Bearing capacity of shallow foundations on sloping ground

Capacité portante des fondations superficielles sur terrains en pente

A.Soriano Peña – *Universidad Politécnica de Madrid, Spain*
M.Valderrama Conde & J.González Galindo – *Ingeniería del Suelo S.A., Madrid, Spain*

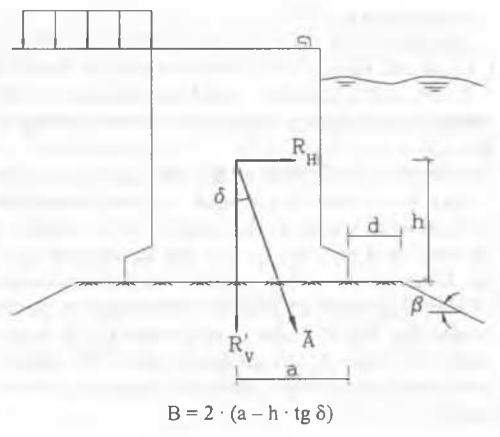
ABSTRACT: The bearing capacity of shallow foundations placed near slope crests can be obtained from that corresponding to a flat horizontal ground, multiplied by a reducing factor. There are simplified methods that allow us to estimate this factor. This paper reviews some of the best-known methods and proposes a procedure that seems to improve somewhat the results obtained by the preceding methods. It takes into consideration the influence of all the main variables that control the problem and has been contrasted, to some extent, with results obtained from numerical methods and with the conclusions of the analysis of the actual failure of a foundation close to a slope.

RÉSUMÉ:La capacité portante des fondations superficielles prochaines à une pente peut s'obtenir en multipliant celle correspondante à un terrain horizontal plain par un coefficient réducteur. Il y a des méthodes simplifiés que permettent estimer ce coefficient. Cet article révise quelques méthodes des plus bien connues et il propose un procédé qui semble ameliorer légèrement les résultats obtenus avec las méthodes precedentes. Il prend in considération toutes las variables principaux qui contrôlent le problème et il a été contrasté, en quelque degré, avec des résultats des modèles numériques et les conclusions de l'analyse d'une rupture réelle d'une fondation près d'un talus.

1 INTRODUCTION

The bearing capacity of shallow foundations located near the crest of a slope is much lower than the bearing capacity that corresponds to flat horizontal ground. The effect of sloping ground near the foundations is of particular importance when, in addition to that, the foundation is completely shallow, without any embodiment into the ground.

This problem has a special influence on the design of vertical breakwaters or quays that are formed by precast concrete caissons founded on top of a submerged rockfill. See Fig. 1. One of the main modes of failure for this type of structures is the so-called "plastic overturning" as described in ROM 05-94. The amplitude of the extra width "d" of the crest of the rockfill which is needed to ensure the stability of the foundation is a technical problem that should be analyzed for each particular situation by means of best available methods. Simple methods, however, can be used in order to see the influence of different details on the geotechnical safety of this type of structures.



R_H = Resultant of horizontal components of loads.
R'_V = Resultant of effective vertical components on the foundation.

Fig. 1.- Geometry and loads on a gravity quay.

2 CONSIDERATION OF SOME SIMPLIFIED PROCEDURES

The method proposed by J.J. Meyerhof (1957) has been widely spread in Spain since a reference to it and a summary of its results were published in the textbook written by J.A. Jiménez Salas et al. (1976).

According to his procedure, and for the particular case of interest here of completely shallow foundations (embedment depth D = 0) resting on a granular fill (c = 0), the ultimate bearing pressure can be evaluated by means of the equation:

$$p_h = \frac{1}{2}\gamma\, B\, N_\gamma\, t_\gamma \qquad (1)$$

where γ = effective unit weight of the rockfill; B = foundation width; N_γ = bearing capacity factor and t_γ = factor that accounts for the proximity to the edge of the slope.

This expression is valid for loads acting in the vertical direction. The effect of the deviation of the load from the vertical has to be considered by other procedures. Values of t_γ are published in the form of nomograms.

The method published by Giroud et al. (1972) has been applied in Spain by a good number of engineers and is considered next. They focus the problem in two steps. First, the actual geometry of the foundation is changed to a case where the load is acting just at the edge of the slope. The difference between the real slope angle "β" and the modified equivalent slope angle "Ψ" increases as the acting load moves further away from the crest of the slope.

That publication included tables and nomograms that allow to calculate the equivalent slope angle (Ψ) as a function of the distance of the load to the edge of the slope and the friction angle of the rockfill that supports the foundation.

Once the equivalent angle is obtained, a value of the bearing capacity factor $N_{\gamma\,\psi}$ is given in the form of graphs or tables. When writing this paper, it has been seen that Giroud's modified values of the bearing capacity factors can be quite well approximated by the following analytical equation:

$$N_{\gamma\psi} = (1-0{,}5\ \mathrm{tg}\,\psi)^5\ N_\gamma \tag{2}$$

Later is this paper, use of this equation will be made.

French recommendations (Fascicule 62- Titre V, see references) propose a method that allows to evaluate the factor of interest to this paper. For the particular situation considered in this paper of shallow foundations on granular fills, it can be shown that the French recommended modification factor can be stated by the following equation:

$$t_\gamma = \left(\frac{\sqrt{t_o} - \frac{4\delta}{\pi}}{1 - \frac{4\delta}{\pi}} \right)^2 \tag{3}$$

where δ = deviation of the acting load with respect to the vertical direction (in radians) and t_o = factor to modify bearing capacity when the acting load is vertical.

The main factor of the above equation is:

$$t_o = 1 - 0{,}9\ \mathrm{tg}\beta\,(2-\mathrm{tg}\beta)\left(1-\frac{d}{8B}\right)^2 \tag{4}$$

where β = actual inclination of the slope; d = distance from the load to the edge of the slope and B = foundation width.

It should be clear that when d > 8B a value of t_o = 1, should be assumed. This formula is only applicable when the foundation is shallow (embedment depth D = 0) and when the supporting berm is cohesionless (c = 0).

It is worthwhile to say that the publication of Garnier, Canepa, Corte and Bakir (1994) indicates that the factor 8B that appears in the above equation could be changed to 6B. This small change would slightly increase the corresponding bearing capacity.

This method of evaluation of the bearing capacity factor t_γ leads to very low values (even equal to zero) when loads are quite deviated with respect to the vertical. For example, for the particular case of d = 0 and tg β = 2/3, a value of t_o = 0.2 is obtained. Although this value could be considered reasonable, when the load is deviated an angle δ = 20° respect to the vertical, the corresponding modification factor results t_γ = 0, irrespective of the angle of friction of the supporting soil. The effect of "δ" on t_γ seems too large for the particular situation considered in this paper (c= 0, D = 0).

Lastly, the solution given by Bowles (1995) is considered. The notation used by, the author is represented in Fig. 2. When the procedure is applied to the particular case of D = 0, the factor that should be applied in order to consider the effect of the presence of sloping ground is written in the following form:

$$t_\gamma = \frac{1}{2}\left(1 - R + \frac{d}{2B}(1-R)\right) \tag{5}$$

where R is a dimensionless parameter defined as the ratio of two theoretical coefficients of passive pressure. Both coefficients are to be obtained by use of Coulomb theory for earth thrust against vertical walls and assuming that the wall-fill friction angle is equal to the friction angle of the soil. One of the coefficients (numerator) is to be obtained for the condition of backfill sloping ground with decreasing angle "β". The other coefficient (denominator) is that corresponding to flat horizontal backfill. Values of R will always be lower than 1.

Values of t_γ obtained by means of the above equation will always lie within the range $0{,}5 < t_\gamma < 1$ for any distance "d". These values seem clearly high as compared with any other method known by the authors.

Limit equilibrium methods that are commonly used for slope stability calculations could also be applied to analyze the problem

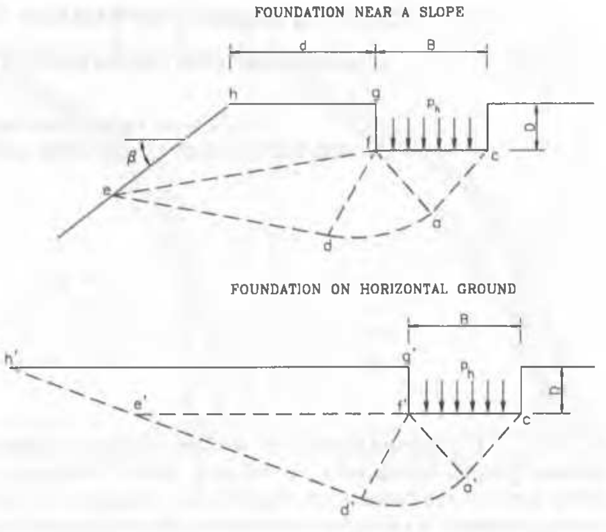


Fig. 2.- Geometrical definition for the Bowles method

posed in this paper. Simplified Bishop method of slices, as an example, could be used. It should be pointed out that it is expected that for loads acting far away from the slope, the method would not be realistic and would lead to results on the unsafe side. Failure lines with negative exit angle (going upwards) would overestimate the strength of the rockfill. Anyway, loads that lead to F = 1 according Bishop's simplified method have been obtained (Fig. 3) and are compared to those obtained for flat ground by Brinch-Hansen's equation for a particular case (ϕ = 40°, N_γ = 106). The corresponding results (values of t_γ) are plotted in Fig. 4.

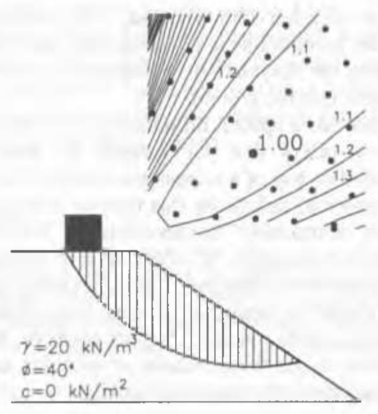


Fig. 3.- Sliding circle calculated by the Bishop method

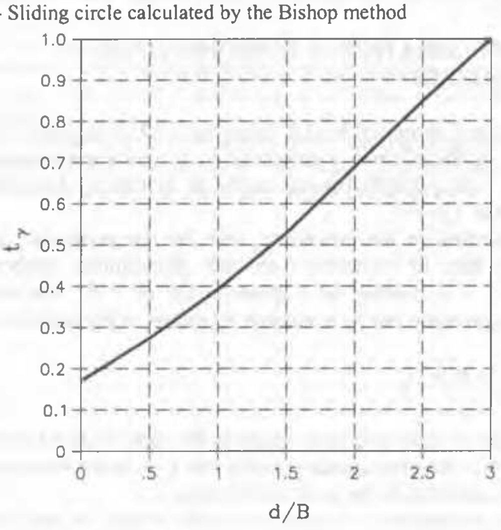


Fig. 4.- Value of t_γ according to the Bishop method.

3 PROPOSED METHOD

The method proposed in this presentation is quite similar to that described in ROM 05-94 but with some modifications made in order to improve its results.

According to this method the problem is defined as indicated in Fig. 5. The first step of the method consists of determining the exit point "M" of the failure surface and the corresponding angle Ψ. In order to do that, a value of the length "L" is estimated by the following equation:

$$L = B\sqrt{N_q i_q} \cdot \exp\left\{-\operatorname{tg}\phi\left(\psi + \frac{\theta}{2}\right)\right\} \qquad (6)$$

where N_q = bearing capacity factor of Prandtl equation; i_q = modification factor to considered the effect of the inclination of the load; ϕ = angle of internal friction of the ground and θ = auxiliary angle defined by:

$$\operatorname{sen}(\theta - \psi) = \frac{\operatorname{sen}\psi}{\operatorname{sen}\phi} \qquad (7)$$

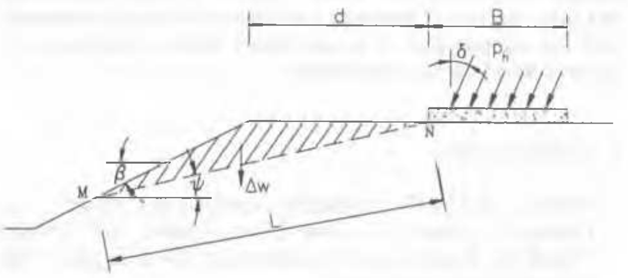


Fig. 5.- Geometrical sketch of the proposed method.

It is pending to investigate some simplification to the above equation, since at its present form it needs an iterative procedure to evaluate the angle Ψ which is needed for the following step.

The second step of the method is devoted to estimate the value of the equivalent earth load on the passive side of the failure line. Several options have been investigated, ranging form neglecting its influence (as the Giroud method indicates) or assuming that its effect is as large as in Prandtl's $\gamma = 0$ solution.

For this particular case, the following value has been considered to be safe:

$$q = 0{,}6\cos\psi\,\frac{\Delta W}{L} \qquad (8)$$

ΔW being the weight of ground situated above the line MN in Fig. 5.

The third and final step allows to calculate the failure load:

$$p_h = \left(q\,N_q\,i_q + \gamma\frac{B}{2}N_\gamma i_\gamma\right)\left(1 - 0{,}5\operatorname{tg}\psi\right)^5 \qquad (9)$$

In this equation, the last term has been obtained by an analytical approximation of Giroud solution.

According to that equation, the value of t_γ is:

$$t_\gamma = \left(1 - 0{,}5\operatorname{tg}\psi\right)^5\left(1 + 2q\,\frac{N_q\,i_q}{\gamma B N_\gamma i_\gamma}\right) \qquad (10)$$

For the purpose of illustration of the values of "t_γ" the following values of i_q and i_γ are assumed: $i_q = (1 - 0.7\operatorname{tg}\delta)^2$ and $i_\gamma = (1 - \operatorname{tg}\delta)^3$.

4 COMPARISON OF DIFFERENT METHODS

In order to compare different methods a simple example is considered defined by the following data:

$\phi = 40°$ $\quad N_\gamma = 2(N_q - 1)\operatorname{tg}\phi$
$\delta = 0$ $\quad \operatorname{tg}\beta = 2/3$

Values of t_γ factor for different distances between the load and the slope, obtained by different methods, are plotted in Fig. 6. It can be seen from this figure that results are quite different, Bowles method clearly giving the higher results and Giroud method being the most conservative.

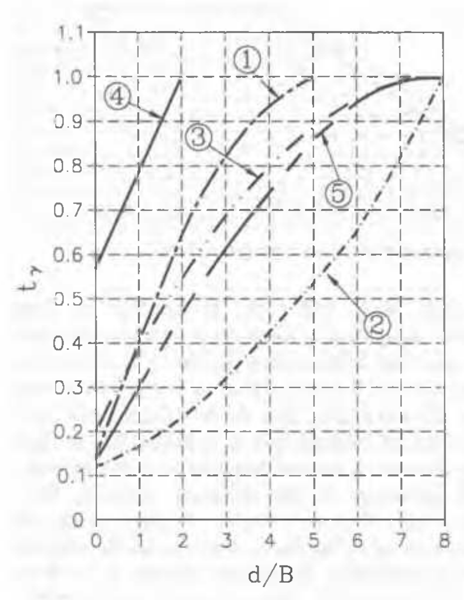


Fig. 6.- Comparison of t_γ values according to different methods:
1 Meyerhof, 2 Giroud, 3 French Norm, 4 Bowles, 5 Proposed.

The effect of the inclination of the load (angle δ) on the value of t_γ is illustrated in Fig. 7. Other methods do not allow this correction, since they do not consider this aspect or yield very unrealistic results.

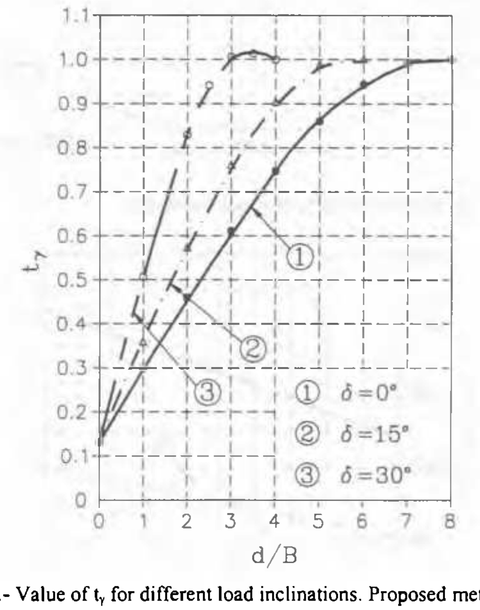


Fig. 7.- Value of t_γ for different load inclinations. Proposed method.

A detail of importance is the solution of this problem for the particular situation of d = 0 (load acting just at the edge of the slope). For this particular case most methods lead to a value within the range $0.10 < t_\gamma < 0.20$. Calculations by means of numerical methods (FLAC finite difference program, as indicated in Fig. 8) lead to a value of $t_\gamma = 0.12$, quite close to the value obtained by the proposed method ($t_\gamma = 0.13$).

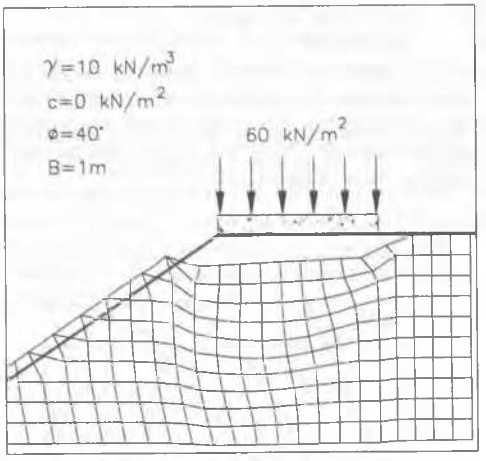


Fig. 8.- Computation made with program FLAC.

As a case study that could be applied to illustrate this problem, the analysis of a foundation failure is considered. That particular case had a foundation geometry as indicated in Fig. 9. A submerged rockfill was constructed over a trench dredged on a sandy soil. On top of this fill a shallow foundation was built that was supporting an inclined load as indicated in that figure. When the acting pressure is plotted together with the bearing capacity computed according to the proposed method, the situation indicated in Fig. 10 results. Factor of safety against foundation failure, in terms of acting loads, depends on the angle of friction assumed for calculation and ranges between F = 0.9 for $\phi = 35°$ and F = 1.9 for $\phi = 40°$. Those values are compatible with the expected average value of the angle ϕ for this foundation (a limestone rockfill placed over a sandy soil that had some influence on this failure).

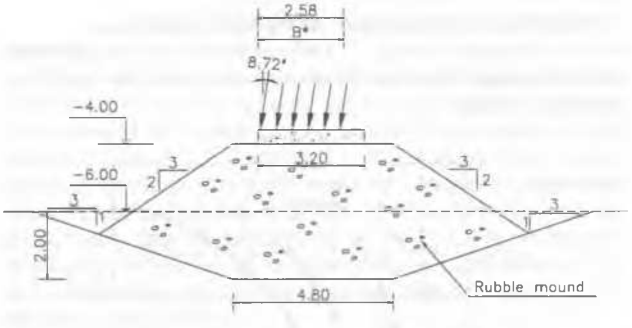


Fig. 9.- Geometry of the analysed actual foundation.

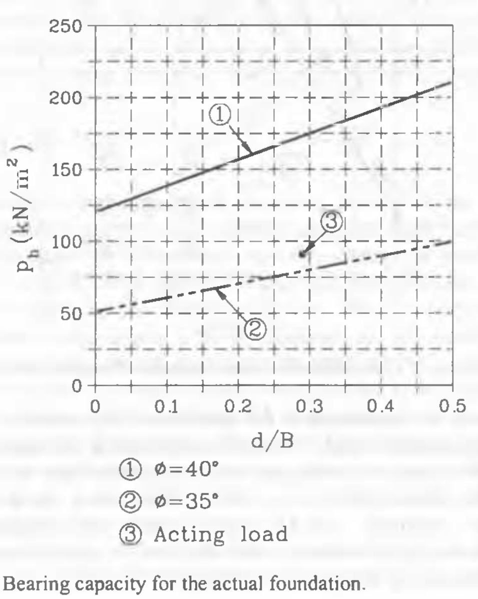


Fig.10.- Bearing capacity for the actual foundation.

5 CONCLUSION

The bearing capacity of shallow foundations is greatly affected by the presence of sloping ground close to the loaded area. There are several simplified methods that permit to evaluate a modification factor to the simpler case of inexistance of sloping ground. For the particular case analyzed in this paper (no embedment and cohesionless foundation) this factor, called t_γ is of special importance, given the large dispersion found.

Methods considered in this paper are those proposed by Meyerhof (1), Giroud (2), French normative (3), Bowles (4) and modified ROM 05-94 (5). The last is proposed here by the authors.

Values of t_γ should depend not only on the distance between the slope and the loaded area but also on the slope and friction angles and on the direction of the load. Not all methods do consider the direction of the load (1) or follow an unrealistic approach to simulate its effect (3) or are apparently quite unsafe (4) or seem to err on the safe side (2).

The method proposed in this paper considers the effect of the main variables that influence the value of the factor t_γ and is compatible not only with results obtained by limit-equilibrium and other numerical methods, but seems also to be consistent with the interpretation of a case history where a foundation of this type failed during construction.

6 REFERENCES

- Bowles, J. E. (1996). "Foundation Analysis and Design".
- Garnier, J, Canepa, Y., Corte J.F. and Bakir, N.E. (1994). "Étude de la portance de fondations en bord de talus". III ICSMFE. New Delhi. India.
- Giroud, J.P. (1972). "Tables pour le calcul des fondations. Tome 3. Force portante".
- Jiménez Salas, et al. (1976). "Geotecnia y Cimientos II. Mecánica del Suelo y de las Rocas". Ed. Rueda.
- Meyerhof, G.G. (1957). "The ultimate capacity of foundations on slopes". IV International Conference on Soil Mechanics and Foundation Engineering. London.
- Règles techniques de conception et de calcul des fondations des ouvrages de génie civil. (1993). Ministère de L'equipement, du logement et des transports. Fascicule n° 62 – Titre V.
- ROM 05-94. (1994). "Recomendaciones geotécnicas para el proyecto de obras marítimas y portuarias". Recomendaciones para obras marítimas. Ministerio de Obras Públicas, Transportes y Medio Ambiente. Puertos del Estado.
- Soriano, A. y González, J. (2000). "Evaluación de la seguridad de cimentaciones superficiales de estructuras de contención". Libro homenaje a José Antonio Jiménez Salas. Geotecnia en el Año 2000. Ministerio de Fomento- CEDEX- Sociedad Española de Mecánica del Suelo e Ingeniería Geotécnica.