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GEOTECHNICAL ULS DESIGN ISSUES OF BRIDGE SHALLOW FOUNDATIONS

Konstantina Papadopoulou, George Gazetas
National Technical University of Athens, Greece

Abstract

Some important issues referring to the Ultimate Limit States of geotechnical design of bridge shallow foundations are discussed using results of 2D and 3D FE analyses, as follows: (a) The effects of highly eccentric and inclined loadings on the bearing capacity of footings on cohesionless soils, (b) the effects of soil inhomogeneity in the special case of 2-layered clay, (c) the scour effects in case of abutment and piers in riverbed, from the geotechnical point of view.

Keywords: bearing capacity, cohesionless soils, FE analyses, layered clay, scour effects

1 Introduction

Spread footings continue to be an attractive type of bridge foundations due to their well known advantages, as the simplicity and low cost. However, deep foundations as bored or driven piles and drilled shafts are chosen in many cases by reason of the limitation of vertical and horizontal displacements. After systematic observations and evaluation of data, now it is widely accepted that bridges on spread footings can tolerate considerably larger displacements than those adopted at the past. Consequently, the Ultimate Limit States (ULS) criteria may decisively influence the foundation type and the estimation of the vulnerability of existing bridges on shallow foundations, as well.
In the present paper selected issues are presented and discussed based on FE results under 2D and 3D conditions: (a) The main factors affecting the bearing capacity of shallow foundations on cohesionless soils, especially in case of highly inclined and eccentric loads. (b) The effect of soil inhomogeneity due to the two layered clay system. (c) The effects of scour on the bearing capacity of footings in waterway. The case is of peculiar interest, since scour is the main cause of bridge geotechnical failures in many countries.

2 Factors affecting the bearing capacity of shallow foundations

The bearing capacity (BC) of footings based on homogeneous soil and subjected to combined loadings (V,M,H) has been extensively investigated. Such problems since today are analyzed by trinomial equations, loosely based on the solutions from the theory of plasticity for strip footings, using correction coefficients, to assess the effects of shape, eccentricity and inclination of loadings. In the important case of cohesionless soil, the characteristic resistance or ultimate vertical load ($R_k = V_u$), according EN 1997-1, Annex D [1] is given by the simplified equation (base inclination factors, $b_c = b_q = b_\gamma = 1$):

$$V_u = A'\cdot(q'\cdot N_q\cdot s_q\cdot i_q+0{,}5\cdot\gamma'\cdot B'\cdot N_\gamma\cdot s_\gamma\cdot i_\gamma) \qquad (1)$$

where

A′ - the effective contact area,

B′ - the effective width,

N_q - and N_γ the BC factors,

s_q, s_γ - the shape factors and

i_q, i_γ - the inclination correction factors.

The key figures indicating the symbols in this paper are presented in Fig.1 (D is the embedment depth).

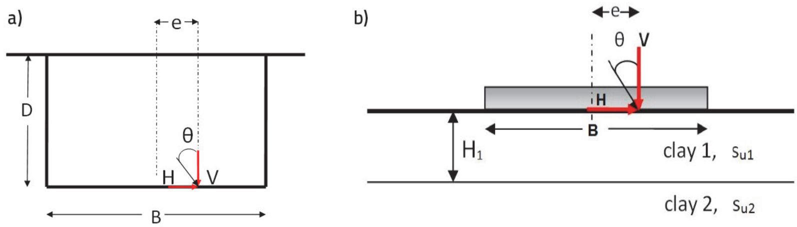

Figure 1 Combined loading on rectangular footing: a) Homogeneous soil, b) Two-layered clay

Even in simple cases, several uncertainties are related with the correction factors of Eq. (1). For example, the inclination factor i_γ for strip on cohesionless soil is given by different equations. Some proposals are compared in Fig. 2a. According to Eurocode 7.1 [1] and [2], the factor i_γ is related only with the inclination of the resultant load, tanθ, independently of the friction angle, φ′, thus it seems that the sliding for high ratios H/V is not taken into account. On the contrary, according to [3] i_γ depends on both the parameters tanθ and φ′. In order to separate the effects of i_q and i_γ, FE analyses are carried out for strip on the surface, which verify that i_γ depends also on the friction angle, φ′, according to Fig. 2. In any case, $i_\gamma \rightarrow 0$ for extremely high inclinations, as θ→φ′.

The depth effect on the BC, according to Eq. (1) is taken into consideration through the term q′, equal to the effective overburden pressure at the base of the footing. This simplification is usual, even in FE analyses, as for example [4]. In order to examine the contribution of this factor on the BC, FE analyses are carried out under 2D or 3D conditions, by the more realistic geometrical simulation shown in Fig. 1a. In the simple case of vertical centric load, the results from 2D analyses are presented in Fig. 3, in comparison with those from Eq. (1).

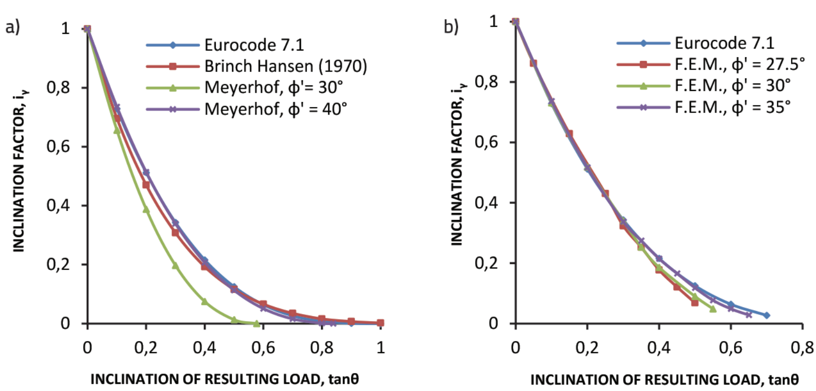

Figure 2 Inclination factor, i_γ: a) Comparison of proposal, b) FEM results (D=0)

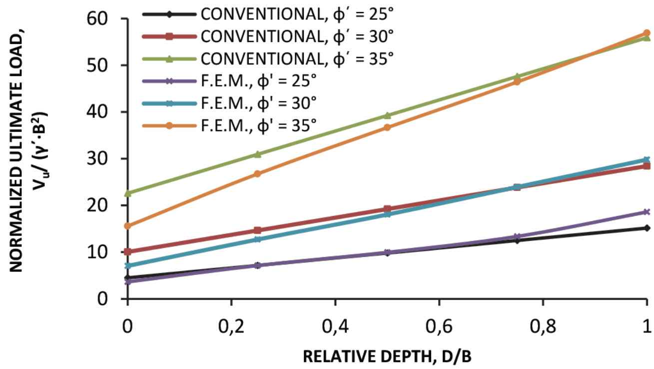

Figure 3 Effect of the foundation depth on the normalized ultimate load : cohesionless soils, vertical loads

The normalized ultimate load according to the conventional method increases linearly with the relative foundation depth (Eq. 2).

$$\frac{V_u}{\gamma' \times B^2} = \left(\frac{D}{B}\right) \times N_q + \frac{1}{2} \times N_y \tag{2}$$

On the contrary, from the FE results considerably higher rate of increase is shown (Fig.3), which indicates that the foundation depth has a significant effect.

For the general loading case (V,M,H), it is well known that high eccentricities of the resultant on the foundation base decrease drastically the bearing capacity. Apart from these effects, several Codes impose limitation in eccentricity. DIN 1054 [5] directly correlates the biaxial eccentricity with the safety against overturning. For Load Case LC3 (corresponding to accidental design situations and seismic loadings), the verification of safety against overturning may be omitted if the bearing resistance is verified. Obviously, the effect of high eccentricities on the bearing capacity is of peculiar interest in such cases. According to AASHTO [6] for bridges, the restriction of normalized eccentricity is related with the safety against overturning for soils and rocks. Finally, according to [1], if e/B›1/3, special precautions shall be taken. In the spirit of this European Code, the investigation of bearing capacity has significant importance. From the extensive parametric analyses some assumptions or relationships incorporated in Eq.(1) are verified for both cohesionless or clayey soils under undrained conditions [7]. Nevertheless, these verifications refer only to simplified cases and not to the simultaneous effects of eccentric and inclined loadings, of shape and depth of foundations, as well.

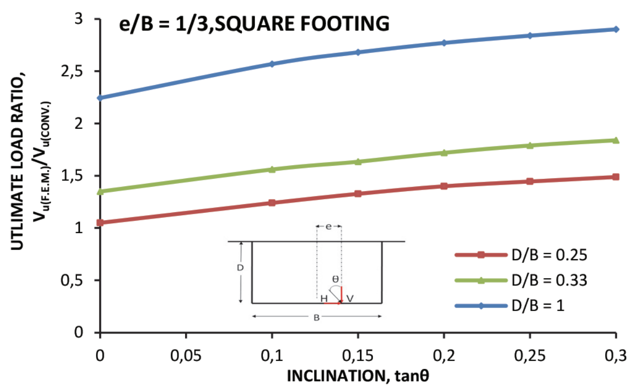

Figure 4 Effect of depth and inclination on the ultimate load ratio: Square footing on cohesionless soil, φ′= 40°

It is concluded that the conventional analyses result into significant higher reduction of the BC than the FEM, so it seems that the simultaneous effects cannot be approached by the product of individual parameters, as the effective width, inclination and shape factors. For example, in case of square footing (Fig. 4) under eccentric and inclined loading, the conventional equations considerably underestimate the BC, especially for higher values of depth and inclination. In the general case of loading of footing in homogeneous soil, the locus of all possible combinations of vertical, moment and horizontal loads, which lead to shear failure forms the BSS, i.e. the bearing strength surface, which reduce to BC lines in the M, V plane. Such lines (in homogeneous soils) have been examined, as for example [8], [9]. From the present FE analyses the interaction diagrams refer to the normalized values:

$$v = \frac{V_u}{V_{u,o}}, \quad m = \frac{M_u}{V_{u,o} \times B} \tag{3}$$

where $V_{u,o}$ the ultimate centric vertical load.

From Fig. 5a, it is observed that the curves from Eq. (1) and FE, for strip and θ = 0 are almost identical, while for tanθ = 0.20, the former was clearly underestimate the BC. The effects of the shape of foundations in this comparison are clear in Fig. 5b, where differences are shown for both cases θ = 0 and tanθ = 0.20.

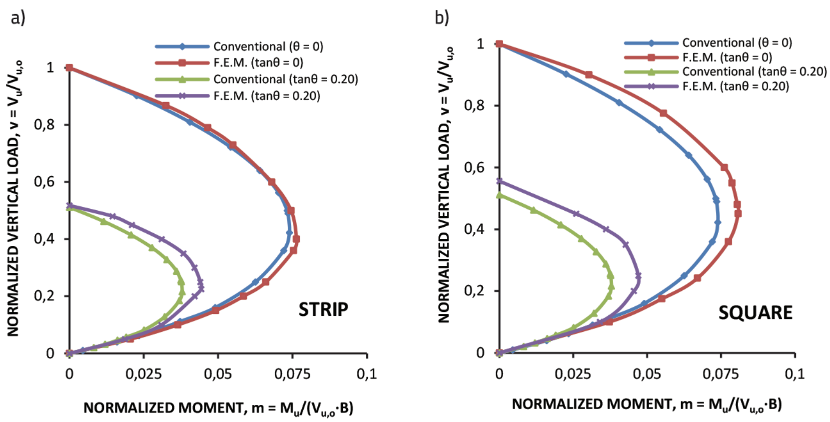

Figure 5 Comparison of interaction diagrams, cohesionless soil, φ′ = 30°

3 Inhomogeneity effects in clayey soils

Several results from FE analyses, in the special case of two-layered clay are presented for strip, rectangular or square footings. For eccentric loading on a rectangular area L·B (Fig. 1b), the ultimate vertical load can be expressed according to authors [10], in the following form:

$$V_u = N^*_{C1,e} \cdot s_{u,1} \cdot L \cdot (B-2e) \tag{4}$$

where $N^*_{C1,e}$ the BC factor depending on the normalized thickness of the upper layer, H_1/B, the strength ratio $SR = s_{u2}/s_{u1}$ and the normalized eccentricity e/B, incorporating also the shape effects. In the special case, where e/B = 0, the corresponding ultimate vertical load is:

$$V_{u,o} = N^*_{C,1} \cdot s_{u,1} \cdot L \cdot B \tag{5}$$

The impact of soil inhomogeneity on the BC for eccentric loadings is clearly satisfied by the interaction diagrams. From Eqs (3), (4) and (5) the following relationship results:

$$m = \cdot v \cdot (1 - v \cdot) \tag{6}$$

For SR ‹ 1, $N^*_{C1,e}$ › N^*_{C1}, thus for any value v the ratio m is higher than this for the homogeneous clay. On the contrary, for SR › 1, $N^*_{C1,e}$ ‹ N^*_{C1} and consequently the value m is now lower than this for SR = 1 and a given v. It is expected that the curve v-m for SR = 1 comes in-between the lines for SR ‹ 1 or SR › 1. For the cases of $s_{u,2} = s_{u,1}/5$ and $s_{u,2} = 5s_{u,1}$ (SR = 0.2 or 5), the V-M failure envelopes, in Fig.7a (square) and Fig.7b (rectangular, L/B = 2), verify the above-mentioned. The maxm values for SR = 0.2 are significantly higher than these for homogenous soil, in both cases. Figure 6 refers to $H_1/B = 0.25$ and the differences between the envelopes for SR = 1 and SR = 5 are not very important, mainly in the case of square footing. For higher normalized thickness H_1/B these curves (SR = 1 and SR = 5) become almost identical.

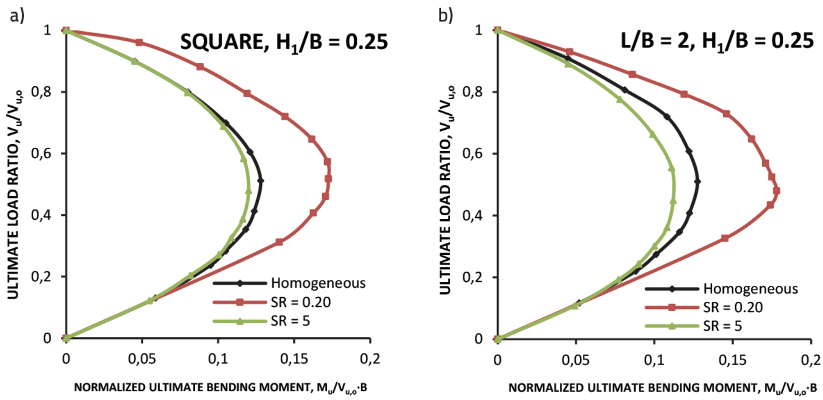

Figure 6 Interaction diagrams v-m of rectangular footing on two-layered clay

4 Scour effects on the BC of shallow bridge foundations

The erosion of the foundation soil in riverbed is associated with three distinct mechanisms, from which local scour is the most significant, since this may quickly reach great depths, causing the foundations instability. The hydraulic performance of shallow bridge foundations has been extensively investigated, i.e. [11]. However, according to [12], the procedures to appraise the vulnerability of river bridge piers often overlook the geotechnical factors. The same authors [12] presented a simple method to estimate vulnerability of such foundations.

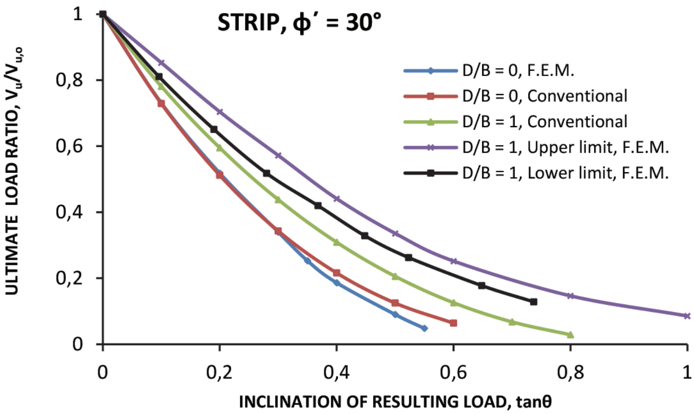

Figure 7 Effect of the inclination and depth on the ultimate load ratio, $V_u/V_{u,o}$

The simultaneous effect of the foundation depth and loading inclination on the normalized ultimate load is clearly defined in Fig. 7. Although for D = 0, the results from conventional methods and FEM are almost identical, for the higher foundation depth the former ones significantly underestimate the V_u values. A main factor affecting the vulnerability of the footing is the relative scour depth, D_s/D, where D is the initial foundation depth. The comparison of failure mechanisms for general erosion (corresponding to the remaining depth after the scour, $\Delta D = D\text{-}D_s$) and this for local scour is indicatively illustrated in Fig. 8.

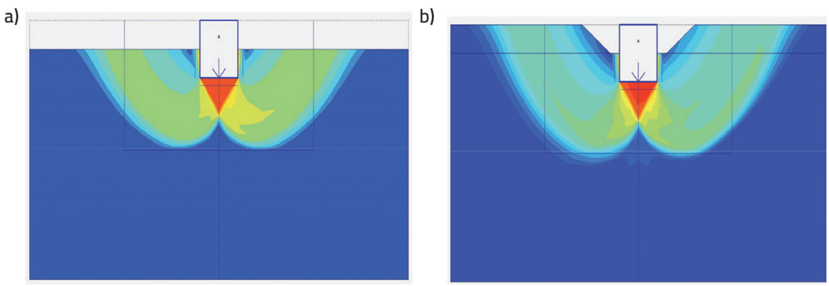

Figure 8 Comparison of failure mechanisms for two scour cases

The differences of failure mode for the two cases reflect on the diagrams of normalized ultimate load versus the relative scour depth, presented in Fig. 9. Although a representative geometry of the local scour is simplified, in order to carry out the FE analyses, it can be concluded that the case of general erosion is more unfavourable for a given ratio D_s/D.

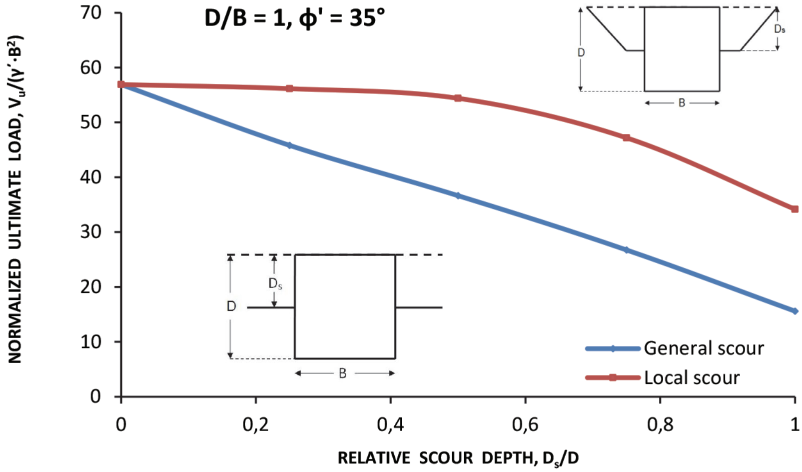

Figure 9 Effect of relative scour depth on the normalized ultimate load

5 Conclusions

The results from 2D and 3D FE analyses indicate that the simultaneous effects of high eccentricity and inclination cannot be approached by the product of the partial factors in the conventional equation of BC. As a result, it seems that in such cases, the BC is considerably underestimated. In the case of two-layered clay, the eccentricity of loading leads to moving up the failure mechanism, thus the effects of the second layer (either unfavourable or beneficial) tend to be less important. For the assessment of the vulnerability of bridge shallow foundations associated with scour, the simultaneous effect of all geotechnical data and parameters involved, should be taken into account.

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