Footing on the Crest of Slope: Slope Stability or Bearing Capacity?

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Abstract

A footing on the crest of a slope may be considered as either a slope stability or a bearing capacity problem. Traditional slope stability analysis delivers the safety factor with respect to shear strength, while traditional bearing capacity analysis delivers the safety factor with respect to loading. These two strategies indicate quite different safety levels, even when applied to the same problem. Eurocode 7 (EC7) allows for the use of both strategies. Indeed, in the limit state framework of EC7 slope stability and bearing capacity problems do not share the same partial factors. Since, EC7 does not have a special provision for the problem of a footing on the crest of slope, the question whether it is a bearing capacity or a slope stability problem remains. The parametric studies presented in this paper based on EC7 design guidelines and different factoring strategies, shows that the kind of failure mechanism observed strongly depends on the magnitude and position of the footing loading.

Keywords

Eurocode 7 • LRFD • Slope stability • Bearing capacity • Footing on slope

215.1 Introduction

A footing on the crest of a soil slope may be considered as either a *slope stability* or *bearing capacity* problem. Site specific conditions, such as, slope geometry, soil characteristics (especially shear strength and heterogeneity), distance of footing from the edge, width of footing and magnitude of loading, may define the prevailing failure mode. Various methods of analysis, such as, limit equilibrium methods, analytical solutions and finite elements, are used along with different design procedures for the determination of the safety level of slopes or foundations. Among the most popular design procedures are the traditional Allowable Stress Design (ASD) and the more modern Limit State Method.

Generally, when considering an ultimate limit state with Eurocode 7 (EN 1997-1 2004), it shall be verified that:

$$E_d \leq R_d \quad (215.1)$$

where, E_d is the design value of the effect of actions and R_d is the design value of the resistance to actions. The above equation can be rewritten in a safety factor form as:

$$F_\tau = R_d / E_d \geq 1.0 \quad (215.2)$$

The manner by which the above equations are applied is determined by the Design Approach (DA) of Eurocode 7 (EC7). The Design Approach adopted by each European country can be found in Bond and Harris (2008). The recommended (EN 1997-1) values for partial factors for each of the three Design Approaches are given in Table 215.1. As shown, both combinations of DA1 treat slopes and spread

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Table 215.1 Partial factors γ_x for each Design Approach (DA) of EC7

DA	Actions		Soil parameters				Resistances
	γ_G (permanent)	γ_Q (variable)	$\gamma_{\tan\varphi'}$	$\gamma_{c'}$	γ_{cu}	γ_γ	γ_R
DA1-a	1.35	1.5	1.0	1.0	1.0	1.0	1.0
DA1-b	1.0	1.3	1.25	1.25	1.4	1.0	1.0
DA2	1.35	1.5	1.0	1.0	1.0	1.0	S:1.1, F:1.4
DA3	S:1.0, F:1.35	S:1.3, F:1.5	1.25	1.25	1.4	1.0	1.0

Notes when not the same value applies to both slopes and foundations, the values indicated by 'S' and 'F' refer to slopes and spread foundations respectively

foundations equally. On the other hand, in DA2 and DA3 spread foundations are treated with more conservatism than slopes by applying greater partial factors to Resistances (DA2) or Actions (DA3). This conservatism is reminiscent of the traditional Allowable Stress Design in bearing capacity calculations, where safety factors as large as 3 or 4 are usually acceptable:

$$F_{q,f} = q_u / q \qquad (215.3)$$

where, q is the soil bearing stress and q_u is the ultimate soil bearing strength usually obtained by a well-established bearing capacity theory (e.g. Terzaghi 1943; Meyerhof 1951, 1957). The allowable soil bearing stress is $q_a = q_u / F_{q,f}$.

Both Eqs. 215.1 and 215.2, in the particular problem of footing of slope, provide estimation for the *stability condition of slopes* with respect to shear strength of soil. Pantelidis and Griffiths (2011) indicate that, the safety factor with respect to shear strength should not be considered as an absolute procedure in slope stability analysis, proposing alternative factoring strategies. In this respect, among other expressions, the safety factor could be expressed as for the footing surcharge:

$$F_{q,s} = \frac{q_{max}\ \text{(load that the slope can bear)}}{q\ \text{(actual load)}} \qquad (215.4)$$

which is the factor by which the available load must be multiplied in order to bring the slope to the point of failure.

In the current work, the factor of safety of a footing on the crest of a slope is further investigated. The goal is to reach conclusions on a unified approach for defining the factor of safety in problems where load and resistance factors are interrelated. Following EC7, Eq. 215.2 will be used both from the slope stability and bearing capacity point of view. Since, the sample analytical method for bearing resistance calculation in the *informative* Annex D of EC7 does not apply to the case of footing on the crest of the slope, Meyerhof's (1957) method will be used; this method deals only with purely cohesive or purely frictional soils, thus, for comparison purposes, only purely cohesive soils will be considered here. In addition, Eqs. 215.3 and 215.4 will be used for the calculation of the safety factor of the same examples. Allowing for the direct comparison with EC7, the partial factors given in Table 215.1 will be applied, expanding, in essence, the use of the concept of Design Approaches.

215.2 Analysis Based on the Limit State Method (Eurocode 7)

The stability under undrained conditions of a number of homogenous slopes having a perfectly flexible footing on the crest has been assessed based on EC7. As the general behavior of these slopes was similar, extensive parametric analysis was carried out on a specific slope, the geometry and strength characteristics of which are given in Fig. 215.1a. A total of 1,152 loading combinations were considered covering all design approaches of EC7 (DA1, DA2 and DA3), two footing widths (B = 2.5 m and B = 5 m), six different distances of footing from the edge (d = 0, 2.5, 5.0, 7.5, 10.0 and 12.5 m; measured from the outer point of footing) and six different loads (q = 0, 50, 150, 250, 350 and 450 kN/m^2). The footing has been treated both as permanent and variable action, whilst EC7 has been applied both from the slope and bearing capacity point of view. All safety factor values have been obtained by the freely available elastic-plastic finite element (FE) program *footing_on_slope* (www.mines.edu/~vgriffit/4th_ed/Software/). The most important conclusions are highlighted below.

A first and very important observation is that, the failure mechanism depends strongly on the magnitude of the imposed loading. Indeed, two failure mechanisms may exist at the same time. Originally, the unloaded slope of the above mentioned example gives a deep-seated failure surface. As the footing load increases while the distance of footing from the crest is kept constant, a second failure surface makes its appearance along with the deep-seated surface (loading range from point 0 to 1; see Figs. 215.1 and 215.2). The deep-seated surface fades-away completely at point 2 leaving the toe failure surface alone until point 4, where, the

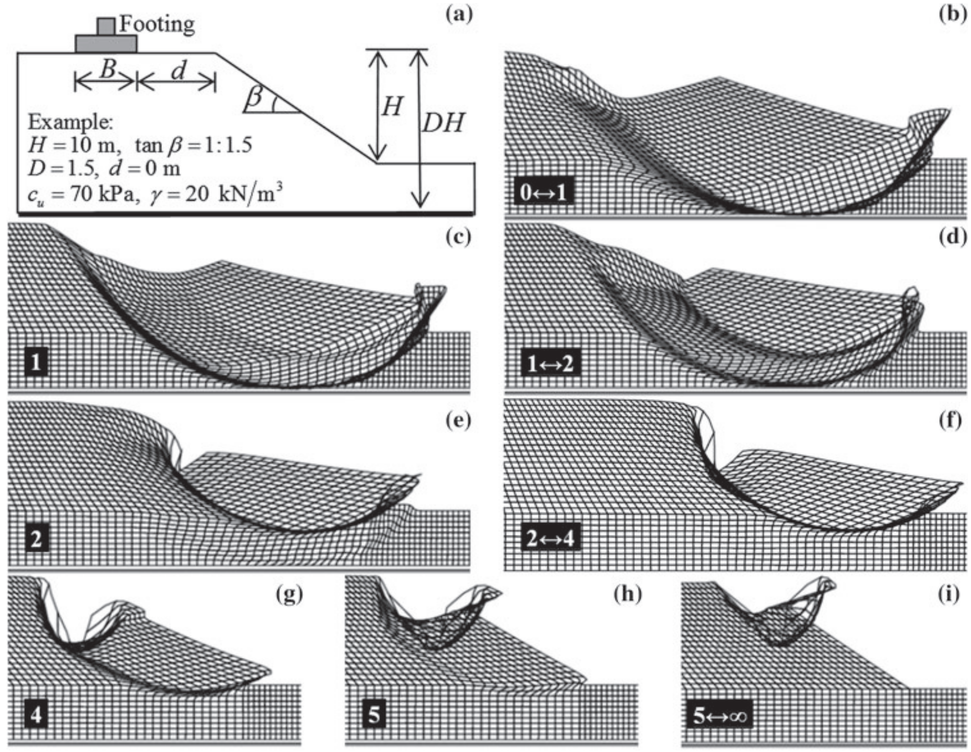


Fig. 215.1 Example: Different failure mechanisms caused by different footing loadings. The numbers in *black* fields indicate different loadings or loading ranges; they should be read in conjunction with Fig. 215.2. All plots have been produced based on DA3 of EC7, however, they are typical failure surfaces

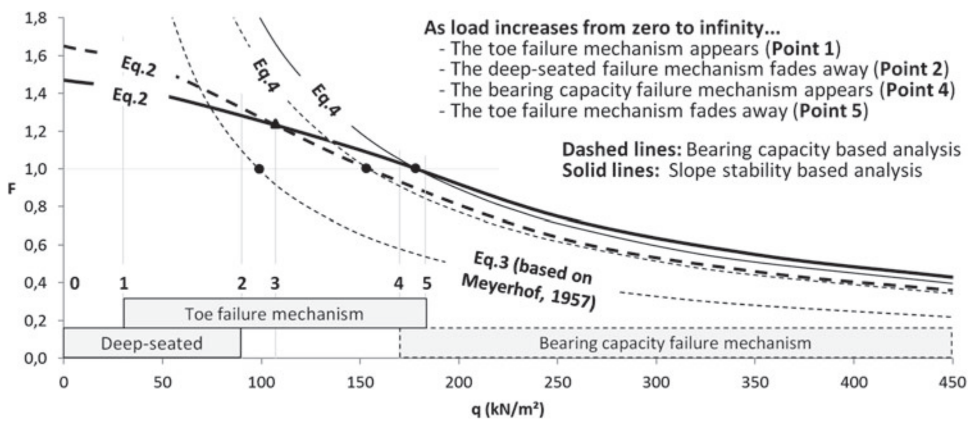


Fig. 215.2 Example: F versus q chart. To be read in conjunction with Fig. 215.1. All curves have been produced based on DA3 of EC7. Limits 0 to 5 stand both for the slope stability and bearing capacity type of analysis

bearing capacity failure mechanism is activated. Toe and bearing capacity failure mechanisms exist together only for a small loading range (point 4 to 5). Beyond point 5, the problem is purely of bearing capacity nature.

Generally, the most conservative design approaches for slopes are DA3 and DA1-b (these two approaches use the same partial factors). On the other hand, DA2 is the most conservative approach for bearing capacity problems (Fig. 215.3). As each European Union country has adopted one of the three design approaches, care should be taken for the selection of the right treatment for the rather complicated problem of footing on the crest of slope. Rationally thinking, for example, as the most likely failure mechanism from point 0 to 4 (see Fig. 215.2) is the deep-seated or toe one, the problem should be treated using the partial factors for slopes, despite the fact that, from point 3 to 4 the bearing capacity partial factors result in more conservative F values. Point 3 is the point of intersection between the bearing capacity and slope stability curve obtained by Eq. 215.2. Moreover, point 3 is the point of symmetry for the loading range that gives toe failure mechanism (Fig. 215.2). Beyond point 5, the bearing capacity nature of the problem prevails. For the small loading range between point 4 and 5, the problem is rather unclear as both slope and bearing capacity failure mechanisms exist together. In this case, the most conservative one should be adopted, in this respect, the bearing capacity one. The safety factor expression with respect to bearing stress of Eq. 215.4 produces F – q curves of hyperbolic form (see Fig. 215.2). Indeed, these curves cross-over the respective curves derived from Eq. 215.2 at F = 1.0, as expected. Generally, Eq. 215.4

Fig. 215.3 Example: F versus q chart for all Design Approaches of EC7

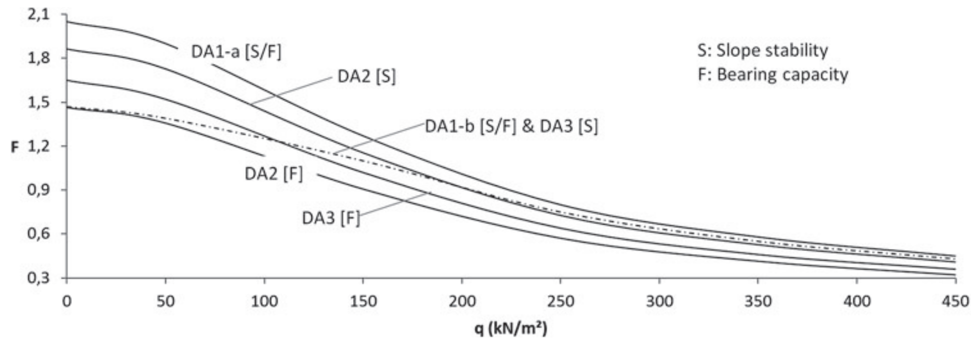
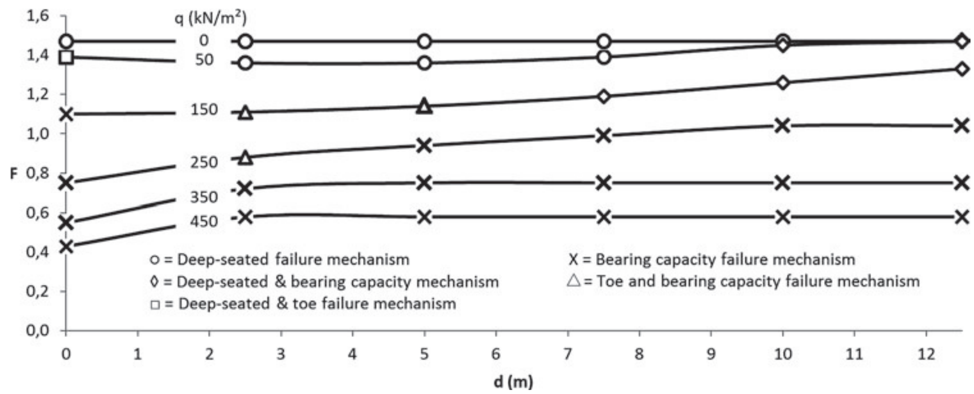


Fig. 215.4 Example: F versus d chart: All curves have been produced based on DA3 of EC7



gives F values slightly smaller for $F < 1$ (comparing to Eq. 215.2) and much greater as the available q decreases. This is how the equations of hyperbolic form, such as Eq. 215.4 and the traditional one of Eq. 215.3 (used in bearing capacity problems), work.

On the other hand, the hyperbolic $F - q$ curve obtained by Eq. 215.3 and Meyerhof's (1957) solution (see Fig. 215.2), is, generally, more conservative comparing to those obtained by the other methods. However, for very small footing loads the opposite is observed. The curve in question has also been drawn based on the limit state framework of EC7. Finally, it is noted that, the effect of footing on the safety level of slopes decreases as the distance d increases and vanishes for great distances d (Fig. 215.4). Usually, the minimum safety factor value corresponds to $d = 0$m. However, for small loadings, the most unfavorable position of footing is not very close to the edge of the crest. Figure 215.4 also shows the change in the failure mechanism with respect to d.

215.3 Conclusions

The classical problem of a footing on the crest of a slope has elements of both slope stability and bearing capacity. In the limit state framework of EC7, the problem is treated either as a slope or a foundation, assessing, in essence, stability with respect to shear strength or loading respectively. It is well known that, even when applied to the same problem, these approaches may indicate quite different safety levels. In the current work, the safety level of a footing on the crest of a slope has been further investigated. The extensive parametric analysis that carried out based on EC7 and different factoring strategies has shown that key issue for the analysis is the kind of failure mechanism that strongly depends on the magnitude and position of loading.

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