Computers and Geotechnics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

The bearing capacity and failure mechanism of a vertically loaded strip footing placed on the top of slopes

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ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 28 June 2017
Accepted 16 August 2017
Available online xxxx

Keywords:
Bearing capacity
Footing
Slope stability
DLO

ABSTRACT

This study evaluates the bearing capacity and failure mechanism of strip footings placed on the top of slopes. A set of design charts containing the detailed critical failure mechanism information is presented for engineering practice. The results show that six distinct failure modes can be attributed to the bearing capacity of footings or to the slope stability issues based on the contribution of the soil self-weight. The occurrence of toe failure (S) is the threshold between the two geotechnical issues. The analytical solution based on the face failure mode is a conservative solution for bearing capacity issue.

1. Introduction

A building constructed near a slope is common in engineering practice, and the performance of a vertically loaded strip footing is strongly influenced by the presence of a slope. Based on the assumed failure mechanism, several analytical solutions have been conducted to evaluate the bearing capacity of a footing on a purely cohesive (i.e., $\varphi = 0$) and frictional (i.e., $c = 0$) slope, ranging from the limit equilibrium method [2,16,21], to limit analysis [7,11,17] and to the slip line method [8].

In contrast to the conventional analytical solutions, a numerical model does not require assuming a critical collapse mechanism. Georgiadis [5,6] constructed a numerical model to estimate the undrained bearing capacity of a footing placed on the top of a slope under vertical and inclined loads. A parametric study was then performed to develop design charts for purely cohesive soils, and three typical failure modes were discussed. Shiau et al. [22] used finite element limit analysis [25,26] to evaluate the undrained bearing capacity of a strip footing on a slope and briefly discussed the effect of surface surcharge.

Leshchinsky [12] reported that limited studies focus on the slope of c-φ soils [23]. The current design method [1] does not rigorously address various scenarios of c-φ soils. Griffiths [9] used finite element analysis to calculate the bearing capacity of c-φ soil, but substantial computational effort was required to obtain the ultimate load for soil with a high friction angle. Leshchinsky [12] studied the bearing capacity of a footing placed on the crest of a c-φ slope using the discontinuity layout optimization (DLO) approach. The influence of soil strength properties, footing width, and slope angle on the failure mechanism and bearing capacity was investigated. More recently, Leshchinsky and Xie [14] presented design charts for spread footings placed near slopes. They applied a set of reduction factors to the ultimate bearing capacity solution for a variety of scenarios.

The main objective of this investigation is to acquire an intensive understanding of the collapse mechanism of a vertically loaded strip footing placed at the top of a native slope containing c-φ soils, particularly for the effect of footing placement on the failure mode. When a footing is located on a steep slope, the bearing capacity of the footing is significantly reduced. In this case, an earth retaining system (e.g., piles and geotextiles) is necessary to stabilize the slope [32]. Thus, the design charts that we present here describe a native slope with a gentler slope angle than that discussed by Leshchinsky and Xie [14] but consider a wider range of slope height. Detailed information regarding the critical failure mechanism is incorporated into the design charts. Based on the analysis of the design charts, the shift in the failure mechanism, the limitations of the analytical solution and the critical normalized footing distance are discussed.

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http://dx.doi.org/10.1016/j.compgeo.2017.08.009
0266-352X/

2. Problem definition and validation of DLO

A rigid footing of width B is placed on c-φ sloping ground with slope angle β and slope height H at a normalized footing distance λ (=footing distance/footing width) from the crest of the slope, as shown in Fig. 1. The normalized bearing capacity for a footing can be expressed as

$$\frac{q}{\gamma B} = f\left(\lambda, \beta, \varphi, \frac{c}{\gamma B}, \frac{H}{B}\right) \quad (1)$$

where q = average limit pressure under the footing; B = footing width; H = slope height; λ = normalized footing distance; γ = unit weight of soil; c = cohesion of soil; and φ = friction angle of soil.

In limit analysis, soil is treated as a perfectly plastic material that obeys the associated flow rule [3]. The DLO procedure combined with upper-bound limit analysis provides a highly efficient tool for directly determining the critical layout of discontinuities and the associated ultimate load of complex geotechnical stability problems without assuming a slip surface. The upper-bound theorem states that the total rate of external work attributable to the force on the footing and the self-weight of the soil is greater than or equal to the total rate of energy dissipation by the shear strength in a kinematically admissible velocity field (i.e., the actual collapse load cannot exceed the calculated limit load). The DLO automatically identifies the critical layout of slip-lines in a soil mass to find the minimum upper-bound solution, as shown in Fig. 2. It has been successfully used to evaluate slope stability [13], the ultimate failure load of footings on the crest of a c-φ slope [12] and other geotechnical problems [27,28]. The software program LimitState: GEO [15] employs the DLO technique to evaluate the critical plastic collapse mechanisms and the associated upper-bound solutions. In this study, DLO was used to evaluate the performance of a vertically loaded footing placed on the top of a slope. A sensitivity analysis was performed to ensure that the quantity of nodes used in the discretization was adequate for an accurate calculation [12,13]. A consistent solution (<2% discrepancy is considered in this study) can be achieved at 2000–5000 nodes, depending on the geometric parameters.

To verify the DLO approach, the bearing capacity predicted by DLO is compared with the results obtained in the literature. First, the results of this study are compared to those calculated by Meyerhof [16] and Leshchinsky [12] for the case of a footing placed at the crest (λ = 0) of a purely frictional slope (c = 0). Three different friction angles (30°, 40° and 45°) are considered, and the results of the current implementation match those of the others, as shown in Fig. 3 (a). Next, the proposed method is compared with the undrained solutions of Kuskkabe et al. [11] and Georgiadis [7]. The influence of the distance of a footing from the edge of an undrained slope on the bearing capacity factor is investigated for the cases of β = 30° and 45° with $c_u/\gamma B$ = 2.5 (Fig. 3(b)). The solutions of Kuskkabe et al. [11] are not conservative for λ > 0 because the changes in the stress boundary conditions lead to varying principal stress directions in the failure mechanism of the upper-bound solution [5]. However, the DLO results satisfy the equilibrium and compatibility requirements and show excellent agreement with the more rigorous solutions of Georgiadis [7].

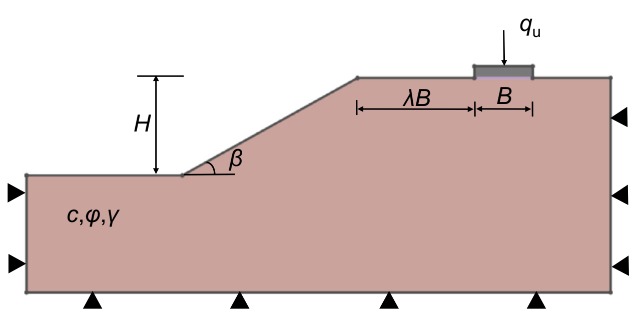

Fig. 1. Schematic of the model.

3. Failure mechanism

This section examines the bearing capacity and failure mechanism of footings on the top of a slope for various normalized slope heights H/B and for different values of λ (i.e., distance from the crest). For this purpose, a relative steep slope of β = 40° with soil strength φ = 20° and $c/\gamma B$ = 0.5 is selected, as shown in Fig. 4. Following Georgiadis [5], a 2 m wide footing is used in the simulations, and the results are normalized. Pantelidis and Griffiths [19] and Xie and Leshchinsky [31] stated that there are two geotechnical issues exist in a footing-on-slope system: (1) the bearing capacity of a rigid footing and (2) the stability of a slope under a vertical load and the gravitational load from the soil mass. To further study this problem, the effect of the soil self-weight is discussed in detail. In classical bearing capacity theory of on the horizontally leveled ground, the contribution of soil weight represented by N_γ is determined by the limit load of weighted and weightless materials, the soil weight, and the footing width [20]. This calculated method is adopted here to examine the effect of soil weight (represented by N_γ^*) on the footing-on-slope system, as shown in Fig. 4(b). Note that the N_γ^* is not fully consistent with the N_γ in classical bearing capacity theory. As shown in Fig. 4(a), there are six distinct failure modes for the two geotechnical failure modes.

3.1. Bearing capacity failure

Generally, the collapse mechanism of a bearing-capacity type failure contains an active wedge, a slip fan zone and a passive wedge. For this issue, the weight of the soil, considered as the external force, contributes to the bearing capacity (coefficient N_γ). The self-weight of the soil in the passive wedge provides a resistance force for the footing [29]. The performance of the footing is directly related to the geometry of the slope and the strength of the soil, and the bearing-capacity type failure modes can be described as follows:

(B-1) Face failure mode: a typical single-side failure mechanism is observed, and an unsymmetrical rigid wedge occurs directly beneath the footing. The failure slip extends to the slope face. The presence of a slope has an adverse effect on the bearing capacity as the reduction of resistance in the passive wedge, and the influence of the slope height on the ultimate load is negligible.

(B-2) Toe failure mode (B): a failure surface develops from the back corner of footings to the toe of the slope. Relative to the face failure mode, the added cohesion resistance along the lengthened failure slip contributes to a larger limit load.

(B-3) Base failure mode: a failure slip extends beneath the toe of the slope, which tends to mobilize a larger volume of shear resistance than those of the face failure and toe failure modes. The passive resistance recovers as the influence of the slope decreases.

(B-4) Prandtl-type failure mode: a general failure mechanism occurs for a footing placed sufficiently far from the slope crest. A rigid wedge with a base angle of 45° + φ/2 with respect to the horizontal axis is generated beneath the footing. This wedge resembles the case of a footing on the horizontally leveled ground.

3.2. Slope stability failure

The coefficient N_γ^* in Fig. 4(b) represents the contribution of the unit weight to the bearing capacity of the footings. To discuss the

Please cite this article in press as: Zhou H et al. The bearing capacity and failure mechanism of a vertically loaded strip footing placed on the top of slopes. Comput Geotech (2017), http://dx.doi.org/10.1016/j.compgeo.2017.08.009