate the obtained result of the developed no-dimensional parameters, they were compared with the extracted results from such previous studies. Ling *et al*. (1997) have offered an analytical method on the basis of the pseudo-static limit analysis. The study format has reviewed the internal and external slope stabilization factors using analytical slope stability. Ausilio *et al*. (2000) have also

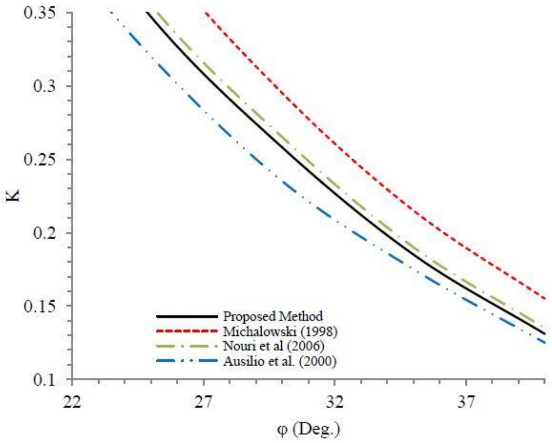


β=90°

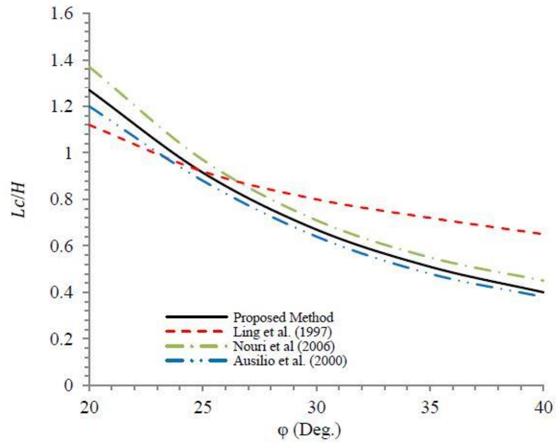


β=60°

Fig. 6 Results of the no-dimonsial parametr L_c/H Vs. internal friction with an emphasis on slope inclination



β=90°



β=60°

Fig. 7 Results of the no-dimonsial parametr K vs internal friction with in a comparision with the previous research

Table 3 Result of a variety of wall condition as the case study vs proposed method

Parameters	Amagasaki wall	Gould wall	Valencia wall	Seiken walls
H (m)	4.7	4.6	6.4	5.5
b (degrees)	90	86.4	86.4	78.7
f (degrees)	35	33	33	37
g (kN/m^3)	20	20	20	18
T_u (kN/m)	38	36	36	20
k_h	0.27	0.3	0.5	0.326
no-dimensional parameters K Ling *et al*. (1997)	0.452	0.482	0.773	0.375
no-dimensional parameters K proposed method	0.482	0.502	0.771	0.388

done a seismic stability analysis of reinforced slopes using the framework of the pseudo-static approach by applying limit analysis kinematic theorem for different modes of failure. Furthermore, the horizontal slices method and particularly developed relationships that extracted from Nouri *et al*. (2006) have been used to analyze the slopes of the reinforced soil in a pseudo-static mode. The compared result has illustrated the good agreement with those of other research results (Fig. 7). The minimum difference of comparison has been illustrated with Nouri *et al*. (2006). While the maximum difference observed in comparison with the method of Michalowski (1998).

Another type of comparison to validate the result has been performed in Table 3. The outcomes of the developed no-dimensional parameter are compared with the different case studies that explained in the research of Ling *et al*. (1997).

4. Proposed method to evaluate the reinforced slope with an emphasis on the surcharge

To modify the last analytical relationships and to consider the effect of uniform surcharge on the reinforcement, the previous relationships at Table 1 have been exclusively reconsidered. Accordingly, the 5n equation and 5n unknown parameters have been clearly presented in Table 4. The last equation is developed as the representative of uniform surcharge effect and will be considered to the future estimations of reinforcement's tensile force.

Due to the 4n relationship, the vertical stress on the slices has been assumed equal to the weight of the soil on the slice. While the vertical stress on the slices according to

Table 4 Equations and unknowns for formulating horizontal slices method to calculate the force of reinforcements with an emphasis on the effect of surcharge

Equations	Numbers	Unknowns	Numbers
$\sum F_x=0$	n	S_i Shear forces at base of each slice	n
$\sum F_y=0$	n	N_i Normal forces at base of each slice	n
$\sum M_o=0$	n	T_i Tensile forces of each slice	n
$S_i\ N_i \tan\varphi+C$	n	H_i Inter-slice shear forces	n
$H_i=\lambda\ V_i$	n	V_i Inter-slice vertical forces	n
Summation	5n	Summation	5n

the 5n relationships have been unknown. Considering the number of unknown parameters, it is necessary that an extra equation for getting all number of mentioned parameters would be developed as well. The proposed equations have been obtained by the assumption of the relation between vertical interstice force (V_i) and the horizontal interstice force (H_i). Consequently, with an emphasis on the assumption of Morgenstern and Price (1965), the Eq. (16) has been developed.

$$H_i = \lambda \times V_i \times f_i(y) \tag{16}$$

Where λ is a fixed number for each slice that would be obtained by the 4n relationship considering the same geometrical and geotechnical conditions of the reinforced soil slopes. The achieved values would be entered the solution cycle before solving the 5n relationship. Its results have been used in every solving stage of the survey that has completely been illustrated at Eq. (17).

$$\left(\frac{H_i}{V_i}\right)_{With\ surcharge} = \left(\frac{H_i}{V_i}\right)_{No\ surcharge} \tag{17}$$

The depth in the examination in the slope (Eq. (18)), has been considered by $f_i(y)$ that is a selective function of (Lo and Xo 1992). Current evaluation has assumed that it is a fixed function and is considered equal to one. Also, it is assumed that the vertical forces caused by linear surcharge can be added to the static vertical forces (gravity) of the soil weight. The schematic view of a reinforced soil slope considering the uniform surcharge is shown in Fig. 8.

Where q is the intensity for the uniform surcharge that would be located the top of the slope and has a known distance from the top edge of the slope "a". In addition, "b" is the representative of the uniform surcharge's length. Both lengths of "a" and "b" will generate the new parameter "L_c". The effect of this surcharge on the slope stabilization with a pseudo-static mode and vertical factor k_{vqb} upwards and the horizontal factor k_{hqb} outwards have been entered into the developed relationship in each slice. The modified equations to consider both seismic and surcharge effects have been completely developed as following Eqs. (18) to (20).

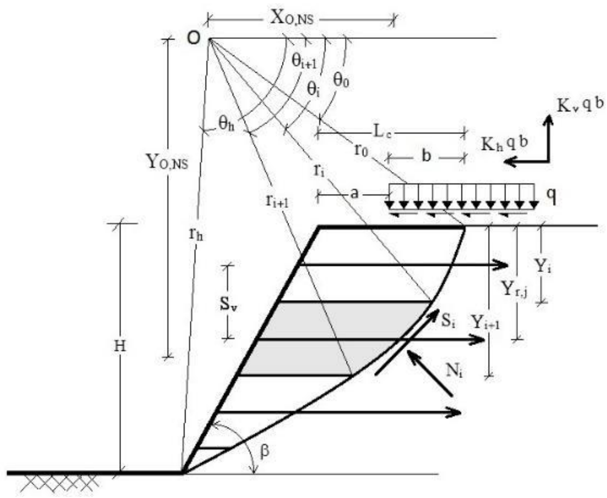


Fig. 8 Schematic view of the reinforced soil slope under the uniform surcharge effect

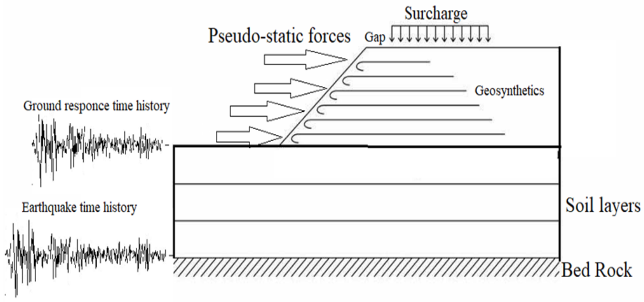


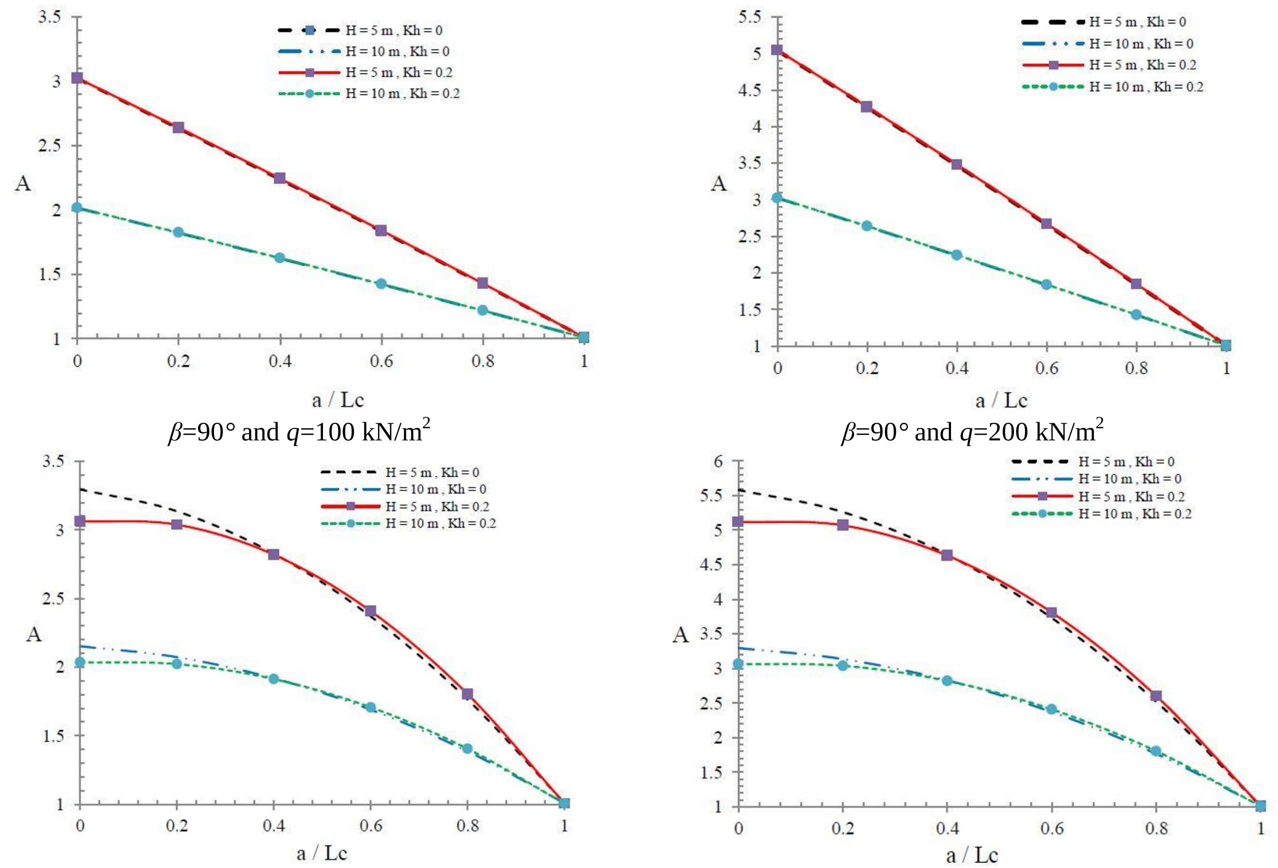
Fig. 9 A schematic of the reinforced slope that affected by the earthquake and its changed effect to Pseudo-static force

$$\begin{aligned}&\sum F_x = 0\ \left(for\ \ first\ \ slice\right)\\&S_1\cos\alpha_1 - N_1\sin\alpha_1 + T_1 - H_1 + H_2 - k_h W_1 - \left(k_h \times q \times b\right) = 0\end{aligned} \tag{18}$$

$$\begin{aligned}&\sum F_y = 0\ \left(for\ \ first\ \ slice\right)\\&S_1\sin\alpha_1 + N_1\cos\alpha_1 - V_1 + V_2 - \left(1-k_v\right)W_1 - \left(1-k_v\right)\times q\times b = 0\end{aligned} \tag{19}$$

$$\begin{aligned}&\sum M_o = 0\ \left(for\,each\,slice\right)\\&\left(S_1\sin\alpha_1 + N_1\cos\alpha_1\right)\left(X_{O,NS}\right) + \left(S_1\cos\alpha_1 - N_1\sin\alpha_1\right)\left(Y_{O,NS}\right) +\\&T_1\left(Y_{r,1} + r_0\sin\theta_0\right) - H_1\left(r_1\sin\theta_1\right) + H_2\left(r_2\sin\theta_2\right) -\\&V_1\left(r_1\cos\theta_1 - L_1 + X_{v,1}\right) + V_2\left(r_2\cos\theta_2 - L_2 + X_{v,2}\right) -\\&\left(1-k_v\right)W_1\left(r_1\cos\theta_1 - L_1 + X_{G,O_1}\right) - k_h W_1\left(r_1\sin\theta_1 + Y_{G,O_1}\right) = 0\end{aligned} \tag{20}$$

By establishing the formulation of the 5n equation and 5n unknown and defining the amount of surcharge and its distance from the slope edge, the intended unknowns would be achieved. Another required parameter to extend the mentioned innovated relationship is considered T_i which has been assumed equal to the number of selected horizontal slices. In this study, the selected distance for reinforcement layers is assumed 50 cm and the parameters S_v=0.5 and S_h=1.0 are considered. The amount of earthquake coefficient has been extracted from ground responses analysis. In addition, a schematic of the problem has been illustrated to Fig. 9.



β=90° and q=100 kN/m^2 β=90° and q=200 kN/m^2

β=60° and q=100 kN/m^2 β=60° and q=200 kN/m^2

Fig. 10 Results of no-dimensional parameters "A" vs "A/L_c" with an emphasis on slope inclination and surcharge magnitude

5. Results of the reinforced slopes with an emphasis on the uniform surcharge

To show the effect of the surcharge distance from the slope edge at reinforcement force a new parameter entitled "A" has been defined by the Eq. (21). It is equal to the ratio of the total force of the reinforcements in surcharge mode to the mode without surcharge. In this work, four different modes of surcharge distances from the slope edge and several rates of surcharge intensity have been carried out.

$$A = \frac{\left(\sum_{j=1}^{m} T_j\right)_{With surcharge}}{\left(\sum_{j=1}^{m} T_j\right)_{No\ surcharge}} \tag{21}$$

The total tensile force of the reinforcement with intended surcharge has been achieved by 5n developed relationship. To show the effect of the surcharge, the distances length parameter "L_c" to obtain the no-dimensional parameter has been calculated. It is observed that in the case of the no-surcharge will be affected on the edge point of the slope the mentioned parameters will be changed to zero. While considering the gaped surcharge loading from the slope edge, the mentioned parameter will increase until the surcharge exits the failure surface wedge and reaches its maximum amount which is one. The mentioned no-dimensional parameter would be achieved by, $0 \leq a/L_c \leq 1$. L_c, which has been extracted from the 4n relationship. The changes of no-dimensional parameter "A" Vs no-dimensional parameter of "a/L_c" have been illustrated in Fig. (10). The highest influence on the reinforcement tensile force according to the surcharge distance has completely been presented in the mentioned figures as well. The maximum tensile force in case of the surcharged slope has been quantified by multiplying the ratio "A" at the total reinforcement tensile force that has directly been achieved by no-surcharge slope condition. It is observed that the lowest slope tendency angle has the highest effect on the horizontal seismic coefficient on parameter A. Furthermore, the ratio "A" would be increased due to the increase in surcharge length. While results show that the slope height and internal friction angle (φ) have the highest and lowest influence on increasing the parameter "A" respectively.

The reinforcement tensile force based on the slope height has been shown in Figs. 11 and 12. Slopes with 5 and 10-meter height, the surcharges with intensity 100 kN/m^2 and 200 kN/m^2 and slopes with the angle of 90° and 60° have been evaluated and their achieved results are illustrated in the figures. According to the obtained result, the limit of friction angle has been considered among 30° to 40°. The unit weight of the soil has been applied 20 kN/m^3. In addition, the critical distance considering the maximum force effect, for each case has been evaluated in the

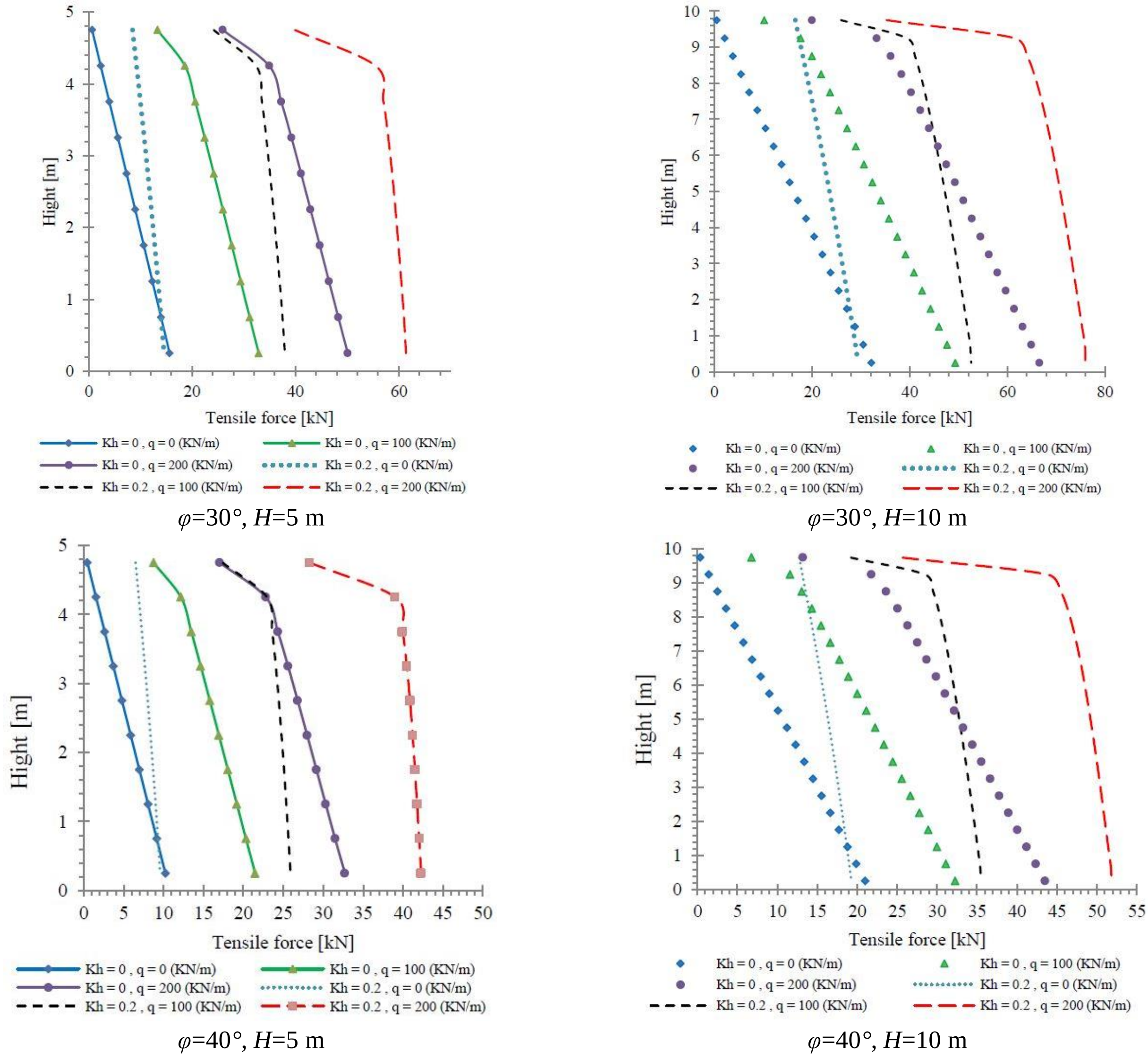


Fig. 11 Results of tensile reinforcement distribution along the slope height in case of slope inclination 90-degree

mentioned figures. Results show that to decrease the slope inclination (β), would increase the tensile forces at the upper layers of reinforcements. Obtained results have also shown that by increasing the surcharge intensity (q) and horizontal seismic coefficient (k_h), the reinforcement force significantly will increases. While it is illustrated that by increasing the internal friction angle, reinforcements can experience less force.

To check the performance of the proposed analytical method and its innovated relationships to estimate the tensile forces of reinforcement in case of the surcharged slope, the obtained results were compared with the results of Labba and Kennedy (1986). The static and seismic condition by using limit equilibrium was used by Labba and Kennedy (1986). The observed difference between the results can be due to the fact that in the present study, applying a horizontal slice increased the accuracy of this problem-solving. The achieved result of proposed method good agreement with results presented by Labba and Kennedy (1986) where the maximum difference for estimated tensile force in case of the seismic condition is about 20% which occurred in the top of the slope. While the observed difference in the bottom of the slope is estimated at 2% as well. Considering the static condition the difference of tensile force was illustrated about 23% and 30 % for the top and bottom of the slope respectively (Fig. 13).

6. Conclusions

A new procedure based on the analytical method to calculate the reinforcement tensile force in case of slopes with respect to uniform surcharge has been developed in this study. The proposed relationships have basically extracted from horizontal slices method. The developed relationship has the considerable ability to calculate the distribution of reinforcement force at geosynthetic with an emphasis on the uniform surcharge in both static and pseudo-static modes. The proposed formulation for no-surcharge slope has 4n equation with 4n unknowns. While in case of surcharged slopes the procedure has been extracted from 5n equation with 5n unknowns. The

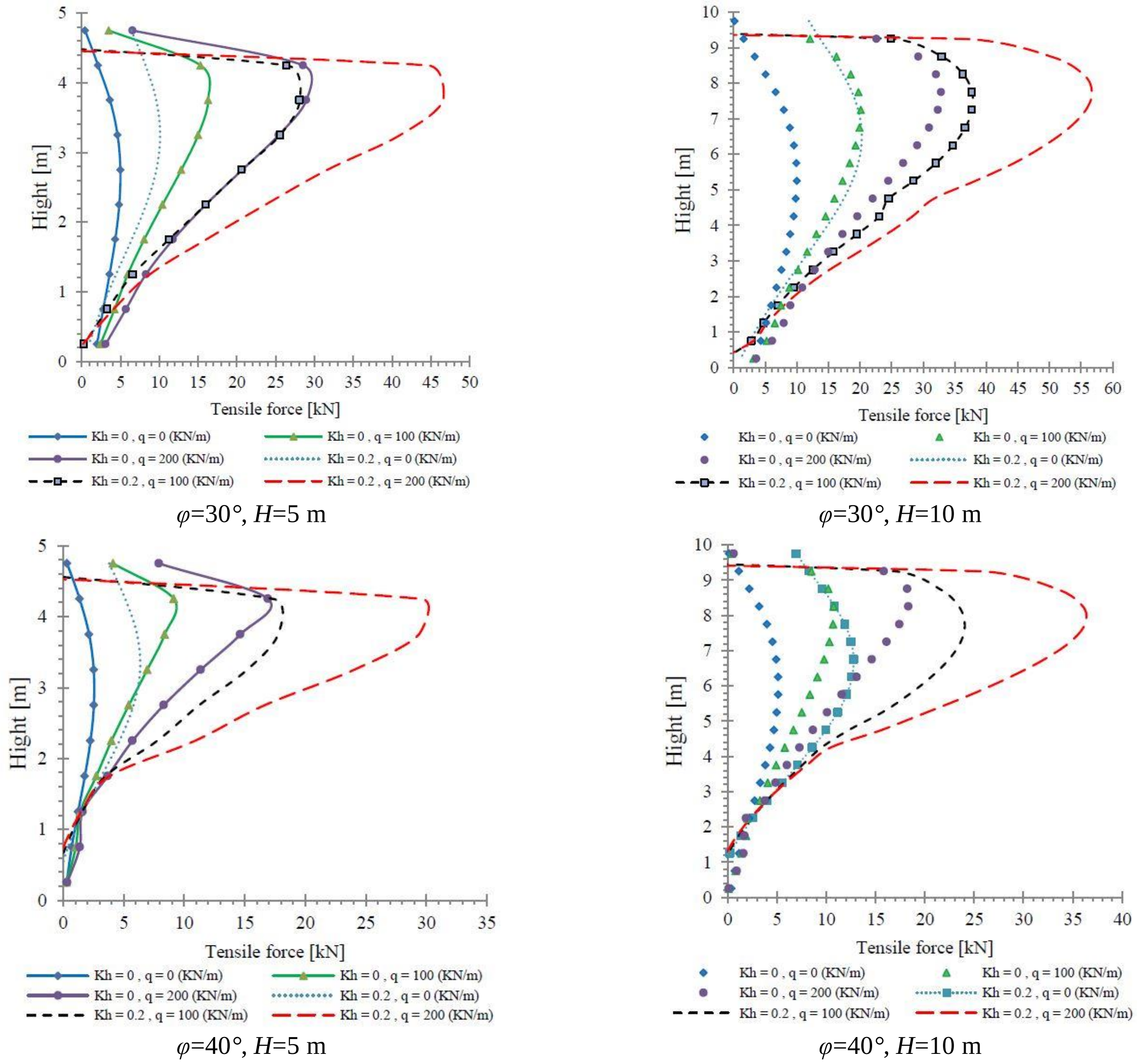


Fig. 12 Results of tensile reinforcement distribution along the slope height in case of slope inclination 60-degree

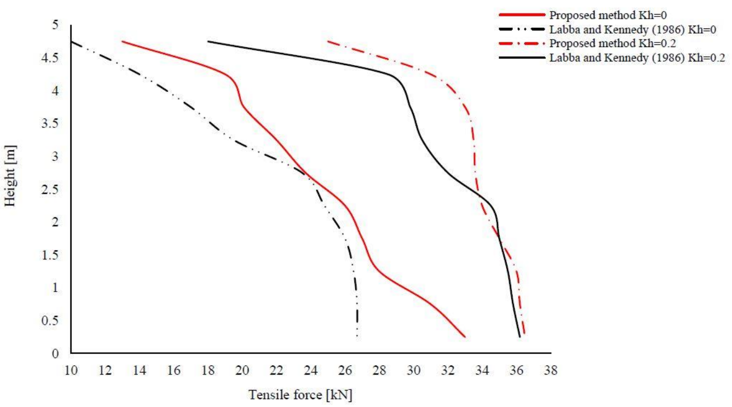


Fig. 13 Comparison between the proposed method and that by Labba and Kennedy (1986) β=90°, φ=30°, H=5 m, q=100 kN/m^2

developed method is capable to calculate the crisis wedge which creates most of the reinforcements force by the uniform surcharge. Also it is able to estimate the tensile force of reinforcement according to the distance of surcharge from slope edge.

Obtained result of the suggested method shows both horizontal seismic coefficient and internal friction angle have the considerable effect on the total force of reinforcements and the least required length of reinforcement has significantly been depended to both factors. The maximum tensile force in case of the surcharged slope has been quantified by multiplying the ratio "*A*" at the total reinforcement tensile force that has directly been achieved by no-surcharge slope condition. Obtained results show that the lowest slope tendency angle has the highest effect on the horizontal seismic coefficient on parameter "*A*". Furthermore, the ratio "*A*" would be increased due to the increase in surcharge length. While results show that the slope height and internal friction angle (φ) have the highest and lowest influence on increasing the parameter "*A*" respectively.

Results showed that the reinforcement force distribution at the vertical slope is a triangle like. So that most of the equipper forces are created at lower layers. Results show that to decrease the slope inclination (β), would increase the tensile forces at the upper layers of reinforcements. Obtained results have also shown that by increasing the surcharge intensity (q) and horizontal seismic coefficient (k_h), the reinforcement force significantly will increases. While it is illustrated that by increasing the internal friction angle, reinforcements can experience less force. Outcomes have proved that the increase of the horizontal seismic coefficient and the intensity of the surcharge have an increasing effect on the reinforcements force distribution. Finally, the obtained results have been compared with the results of previous studies and have illustrated the acceptable variation. Maximum 20 and 25 percent difference have been reported in cases of static and seismic condition respectively.

References

AASHTO (2007), Standard specifications for highway bridges. American Association of State Highway and Transportation Officials, Washington, D.C.

Abbasi Maedeh, P., Ghanbari, A. and Wu, W. (2017), "Estimation of elevated tanks natural period considering fluid- structure- soil interaction by using new approaches", *Earthq. Struct*., **12**(2), 145-152.

Ahmadabadi, M. and Ghanbari, A. (2009), "New procedure for active earth pressure calculation in retaining walls with reinforced cohesive-frictional backfill", *Geotext Geomem..*, **27**(6), 456-463.

Allen, T.M., Bathurst, R.J., Lee, W.F., Holtz, R.D., Walters, D.L. (2003), "A new working stress method for prediction of reinforcement loads in geosynthetic walls", *Can. Geotech. J.*, **40**(5), 976-994.

Aminpoor, M.M. and Ghanbari, A. (2014), "Design charts for yield acceleration and seismic displacement of retaining walls with surcharge through limit analysis", *Struct. Eng. Mech*., **52**(6), 1225-1256.

Ausilio, E., Conte, E. and Dente, G. (2000), "Seismic stability analysis of reinforced slopes", *Soil Dyn. Earthq. Eng*., **19**, 159-172.

Azad, A., Yasrobi, S. and Pak, A. (2008), "Seismic active earth pressure distribution behind rigid retaining walls", *Soil Dyn. Earthq. Eng*., **28**(5), 365-375.

Basha, B.M. and Babu, G.L.S. (2011), "Reliability based earthquake resistant design for internal stability of reinforced soil structures", *Geotech. Geol. Eng.*, **29**, 803-820.

Basha, B.M. and Basudhar, P.K. (2010), "Pseudo static seismic stability analysis of reinforced soil structures", *Geotech. Geol. Eng*., **28**, 745-762.

Bathurst, R.J. and Hatami, K. (1998), "Seismic response analysis of a geosynthetic reinforced soil retaining wall", *Geosynth. Int*., **5**(1-2), 127-166.

Bathurst, R.J., Allen, T.M. and Walters, D.L. (2005), "Reinforcement loads in geosynthetic walls and the case for a new working stress design method", *Geotext. Geomemb*., **23**(4), 287-322.

Caltabiano, S., Cascone, E. and Maugeri, M. (2000), "Seismic stability of retaining walls with surcharge", *Soil Dyn. Earthq. Eng*., **20**(5-8), 469-476.

Caltabiano, S., Cascone, E. and Maugeri, M. (2011), "Static and seismic limit equilibrium analysis of sliding retaining walls under different surcharge conditions", *Soil Dyn. Earthq. Eng*., **37**, 38-55.

Choudhury, D., Nimbalkar, S.S. and Mandal, J.N. (2007), "External stability of reinforced soil walls under seismic conditions", *Geosynth Int*., **14**(4), 211-218.

El-Emam, M.M. and Bathurst, R.J. (2007), "Influence of reinforcement parameters on the seismic response of reduced-scale reinforced soil retaining walls", *Geotext Geomemb*., **25**(1), 33-49.

Georgiadis, M. and Anagnostopoulos, C. (1998), "Lateral pressure on sheet pile walls due to strip load", *J. Geotech. Geoenviron. Eng*., **124**(1), 95-98.

Gerber, E. (1929), *Unter Suchungen Uber Die Druck Verteil Ungimor Lichbel Asteten Sand*, Technis che Hochscule, Zurich.

Ghanbari, A. and Ahmadabadi, M. (2010a), "Pseudo-dynamic active earth pressure analysis of inclined retaining walls using horizontal slices method", *Scientica Iranica*, **17**(2), 118-130.

Ghanbari, A. and Ahmadabadi, M. (2010b), "Active earth pressure on inclined retaining walls in static and pseudo-static conditions", *Int. J. Civil Eng*., **8**(2), 159-173**.**

Ghanbari, A. and Ahmadabadi, M. (2010c), "New analytical procedure for seismic analysis of reinforced retaining wall with cohesive-frictional backfill", *Geosynth. Int*., **17**(6), 364-379

Ghanbari, A. and Taheri, M. (2012), "An analytical method for calculating active earth pressure in reinforced retaining walls subject to a line surcharge", *Geotext Geomemb*., **34**, 1-10**.**

Giri, G. (2011), "Pseudo-dynamic approach of seismic earth pressure behind cantilever retaining wall with inclined backfill surface", *Geomech. Eng*., **3**(4), 255-266

Greco, V.R. (1999), "Active earth thrust on cantilever walls in general conditions", *Soil. Found*., **39**(6), 65-78**.**

Greco, V.R. (2003), "Pseudo-static analysis for earth thrust computations", *Soil. Found*., **43**(2), 132-140**.**

Greco, V.R. (2005), "Active earth thrust by backfills subject to a line surcharge", *Can. Geotech. J*., **42**(5), 1255-1263**.**

Greco, V.R. (2006), "Lateral earth pressure due to backfill subject to a strip surcharge", *Geotech. Geol. Eng*., **24**, 615-636.

Hausmann, M.R. and Lee, K.L. (1978), "Rigid model wall with soil reinforcement", *Proceedings of Symposium on Earth Reinforcement*, ASCE, 400-428.

Huang, C.C. and Luo, W.M. (2010), "Behavior of cantilever and geosynthetic-reinforced walls on deformable foundations", *Geotext. Geomemb*., **28**, 448-459.

Huang, C.C. and Wang, W.C. (2005), "Seismic displacement charts for the performance-based assessment of reinforced soil walls", *Geosynth Int*., **12**(4), 176-190.

Huang, C.C. and Wu, S.H. (2006), "Simplified approach for assessing seismic displacements of soil retaining walls", *Geosynth. Int*., **13**(6), 219-233.

Huang, C.C. and Wu, S.H. (2007), "Simplified approach for assessing seismic displacements of soil-retaining walls. Part II: Geosynthetic-reinforced walls with rigid panel facing", *Geosynth. Int*., **14**(5), 264-276.

Huang, C.C., Wu, S.H. and Wu, H.J. (2009), "Seismic displacement criterion for soil retaining walls based on soil strength mobilization", *J. Geotech. Geoenviron. Eng.*, **135**(1), 74-83.

Janbu, N. (1957), "Earth pressure and bearing capacity calculations by generalized procedures of slices", *Proceedings of 4th International Conference on Soil Mechanics and Foundation Engineering*, London.

Jarquio, R. (1981), "Total lateral surcharge pressure due to strip load", *J. Geotech. Eng. Div.*, **107**(10), 1424-1428.

Jewell, R.A. (1991), "Application of revised design charts for steep reinforced slopes", *Geotext. Geomemb.*, **10**(3), 203-233.

Jones, C.J.F.P. and Clarke, D. (2007), "The residual strength of geosynthetic reinforcement subjected to accelerated creep testing and simulated seismic events", *Geotext. Geomemb.*, **25**(2), 155-169.

Juran, I., Baudrand, G. and Farrag, K. (1990), "Kinematical limit analysis for design of soil-nailed structures", *J. Geotech. Eng.*, **116**(1), 54-72.

Koseki, J., Bathurst, R.J., Guler, E., Kuwano, J. and Maugeri, M. (2006), "Seismic stability of reinforced soil walls", *Proceedings of 8th International Conference on Geosynthetics*, 51-77.

Laba, J.T. and Kennedy, J.B. (1986), "Reinforced earth retaining wall analysis and design", *Can. Geotech. J.*, **23**(3), 317-326.

Lareal, P., Benameur, F. and Collas, P. (1992), "Active earth pressure reducing perusal: experimental tests", *Proceedings of Conference on Retaining Structures*, Inst. of Civil Eng., Robinson College, Cambridge.

Leshchinsky, D. (2001), "Design dilemma: use peak or residual strength of soil", *Geotext. Geomemb.*, **19**(2), 111-125.

Leshchinsky, D., Ling, H.I., Wang, J.P., Rosen, A. and Mohri, Y. (2009), "Equivalent seismic coefficient in geocell retention system", *Geotext. Geomemb.*, **27**, 9-18.

Ling, H.I., Leshchinsky, D. and Mohri, Y. (1997), "Soil slopes under combined horizontal and vertical seismic accelerations", *Earthq. Eng. Struct. Dyn.*, **26**, 1231-1241.

Ling, H.I., Leshchinsky, D. and Perry, E.B. (1997), "Seismic design and performance of geosynthetic-reinforced soil structures", *Geotechnique*, **47**(5), 933-952.

Lo, S.C. and Xu, D.W. (1992), "A strain based design method for the collapse limit state of reinforced soil walls and slopes", *Can. Geotech. J.*, **29**(8), 832-842.

Michalowski, R.L. (1997), "Stability of uniformly reinforced slopes", *J. Geotech. Geoenviron. Eng.*, **123**(6), 546-556.

Michalowski, R.L. (1998), "Limit analysis in stability calculations of reinforced soil structures", *Geotext. Geomemb.*, **16**(6), 311-331.

Mishra, B. (1980), "Lateral pressures on retaining walls due to loads of surface of granular backfill", *Soil. Found.*, **20**(2), 31-44.

Moghaddas Tafreshi, S.N., Shaghaghi, T., Tavakoli Mehrjardi, G., Dawson, A.R. and Ghadrdan, M. (2015), "A simplified method for predicting the settlement of circular footings on multi-layered geocell-reinforced non-cohesive soils", *Geotext. Geomemb.*, **43**(4), 332-344.

Mojalla, M. and Ghanbari, A. (2012), "Prediction of seismic displacements in gravity retaining walls based on limit analysis approach", *Struct. Eng. Mech.*, **42**(2), 247-267.

Mojalla, M., Ghanbari, A. and Askari, F. (2012), "A new analytical method for calculating seismic displacements in reinforced retaining walls", *Geosynth. Int.*, **19**(3), 212-231.

Morgenstern, N.R. and Price, V.E. (1965), "The analysis of the stability of generalized slip surfaces", *Geotechnique*, **15**, 79-93**.**

Motta, E. (1994), "Generalized Coulomb active-earth pressure for distanced surcharge", *J. Geotech. Eng.*, ASCE, **120**(6), 1072-1079.

Nouri, H., Fakher, A. and Jones, C.J.F.P. (2006), "Development of horizontal slices method for seismic stability analysis of reinforced slopes and walls", *Geotext. Geomemb.*, **24**, 175-187.

Nouri, H., Fakher, A. and Jones, C.J.F.P. (2008), "Evaluating the effects of the magnitude and amplification of pseudo-static acceleration on reinforced soil slopes and walls using the limit equilibrium horizontal slices method", *Geotext. Geomemb.*, **26**(3), 263-278.

Rankine, W.J.M. (1857), "On the stability of loose earth", Transactions of the Royal Society of London.

Rowe, R.K. and Skinner, G.D. (2001), "Numerical analysis of geosynthetic reinforced retaining wall constructed on a layered soil foundation", *Geotext. Geomemb.*, **19**(7), 387-412.

Sandri, D. (1998), "A performance Summary of reinforced soil structures in the greater Los Angeles area after the Northridge earthquake", *Geotext. Geomemb.*, **15**, 235-253.

Saran, S., Garg, K.G. and Bhandari, R.K. (1992), "Retaining wall with reinforced cohesionless backfill", *J. Geotech. Eng.*, ASCE, **118**, 1869-1888.

Sawada, T., Chen, W.F. and Nomachi, S.G. (1993), "Assessment of seismic displacements of slopes", *Soil Dyn. Earthq. Eng.*, **12**(3), 357-362.

Segrestin, P. (1992), "Design of sloped reinforced fill structure", *Proceedings of Conference on Retaining Structures*, Inst. of Civil Eng., Robinson College, Cambridge..

Shahgholi, M., Fakher, A. and Jones, C.J.F.P. (2001), "Horizontal slice method of analysis", *Geotechnique*, **51**(10), 881-885.

Shekarian, S., Ghanbari, A. and Farhadi, A. (2008), "New seismic parameters in the analysis of retaining walls with reinforced backfill", *Geotext. Geomemb.*, **26**, 350-356.

Skinner, G.D. and Rowe, R.K. (2005), "Design and behavior of a geosynthetic reinforced retaining wall and bridge abutment on a yielding foundation", *Geotext. Geomemb.*, **23**(3), 234-260.

Spangler, M.G. (1938), Horizontal Pressure on Retaining Walls Due to Concentrated Surface Loads, Iowa State University Engineering Experiment Station, Bulletin 140.

Spencer, E. (1967), "A method of analysis of stability of embankments assuming parallel inter-slice forces", *Geotechnique*, **17**(1), 11-26.

Tatsuoka, F., Koseki, J., Tateyama, M., Munaf, Y. and Horii, K. (1998), "Seismic stability against high seismic loads of geosynthetic-reinforced soil retaining structures", *Proceedings of the 6th International Conference on Geosynthetic*s, Atlanta.

Tavakoli Mehrjardi, G. and Khazaei, M. (2017), "Scale effect on the behaviour of geogrid-reinforced soil under repeated loads", *Geotext. Geomemb.*, **45**(6), 603-615.

Tavakoli Mehrjardi, G. and Motarjemi, F. (2018), "Interfacial properties of geocell-reinforced granular soils", *Geotext. Geomemb.*, **46**(4), 384-395.

Tavakoli Mehrjardi, G., Ghanbari, A. and Mehdizadeh, H. (2016), "Experimental study on the behaviour of geogrid-reinforced slopes with respect to aggregate size", *Geotext. Geomemb.*, **44**(6), 862-871.

Wihelm Ernest and Sohn (2002), *Beton Kalendar*, Verlag von Wihelm Ernest and Sohn, Munich, Germany.

Yamagami, T., Jiang, J. and Ahmed Khan, Y. (1999), "Progressive failure analysis based on a method of no-vertical slices", *Proceedings of Slope Stability Engineering*, **2**.

Zornberg, J.G., Sitar, N. and Mitchel, J.K. (1998b), "Performance of geosynthetic reinforced slopes at failure", *J. Geotech. Geoenviron. Eng.*, **124**(8), 670-683.

Zornberg, J.G., Sitar, N. and Mitchell, J.K. (1998a), "Limit equilibrium as basis for design of geosynthetic-reinforced slopes", *J. Geotech. Eng.*, **124**(8), 684-698.

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Notations

Basic SI units are given in parentheses.

A the ratio of reinforcement force dimension under surcharge or without surcharge mode

A_i area of *i*th slice (m^2)

a uniform surcharge distance from the edge of the slope (m)

b the length of the uniform surcharge which is left inside the failure surface wedge (m)

c cohesion of soil (kN/m^2)

$f_i(y)$ function of the depth in Morgenstern and Price method

H height of slope (m)

H_i horizontal force at top of *i*th slice (kN/m)

H_{i+1} horizontal force at bottom of *i*th slice (kN/m)

h_i height of *i*th slice (m)

K normalized form of the required total force to maintain the stability of slope

k_h horizontal seismic coefficient

k_v vertical seismic coefficient

L_c maximum distance between failure surface &slope surface (m)

L_i upper side length of the *i*th slice (m)

m number of reinforcement layers

N_i normal force on failure surface for ith slice (kN/m)

n number of the horizontal slices

q Intensity of the uniform surcharge (kN/m)

r_0 , r_h radius of the Log-spiral with respect to angles θ_0 and θ_h (m)

S_i shear force on failure surface for ith slice (kN/m)

S_v vertical spacing of reinforcements (m)

T_i tensile force in reinforcement for ith slice (kN/m)

$\sum T_i$ total tensile force in the reinforcements (kN/m)

V_i normal force at top of *i*th slice (kN/m)

V_{i+1} normal force at bottom of *i*th slice (kN/m)

W_i weight of *i*th slice (kN)

$X_{O,NS}$,$Y_{O,NS}$ coordinates of the point where N_i and S_i act on the base of the slice with respect to Log-spiral center (m)

$X_{G,O1}$,$Y_{G,O1}$ coordinates of the center of mass of the slice with respect to O_i (the left top corner point of the i^{th} slice) (m)

$X_{v,i}$ coordinate of the point of application of vertical inter slice force (V_i) on the slice with respect to the left top corner point of the slice (m)

$Y_{r,i}$ depth of the reinforcement i layer in relation to slope crown (m)

α_i inclination angle of the base of the i^{th} slice (degree)

β inclination angle of the slope (degree)

θ polar coordinates

θ_0 , θ_h size of the applied polar dimensions to describe log-spiral failure surface

γ total unit weight (kN/m^3)

φ internal friction angle of the soil (degree)

λ unknown constant for all the slices in Morgenstern and Price method