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The Ultimate Bearing Capacity of Foundations on Slopes

La Force Portante des Fondations sur Talus

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Summary

The author's recently published theory of the bearing capacity of foundations on level ground is extended and combined with the theory of slope stability. First, an analysis is given for the bearing capacity of foundations on the face of a slope and is evaluated for purely cohesive and cohesionless materials. Secondly, the theory is extended to foundations on the top of a slope and is again evaluated for purely cohesive and cohesionless materials to illustrate the influence of various soil and foundation conditions.

Sommaire

La théorie, récemment publiée par l'auteur, sur la force portante des fondations sur sol horizontal, est étendue aux sols inclinés, et combinée avec la théorie de la stabilité des talus. On a étudiée tout d'abord la force portante des fondations construites sur le talus, dans le cas des sols purement cohérents, et dans le cas des sols pulvérulents. Dans la seconde partie de l'étude, on a étendu la théorie aux fondations construites sur le sommet du talus, toujours dans le cas des sols purement cohérents et dans le cas des sols pulvérulents; ceci pour illustrer l'influence des conditions diverses de sols et de fondations.

Introduction

Foundations are sometimes built on sloping sites or near the top edge of a slope. The bearing capacity theory recently published by the author (MEYERHOF, 1951 and 1955) can readily be extended and combined with the theory of the stability of slopes to cover such loading conditions as shown in the present paper.

Bearing Capacity of Foundation on Face of Slope

When a foundation located on the face of a slope is loaded to failure, the zones of plastic flow in the soil on the side of the

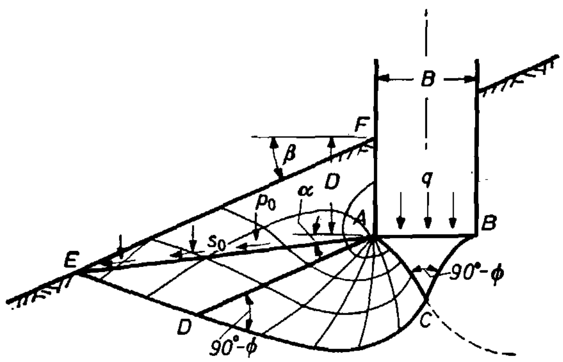

Fig. 1 Plastic zones near rough strip foundation on face of slope (foundation failure)

Zônes plastiques au voisinage d'une semelle de fondation rugueuse construite sur un talus (rupture du sol sous la fondation)

slope are smaller than those of a similar foundation on level ground and the ultimate bearing capacity is correspondingly reduced. The region above the failure surface of a shallow rough strip foundation is assumed to be divided into a central elastic zone *ABC*, a radial shear zone *ACD* and a mixed shear zone *ADEF* (Fig. 1). Ignoring the small effect of the unbalanced active earth pressure on the foundation shaft, which could be taken into account as for foundations under eccentric and inclined loads (MEYERHOF, 1953), the stresses in the zones of plastic equilibrium can be found as shown (MEYERHOF, 1951) for a horizontal ground surface, by replacing the weight of the soil wedge *AEF* by the equivalent stresses p_o and s_o, normal and tangential, respectively, to the plane *AE* inclined at angle α to the horizontal.

For a material the shearing strength of which is given by

$$\tau_f = c + \sigma \tan \phi \qquad \ldots. \ (1)$$

where c = apparent cohesion, ϕ = angle of internal friction or shearing resistance, and σ = normal pressure on shear plane,

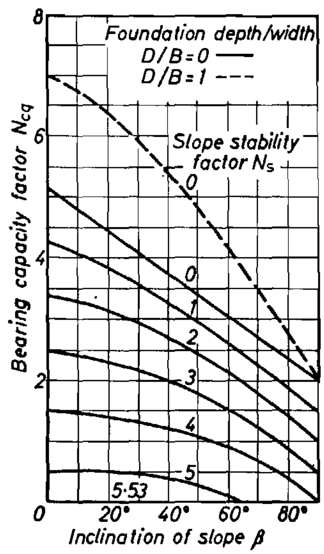

Fig. 2 Bearing capacity factors for strip foundation on face of slope of purely cohesive material

Coefficient de force portante d'une semelle de fondation, construite dans un talus en sol purement cohérent

the bearing capacity of a foundation on a slope of inclination β can be represented by (TERZAGHI, 1943)

$$q = cN_c + p_oN_q + \gamma\frac{BN}{2}\gamma$$

or, more generally (MEYERHOF, 1951 and 1955),

$$q = cN_{cq} + \gamma\frac{BN}{2}\gamma q \qquad \ldots. \ (2)$$

where γ = unit weight of soil, B = width of foundation, and N_{cq} and $N_{\gamma q}$ = resultant bearing capacity factors depending on β, ϕ and the depth/width ratio D/B of the foundation.

These bearing capacity factors are given in Figs. 2 (upper part) and 3 for a strip foundation in purely cohesive ($\phi = 0$) and cohesionless ($c = 0$) materials, respectively. The factors

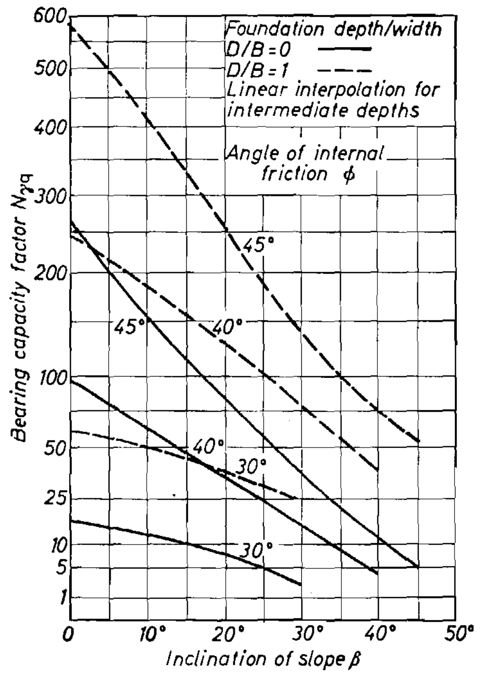

Fig. 3 Bearing capacity factors for strip foundation on face of slope of cohesionless material

Coefficient de force portante d'une semelle de fondation, construite dans un talus en sol pulvérulent

decrease with greater inclination of the slope to a minimum for $\beta = 90$ degrees on purely cohesive material and $\beta = \phi$ on cohesionless soil, when the slope becomes unstable. For inclinations of slopes used in practice ($\beta < 30$ degrees) the decrease in bearing capacity is small in the case of clays but can be considerabie for sands and gravels because the bearing

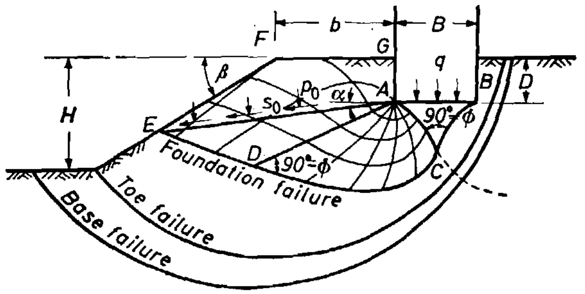

Fig. 4 Plastic zones and slip surfaces near rough strip foundation on top of slope

Zônes plastiques et courbes de rupture sous une semelle à surface rugueuse construite sur le sommet d'un talus

capacity of cohesionless soils is found to decrease approximately parabolically with increase in slope angle.

The bearing capacity of a foundation on completely submerged material below a stationary water table is given by equation 2 with γ replaced by γ' = submerged unit weight of the soil. If the water percolates through the soil, a flow net analysis is required to determine the neutral stresses on the failure surface, while the bearing capacity after rapid drawdown of the water table of a completely submerged foundation can be estimated from equation 2 using a reduced angle of internal friction

$$\phi' = \tan^{-1}\left(\frac{\gamma'}{\gamma}\tan\phi\right) \quad \ldots . (3)$$

as for unloaded slopes (TERZAGHI, 1943). The bearing capacity of foundations of shapes other than a strip can at present only be based on empirical evidence to obtain shape factors in conjunction with equation 2 on account of the variable boundary conditions of the problem.

In cohesive material with a small or no angle of shearing resistance the bearing capacity of a foundation may be limited by the stability of the whole slope with a slip surface intersecting the toe or base of the slope, as indicated in Fig. 4. For slopes in practice in purely cohesive soil of great depth, base failure of an unloaded slope occurs along a critical mid-point

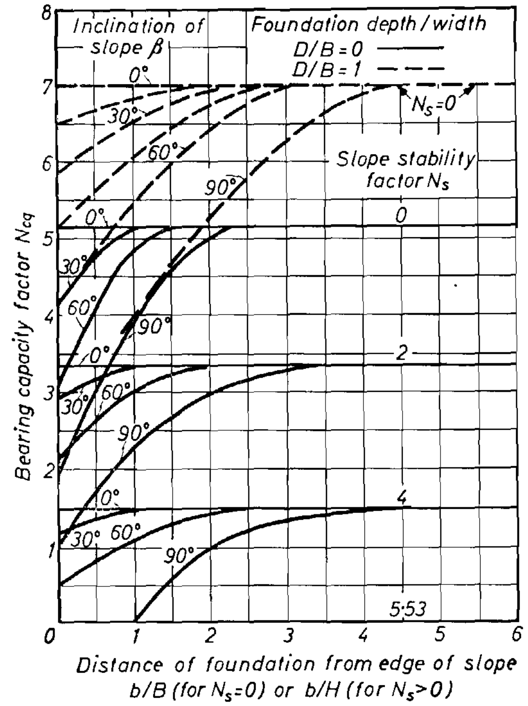

Fig. 5 Bearing capacity factors for strip foundation on top of slope of purely cohesive material

Coefficient de force portante d'une semelle de fondation construite au sommet d'un talus en sol purement cohérent

circle (FELLENIUS, 1927) so that foundations below the mid-point section increase the overall stability of the slope and *vice versa*. The upper limit of the bearing capacity can then be estimated from the expression

$$q = cN_{cq} + \gamma D \quad \ldots . (4)$$

where the factor N_{cq} is given in the upper part of Fig. 2. The lower limit of the bearing capacity is obtained if the foundation rests on top of the slope as considered in the next section.

Bearing Capacity of Foundation on Top of Slope

When a foundation located on the top of a slope is loaded to failure, the zones of plastic flow in the soil on the side of the slope are shown in Fig. 4 for foundation failure and for slope failure through toe or base. For a shallow rough strip foundation at a distance b from the edge of a horizontal top surface of a slope, the stresses in the zones of plastic equilibrium for the case of foundation failure can be found as indicated above for a foundation on the face of a slope. The bearing capacity of the foundation can then be represented by equation 2 where the resultant bearing capacity factors N_{cq} and $N_{\gamma q}$ depend on b as well as β, ϕ and D/B of the foundation. These bearing capacity factors are given in Figs. 5 (upper part) and 6 for a strip foundation in purely cohesive and cohesionless materials, respectively. While the factors decrease with greater inclination of the slope, they increase rapidly with greater foundation distance from the edge of the slope. Beyond a distance of about 2 to 6 times the foundation width (depending on ϕ and D/B) the bearing capacity is independent of the inclination of the slope and becomes the same as that of a foundation on an extensive horizontal ground surface.

An analysis for the case of slope failure (through toe or base) under a foundation load can be made on the assumption of a cylindrical slip surface as for unloaded slopes (Fellenius, 1927), and the average load over the whole foundation area may

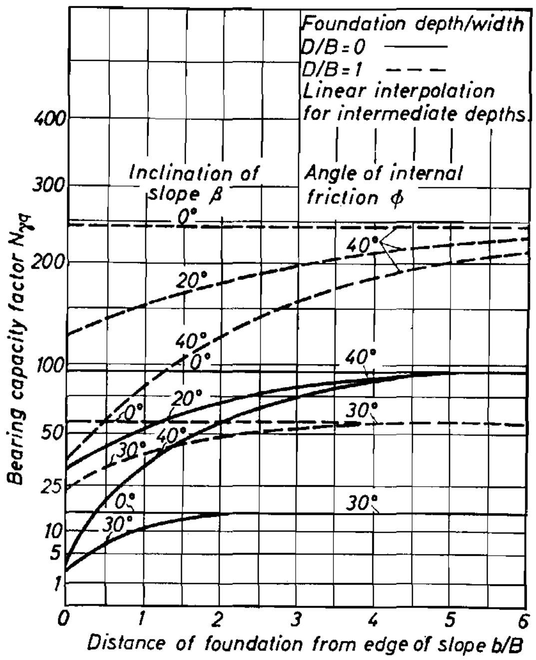

Fig. 6 Bearing capacity factors for strip foundation on top of slope of cohesionless material

Coefficient de force portante d'une semelle de fondation construite au sommet d'un talus en sol pulvérulent

be replaced by a uniform surcharge. For a surcharge on the whole horizontal top surface of a slope a solution of the slope stability has been obtained on the basis of dimensionless parameters (Janbu, 1954), and this analysis can readily be extended to cover the case of a wide foundation (width B greater than slope height H) at any distance from the edge of the top of the slope. The bearing capacity of a foundation on purely cohesive soil of great depth can then be represented by equation 4 where the bearing capacity factor N_{cq} depends on b as well as β and the stability factor of the slope

$$N_s = \gamma H/c \qquad \ldots . (5)$$

This bearing capacity factor, which is given in the lower parts of Figs. 2 and 5, decreases considerably with greater height and, to a smaller extent, with inclination of the slope; the bearing capacity is found to decrease approximately linearly with greater slope height to zero for a height equal to the critical height of an unloaded slope, as would be expected. For a given height and inclination of the slope the bearing capacity factor increases with greater foundation distance from the edge of the slope, and beyond a distance of about 2 to 4 times the height of the slope the bearing capacity is independent of the slope angle. Figs. 2 and 5 also show that the bearing capacity of foundations on top of a slope is governed by foundation failure for a small slope height (N_s approaches zero) and by overall slope failure for greater heights.

The influence of ground water conditions on the bearing capacity of foundations on top of a slope can be taken into account as mentioned above for foundations on the face of a slope. The effect of a tension crack on the bearing capacity on top of a slope of purely cohesive material can be estimated, with good approximation, from equation 4 using a reduced cohesion

$$c' = \left(1 - \frac{0{\cdot}8\beta z_c}{90^\circ H}\right)c \qquad \ldots . (6)$$

where z_c = depth of tension crack completely filled with water, which is obtained from the results of an analysis of unloaded slopes (Janbu, 1954).

The mechanism of foundation failure assumed in the present theory (Figs. 1 and 4) is supported by the results of a study of soil movements below ground level in tests carried out on model footings on slopes of dry sand (Peynircioglu, 1948). However, published observations on the magnitude of the ultimate bearing capacity of such footings do not appear to be available at present for comparison with the proposed method of analysis.

Conclusions

The previous bearing capacity theory of foundations on level ground has been extended and combined with the theory of the stability of slopes to cover the stability of foundations on slopes. The theory indicates that the bearing capacity of foundations on the face of a slope or near the top edge of a slope decreases with greater inclination of the slope, especially for cohesionless soils; at greater distances from the edge of a slope, the bearing capacity becomes independent of the slope angle. The theory also indicates that the bearing capacity of foundations on the top of clay slopes decreases considerably with greater height of the slope and is frequently governed by overall slope failure. While the theoretical mechanism of foundation failure is supported by previous observations of soil movements below model footings on sand slopes, no published information on the ultimate bearing capacity of foundations on slopes in practice appears to be available yet as a check.

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