Pamukkale Üniversitesi
Mühendislik Bilimleri Dergisi,
Cilt 15, Sayı 2, 2009, Sayfa 194-202

Determination of Lateral Loads on Slope Stabilizing Piles

Şev Stabilitesi Kazıklarına Etkiyen Yatay Yüklerin Belirlenmesi

Mehmet Rıfat KAHYAOĞLU, Gökhan İMANÇLI * and Gürkan ÖZDEN

Dokuz Eylul University, Department of Civil Engineering, Faculty of Engineering, 35160, İzmir/Türkiye

Geliş Tarihi /Received : 06.01.2009, Kabul Tarihi/Accepted : 05.05.2009

ABSTRACT

Slope reinforcement using piled structures is one of the most appropriate methods for preventing slope movements. The prediction of loads acting on piles is important in order to properly design of slope stabilizing piles. Despite, different uncoupled analysis methods to estimate the loads on piles are available in literature; the loads acting on piles predicted using these methods may differ depending on soil-pile interaction and loading conditions. Comprehensive experimental works are needed in order to ensure the reliability of these analytical methods. In this study, the simulations of designed experiment for determining the load acting on the flexible piles were performed via two dimensional finite element methods. The parametric study was carried out to determine the effects of the center to center pile spacing on the load transfer behavior. Corresponding to the numerical results, the load acting on the flexible piles was investigated.

Keywords : *Lateral soil movement, Slope stabilizing piles, 2-D Finite element analyses, Pile spacing ratio, Soil-pile interaction.*

ÖZET

Şevlerin kazıklı sistemler kullanılarak güçlendirilmesi, şevlerde oluşabilecek hareketleri önlemek için kullanılan en uygun yöntemlerden birisidir. Kazıklara etki eden yüklerin tahmini, şev stabilitesi kazıklarının doğru dizaynı için önemlidir. Bu yüklerin tahminine yönelik literatürde birçok yöntemler bulunmasına karşın, bu yöntemler kullanılarak hesaplanan yükler kazık zemin etkileşimi ve yükleme koşullarına bağlı olarak farklılıklar gösterebilmektedir. Bu analitik yöntemlerin güvenilirliklerden emin olmak için kapsamlı deneysel çalışmalara ihtiyaç vardır. Bu çalışmada, esnek kazıklara etki eden yüklerin belirlenmesi için tasarlanan deneysel çalışmanın simulasyonu iki boyutlu sonlu elemanlar yöntemi ile gerçekleştirilmiştir. Merkezden merkeze kazık mesafesinin yük aktarma davranışına etkisini belirlemek amacıyla parametrik çalışma gerçekleştirilmiştir. Elde edilen sonlu elemanlar sonuçları ile ilişkili olarak esnek kazıklara etki eden yükler belirlenmiştir.

Anahtar kelimeler : *Yanal zemin hareketi, Şev stabilitesi kazıkları, 2 Boyutlu sonlu eleman analizleri, Kazık mesafesi, Zemin-kazık etkileşimi.*

1. INTRODUCTION

Lateral loading of a pile may be due to 'active' loading where external loads are applied to the pile head or due to 'passive' loading where lateral movement of the soil induces bending stresses in the pile (Fleming et al., 1994). Typical examples of passive loading are; piles adjacent to deep basement excavations, tunnel operations, slope stabilizing piles, and piles supporting bridge abutments adjacent to approach embankments.

Passive piles installed beyond the depth of a potentially sliding surface and often into a hard soil layer to prevent excessive movement of a slope. Since the displacement of the soil mass above a potentially sliding surface is expected to be more than that beneath the sliding surface, a shear force and bending moment would arise in the pile at the location close to the potential sliding surface. Passive piles behave similar to a cantilever beam with the earth pressure on the pile as load and the part socketed in rock of the pile as fixed end (Poulos et al., 1995).

Load redistribution and its transfer to the piles

* Yazışılan yazar/Corresponding author. E-posta adresi/E-mail adress: gimancli@gmail.com (G. İmançlı)

due to the relative movement between the piles and the sliding soil is a fairly complex soil-structure interaction problem. This interaction is a function of soil type, spacing and sectional properties of the piles. The problem was extensively studied by researchers in the past (Broms, 1964a and 1964b; Poulos, 1973 and 1995; Wang and Yen, 1974; Ito and Matsui, 1975 and 1977; Ito et al., 1981; Viggiani, 1981; Reese et al., 1992; Poulos et al., 1995; Goh et al., 1997; Pan et al., 2000; Zeng and Liang, 2002). It can be concluded that a widely accepted design methodology has not been established yet possibly because of the complexity of the problem and variety of affecting factors.

To understand the passive pile performance, experimental work is needed to verify and supplement the theoretical predictions. Full-scale tests in the field often are not possible due to economic considerations. Hence, small scale experiments with useful quantitative dimensions usually utilized to simulate the reel situation in the nature considering the soil behavior which is strongly dependent on stress level.

In this study, a series of finite element simulations via PLAXIS 2D (Version 8.2) have been performed to figure out the load acting on flexible passive piles with different pile spacing. In order to reflect the real behavior of flexible passive piles in a landslide, a large box, open at top and base, filled with soil is slid on an inclined sliding surface against bottom fixed piles embedded in the box. The dimensions of the testing box are determined after considering the presented case studies which were analyzed with mentioned empirical and theoretical limit equilibrium methods. Corresponding to the two dimensional finite element analyses results, the effect of pile spacing upon load acting on piles was investigated.

2. ANALYTICAL METHODS TO ESTIMATE THE LOADS ON PILES

There have been numerous efforts executed in the past to develop a cost effective method to compute limit soil pressure on landslide stabilizing piles. Many were developed for individual piles based on empirical relations from field lateral load tests, while others were based on theoretical and numerical models. The empirical limit soil pressure analyses (Broms, 1964a and 1964b), the theoretical limit soil pressure analyses (Wang and Yen, 1974; Ito and Matsui, 1975), and the limit equilibrium analyses (Zeng and Liang, 2002) are selected for the comparison of loads acting on piles in this study.

Broms (1964a and 1964b) proposed equations to estimate the ultimate soil pressure on piles based on empirical data from lateral load tests for cohesive and cohesionless soil, respectively. On the basis of the measured and calculated lateral resistance of laterally loaded piles in cohesive soils (ϕ=0), Broms (1964a) assumed that the ultimate soil pressure is equal to zero from the ground surface to a depth of 1.5 pile diameters (1.5d) and equal to nine times the undrained shear strength of cohesive soil ($P_u=9c_u$) at greater depths. For the cohesionless soil (c=0), Broms (1964b) assumed that the ultimate soil pressure which develops at failure is equal to three times the passive Rankine earth pressure ($P_u=3\sigma_p$) at all depths.

Wang and Yen (1974) reported a design method based on a rigid-plastic soil arching, which is a phenomenon of stress transfer from a yielding mass of soil onto the adjoining stationary part of soil (Terzaghi, 1936). Their study comprises a classic infinite slope analysis where the soil behaves as a rigid plastic solid and into which piles are rigidly embedded in a single row. The theory also indicates a relationship between slope length and arching potential while the necessary slope length to develop arching fully is approximately 6 fold inner distance between pile faces. The uniform soil pressure, p(z), parallel to the ground surface is a function of the soil unit weight, angle of internal friction, cohesion intercept of yielding layer and angle of internal friction, cohesion intercept of potential failure surface, coefficient of lateral pressure at rest and slope angle. The load on each pile embedded in sandy slopes is the summation of two loads, one from the pressure at rest, acting on the pile, similar to the lateral pressure on a retaining wall. The other is the soil arching pressure transferred to the adjacent piles as if each pile is an abutment of an arc dam.

Ito and Matsui (1975) present a method to predict the limit soil pressure on stabilizing piles in a row based on the theory of plastic deformation. The main assumption in this approach is that the soil is soft and able to deform plastically around the piles. The other assumptions are; the piles are rigid, the frictional forces between the pile and the soil are neglected, the active earth pressure acts on inner distance between pile faces, two sliding surfaces occur making an angle of (45+ϕ/2) with soil movement direction with the soil deformation (Figure 1).

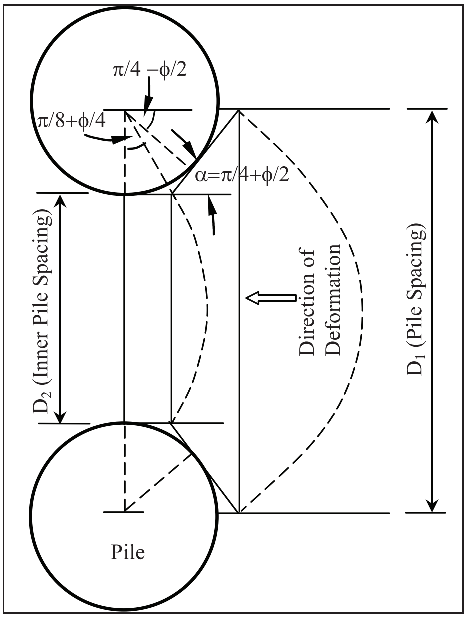


Figure 1. State of plastic deformation in the ground just around piles (After Ito and Matsui, 1975).

The limit force per unit length of pile, p(z) at any depth *z*, is a function of the soil unit weight, angle of internal friction, cohesion intercept, pile spacing, and inner distance between pile faces. p(z) may vary from zero when there is no movement to limit pressure at large lateral deformations. Soil arching was not mentioned and the sloping ground was not taken into account either.

The linear distribution of the calculated load is show in Figure 2. The limit soil pressure per unit area of pile face, P_z, is obtained by dividing the limit force computed from equation by the length of the pile.

Ito and Matsui (1975) compared their results of the Theory of Plastic Deformation to field measurements in the landslide areas of Niigata in Japan. The comparison revealed that the forces estimated by the Theory of Plastic Deformation agreed for the most part with the observed values. A series of field and model tests were performed to show that the theory can be used to closely predict the forces on both rigid and flexible piles embedded in deforming soil (Ito et al., 1982). Therefore, to analyze this type of problem, the method developed by Ito and Matsui (1975) and Ito et al. (1981), was selected to use for further studies. Although the equations are valid for the rigid piles, it may be expected that these equations can be also applied to the elastic piles, because, according to the assumption of the surrounding ground described above, the ground deformation just around pile is small and consequently, the effect of the pile deformation may be negligible.

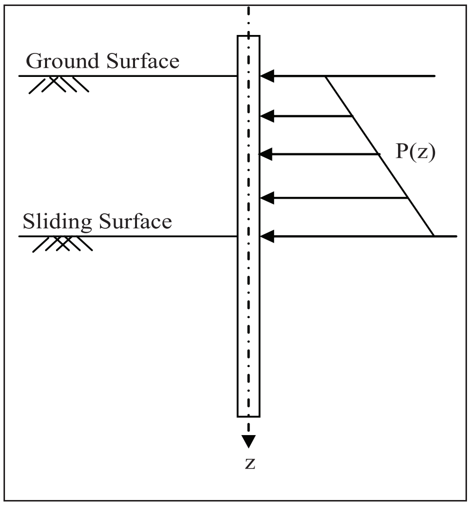


Figure 2. Load distribution diagram of Ito and Matsui Method.

Zeng and Liang (2002) proposed a mathematical formulation based on interslice force equilibrium to predict the factor of safety for slope reinforced with piles. This approach would allow for not only the determination of the safety factor of the reinforced slope, but also the forces acting on the piles. The influence of pile location, size and spacing on the computed factor of safety can be examined utilizing this approach. As the soil mass moves through the piles, the driving force transmitted to the soil mass behind the piles is reduced by a reduction factor (R), which is related to both pile and soil parameters, leading to a higher stability of the slope as a result of soil arching. The cross-section of piled slope is illustrated in Figure 3.

The forces acting on the slice are W_i, the weight of the slice; P_{i-1}, P_i, the resultant interslice forces on the (i-1)th and ith interfaces, respectively; N_i, the normal force reaction on the base of the slice; and T_i, the shear force reaction on the base of the slices. Also, α_{i-1} and α_i are the average slopes of the bases of the slices i-1 and i, respectively. The resultant interslice force is assumed to be parallel to the base of the previous up-slope slice, with the point of application located at one third from the bottom of the interface (Figure

4).

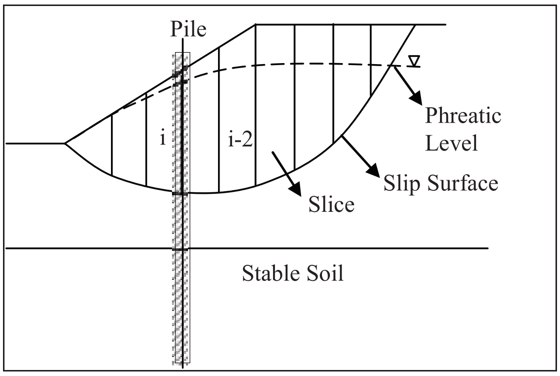


Figure 3. Cross section of slope stabilizing pile.

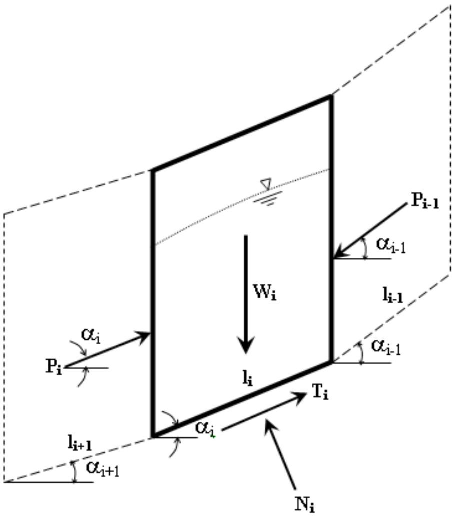


Figure 4. Forces acting on a typical slice.

$$P_i = W_i \sin\alpha_i - \left[\frac{c_i l_i}{F} + (W_i \cos\alpha_i - u_i l_i)\frac{\tan\phi_i}{F}\right] + k_i R P_{i-1} \qquad (1)$$

Where,

$$k_i = \cos(\alpha_{i-1} - \alpha_i) - \sin(\alpha_{i-1} - \alpha_i)\frac{\tan\phi_i}{F}$$

P_i depends on the safety factor (F), thus an iterative computational scheme is required. Iterative computational process should continue until the calculated P_n at the toe slice matches zero. The development of soil arching was assessed by the degree to which the driving force was transferred to the piles. The soil pressure acting on the soil mass between the piles due to soil arching was calculated and normalized with respect to the initial pressure to obtain a percentage factor (R_p) and given in Figure 5.

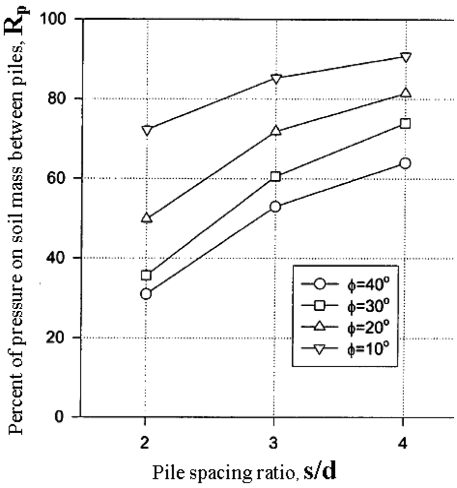


Figure 5. Effect of variation in internal friction angle on R_p (after Zeng and Liang, 2002).

If the value of R_p is 100%, it means that no arching effect exists and all soil pressure would be fully transmitted to the soil mass downslope. The stronger the soil arching effects (the smaller R_p), the more net force would act on the pile. Reduction factor (R) is given below in the expression with pile spacing (s) and R_p.

$$R = \frac{1}{s/d} + \left(1 - \frac{1}{s/d}\right)R_p \qquad (2)$$

The net load acting on one pile is;

$$P_{pile} = \frac{(1-R_p)P_{i-1}}{\frac{s}{d}} \qquad (3)$$

For any reason, if there is no relative movement between soil mass and the piles, then there would be no arching effect and no net force acting on the piles.

3. CASE STUDIES

Two studies, illustrating slope remediation projects with passive piles, were investigated to compare the proposed methods described above.

3. 1. Case Study 1

The selected case history was a slope stabilization analysis of Söke landslide where the slope is underlain by a weak layer. Shown in Figure 6 is a typical cross-section of slope together with the corresponding soil properties for each layer. The installation of piles was chosen a remedy means for slope stabilization.

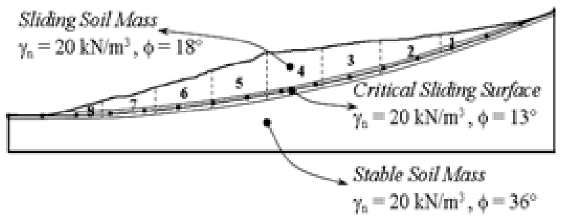


Figure 6. Typical cross section of slope.

The load acting on slices and global factor of safety of the selected section obtained by the proposed method of Zeng and Liang are given in Table 1.

Table 1. Loads acting on each slice without piles.

Slice No	W_i (kN/m)	α_i (°)	L_i (m)	k_i	Global Factor of Safety (F=1.006) Force acting on Slice (P_i) (kN/m)
1	567.2	31.0	14.99	1.024	292.15
2	1091.0	26.3	11.16	0.970	450.92
3	1479.9	22.5	10.82	0.976	565.00
4	1661.0	18.7	10.56	0.976	576.05
5	1640.9	15.0	10.35	0.977	475.62
6	1441.0	11.4	10.20	0.978	293.64
7	1069.2	7.8	10.09	0.978	90.07
8	355.5	4.2	10.03	0.978	-0.41

The maximum net force is acting 47.53 m far away from the toe with a max factor of safety of 1.006. So the installation place for the piles is determined as the fourth slice of the section.

The piled retaining system was designed to consist of double-row 49 reinforced bored piles with 120 cm diameter and 15 m length goes through the slide surface with minimum socket length of 9 m. Center to center spacing between the piles in a row was 2.4 m.

Regarding the value of R_p determined as 0.5 for s/d=2 and ϕ=18°, the value of R was calculated as 0.75. Soil pressure acting on piles and global factor of safety of reinforced slope with piles were calculated via the proposed method of Zeng and. Liang. The calculated results are given in Table 2.

For the given conditions of piles and the slope section, because of the presence of piles the global factor of safety is found to be increased from 1.01 to 1.06.

Table 2. Loads acting on each slice with piles.

Slice No	k_i	Global Factor of Safety (F=1.062)		
		P_i (kN/m)	Force acting on a Pile (kN/m)	Pressure acting on a Pile (kN/m²)
		0		
1	1.015	292.15		
2	0.972	467.99		
3	0.978	605.48	151.36	25.23
4	0.978	495.08		
5	0.978	424.05		
6	0.979	267.72		
7	0.979	83.06		
8	0.979	-1.14		

The pressure acting on the pile is calculated as 25 kPa. The force and the pressure acting on piles are also calculated by Ito and Matsui method. The comparisons of pressure acting on piles are given in the Table 3.

Table 3. Calculated pressure acting on piles.

Method	Depth (m)	Force (kN/m)	Pressure (kN/m²)
Ito-Matsui	z = 0	72.412	21
	z = 8	264.412	
Zeng-Liang	z = 0	149.84	19
	z = 8	149.84	
Broms	z = 0	0	13.8
	z = 8	220.90	

The results of analysis show that the load distributions developed along piles are linear or uniform with depth. If the linear distribution of load calculated by Ito and Matsui method is changed to the uniform distribution, the pressures are seemed to be nearly equal to the pressures calculated by Zeng and Liang method.

3. 2. Case Study 2

Figure 7 shows an example problem considering landslide analyses which were performed for a case study in Muğla. The program STABLE, Mz Associates Geotechnical Software, was applied to locate the failure surface as shown in Figure 7.

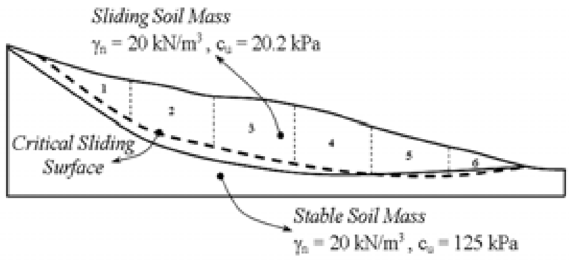


Figure 7. Typical cross section of slope.

The maximum height of the sloping ground and the radius of the slip circle are approximately 8 m and 70 m, respectively. The determined load acting on slices and global factor of safety via Zeng and Liang method are given in Table 4.

Table 4. Loads acting on each slice without piles.

Slice No	W_i (kN/m)	α_i (°)	L_i (m)	k_i	Global Factor of Safety (F=1.023) Force acting on Slice(P_i) (kN/m)
1	517.36	29.6	11.51	0.869	28.27
2	1261.82	21.6	10.76	0.990	280.04
3	1686.35	14	10.31	0.991	481.97
4	1664.41	6.7	10.07	0.992	473.41
5	1403.41	-0.6	10.00	0.992	257.42
6	520.07	-7.8	9.36	0.992	-0.02

The maximum net force acting on a slice with 1.023 global factor of safety was 481.97 kN/m and occurred 32.58 m far away from the toe. Hence the piles are installed in the third slice.

The piled retaining system was designed to consist of one-row of piles with 16 m length and 120 cm diameter (d). Center to center spacing between the piles (s) in a row was 1.2 m. Regarding the value of R_p determined as 0.1 for s/d=2 and c_u=20.2 kPa, the value of R was calculated as 0.55. The results of soil pressure acting on piles and global factor of safety of the slope reinforced with piles are given in Table 5.

Table 5. Loads acting on each slice with piles.

Slice No	k_i	Global Factor of Safety (F=1.164)		
		P_i (kN/m)	Force acting on a Pile (kN/m)	Pressure acting on a Pile (kN/m²)
		0		
1	0.870	55.77		
2	0.990	332.97		
3	0.991	410.54	149.84	18.73
4	0.992	426.62		
5	0.992	234.90		
6	0.992	0.00		

The global factor of safety of the slope is increased from 1.02 to 1.16 as a result of pile installation. The soil pressure acting on piles is calculated as 19 kPa. The force and the pressure acting on piles are also calculated by Ito and Matsui method for comparison. The results of pressure acting on piles are given in the Table 6.

Table 6. Calculated pressure acting on piles.

Method	Depth (m)	Force (kN/m)	Pressure (kN/m²)
Ito-Matsui	z = 0	0	28
	z = 6	336.05	
Zeng-Liang	z = 0	151.36	25
	z = 6	151.36	
Broms	z = 0	218.16	36.4
	z = 6	218.16	

Due to presence of piles, the global factor of safeties increased approximately 5 % and 14 %. The results are in good agreement with the previous field measurements given in the literature which are in the range of 5 % to 25 %.

4. THE DETERMINATION OF TESTING BOX DIMENSIONS

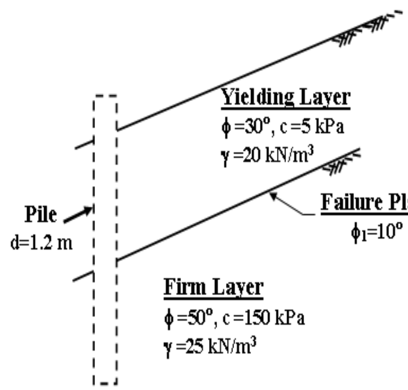
As a result of the similar soil pressures via Ito & Matsui and Zeng & Liang methods, it is decided to use these methods in order to determine the dimensions of the model test box with a 20° inclination, simulating a piled slope problem the properties of which are given in Figure 8. It can be clearly seen from the Figure 8 that the calculated forces on piles were also equal where the ratio of s/d is 2.5.

To investigate the behavior of flexible piles in this model test box filled with sand having 30° internal friction and 20 kN/m^2 unit weight, the first step should be the determination of pile embedded length.

Aluminum pipes with smooth surfaces are used to represent the small scale testing flexible piles having an outer diameter of 20 mm and 1 mm thickness with flexural rigidity (E_pI_p) as 1.89x10^8 Nmm^2. Pile flexibility can be expressed with stiffness factor, *T*. According to Broms' suggestion, the embedment depth of the pile has to be greater than 4*T*, for the flexible pile behavior. For cohesionless soils, this factor is given as

$$T = \sqrt[5]{\frac{E_p I_p}{n_h}} \tag{4}$$

where, E_pI_p, is the flexural rigidity of the pile and n_h, is the constant of subgrade reaction which is 6000 kN/m^3 for medium sands (Terzaghi, 1955).



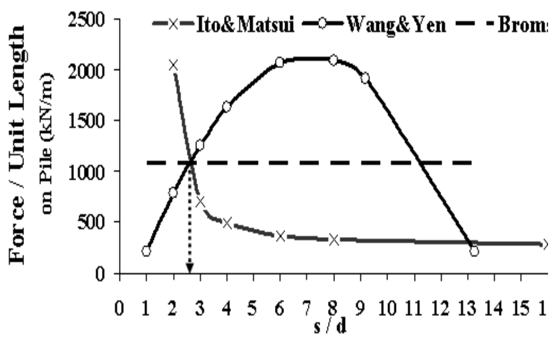


Figure 8. Loads acting on pile as a function of s/d.

The height of the box is selected as 50 cm regarding the necessary pile length embedded in the box in order to reflect the flexible pile behavior. The box length with piles, having 20 mm diameter, 50 cm embedded length and s/d=2.5, should also provide soil reaction as 1.67 kN/m^2 (via Ito and Matsui method). The most important question where the piles are placed to achieve this calculated soil reaction is answered with interslice force equilibrium based method proposed by Zeng and Liang. Preliminary box length is selected as 2 m long which is divided into 8 equal parts. The results are given below in the Table 7.

Table 7. Pressure acting on pile installed in the fifth slice of the testing box.

Slice No	k_i	P_i (kN/m)	Force acting on a Pile (kN/m)	Pressure acting on a Pile (kN/m^2)
1	0.94	0.85	0	
2	1	1.71	0.21	
3	1	2.57	0.41	
4	1	3.42	0.62	
5	1	3.04	0.82	1.64
6	1	2.03	0.73	
7	1	1.01	0.49	
8	1	0.00	0.24	

If the piles are placed in the fifth slice, the pressure acting on piles is 1.64 kN/m^2 which is approximately equal to the pressure calculated by Ito and Matsui method. So the box length in front of the piles is the length of five slices which is equal to 125 cm.

5. 2D FINITE ELEMENT ANALYSES

In this study, piled slope on an inclined plane was examined via finite element method using a commercially available FEA program, PLAXIS 2D (version 8.2) (Brinkgreve and Vermeer, 2001), to investigate the interaction between the pile and the sliding soil.

The complex system was comprised of a box open at top and bottom, flexible piles, moving soil in the box, stable soil under the box, linear elastic compressible soil, and prescribed sliding surface material.

The behaviors of moving soil (sand), inclined stable soil (rigid block), and the sliding surface material (weak soil) were simulated by an elastic perfectly-plastic model with Mohr-Coulomb yield criterion while linear elastic model, based on Hooke's Law, was selected to represent the behavior of the compressible soil (elastic soil) that enables the box movement. Soil elements were also assumed to be homogeneous and isotropic.

In PLAXIS 2D, selection of plane strain condition results in a two-dimensional finite element model with only two translational degrees of freedom per node. The 6-node triangle soil elements providing a numerical integration that involves three Gauss iteration points (stress points) is selected for displacement interpolations instead of 15-node triangle soil elements. The use of 15-nodes triangles leads to relatively high memory consumption and relatively slow calculation and operation performance. Therefore a more simple type of elements is also available. The 6-node triangle is a fairly accurate element that gives good results in standard deformation analyses, provided that sufficient numbers of elements are used. 5-node beam elements were used to simulate the flexible piles and the experimental box with high flexural rigidity. Prescribed displacement process was used to simulate the displacement control. The box was forced to move by applying prescribed displacements on both right and left sides of the box.

The piles and the surrounding soil were discretized using a mesh consisting of 1631 elements. Numerical experiments with different numbers of elements in the mesh around the pile were performed to investigate the model including mesh refinement. In this study, a relatively fine mesh is used adjacent to the piles and become coarser further from the piles.

The soil-pile interface strength parameter is set to two-thirds and two-tenths of the corresponding soil strength parameters by means of the interface parameter (R_{inter}) so that strength reduction due to slippage of the soil around the pile is taken into consideration.

The input parameters of each soil layer and a typical model with the finite element mesh are given in Table 8 and Figure 9, respectively. In the FEA, the pile stiffness is changed in accordance with the pile spacing in order to determine the accurate loads acting on pile groups having different pile spacing.

By means of the prescribed displacement increments, the box slid and the piles were loaded due to the moving soil. The maximum pile head displacement (y_{max}), shear force (T_{max}) and moment (M_{max}) acting on the piles for the same box displacements are summarized in the Table 9.

Table 8. Material properties.

Item	Soil Properties					
	Material Model	Stiffness		Strength		R_{inter}
		E (kPa)	υ	c (kPa)	φ (°)	
Sand	Mohr-Coulomb	10000	0.3	5	30	0.2
Weak Soil	Mohr-Coulomb	10000	0.3	1	5	0.2
Rigid Block	Mohr-Coulomb	$5x10^5$	0.15	150	50	0.67
Elastic Soil	Linear-Elastic	$5x10^5$	0.15	-		0.67

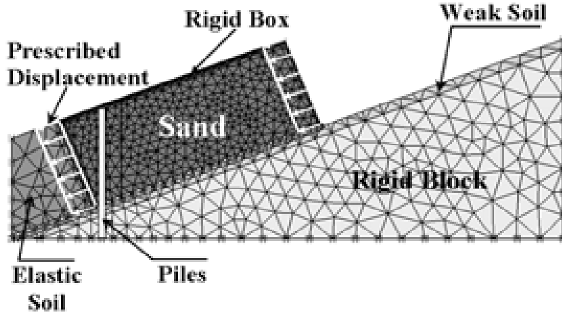


Figure 9. Section view of experimental simulation.

Table 9. FE Analyses results.

s/d	EI kNm^2 $*10^2$	EA kN $*10^{-2}$	y_{max} mm		M_{max} kNm $*10^{-2}$	T_{max} kN
			Pile	Soil		
1*	18.9	42	9.27	9.62	21.1	4.1
2	9.5	21	9.26	9.56	13.9	3.2
3	6.3	14	9.25	9.50	10.5	2.7
4	4.7	10	9.25	9.47	8.5	2.5
6	3.2	7	9.25	9.40	6.1	2.1
8	2.4	5	9.25	9.37	4.9	1.9
12	1.6	3	9.25	9.33	3.6	1.7
24	0.8	1	9.25	9.25	2.3	1.3

* Continuous curtain.

6. CONCLUSIONS

Although there are many theories available on estimating the loads on slope stabilizing piles, an experimental work is needed to verify and contribute the theoretical approaches. 2-D finite element analyses were performed in order to simulate the real behavior of flexible piles used for landslide remediation. In the analyses, a large box filled with soil was slid on an inclined sliding surface against bottom fixed piles embedded through the box to the stable soil. The dimensions of the testing box were determined considering the theoretical methods.

It was observed that maximum shear forces and moments on piles decrease due to the decreasing of the relative displacements between soil and pile while the s/d is increasing. It should be noted that the loads on the piles varied depending on the relative displacement between pile and soil. In other word, loads on piles began to appear when the soil movements exceed the pile deflection.

3-D analyses are required to accurately model the complex soil-structure interaction associated with stabilizing piles in slopes, and to predict the limit loads on piles. The investigation of 3-D analyses of pile-soil interaction is considered as the initial future work.v

REFERENCES

Brinkgreve, R.B.J. and Vermeer, P.A. 2001. Finite element code for soil and rock analyses, Version 8.2. Balkema Printers, Rotterdam, Netherlands.

Broms, B.B. 1964a. Lateral resistance of piles in cohesive soils. ASCE, Journal of the SMFE, 90 (SM2), 27-63.

Broms, B. B. 1964b. Lateral resistance of piles in cohesive soils. ASCE, Journal of the SMFE, 90 (SM3), 123-156.

Fleming, W.G. K., Weltman, A. J., Randolph, M. F., and Elson, W. K. 1994. Piling engineering (2nd ed). Blackie, Glasgow, and London, U.K. Taylor &Francis.

Goh, A. T. C., Teh, C. I., and Wong, K. S. 1997. Analysis of piles subjected to embankment induced lateral soil movements. Journal Geotechnical and Geoenvironmental Engineering. 123 (9), 792-801.

Ito, T. and Matsui, T. 1975. Methods to estimate lateral force acting on stabilizing piles. Soils and Foundations. 15 (4), 43-59.

Ito, T. and Matsui, T. 1977. The effects of piles in a row on the slope stability, **Proceedings, 9th I.C.S.M.F.E., Specialty Session. 10**, Tokyo.

Ito, T., Matsui, T., and Hong, W.P., 1981. Design method for stabilizing piles against landslide-one row of piles. Soils and Foundations. 21 (l), 21-37.

Matsui, T., Hong, W.P. and Ito, T., 1982. Earth Pressures on Piles in a Row due to Lateral Soil Movements. Soils and Foundations. 22 (2), 71-81.

Pan, J. L., Goh, A. T. C., Wong, K. S. and Teh, C. I. 2000. Model tests on single piles in soft clay. Canadian Geotechnical Journal. 37, 890-897.

Poulos H.G., Chen, L.T., and Hull T.S. 1995. Model tests on single piles subjected to lateral soil movement, Soils and Foundations. 35 (4), 85-92.

Poulos, H. G. 1973. Analysis of piles in soil undergoing lateral movement. Journal of Soil Mechanics and Foundation Engineering Division, ASCE. 99, 391-406.

Poulos, H.G. 1995. Design of reinforcing piles to increase slope stability. Canadian Geotechnical Journal. 32, 808-818.

Reese, L., Wang, S., and Fouse, J. 1992. Use of shafts in stabilizing a slope, slopes and embankments-II, A.S.C.E., Specialty Session.

Terzaghi, K. 1936. "Stress distribution in dry and saturated sand above a yielding trap door". **Proceeding, 1st I.C.S.M.F.E.** 307-311.

Terzaghi, K. 1955. "Evaluation of Coefficients on subgrade Modulus". Geotechnique. 297-326.

Viggiani, C. 1981. "Ultimate Lateral Load on Piles Used to Stabilize Landslides". **Proceeding. 10th I.C.S.M.F.E.** 3, 555-560, Stockholm.

Wang, W.L., and Yen B.C. 1974. Soil arching in slopes. ASCE. Journal of the SMFE, 100 (GT1). 61-78.

Zeng S. and Liang, R. 2002. "Stability analysis of drilled shafts reinforced slope. Soils and Foundations. 42 (2): 93-102.