Performance of strip footings on slopes

Execution de foundation de bande sur les pentes

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ABSTRACT: The performance of strip footings situated on top of a slope and subjected to a vertical central or eccentric loading was investigated using a two-dimensional plane-strain elasto-plastic finite element computer program. The analysis was made for a wide range of soil type, footing location, and slope conditions, including slope angle and slope height. From the results of the analysis, the effect of soil type, footing location, slope angle, slope height, and load eccentricity on the ultimate bearing capacity of the footing was presented. The engineering significance of the results of study was also discussed.

RÉSUMÉ: L'exécution de fondations de bande situés sur une pente et sous réserve d'un chargement vertical, central ou excentrique a été examinee par l'utilisation d'un plan-tend à deux dimensions, elasto-plastic programme d'analyse d'élément fini. L'analyse a été faite pour une portée large de type de sol, l'emplacement de fondations de bande, et conditions de pente, y compris la hauteur et l'angle de pente. Des résultats de l'analyse, l'effet de type de sol, l'emplacement de fondations de bande, l'angle de pente, la hauteur de pente, et l'excentricité de chargement sur la capacité ultime de fondation ont été présentés. La signification geniale des résultats d'étude a été aussi discutée.

1 INTRODUCTION

There are instances that shallow foundations are constructed on top of a slope. The less soil constraint on the slope side tends to reduce the foundation stability. As a result, the structure performance may be adversely affected, possibly causing considerable structural damage and even loss of life.

Presently, the stability of such foundation/slope systems is often analyzed using the classical bearing capacity theory. The classical theory is developed based on the theory of plasticity with an assumption that the soil behaves as a rigid-plastic material. Thus, it is difficult to consider footing settlement as well as progressive soil yielding in the foundation stability analysis using the classical theory.

Footings on a slope may be subjected to eccentric loading; and eccentric loading for footings on a slope may be more critical than those on the level ground. Since very little information on the performance of strip footings on top of a slope with vertical eccentric loading is currently available, this study investigates the performance of such foundation systems using a two-dimensional plane-strain elasto-plastic finite element computer program. The analysis was made for a wide range of soil type, footing size and location, and slope conditions, including slope angle and slope height for both central and eccentric vertical loadings. This paper presents the findings as well as their engineering significance.

2 ANALYSIS

A two dimensional plane-strain elasto-plastic finite element computer program was used for the analysis. In the analysis, the foundation soil was idealized as a nonlinearly elastic-perfectly plastic material. Within the elastic range, the Duncan-Chang hyperbolic stress-strain law was used; whereas, the Drucker-Prager yield criterion was adopted to model the plastic behavior. Other important features of the computer program have been presented by Jao and Wang (2000); the details and validation of the computer program have been presented by Jao (1995).

In the analysis, the strip footing was a 3-ft (914-mm) wide reinforced concrete footing embedded to a depth of 3 ft (914 mm), i.e. D_f= 3 ft (914 mm). Three different foundation soils encompassing sufficiently broad soil conditions were selected for investigation; they were a medium silty clay, a stiff kaolin, and a medium dense clayey sand. The properties of the three soils and the concrete footing are shown in Table 1. The slope geometry, footing size, and footing location were selected to represent conditions commonly found in engineering construction. The ranges of slope angle (β), load eccentricity (e), slope height (H), and the horizontal distance between footing edge and the crest of the slope (b) investigated were 18° (3H: 1V) to 45° (1H:1V), -1/6 B to 1/6 B, 6B to 12B, and 1B to 6B, respectively; in which B is footing width, and the negative value of load eccentricity signifies a load location between footing center and slope crest. A schematic view of the footing/slope system with the finite element mesh is shown in Figure 1.

Table 1. Material properties of soils and concrete footing

Material Properties	Silty Clay	Kaolin	Kaolin-sand	Concrete
Initial modulus in compression, psi (kN/m^2)	677 4,670	2,880 19,843	6,100 42,029	3.3 x10^6 2.27x10^7
Poisson's ratio	0.28	0.23	0.32	0.3
Dry unit weight, pci (kN/m^3)	0.058 (15.7)	0.052 (14.1)	0.061 (16.5)	0.090 (24.39)
Cohesion, psi (kN/m^2)	9.5 (65.5)	23.0 (158.5)	1.33 (9.5)	810 (5,581)
Internal friction angle (deg.)	13.5	8	31	39.6
Moisture Content (%)	17.0	23.0	11.8	N/A
Soil constant (R_f)	0.8	0.77	0.86	N/A

3 ULTIMATE BEARING CAPACITY

Excessive footing settlement and soil yielding may result in a loss of footing serviceability and even footing collapse. With a consideration of both footing settlement and soil yielding, the ultimate bearing capacity of each footing analyzed was determined as follows:

(1) On the footing pressure vs. settlement curve, the pressure beyond which the slope of the curve becomes a minimum constant value is chosen; it is a criterion proposed by Vesic (1963).
(2) On the curve relating footing pressure to the area of yielded soil elements, the pressure beyond which the curve

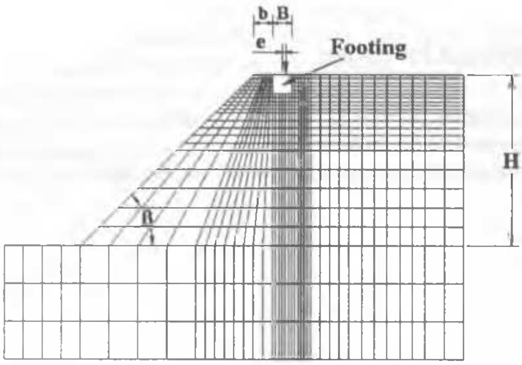

Figure 1. Schematic diagram and finite element mesh of the footing/slope system

becomes a minimum constant value is chosen; it is a criterion proposed by Wang, et al. (1994).

(3) The pressure under which soil yielding spreads to the face of the slope as illustrated in Figure2.

(4) The least value of the three footing pressures above is taken as the ultimate bearing capacity of the footing analyzed.

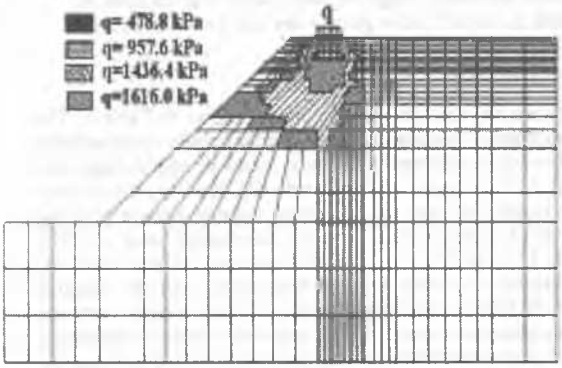

Figure 2. Yield area pattern at different loading for a footing on Kaolin with a 1H:1V slope

4 SLOPE GEOMETRY EFFECT

In the analysis, each of the bearing capacity values determined for different conditions is divided by the bearing capacity of the footing on the level ground with a central vertical loading to obtain a bearing capacity ratio. The variations of bearing capacity ratios with slope angles for the three different soils analyzed for b=1B, H=8B and e=0 conditions are presented in Figure 3. As shown, the bearing capacity ratio decreases as the slope angle increases. This can be attributed to the decreased shearing resistance of the supporting soil near the slope face due to either the reduced slip line field or decreased confinement effect or both. For the three different soils analyzed, the reduction in the bearing capacity due to slope is maximum for footings on kaolin-sand and minimum for footings on kaolin. Also, for footings on kaolin-sand, the bearing capacity ratio decreases very rapidly with an increase in the slope angle; whereas, for footings on kaolin and silty-clay, the bearing capacity ratio decreases gradually as the slope angle increases. The much greater reduction in bearing capacity for footings on kaolin-sand is primarily due to its low cohesion. The shear resistance of soils having low cohesions depends greatly on the confinement effect. For footings on top of a slope, the supporting soil near the slope face is under less confinement. Since the confinement effect decreases with increasing slope angle, the ultimate bearing capacity will decrease with increasing slope angle. Meanwhile, the effect of confinement on shearing resistance is smaller for soils having higher cohesions. As a result, the reduction in ultimate bearing capacity due to slope decreases with increasing cohesion as shown.

Figure 3 also presents the bearing capacity ratios determined for kaolin-sand using the limiting equilibrium approach developed by Bowels (1996). Note that the bearing capacity ratios are determined only for slope angles smaller than 31 degrees because of the limitation of the approach. A comparison between the results of Bowles's approach and those of computer analysis shows that Bowles's approach considerably underestimates the slope effect on the reduction of bearing capacity for footings on kaolin-sand. This is possibly due to the inability of the limiting equilibrium approach to consider the combined effect of progressive soil yielding as well as shear strength reduction caused by the decreased confinement effect. Such limitations also result in the little bearing capacity decrease with slope angle shown by the near horizontal line in the figure.

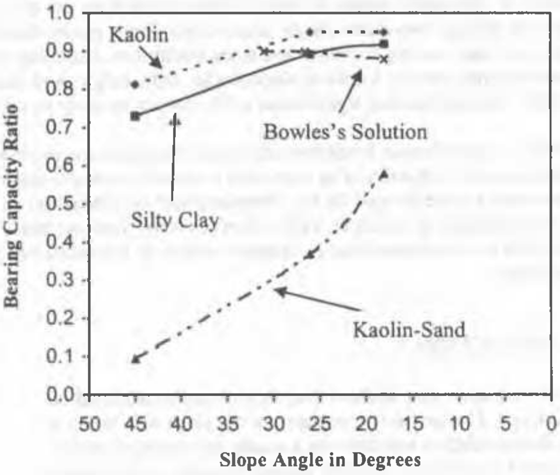

Figure 3. Variation of bearing capacity with slope angle

For a centrally loaded footing on a 2(H):1(V) slope (β=26.6°) with a b/B=1, the bearing capacity ratios are plotted against slope height in Figure 4. As shown, the bearing capacity ratios remain almost constant for kaolin and decrease slightly with slope height for the other soils. This indicates that the effect of slope height is slightly greater for cohesionless soils than for cohesive soils. The decrease in bearing capacity with increasing slope height probably can be attributed to either the propagation of soil yielding to the slope face or the greater footing settlement or both. Note that the results are for a 2(H):1(V) slope with b=B. For steeper slopes with b<B, the effect of slope height could possibly be more prominent.

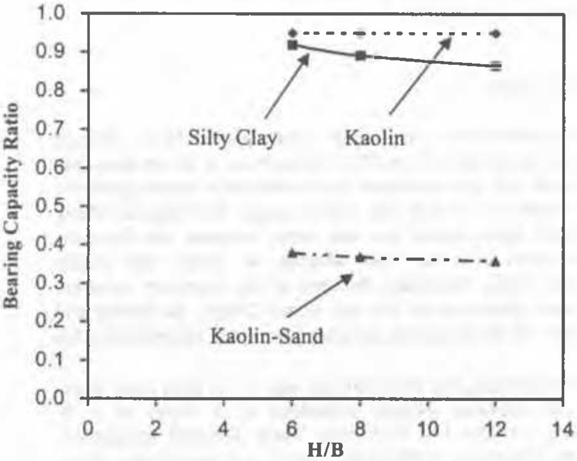

Figure 4. Variation of bearing capacity with H/B

5 FOOTING LOCATION EFFECT

For a given slope, the location of footing on top of the slope is an important factor affecting the ultimate bearing capacity as illustrated in Figure 5, which plots the bearing capacity ratio of a centrally loaded footing vs. b/B for a slope height of 8B with a slope angle of 26.6° (2H:1V). It is seen that as the footing is moved away from the slope crest, the bearing capacity ratio increases, i.e., the effect of slope on bearing capacity decreases. According to the figure, slope effect diminishes when the footing is located approximately at 3B, 5B, and 7B from the crest for kaolin, silty-clay, and kaolin-sand, respectively. Since the cohesions of these three soils decreases in the order of kaolin, silty-clay, and kaolin-sand, the data indicate that to avoid slope effect, the required minimum footing distance from the crest increases with decreasing cohesion. In other words, footings on a cohesionless soil slope should be located farther from the crest than a cohesive soil slope to avoid slope effect on the ultimate bearing capacity.

The bearing capacity ratios for footings on a slope in kaolin-sand are also determined using Bowles's approach and are included in Figure 5 for comparison. As before, the results of Bowles's approach show only a little slope effect on ultimate bearing capacity, due possibly to its inability to consider the combined effect of progressive soil yielding and the decreased confinement effect on shear strength.

6 LOAD ECCENTRICITY EFFECT

The effect of load eccentricity on bearing capacity ratios for vertically loaded footings on slopes in silty clay with H/B=8.0 and b/B=1.0 is shown in Figure 6. There are three curves in the figure—one for central loading (e=0) and the others for eccentric loadings with e=+B/6 and –B/6 (loading near crest). It appears that eccentric load effect varies with slope angles, being greater for steeper slopes. It also varies with load locations, being smaller for the loading on the same side than on the other side of the crest. In other words, for the same magnitude of eccentricity, the ultimate bearing capacity decreases more when the loading is located on the inner side of the slope. The soil yielding pattern reveals that, when the loading is on the inner side of slope, soil yielding spreads outward toward the slope face more than inward, possibly due to the tilting of footing base toward the slope face caused by the greater settlement at the inner footing edge than at the outer edge. Such a soil yielding pattern could be a major factor for the smaller ultimate bearing capacity for the loading on the inner side of the slope.

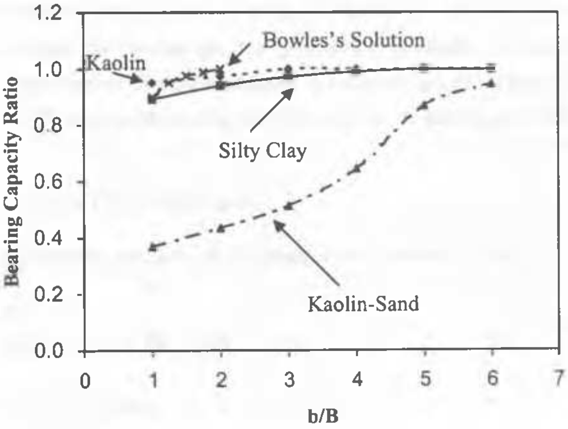

Figure 5. Variation of bearing capacity with b/B

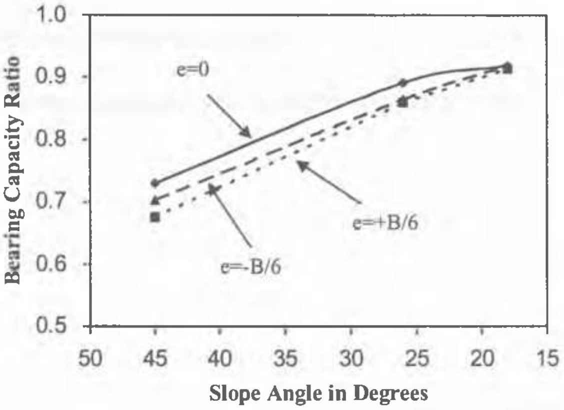

Figure 6. Variation of bearing capacity with slope angle for footing with eccentric loading on silty clay

7 SUMMARY AND CONCLUSIONS

The stability of strip footings on top of slopes has been investigated using the method of finite element analysis. In the analysis, various factors influencing the performance of the slope/footing system were considered. Based on the results of the analysis, the following conclusions can be made:

- The presence of slope reduces the bearing capacity of the footing. The amount of bearing capacity reduction varies with slope angle, footing location, and soil type.
- To avoid slope effect on footing stability, the required minimum distance between footing and slope crest is greater for cohesionless soils than for cohesive soils.
- Load eccentricity further reduces the bearing capacity of the footing on slopes. For a given load eccentricity, the bearing capacity reduction is smaller when the load acts between footing center and slope crest.
- The limiting equilibrium approach proposed by Bowels (1996) greatly overestimates the bearing capacity, probably due to the inability of the approach to consider the effect of progressive soil yielding as well as confinement effect on soil shear strength.

REFERENCES

Bowles, J. E. (1996). "Foundation Analysis and Design," 5th edition, McGraw-Hill Book Co., New York, N.Y.

Das, B. M. (1999). "Principles of Foundation Engineering," Brooks/Cole Publishing Co., Pacific Grove, CA.

Duncan, J. M. and Chang, C. Y. (1970). "Nonlinear Analysis of Stress and Strain in Soils," ASCE Journal of Soil Mechanics and Foundation Division, Vol. 96, No. 5, pp. 1629-1653.

Drucker, K. and Prager, W. (1952). "Soil Mechanics and Plastic Analysis in Limit Design," Quarterly of Applied Mathematics, Vol. 10, No. 2, pp. 157-165.

Jao, M. and Wang, M. C. (2000). "Behavior of Soft Ground Tunnel under Strip Footing," Trends in Rock Mechanics, ASCE. Geotechnical Special Publication, No. 102, pp. 78-92.

Jao, M. (1995). "Interaction between Strip Footings and Concrete-Lined Soft Ground Tunnels," Ph.D. Dissertation, Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park.

Vesic, A. (1963). "Bearing Capacity of Deep Foundations in Sand," National Academy of Science, National Research Council, Highway Research Board, 39, pp. 112-153.

Wang, M. C., Jao, M., and Hsieh, C. W. (1994). "Effect of Underground Cavity on Footing Interaction," Proceedings, XIII International Conference on Soil Mechanics & Foundation Engineering, New Delhi, India, Vol. 2, pp. 575-578.