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Revisiting the effect of foundation embedment on elastic settlement: A new approach

E. Díaz *, R. Tomás

Departamento de Ingeniería Civil. Escuela Politécnica Superior, Universidad de Alicante, P.O. Box 99, E-03080 Alicante, Spain

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ABSTRACT

The effect of foundation embedment on settlement calculation is a widely researched topic in which there is no scientific consensus regarding the magnitude of settlement reduction. In this paper, a non-linear three dimensional Finite Element analysis has been performed with the aim of evaluating the aforementioned effect. For this purpose, 1800 models were run considering different variables, such as the depth and dimensions of the foundation and the Young's modulus and Poisson's ratio of the soil. The settlements from models with foundations at surface level and at depth were then compared and the relationship between them established. The statistical analysis of this data allowed two new expressions, with a mean maximum error of 1.80%, for the embedment influence factor of a foundation to be proposed and these to be compared with commonly used corrections. The proposed equations were validated by comparing the settlements calculated with the proposed influence factors and the true settlements measured in several real foundations. From the comprehensive study of all modelled cases, an improved approach, when compared to those proposed by other authors, for the calculation of the true elastic settlements of an embedded foundation is proposed.

1. Introduction

Engineers must consider settlements when designing foundations, in order to avoid excessive, unacceptable vertical deformations. Therefore, it is important to calculate foundation settlements as accurately as possible, considering the contact pressure at the base of the foundation. Foundations are usually buried at depth in order to increase the bearing capacity of soil, reduce settlements in the foundation or provide protection against frost, desiccation and erosion. Multiple methods exist for calculating foundation settlements, although due to their ease of use compared with accuracy, the most commonly used in practice are analytical methods based on elastic theory and influence factors.

The general expression for calculating the elastic settlement of a foundation with a uniform net contact pressure distribution (q_{net}) resting on an elastic, homogeneous and isotropic medium is [1]:

$$S = q_{net} B \frac{(1-\nu^2)}{E} I \quad (1)$$

where S is the settlement of the foundation, B is the foundation width, E is the Young's modulus of the soil, ν is the Poisson's ratio of the soil and I is the displacement influence factor.

The displacement influence factor (I) from Eq. (1) mainly depends on the foundation shape [1]. However, this factor is also related to the relative foundation-soil stiffness, the existence of incompressible layers at a certain depth, the embedment of the foundation, the variation of E with depth (Gibson's profile), etc. [1]. Therefore, this factor modifies the value of the calculated settlement according to the conditions of the foundation to provide a more accurate settlement calculation. Among all displacement influence factors considered by Poulos and David [2], Milovic [3] and Mayne and Poulos [1], one of the most controversial is that related to the depth of the foundation (I_E).

The first proposed method for quantitatively evaluating the effect of foundation embedment on settlement magnitude was proposed by Fox [4], who studied the relationship between the settlement of a foundation resting at a certain depth and the settlement of the same foundation at the surface. To this end a constant ν value of 0.5 was considered with a uniformly loaded flexible foundation, applying Mindlin [5] solution. The relationship between both settlements (i.e. the displacement influence factor, I_E), obtained for different L/B ratios, was plotted in a graph. The results show that for a given L/B ratio, the greater the embedment

* Corresponding author. Tel.: +34 965 90 34 00x2933.
E-mail address: esteban.diaz@ua.es (E. Díaz).

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Nomenclature

B	width of the foundation
D	foundation embedment depth
E	Young's modulus of soil
E_0	surface Young's modulus of soil
FEM	Finite Element Method
γ	unit weight of soil
I	displacement influence factor
I_E	displacement influence factor for foundation embedment
L	length of the foundation
MRE	mean relative error
ν	Poisson's ratio
q	uniform contact pressure
q_0	overburden pressure at foundation level
q_{gross}	uniform gross pressure
q_{net}	uniform net pressure
Q	axial force
R^2	coefficient of determination
s	area of the foundation
S	elastic settlement of foundation
S_{emb}	elastic settlement of a foundation embedded at certain depth (D)
S_{sur}	elastic settlement of a foundation resting on ground surface ($D = 0$)
σ	normal stress
σ_ν	normal stress in a soil mass
τ	shear stress

depth (D), the lower the displacement influence factor, which varies from 1.0 (for zero embedment depth) to 0.5 (for an infinite embedment depth). The main drawback of this method is that it is only valid for ν values equal to 0.5. Janbu et al. [6] obtained similar results considering circular and square foundations, resting at different depths. Nishida [7] studied the influence of the depth of a circular foundation considering different ν values, and concluded that for greater depths, the obtained displacement influence factors are similar to those proposed by Fox [4] for a ν value equal to 0.5. Schmertmann [8] used cone penetration tests (CPT) to propose an expression considering the embedment effect, concluding that, as Fox [4] and Janbu et al. [6] had previously asserted, the displacement influence factor is lesser than 0.5. Burland [9] revised the I_E values proposed by Fox [4] and Janbu et al. [6], by calculating the settlements of circular foundations by means of the FEM. It was concluded that the effect of the foundation depth is lesser than that considered by the aforementioned authors (mainly for cases in which the embedment is high), and proposed a new expression for calculating I_E. Butterfield and Banerjee [10], developed a numerical model based on the Mindlin [5] solution for different depths and a rigid circular foundation embedded in an elastic half-space, recommending I_E values even lower than those proposed by Fox [4]. Christian and Carrier [11], also performed a detailed analysis of this problem, concluding that the I_E values proposed by Fox [4] and Janbu et al. [6] are essentially the same and must be reviewed because they provide unsafe values which underestimate settlements. These authors proposed a chart to consider the existence of a non-deformable layer at a certain depth (depth correction factors, proposed by Giroud [12]) and the effect of the foundation embedment (embedment correction factors proposed by Burland [9]). However, they do not explicitly consider ν. Pells and Turner [13], reproduced Burland's calculations [9], concluding that his proposed values are inaccurate. They proposed charts, were derived from FEM analysis, for obtaining I_E, considering both rigid and flexible foundations. Yamaguchi [14], proposed an expression which considers soil deformability, the net contact pressure of the foundation and the bearing capacity of the soil. Due to the high number of variables considered by this author the expression is not easy to apply. Bowles [15] advised against using the formula proposed by Fox [4], as the author considered this approach to give unsafe values. Christian and Carrier [16] reaffirmed their previous conclusions [11] in response to the comments made by Bowles [15] about their method. Johnson et al. [17] and Kausel and Ushijima [18] analysed circular and strip foundations with vertical sides in contact with the ground. Gazetas et al. [19] applied a parametric boundary element method and proposed an analytical expression for calculating vertical elastic settlements of rigid arbitrarily shaped foundations embedded in a homogeneous and elastic half-space with a maximum error of 20%. Mei and Xu [20] presented an analytical solution for flexible foundations resting on an elastic half-space, based on the study of the most crucial parameters of Groth and Chapman [21]. Currently, although more reliable models which provide more realistic approximations to the problem (e.g. [14]) exist, geotechnical engineers often use traditional methods such as those proposed by Fox [4], Janbu et al. [6] or Burland [9]. For example, Mayne and Poulos [1], who proposed one of the most complete and widely used formula for the calculation of settlements, recommend the use of the I_E values proposed by Burland [9].

Consequently, there is an evident controversy in the use of this displacement influence factor and there is no consensus in the magnitude of settlement reduction due to the effect of foundation embedment. As explained previously, solutions exist in which authors do not consider ν or E, propose algorithms which are difficult to apply, or propose solutions that are only valid for circular and flexible foundations without considering the shape of the foundation, etc. Additionally, due to the fact that this is a problem which involves soil-structure interaction, it cannot be satisfactorily solved by using analytical solutions based on the theory of elasticity [14].

Therefore, the main aim of this investigation is the study of this question, considering all parameters relevant to the problem (including soil-structure interaction), thereby improving upon the limitations of the existing models and proposing a new method.

In the present study the relationship between the settlement of a foundation at a given depth (S_{emb}) and the settlement of the same foundation at surface level (S_{sur}) is analysed, in order to obtain the displacement influence factor (I_E). For this purpose, different models have been developed, varying the key parameters for solving the problem using ANSYS + CIVILFEM v.11 software. This software allows the modelling of settlements suffered by a foundation by means of the FEM.

Additionally, the paper provides analytical expressions for an accurate consideration of the effect of the foundation depth on the calculated settlement. The study will be focused on the most common range of embedment/width (D/B) ratios, which in practice vary from 0 to 1.

The paper is organized as follows: Section 2 describes the effects of the foundation embedment on the calculation of settlements, Section 3 details the model and the geotechnical and geometric parameters adopted in the study and examines the most relevant results obtained from the analysis, Section 4 presents the proposed analytical formulae for considering the effect of