Analysis of some key aspects of soil/foundation interaction- Finite elements modelling

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Abstract. This paper is aimed to contribute to the analysis of three important aspects of soil-foundation interaction, which are not clearly investigated, by means of a detailed parametric study based on a finite elements modelling.
The first aspect focuses on the effect of the bedrock proximity on the load-settlement behaviour of a continuous or circular shallow foundation. It was found there exists a threshold distance between the foundation base and the top of the bedrock layer beyond which the foundation behaves as in an infinitely deep medium.
The second one deals with the behaviour of shallow foundation on a bi-layered soil where the effect of the underlying layer on the bearing capacity as well as on the settlements depends on the distance between the foundation base and the top of the underlying layer, and beyond a threshold value this effect vanishes.
The third aspect studied was the interference between two strip footings installed on saturated clay. It was shown within a threshold distance between these foundations, an important modification of the foundation behaviour may occur. Finally, the numerical results were fitted and interpreted which allowed suggesting simple practical formulae for shallow foundations design.

1 Introduction

These last four decades were marked by an unprecedented scientific interest in the finite element modelling applied to geotechnical engineering. Earliest work was presented by Duncan and Chang (1972) on the use of a hyperbolic stress-strain formulation in a finite element method for computing the settlements of a model strip footing in sand and a circular footing in a saturated undrained clay. Ever since, availability of several non linear constitutive law-based softwares has made possible to explore soil/structure phenomena besides difficult to access by traditional analytical elastic methods [1].

Although the traditional aspect of shallow foundation design based on the analysis of the bearing capacity as well as on the settlement behaviour, it is recognized some aspects related to the soil/foundation interaction are not yet satisfactorily studied, among which the effect of the bedrock proximity on the load-settlement behaviour, the response of shallow foundations on a bi-layered soil, and the interaction between two closely spaced footings.

Based on a non linear 2D finite element modelling, this paper aims at contributing to understand these three aspects of the soil/foundation interaction as well as at proposing simple formulae for practical purposes.

Due to the limited space allowed to this paper, the main results will be briefly presented.

2 Presentation of the method of analysis

The software CRISP v.5 was used as a computational tool to carry out a detailed parametric study of the load-settlement behaviour of rigid circular foundation as well as rigid strip footing. CRISP is a specialized 2D programme of elastic plastic finite elements analysis offering many computational options. Soil material is assumed in this study following a perfectly elastic-plastic constitutive law obeying the Drucker-Prager's failure criterion and the soil properties are assumed homogeneous in space.

The soil studied is a purely cohesive saturated clayey soil exhibiting an undrained behaviour and submerged by a ground water table at surface. Three consistencies were studied: soft, medium consistent and hard clay.

The foundation is modelled as a rigid reinforced concrete slab with no interface elements between the foundation and the soil.

The FEM model is a plane strain mesh for a strip footing and an axisymmetric mesh for a circular footing. Mesh size is 20Bx20B, B being the width of the strip or the diameter of the circle [1]. Mesh refinement was considered within a zone of 4Bx4B beneath the foundation base whereas the remaining area of the mesh was automatically generated by the software.

The small strain analysis option was considered. Moreover, for nearly incompressible materials like a saturated clay it is possible to avoid an "over-stiff response" of the finite elements by using the technique of integration called the $\bar{B}$ method [2].

To model the rigid load-settlement behaviour of the foundation, a series of prescribed displacements up to B/10 was assigned at the nodes of the foundation base.

The bearing capacity q_l was conventionally defined as the vertical pressure corresponding to infinite settlement and determined on the basis of the Asaoka's graphical method, whereas the foundation stiffness K_{v0} which is the initial slope of the load-settlement curve was estimated by the Newton's divided differences technique.

3 Foundation on a finite layered soil

3.1. Formulation of the problem

The load-settlement curve parameters K_{v0} and q_l may be formulated according to the following general equation:

$$f(K_{v0}, q_l, D, B, H, E_s, C_u)=0 \quad (1)$$

D, B and H are respectively the foundation embedded length, the width or diameter of foundation and the soil layer thickness beneath the foundation base. E_s, C_u are respectively the elastic modulus and the undrained shear strength. By using the Vashy-Bukingham's theorem of dimensional analysis, this physical equation is transformed into an equivalent dimensionless equation described by (N-k) dimensionless parameters noted π, k being the number of fundamental units in equation (1). Since N=7 and k=3, the equivalent equation may be written as:

$$g(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \quad (2)$$

$\pi_1 = \frac{K_{v0}B}{E_s}$ is called factor of settlement influence,

$\pi_2 = \frac{q_l}{C_u}$ is the N_c factor,

$\pi_3 = \frac{D}{B}$ is the foundation slenderness ratio,

$\pi_4 = \frac{H}{B}$ is the normalized layer thickness.

The terms π_1 and π_2 should be independent since the first one corresponds to the small displacements whereas the second one corresponds to the large displacements. Consequently, the equation (2) may by uncoupled to the two following equations [3]:

$$\frac{K_{v0}B}{E_s} = h(\frac{D}{B}, \frac{H}{B}) = I_s \quad (3)$$

$$\frac{q_l}{C_u} = j(\frac{D}{B}, \frac{H}{B}) = N_c \quad (4)$$

3.2. Interpretation of results

3.2.1. Analysis of the N_c factor

In all the cases studied it was found this factor does not depend on the consistency of the clay and slightly increases with D/B. However, sensitive dependency of N_c on H/B, as typically illustrated in figure 1, was noticed in both strip and circular foundations. It was shown the existence of a threshold value noted H_{lim} beyond which the foundation behaves as in an infinitely thick layer. The normalized thickness H_{lim}/B was conventionally determined, as shown in figure 1, as the intercept of the straight lines Δ_1 and Δ_2, which led to the margin of values of 0.7-1.0 depending on D/B for a strip footing with an average value of 0.9, and a margin of 0.67-0.80 with an average value of 0.74 for a circular footing.

By comparison with the Matar-Salençon's method which gives H_{lim}/B equal to 0.79 for a strip footing, this latter fall within the margin found in this study [4].

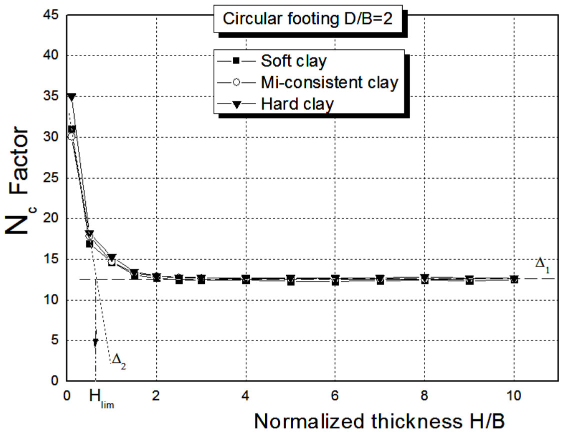

Fig.1. Typical chart giving N_c versus H/B

The function **j** described in equation 4 may be formulated as follows:

$$N_c = \begin{cases} a\left(\frac{H}{B}\right)^b & if\ H < H_{\lim} \\ N_c^\infty & else \end{cases} \quad (5)$$

Coefficients a, b and N_c^∞ are illustrated in figure 2.

3.2.2. Analysis of the factor of settlement

The factor I_s exhibits similar sensitivity to H/B as N_c, showing a high increase when H/B decreases, which leads to define a threshold normalized thickness (H_{lim}/B) for the settlement beyond which the foundation settles as in an infinitely thick layer, following the same graphical procedure used for N_c. It was found a margin of values of 1.48-1.70 depending on D/B for a strip footing with an average value of 1.6, and a margin of 1.30-1.45 with an average value of 1.40 for a circular footing.

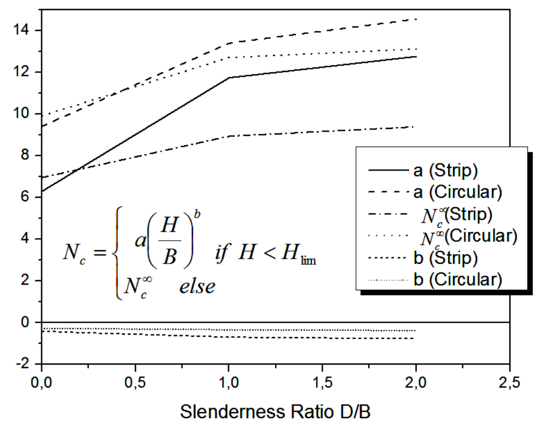

Fig. 2. Chart of coefficients a, b and N_c^{∞}

Analysis by regression of the values of I_s led to a simple formulation of the function **h** described in equation 3 as follows:

$$I_s = \begin{cases} a\left(\dfrac{H}{B}\right)^b & if\ H < H_{\lim} \\ I_s^{\infty} & else \end{cases} \quad (6)$$

Figure 3 illustrates a practical chart to compute the coefficients a, b and I_s^{∞} in order to use equation (6) and evaluate the stiffness K_{v0}.

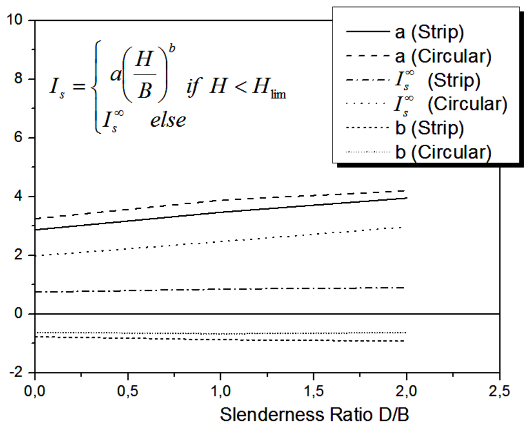

Fig. 3. Chart of coefficients a, b and I_s^{∞}

4 Foundation on a bi-layered soil

4.1. Formulation of the problem

The general configuration of such a problem is illustrated by the scheme of figure 4. Similarly to the previous part, dimensional analysis led to the following equations:

$$\frac{K_{v0}B}{E_{s1}} = k\left(\frac{D}{B}, \frac{E_{s1}}{E_{s2}}, \frac{H}{B}\right) = I_s \quad (7)$$

$$\frac{q_l}{C_1} = m\left(\frac{D}{B}, \frac{C_1}{C_2}, \frac{H}{B}\right) = N_c \quad (8)$$

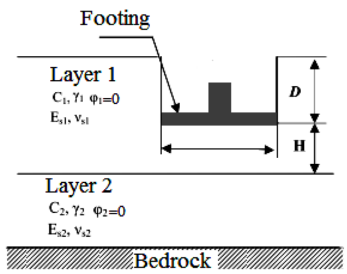

Fig. 4. General scheme of bi-layered soil

4.2. Interpretation of results

4.2.1. Analysis of the N_{c1} factor

It is to be noticed all the cases studied exhibit the same variation of N_c with the normalized distance H/B regardless the shape of foundation and the slenderness ratio. Typical curves illustrated in figure 5 show there exists a threshold normalized distance H_{lim}/B beyond which the effect of the lower layer on the bearing capacity vanishes and the foundation behaves therefore as in a infinitely thick mono-layered soil. This threshold value is about 4 for strip footing and 2.5 for circular footings regardless the ratios C_1/C_2 and D/B.

Figure 5 highlights an important effect of the ratio C_1/C_2 where it can be seen in case of $C_1>C_2$, decrease of H/B results in a decrease in the bearing capacity due to the proximity of the lower layer having a lower undrained shear strength. However, in case of $C_1<C_2$, the bearing capacity increases when H/B decreases.

In case of H< H_{lim}, the effect of proximity of the lower layer should be accounted for. In this regard, the function **m** as described in equation 8 may be written as follows:

$$q_l = f_c N_{c1} C_1 \quad (9)$$

f_c is called the influence factor of the lower layer depending on H/B, D/B and C_1/C_2. It was estimated by least squares regression technique leading to the following formulation:

$$f_c = \begin{cases} a\left(\dfrac{H}{B}\right)^b & if\ H < H_{\lim} \\ 1 & else \end{cases} \quad (10)$$

Values of a and b were found slightly varying with D/B and then tabulated as average values in table 1.

N_{c1} corresponds to the N_c factor of the upper layer considered as infinitely thick and is therefore equal to N_c^{∞} illustrated in figure 2.

Table 1. Values of coefficients a and b

Shape	$C_1 < C_2$		$C_1 > C_2$	
Strip	a	1.25	a	0.64
	b	-0.18	b	0.31
Circular	a	1.11	a	0.87
	b	-0.13	b	0.37

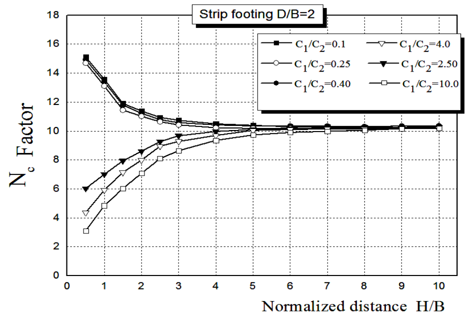

Fig.5. Typical chart giving N_c versus H/B

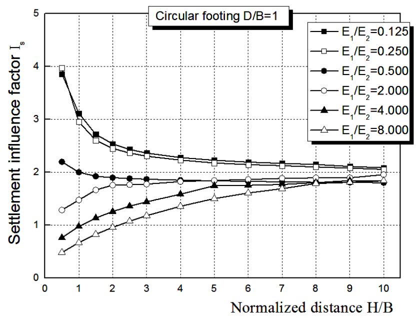

Fig.6. Typical chart giving I_s versus H/B

4.2.2. Analysis of the factor I_s

Similarly to the effect of C_1/C_2 on the bearing capacity, the factor I_s varies sensitively as function of the stiffness ratio E_{s1}/E_{s2}. As shown in figure 6 illustrating a typical variation, in case of $E_{s1}>E_{s2}$ any decrease of H/B results in a decrease of I_s due to the closeness of a looser lower layer. However, in case of $E_{s1}<E_{s2}$, the factor I_s increases when H/B decreases.

It was found the existence of a threshold normalized distance H_{lim}/B regardless the ratios D/B, E_{s1}/E_{s2} and the shape of foundation, beyond which the foundation settles as in an infinitely thick mono-layered soil. This threshold value is about 6.

The function **k** described in equation (7) may be rearranged as follows:

$$K_{v0} = k\frac{E_{s1}}{B} \tag{11}$$

In case of $H<H_{lim}$, the results were fitted by simple power functions and the function **k** may then be formulated as follows:

$$I_s = \begin{cases} a\left(\frac{H}{B}\right)^b & if\ H < H_{\lim} \\ I_s^{\infty} & else \end{cases} \tag{12}$$

Values of a and b were found slightly varying with D/B and then tabulated as average values in table 2.

Table 2. Values of coefficients a and b

Shape	$E_{s1}< E_{s2}$		$E_{s1}>E_{s2}$	
Strip	a	1.83	a	0.22
	b	-0.35	b	0.26
Circular	a	2.68	a	1.14
	b	-0.21	b	0.29

5 Interaction of a two closely spaced Identical strip footings

5.1. Formulation of the problem

As illustrated in figure 7, the general configuration of such a problem leads by dimensional analysis to the following equations:

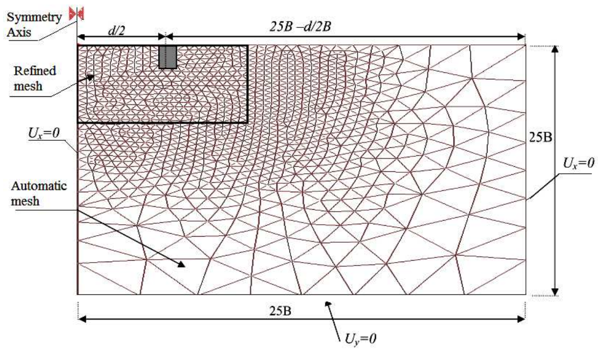

Fig. 7. Typical FEM mesh of two adjacent strip footings

$$\frac{K_{v0}B}{E_s} = n(\frac{D}{B},\frac{d}{B}) = I_s \tag{13}$$

$$\frac{q_l}{C_u} = p(\frac{D}{B},\frac{d}{B}) = N_c \tag{14}$$

d is the horizontal distance between the vertical axes of two identical strip footings embedded at the same depth D. The footings/soil system is identical to that studied in part 3 except for its dimensions which were fixed by gradual increase until the settlement at foundation base nodes start to stabilize. Due to the vertical symmetry only half a plane was modelled.

5.2. Interpretation of results

5.2.1. Analysis of the N_c factor

It was found the consistency of the clay has almost no effect on the N_c factor. Average values of N_c were plotted versus the normalized distance d/B in figure 8 which clearly shows a threshold distance of 3B beyond which both the strip footings behave separately. In order to formulate the function **p** described by equation 14, such curves were fitted by the following hyperbolic function using the least squares regression technique:

$$N_c = \frac{q_l}{C_u} = \frac{\frac{d}{B}}{a + b\frac{d}{B}} \tag{15}$$

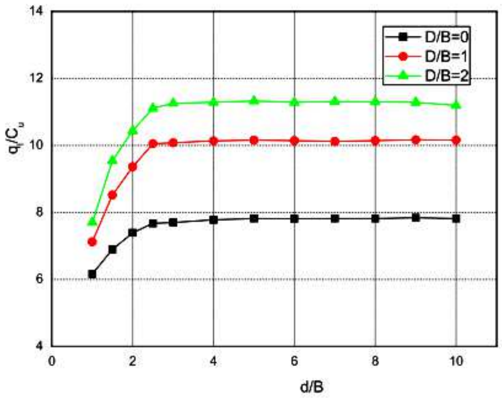

Fig. 8. Chart giving the N_c for different embedments

Table 3 summarized the values of a and b for different values of the slenderness ratio D/B.

Table 3. Values of coefficients a and b

D/B	a	b
0	45.8	0.12
1	43.3	0.09
2	50.5	0.08

5.2.2. Analysis of the factor I_s

In contrast with the N_c factor, the figure 9 shows the factor I_s linearly increases with the normalized distance without exhibiting a threshold value even at distance d of 10B.

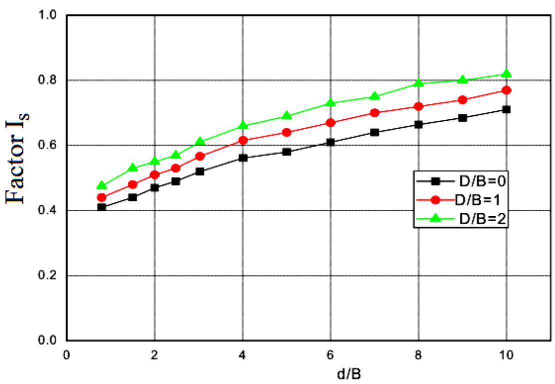

Fig.9. Typical chart giving I_s versus d/B

6 Conclusions

Detailed parametric study based on a non linear 2D finite elements modelling was carried out in order to highlight three important aspects of soil/rigid foundation interaction as well as to suggest simple formulae for practical purposes.

The first aspect is the effect of the proximity of a bedrock on the strip or circular footing behaviour. It was demonstrated the existence of a threshold depth of the bedrock beyond which the foundation behaves as in a infinitely deep layer.

The second aspect is the behaviour of foundations on a bi-layered purely cohesive soil. The results showed also the existence of a threshold normalized distance H_{lim}/B beyond which the effect of the lower layer on the bearing capacity and on settlement vanishes and the foundation behaves therefore as in a an infinitely thick mono-layered soil.

Finally, study of the behaviour of closely spaced identical strip footings on a mono-layered purely cohesive soil illustrated the consistency of the clay has almost no effect on the N_c factor. Moreover, a value of 3B for the distance between the foundations vertical axes is a threshold beyond which both the strip footings behave separately in terms of bearing capacity.

References

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