IJST, Transactions of Civil Engineering, Vol. 37, No. C2, pp 257-269
Printed in The Islamic Republic of Iran, 2013
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BEARING CAPACITY OF FOOTINGS ON PILE-STABILIZED SLOPES*

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Abstract– The present paper reveals the results of an analytical method to calculate the bearing capacity of a footing supported on one or two rows of piles stabilizing slope. The varied parameters here include pile diameter, pile length, location of pile rows, location of footing relative to the slope crest, foundation width, center to center spacing of piles in a row, and fixity of the pile head. Passive pile resistance is determined based on normal and shear resistance of the soil surrounding the pile considering plastic deformation of soil between piles. The Pile resistance obtained through the present method is compared with other analytical as well as 3D numerical ones. The results indicate acceptable agreement. The footing bearing capacity is calculated according to both the limit equilibrium slope stability analysis and soil stability beneath the footing. The predicted results were compared with those reported from other experiments and indicated an acceptable agreement with increasing pile spacing. The results indicate that stabilizing the earth slope with rows of piles has a significant effect on the footing of bearing capacity improvement.

Keywords– Slope stability, passive pile, footing, bearing capacity, limit equilibrium

1. INTRODUCTION

Footings may be constructed on sloping ground or adjacent to a slope crest such as footings for bridge abutments on sloping embankments or building footings on earth slope. When a footing is located on a sloping surface, its bearing capacity may be significantly reduced depending on the location of the footing with respect to the slope, slope height, and soil type. Therefore, it may not be possible to use shallow foundation unless other foundation types or slope reinforcement techniques are considered [1-3].

In the literature, slope stability can increase by using various solutions including geometry modification, soil reinforcement, or installation of continuous or discrete retaining structures such as walls or piles. Such techniques can not only increase the slope stability, but also lead to the footing bearing capacity increase and settlement reduction. These goals may be achieved by using stabilizing piles that tolerate slope active earth pressures. Such piles, which can be installed at the slope crest or within the slope, act as resisting members and are usually subjected to lateral forces as a result of horizontal movements of the slope soil.

In pile reinforced slopes, estimation of the lateral force acting on each pile may be done after multiplying the resisting force per unit width of the pile row by the center-to-center spacing between piles. However, arching between adjacent piles should be taken into consideration in order to find the force acting on piles more accurately. Several studies reported the successful use of passive piles in many situations in order to improve slope stability [4- 9].

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*Received by the editors November 14, 2011; Accepted December 17, 2012.
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Hull and Poulos (1999) described an approach for the design of piles reinforced slopes. In this study, both total shear force and the maximum shear force provided by each pile are necessary to increase the safety factor. Hull and Poulos (1999) considered type, number of piles, and the best location of such piles within the slope [10]. Other analytical methods were presented in design of slopes reinforced with a single row of piles in static and seismic condition [8, 11].

Several studies were carried out to find the best position of the passive pile rows within a slope. This was achieved by determining the position of the pile rows giving the maximum resistance force and factor of safety. However, the reported results were rather different and contradictory [8, 12-17].

Several numerical methods were used to determine safety factor of slope reinforced with a row of pile [18-20]. The behavior of pile reinforced slopes in the field was studied and compared with analytical results [21]. Also, Mostafa et al. reported experimental results of bearing capacity of strip footing on a slope reinforced with a row of piles and sheet pile [22].

In most of the previous studies on pile-stabilized slopes, only slope stability was taken into consideration, and little was done on the improvement of load-carrying characteristics of shallow footings supported on pile stabilized slopes. In the existing study, an analytical method is presented to calculate the bearing capacity of footings constructed on slope reinforced with piles. The various parameters in the paper include pile diameter, pile length, location of pile rows, location of footing relative to the slope crest, foundation width, center to center spacing of piles in a row, fixity of pile head, and the impact of two rows of piles. The main objectives of the present study are to determine the effect of various parameters on improvement of the bearing capacity of footings on pile reinforced slopes in various locations of pile within a slope and also, to find out the best location of pile rows on or within a slope which gives the greatest footing bearing capacity in various conditions.

2. ANALYSIS METHOD

Herein, the footing bearing capacity is calculated in accordance with limit equilibrium slope stability analysis and also the soil stability beneath the footing using a virtual retaining wall method. To achieve this, the first step is to determine the pile resistance against the soil movement. It is assumed here that soil satisfies the Mohr-Coulomb yield criterion.

Ito and Matsui [14] presented a method to calculate lateral pressure on piles located as passive piles in a plastically deforming ground with the consideration of soil squeeze between the piles (Fig. 1). In fact, this method calculates the total force applied on piles and soil (between piles) and then determines subtracted force on soil (between piles) from total force and the force applied on each pile [14]. Ito and Matsui equation is defined below:

$$
\begin{aligned}
p_u = {} & cA\Bigg(\frac{1}{N_\phi \tan\phi}\left\{\exp\left[\frac{D_1-D_2}{D_2}N_\phi \tan\phi \tan\left(\frac{\pi}{8}+\frac{\phi}{4}\right)\right]-2N_\phi^{(1/2)}\tan\phi-1\right\}+\frac{2\tan\phi+2N_\phi^{(1/2)}+N_\phi^{(-1/2)}}{N_\phi^{(1/2)}\tan\phi+N_\phi-1}\Bigg)- \\
& c\left(D_1\frac{2\tan\phi+2N_\phi^{(1/2)}+N_\phi^{(-1/2)}}{N_\phi^{(1/2)}\tan\phi+N_\phi-1}-2D_2N_\phi^{(-1/2)}\right)+ \\
& \frac{\gamma z}{N_\phi}\left\{A\exp\left[\frac{D_1-D_2}{D_2}N_\phi \tan\phi \tan\left(\frac{\pi}{8}+\frac{\phi}{4}\right)\right]-D_2\right\}
\end{aligned}
\qquad (1)
$$

where p_u = lateral resistance of passive pile in various depths, D_1=center to center spacing of piles in a row, D_2=opening between piles in a row, ϕ=soil friction angle, c=soil cohesion, γ=soil unit weight, and z=depth from the ground surface in sliding layer, $N_\phi = \tan^2(\pi/4+\phi/2)$, $A = D_1(D_1/D_2)^{(N_\phi^{(1/2)}\tan(\phi)+N_\phi-1)}$.

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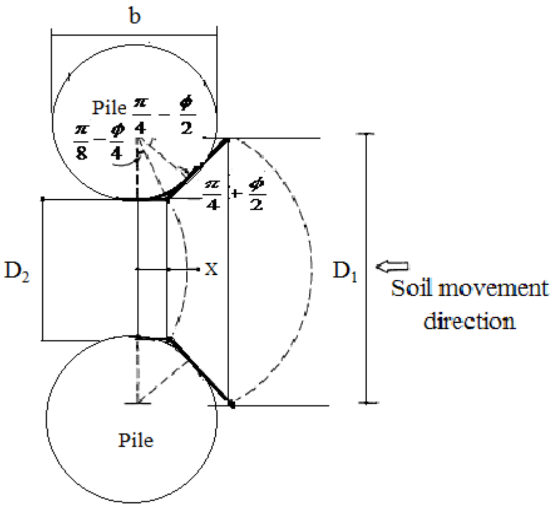

Fig. 1. Plastic deformation of ground around stabilizing piles [14]

Ito and Matsui method has limiting assumptions. This method is valid only for rigid piles, one pile row, and fixed piles in stable layer. It fails to consider the effect of earth slope and seismic loading. The suggested method remedies these limiting assumptions to determine passive pile resistance. Previous studies confirm agreement of results obtained from Ito and Matsui with field data [21]. Therefore, their method is used to indicate the validity of the suggested one.

In the present study, lateral resistance of passive pile is determined by simulating the piles as wall and adding shear resistance of the soil surrounding piles. In addition, plastic deformation of soil between piles in a row affects lateral resistance of piles and power of passive coefficients. The power of passive coefficients indicates the effect of the combination of soil plastic deformation between piles in a row and pile resistance; therefore, it is different in various spacing of piles in a row. It causes the power of K_p and K_{pc} to become equal to 2 (Eq. (2)), when piles spacing in a row becomes minimum ($D_1/b=2.5$). Also, when $D_1/b=8$, the power of passive coefficients is equal to 1 and soil plastic deformation between piles does not affect the lateral resistance of pile, the validity of the suggested method is in good agreement with Ito-Matsui and numerical method presented previously.

The lateral resistance of the passive pile at various depths is determined by using Eq. (2). When the pile spacing in a row is minimum ($D_1/b=2.5$), notably the first and second part of Eq. (2) represent the normal resistance and the third part indicates shear resistance of the soil around the pile (Fig. 2).

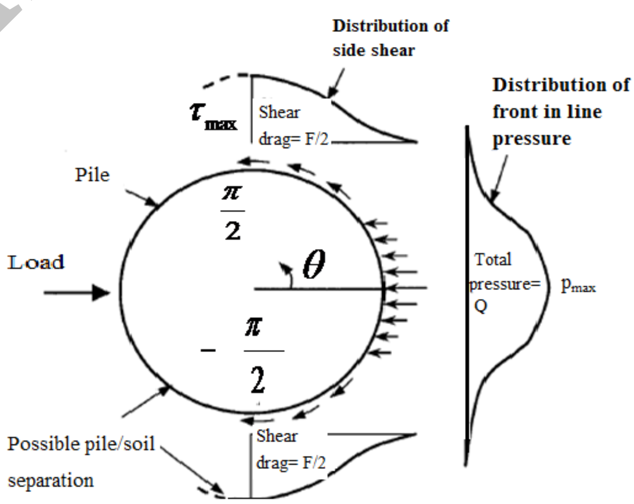

Fig. 2. Proposed distribution of frontal soil resistance and side shear resistance in passive pile [23]

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$$p_u = (K_p^2 \gamma z + K_{pc}^2 c)b + (K\gamma z \tan\delta)b \tag{2}$$

where p_u = lateral resistance of passive pile at various depths, b=pile diameter, K =coefficient of lateral soil pressure, δ = friction between soil and pile, and z represents depth, K_{pc} =passive coefficient of soil cohesion and K_p =passive coefficient. K_p, K_{pc} are given by Eqs. 3, 4 based on the Coulomb lateral earth pressure method.

$$K_p = \frac{\cos^2(\phi + \theta - \psi)}{\cos^2\theta \cos^2\psi \cos(\theta - \delta - \psi)\left[1 - \sqrt{\frac{\sin(\phi+\delta)\sin(\phi+\alpha-\psi)}{\cos(\theta-\delta-\psi)\cos(\theta-\alpha)}}\right]^2} \tag{3}$$

where $\psi = \tan^{-1}\frac{k_h}{1-k_v}$, k_h =horizontal seismic coefficient, k_v =vertical seismic coefficient, θ =angle of pile with vertical direction, α = slope angle, and ϕ =soil internal friction angle.

The value of K_{pc} is given by:

$$K_{pc} = 2\sqrt{K_p(1 + \frac{c_w}{c})} \tag{4}$$

where K_{pc}=passive coefficient of soil cohesion, K_p =passive coefficient based on the Coulomb method; $c_w = 0.5c$ when c <50 kPa and c_w =25 kPa when c > 50 kPa.

In general, the capabilities of the above developed method are outlined as follows:

- The pile fixity in stable layer is considered; therefore, the lateral resistance of flexible piles can be incorporated;
- The spacing between piles in rows can be considered;
- The effect of the ground slope and also seismic effects have been incorporated;
- The variation of bending moment and shear force along the pile can be calculated in sliding and stable layer.

In the following section, it will be shown how the developed method is used to determine the bearing capacity of footing constructed on a slope reinforced with piles.

a) Bearing capacity of footing on slope based on slope stability method

A program was written in MATLAB software and the footing bearing capacity is determined when the slope stability has a safety factor of 1.5. In the first step, the failure surface is defined in a way that the minimum factor of safety is obtained for the slope reinforced with piles (Fig. 3). The rupture surface in the pile reinforced slope row is not similar to that of the same slope without reinforcing piles. The pile resistance is determined with the suggested method and the slope stability analysis is carried out by using Bishop's method. The effect of various parameters on footing bearing capacity is calculated using:

$$FS = \frac{2cR^2 yb_2 + R(W\cos x - k_h W \sin x)\tan\phi + F_p(S_1) + V_B S_3}{(W\sin x + k_h W\cos x)R + q_{ult} b_1 B S_2} \tag{5}$$

where W=weight of the failed wedge, b_2 = slope width, 2y=central angle of failed surface, x= $a\,sin(\frac{H}{2R\,sin\,y})$ as shown in Fig. 3, R=radius of the failed surface, F_p =pile resistance, S_1 =distance of pile force to center of rupture surface, V_B =shear force at pile hinged head, S_3 =distance of shear force at pile head to center of rupture surface, q_{ult} =footing bearing capacity, b_1 =footing length, B =footing width, and S_2 =distance of gravity center of footing to center of rupture surface.

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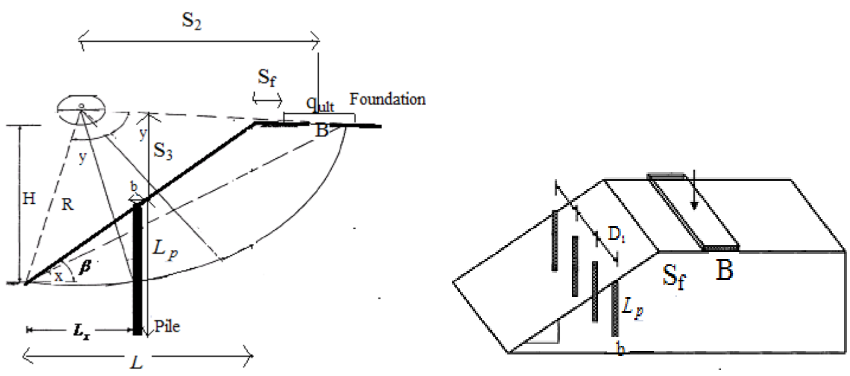

Fig. 3. Slope reinforced with a pile row

The pile resistance **(**F_p**)** is determined through Eq. (2) in which F_p is equal to the pile minimum resistance in sliding and stable layers. If pile length is totally located in the sliding layer, the pile resistance becomes equal to 0 in the slope stability analysis.

b) Bearing capacity based on stability of soil beneath footing based on virtual retaining wall method

In this method, an imaginary retaining wall passing the footing edge and close to the slope crest is assumed for calculation of the bearing capacity of a strip footing on a slope reinforced with piles (Fig. 4). As observed, this wall tolerates active force, P_a, due to the footing loading and the soil beneath the footing. The surrounding soil on the left-hand side of the wall is in the passive condition and exerts P_p on the wall. The values of P_a and P_p are computed from the Coulomb lateral earth pressure method. The bearing capacity of footing is determined by applying equilibrium between active and passive forces shown in Fig. 4. Therefore, the bearing capacity of the footing on the slope reinforced with pile is expressed as follows:

$$q_{ult} = cN_c + \bar{q}N_q + \frac{1}{2}\gamma BN_\gamma + P_p / K_a B \tan(\eta_{ae}) \qquad (6)$$

where $N_c = \dfrac{K_{pc} + K_{ac}}{K_a}$, $N_q = \dfrac{K_p(1-k_v)}{K_a}$, $N_\gamma = -\tan(\eta_{ae})$, $\bar{q} = \gamma D$, η_{ae}=angle of active area with horizontal direction (Fig. 4), K_a =active lateral earth pressure, K_{ac}= active coefficient of soil cohesion in Coulomb method, and D=footing embedded depth, and P_p = passive force.

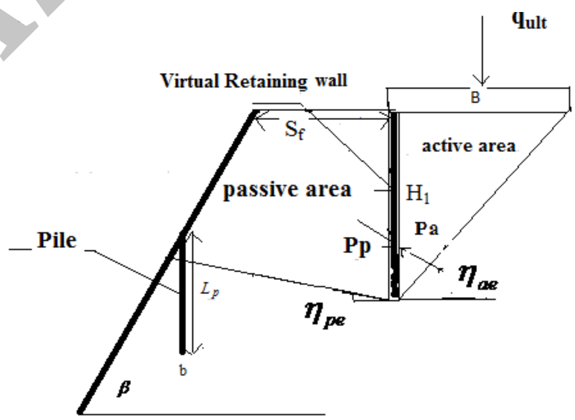

Fig. 4. Active and passive area of soil beneath the footing based on virtual retaining wall method

The passive force within a pile reinforced slope is determined by applying equilibrium between passive zone forces. The outcome is:

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$$P_p = \frac{\dfrac{W_1}{\cot(\eta_{pe}+\phi)} + F_{p1} + V_B}{\dfrac{\sin\delta}{\cot(\phi+\eta_{pe})} + \cos\delta} \tag{7}$$

where η_{pe} =angle of passive wedge with horizontal direction determined with Coulomb method (Fig. 4), W_1 =weight of passive wedge, F_{p1} =resistance of pile in passive zone, and V_B = shear force of pile hinged head.

The slope angle (β) affects W_1 and P_p in Eq. (7) where the pile resistance (F_{p1}) is determined according to Eq. (2), and F_{p1} is equal to resistance of pile in the passive zone. When the pile total length is embedded in the passive zone, its resistance is calculated through its total length in the virtual retaining wall method. The above algorithm is written in MATLAB software to determine q_{ult}.

Here, the shear force in the hinged headed pile is determined by nonlinear stiffness matrix method in which the soil reaction on the pile is modeled with springs. It is assumed that the maximum tolerable lateral pressure by pile is defined according to Eq. (2).

As mentioned before, in the present paper, the effect of two rows of piles is studied on the footing bearing capacity. For this purpose, first the efficiency of pile group against lateral movement of the slope soil is determined. Pile group efficiency depends on the pile spacing in rows, earth slope, seismic coefficients, number of piles in the group, and pile group configuration. It is assumed that the group piles are parallel and the whole piles behave as an equivalent continuous pile [24]. The pile group resistance is determined as shown below:

$$p_u = (K_p^2 \gamma z b + K_{pc}^2 c b) + s_p K \gamma z \tan\delta \tag{8}$$

where s_p is distance of pile rows.

3. RESULTS AND DISCUSSIONS

a) Comparison of suggested method with Ito and Matsui method

The results of the suggested method and those presented by Ito and Matsui are compared in Fig. 5. Here, the same assumptions made by Ito have been considered. The pile length in the sliding layer is 4 m. As seen, there is a good agreement between results. Notably, studies show that results of Ito and Matsui agree with field data [21]. Therefore, the suggested method predictions are valid and reliable. As seen in Eq. (2), the effect of D_1 does not exist in this method. In fact, the suggested method, as presented in Eq. (2), calculates the maximum tolerable lateral pressure by passive pile against soil movement because the minimum possible spacing for piles is D_1 /b= 2.5. The maximum arching effect and plastic deformation of soil between piles exist within this distance.

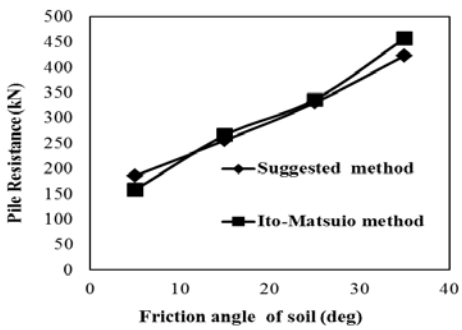

Fig. 5. Effect of soil friction angle on lateral resistance of passive pile (D_1/b=2.5)

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b) Comparing the suggested method with other ones in order to calculate safety factor of single pile row reinforced slope in cohesive soil

The proposed method can be applied to determine the passive pile resistance in cohesive soil. The present study compares the safety factor of reinforced slope with the suggested method and limit equilibrium one with the results of analyses presented by others including 3D numerical method based on FLAC 3D and analytical ones for cohesive soil [19, 8]. To compare, it is assumed that the soil cohesion and friction angle are 23.94 kPa and 10^o, respectively. In addition, the footing is not located on the slope. Fig. 6 illustrates this comparison and the validity of the presented method for cohesive soil. As seen, the suggested method gives $L_x/L=0.63$ for the pile location given the maximum safety factor whose value is closer to $L_x/L=0.5$ dedicated by FLAC3D (L_x/L=ratio of pile location in slope to slope length).

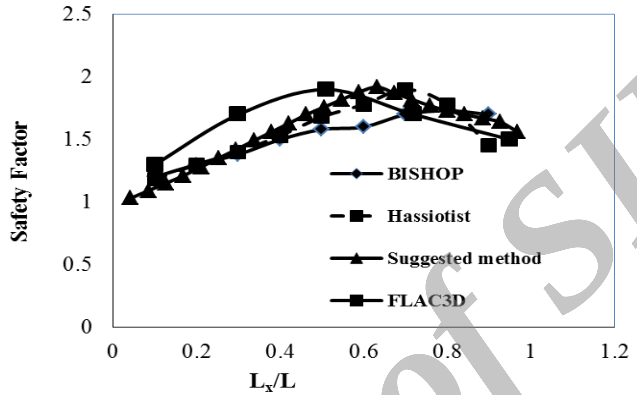

Fig. 6. Comparison between FS determined from suggested method and other methods (L_P=20 m, slope angle =30 deg)

c) Comparing analytical method with experimental in order to calculate footing bearing capacity in cohesionless soil

In this section, the results of the developed analytical method are compared with those obtained from experimental data reported by Mostafa et al. [22]. In experimental method, the ultimate bearing capacity for footing–soil system is found from a pronounced peak of the load displacement variation. Beyond this peak, the footing collapses and the load decreases. In this study, the pile was located at the slope crest. The strip footing B was 8 cm and its distance from the slope crest was 0 m [22].

The sandy slope studied by Mostafa et al. [21] was stable without using reinforcing piles and had $\phi = 42^\circ$ and γ =18.94 kN/m^3. The tested piles had lengths of L_p=8, 16, and 24 cm and diameters of b=0.6, 0.8, and 1.2 cm. The pile intervals were D_1=4, 8, 10 cm, and 20 cm. The slope angle and height (H) were 33.7° and 36 cm, respectively.

The pile length was shorter than the slope height. The pile was located in the failed surface with no intersection between rupture surface and the pile. Thus, considering slope stability analysis, the pile row does not affect the footing bearing capacity. The slope is also stable without stabilizing piles. In the virtual retaining wall method, the total length of the pile that is located at the slope crest is completely in the passive zone. Therefore, its total length is applied to determine its resistance in the developed method.

To investigate the usefulness of piles on the footing bearing capacity, the bearing capacity improvement (BCI) is defined by BCI, a non dimensional factor. The BCI value is defined as the ratio of the footing ultimate pressure with piles stabilized slopes ($q_{u\text{-}pile}$) to the footing ultimate pressure on the same slope with no reinforcing piles (q_u). The variation of BCI values versus b/B determined from the developed method are compared with results of the tests carried out by Mostafa et al. [22] in Fig. 7. As seen, increase in the pile spacing decreases the difference between the analytical and experimental data.

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The results in Fig. 7 indicate that when $D_1/B=0.5$ and b/B=0.075, experimental BCI values are almost 18 percent more than those from analytical results and the agreement is acceptable. However, with increasing D_1/B to 2.5, the difference between experimental and analytical BCI values almost decreases by 5 percent.

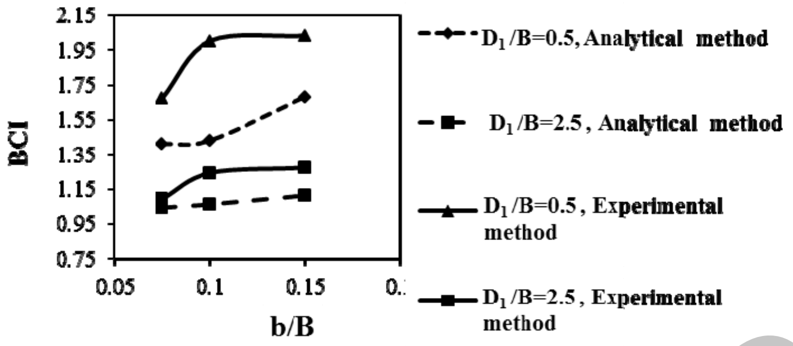

Fig. 7. Comparison between presented analytical data with experimental data ($L_p/B=3$)

Figure 8 shows the effect of pile length and spacing on the footing bearing capacity. As seen, experimental results are greater than analytical ones, especially with decreasing D_1/B. When $D_1/B=0.5$ and L_p=24cm, the experimental bearing capacity is 30 percent more than that determined from analytical method. This difference becomes about 5% with increasing D_1/B to 2.5. Figures 7 and 8 show that pile spacing reduction causes an increase in the difference between analytical and experimental footing bearing capacity, and the pile diameter and length do not remarkably affect such differences. In fact, decreasing pile spacing affects plastic deformation and arching effect between two piles. One reason for the difference between analytical and experimental results is that the angle of passive zone (η_{pe}) in virtual retaining wall method is calculated without considering the effect of the pile row. Any decrease in pile spacing results in an increase in the plastic deformation and arching effects. This, in turn, affects the angle of passive zone and further increases the passive force exerted on the virtual wall. As indicated by the results, when stabilizing piles are not affected, the footing bearing capacity determined from analytical and experimental methods is close. The predicted footing bearing capacity on pile-less slope is 15.52 kPa and 17.3 kPa according to the analytical method and experimental one respectively. This indicates the validity of analytical method. In fact, η_{pe} here shows the condition that lacks stabilizing piles. This angle decreases with an increase in passive force and decrease in pile spacing. Another reason for the difference between analytical and experimental results may be attributed to the scale effect and boundary condition in experiments.

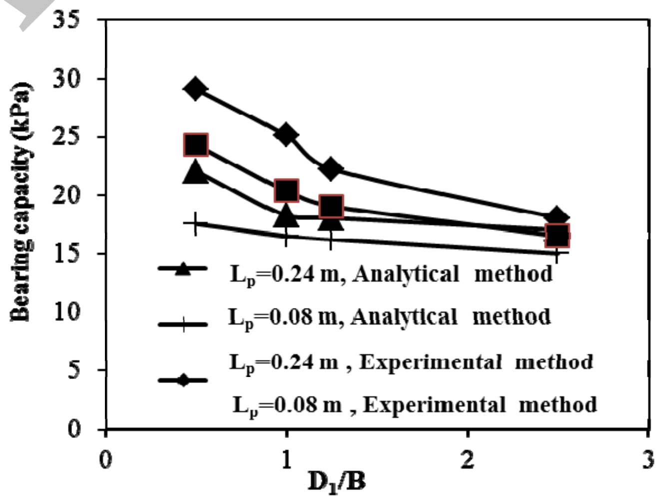

Fig. 8. Effect of pile length and spacing on experimental and analytical footing bearing capacity

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As seen in Fig. 8, when piles do not exist or the pile spacing increases ($D_1/B=2.5$), the difference between analytical and experimental data is negligible. However, when the slope is reinforced with a pile row with short pile spacing ($D_1/B=0.5$), the piles affect the angle of passive zone and enhance the difference between the results of the two methods. In the present study, η_{pe} does not change by altering the pile spacing, and the analytical method gives more conservative results than experiments.

d) Parametric studies

In this section, the effects of pile length (L_p), foundation distance from slope crest (S_f), location of pile rows (L_x), foundation width (B), fixity of pile head, and effect of two rows of pile are studied on the bearing capacity of the strip footing on piles reinforced slope. In the present paper, two methods are used to calculate the bearing capacity that is based on the slope stability and virtual retaining wall methods. It is noted that piles do not affect the footing bearing capacity in virtual retaining wall method when the pile row is located far from the passive zone (Fig. 4). However, the slope stability is affected by the pile presence at various locations within the slope. The pile resistance and the footing bearing capacity depend on the rupture surface shape and the pile length there in the slope stability analysis. Selecting these two methods (slope stability and virtual retaining wall methods) to calculate minimum footing bearing capacity depends on various parameters which are studied later. The soil properties here are assumed to be $\phi=28^o$, $\gamma=19$ kN/m^3, and c=20 kPa. The slope is assumed to have a height of H=10 m and an angle of $\beta=50^\circ$. For piles it is assumed that diameter (b) =1 m, pile head is free, center to center spacing of piles (D_1) =2.5 m. It is noted that when $L_p/H>=2$, the pile is fixed in the stable layer.

1. Effect of foundation width: Generally, the greater the foundation width, the higher the footing bearing capacity becomes. However, this may not be true for footings on piles reinforced slopes which are not fixed in the stable layer ($L_p/H<2$) and are located at the upper half of the slope (Fig. 9), because the slope stability method gives the minimum footing bearing capacity with increasing the foundation width. When piles are fixed in the stable layer, the footing bearing capacity becomes minimum with the virtual retaining wall method and therefore, the bearing capacity increases with more footing width. In this section, two values are considered for foundation width (B) as 2m and 10 m. Fig. 9 shows the footing bearing capacity for B=2 and 10 m for various L_x and S_f. It should be mentioned that the pile is not fixed in the stable layer.

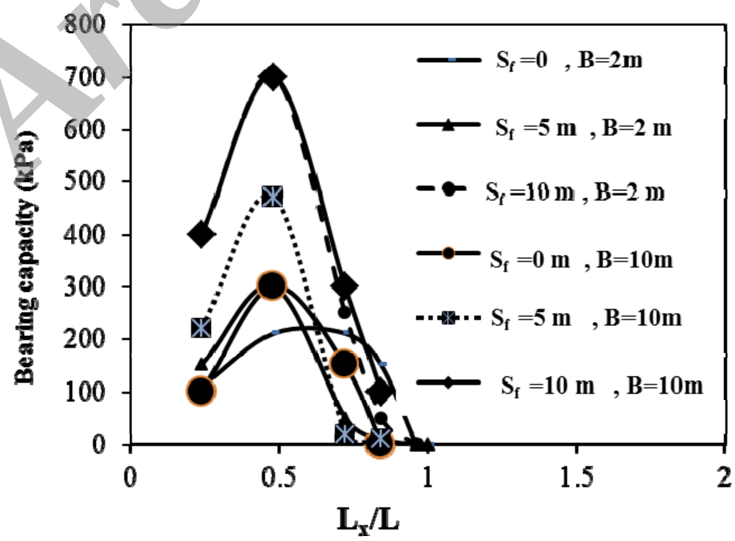

Fig. 9. Effect of foundation width on bearing capacity with analytical method in various distance of footing with respect to slope crest (pile is not fixed in stable layer)

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The results indicate that when S_f=0 and the pile row is located at upper half of the slope (L_x>0.7L), the footing bearing capacity decreases with increase in the foundation width. Because the footing bearing capacity determined from the slope stability method is minimum and the pile length in the stable layer decreases because the foundation width affects the rupture surface. When the pile is located within the lower half of the slope (L_x<0.7L), the footing bearing capacity increases with an increase in foundation width, because increasing the foundation width changes the method for determination of the bearing capacity from virtual retaining wall method to slope stability method. Also, the foundation width affects the pile length in the rupture surface and increases the pile resistance. When the footing is located in the failed zone and the footing distance is more than the foundation width, i.e. 15>S_f>B (S_f=5 m), the slope stability method gives the minimum footing bearing capacity in foundations with various widths. In these cases, the footing bearing capacity decreases with increase in the foundation width when L_x>0.7L. However, this change is not remarkable and the footing bearing capacity increases with increasing the foundation width when the pile row is installed at the lower half of the slope. When S_f=10 m, the effect of the bearing capacity is negligible. This is because the slope stability method gives the minimum bearing capacity in foundations with various widths, and part of the foundation located in the failed zone is almost equal in two foundations with various widths (S_f=10 m). When S_f>15 m (outside the failed zone), any increase in foundation width causes an increase in the footing bearing capacity and the slope does not affect it. The results also indicate that the maximum bearing capacity is achieved when the pile which is not fixed in stable layer is installed at the middle of slope in various values of S_f and B (Fig. 9).

2. Effect of fixity of pile head: In this section, the footing bearing capacity is compared in a free head pile and a hinged head used for slope reinforcement (Fig. 10). The results show that the hinged head affects the footing bearing capacity when the pile row is located near the slope toe and slope crest ($\frac{L_p}{H}$=2). This is because the footing bearing capacity determined from the virtual retaining wall method is minimum when the pile row with hinged head piles is located at the slope toe. In fact, when the pile row is located there, it does not contribute in the virtual retaining wall method. However, the footing bearing capacity determined from the slope stability method is minimum when piles with free heads are located at the slope toe. Therefore, when the pile head is hinged, the footing bearing capacity is more than that of the free head. When the pile row is located near the slope crest, the footing bearing capacity determined from the virtual retaining wall method is minimum for both free and hinged head piles. The footing bearing capacity becomes more in hinged head pile than in the free head one located at the slope crest because of remarkable shear force at the hinged head at slope crest due to increasing the pile length in the passive zone. The effect of pile head fixity is usually ignored when the pile row is located at the middle of the slope. The footing bearing capacity determined from the virtual wall method is minimum and the pile is out of the passive zone in the virtual retaining wall method. Thus, it does not affect the footing bearing capacity in free and hinged head piles. When $\frac{L_p}{H}$=1, the fixity of the pile head does not remarkably affect the footing bearing capacity at various positions of the pile in the slope as a result of not fixing the pile in the stable layer. In addition, the footing bearing capacity computed from the slope stability method is minimum when the pile is installed at slope crest, and toe in free and hinged headed one; further, fixity of pile head does not significantly affect the footing bearing capacity in the slope stability method (Fig. 10). Moreover, the results indicate that the maximum footing bearing capacity is achieved when the fixed pile in stable layer is installed near the slope crest and non-fixed pile in stable layer is installed at the middle of the slope in free and hinged head piles with various B and S_f values.

3. Effect of two rows of pile on the bearing capacity of foundation: In this part, the effect of two pile rows is studied on the bearing capacity of footings on a piles-reinforced slope. The pile group efficiency decreases when the earth slope for various distances of pile rows increases.

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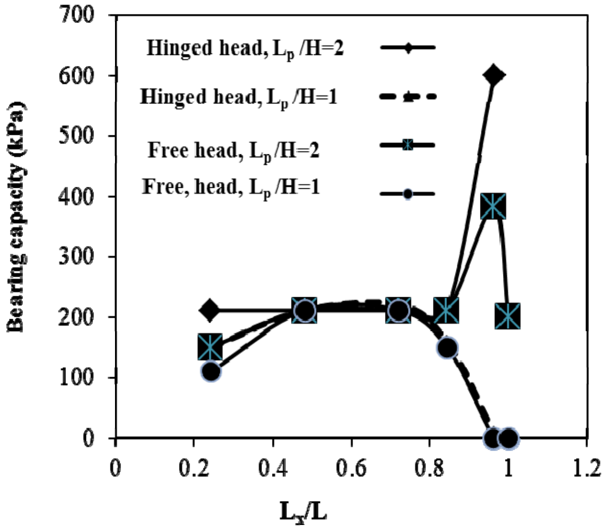

Fig. 10. Effect of fixity of pile head on footing bearing capacity with analytical method (B=2m, S_f =0)

Two spacing values of s_p=2 and 4 m are considered for pile rows. The effect of two rows of piles is studied for various lengths of piles and footing distances from the slope crest (Table 1). When $\frac{L_p}{H}$ =1and S_f=0, two rows of piles can increase the footing bearing capacity with respect to one pile row when the first pile row is located at the slope crest (L_x =8 m), while the second pile row is located at the middle of the slope (L_x =4 m). In fact, slope reinforcement with two rows of piles increases the slope stability, minimum footing bearing capacity is obtained by virtual retaining wall method and the second pile row at the middle of the slope is out of the passive zone. In fact, there is one pile row located at the slope crest in the passive zone.

Table 1. Effect of two pile rows on footing bearing capacity

L_x (m)	q(kPa) (L_p/H=1) S_f/B =0	q(kPa) (L_p/H=2) S_f/B =0	q(kPa) (L_p/H=1) S_f/B =2	q(kPa) (L_p/H=2) S_f/B =2
4	210(wall)	210(wall)	380(wall)	380(wall)
8	0(slope)	358(wall)	0(slope)	485(wall)
Two rows (4, 8)	358(wall)	358(wall)	350(slope)	485(wall)
4	210(wall)	210(wall)	380(wall)	380(wall)
6	170(slope)	210(wall)	200(slope)	380(wall)
Two rows (4, 6)	210(wall)	210(wall)	270(slope)	380(wall)

(slope) means slope stability method gives minimum bearing capacity,
(wall) means virtual retaining wall method gives minimum bearing capacity

As seen in Table 1, in other conditions, two pile rows cannot increase the footing bearing capacity with respect to one pile row condition when the pile is not fixed in the stable layer. The method of determining the footing bearing capacity is indicated in Table 1 for one or two pile rows and various S_f values. The results indicate that the method of determining bearing capacity for two pile rows and also the pile group efficiency affect the bearing capacity of the footing on two pile rows-reinforced slope and it offers less than or equal to the bearing capacity of footing on a single pile row-reinforced slope.

When $\frac{L_p}{H}$ =2, the effect of two pile rows is equal to one pile row for various values of S_f. In fact, the virtual retaining wall method gives the minimum bearing capacity for one pile row and two pile rows due to the pile fixity in the stable layer. In this case, the footing bearing capacity for two pile row condition is

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not more than one pile row condition due to the fact that only one pile row is situated in the passive zone when one of the rows is installed at the slope crest.

4. CONCLUSION

In the present study, the bearing capacity of footing on a pile rows-reinforced slope has been investigated through two analytical solutions based on retaining wall theory and slope stability. The following remarks may be cited from the results:

-The distance of the footing from the slope crest affects the bearing capacity variation of the footing on the pile row-reinforced slope with increasing foundation width. When the footing is located in the failed zone and row piles are not fixed in the stable layer and located at the upper half of the slope, an increase in the foundation width decreases the footing bearing capacity, especially when the footing distance from the slope crest is less than foundation width.

-The effect of the pile head fixity is significant when the row piles are located at the top and toe of the slope for fixed pile in the stable layer. Therefore, the fixity of the pile head affects the maximum bearing capacity of footing. When row piles are not fixed in the stable layer, the fixity of pile head does not affect the footing bearing capacity.

-When the slope is reinforced with two pile rows fixed in the stable layer, the use of two pile rows is ineffective and equal to the effect of one pile row. Two pile rows increase the footing bearing capacity with respect to one pile row when they are not fixed in the stable layer and one pile row is located at the slope crest and the other one is located at the middle of the slope and when the footing becomes close to the slope crest.

-The maximum footing bearing capacity is achieved when non-fixed piles in the stable layer are installed at middle of the slope and fixed piles in stable layer are installed near the slope crest at various positions.

-When the virtual retaining wall method gives the minimum footing bearing capacity and the pile is located in the passive zone, any decrease in the pile spacing in a row causes decrease in the passive zone angle and increase in the passive force on the virtual wall.

In general, the developed analytical method may be confidently used to determine the pile resistance and the bearing capacity of strip footings on both cohesive and non-cohesive sloping ground.

REFERENCES

1. Esmaili, D. & Hataf, N. (2008). Experimental and numerical investigation of ultimate load capacity of shell foundations on reinforced and unreinforced sand. *Iranian Journal of Science & Technology, Transaction B: Engineering*, Vol. 32, pp. 491-500.
2. Binesh, M., Hataf, N. & Ghahramani, A. (2007). Elastic analysis of reinforced soils using point interpolation method. *Iranian Journal of Science & Technology, Transaction B: Engineering*, Vol. 31, pp. 577-581.
3. Mosallanejad, M., Hataf, N. & Ghahramani, A. (2010). Three dimensional bearing capacity analysis of granular soils, reinforced with innovate grid-anchor system. *Iranian Journal of Science & Technology, Transaction B: Engineering*, Vol. 34, pp. 419-431.
4. Chen, L. T., Poulos, H. G. & Hull, T. S. (1997). Model tests on pile groups subjected to lateral soil movement. *Soils and Foundations*, Vol. 37, 1, pp. 1-12.
5. Auslio, E., Conte, E. & Dente, G. (2001). Stability analysis of slopes reinforced with piles. *Computers and Geotechnics*, Vol. 28, pp. 591-611.

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www.SID.ir

6. Chen, Y. & Martin, G. R. (2002). Soil–structure interaction for landslide stabilizing piles. Computers *and Geotechnics*, Vol. 29, pp. 363–386.
7. De Beer, E. & Wallays, M. (1970). Stabilization of a slope in schist by means of bored piles reinforced with steel beams. *Proceedings of 2th International Congress on Rock Mechanics*, Belgrade, pp. 361-369.
8. Hassiotist, S. & Chameau, J. L. (1997). Design method for stabilization of slopes with piles. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 123, No. 4, pp. 314-322.
9. Poulos, H. G. (1995). Design of reinforcing piles to increase slope stability. *Canadian Geotechnical Journal*, Vol. 32, pp. 808-818.
10. Hull, T. & Poulos, H. (1999). Discussion of design method for stabilization of slopes with piles. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, 10, pp. 911–913.
11. Xinpo, L., Siming, H. & Yong, W. (2010). Seismic displacement of slopes reinforced with piles. *Journal of Geotechnical and Geoenvironmental Engineering*. ASCE, Vol. 136, No. 6, pp. 1140-1155.
12. Cai, F. & Ugai, K. (2000). Numerical analysis of the stability of a slope reinforced with piles. *Soils and Foundations*, Vol. 40, pp. 73-84.
13. Cai, F. & Ugai, K. (2003). Response of flexible piles under laterally linear movement of the sliding layer in landslides. *Canadian. Geotechnical Journal*, Vol. 40, pp. 46-53.
14. Ito, T. & Matsui, T. (1975). Methods to estimate lateral force acting on stabilizing piles. *Soils and Foundations*, Vol. 18, No. 4, pp. 43-59.
15. Ito, T., Matsui, T. & Hong, W. P. (1979). Design method for the stability analysis of the slope with landing pier. *Soils and Foundations*, Vol. 19, No. 4, pp. 43–57.
16. Ito, T., Matsui, T. & Hong, W. P. (1981). Design method for stabilizing piles against landslide–one row of piles. *Soils and Foundations*, Vol. 21, pp. 21-37.
17. Ito, T., Matsui, T. & Hong, W. P. (1982). Extended design method for multi-row stabilizing piles against landslide. *Soils and Foundations*, Vol. 22, pp. 1-13.
18. Won, J., Kwangho, Y., Sangseom, J. & Sooil, K. (2003). Uncoupled analysis of stabilizing piles in weathered slopes. *Computers and Geotechnics*, Vol. 30, pp. 671-682.
19. Won, J., You, K., Jeong, S. & Kim, S. (2005). Coupled effects in stability analysis of pile-slope systems. *Computers and Geotechnics*, Vol. 32, No. 4, pp. 304–315.
20. Wei, W. B. & Cheng, Y. M. (2009). Strength reduction analysis for slope reinforced with one row of piles. *Computers and Geotechnics*, Vol. 36, pp. 1176-1185.
21. Won, P., Young, K. & Song, T. (2002). The use of piles to stabilize a cut slope in soft ground. *International Offshore and Polar Engineering Conference*, Kitakyushu, Japan, May, pp. 26–31.
22. Mostafa, A. & Sawwaf, E. (2005). Strip footing behavior on pile and sheet pile-stabilized sand slope. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 6, pp. 705-715.
23. Zhang, L., Silva, F. & Grismala, R. (2005). Ultimate lateral resistance of piles in cohesionless soils. *Journal of Geothecnical and Geoenvironmental Engineerin*g, ASCE, Vol. 131, No. 1, pp. 78-83.
24. Patra, N. R. & Pise, P. J. (2001). Ultimate lateral resistance of pile groups in sand, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 127, No. 6, pp. 481-487.

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