A COMPARATIVE THEORETICAL–EXPERIMENTAL ANALYSIS OF SETTLEMENTS OF SHALLOW FOUNDATIONS ON GRANULAR SOIL

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Abstract. *The paper presents a brief description of experiment within the research project "Theoretical and experimental analysis of interaction of shallow reinforced concrete foundations and soil for the purpose of improvement of national regulations and implementaation of Eurocode system" where in situ tests of a series of reinforced concrete foundation footing were performed, by loading until failure. As a rule, methods for calculation of shallow foundations settlement on granular soils overestimate the expected settlement, and underestimate soil bearing capacity, which results in a conservative foundation design. In order to test accuracy and reliability of the different settlements prediction methods, a comparative analysis of settlements calculated using these methods and those measured during experiment, was performed.*

Key words: *settlements, shallow foundations, granular soil, experiment, accuracy, reliability, comparative analysis.*

1. INTRODUCTION

Although the analysis and design of foundations usually begins with the study of the bearing capacity of the foundation–soil system, in general, the settlement of the foundation controls the design. Behavior of the foundation under load depends on the characteristics of the bedding (soil), on foundation material, and on the load scale. Complexity of the stress state in the foundation supported by soil requires detailed theoretical analysis and experimental research in order to draw correct conclusions and confirm or alter the introduced theoretical assumptions.

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action of shallow reinforced concrete foundations and soil for the purpose of improvement of national regulations and implementaation of Eurocode system", financed by Ministry of Science and Technological Research of Republic of Serbia is in progress. The aim of the project is to identify behavior of the shallow foundation made of reinforced concrete rested on deformable subgrade soil and loaded by controlled external load up to failure, using theoretical and experimental means. In the framework of realization of this project, an experimental research of the series of shallow reinforced concrete foundations and soil interactions, by loading the large scale foundation model until failure, was performed.

According to the scientific literature data, only a few experiments with foundations in real soil were performed until now [1], [2], [3]. Main reason for that is considerable material cost and complex organization of the experiment, so in the majority of other experiments natural bedding under foundation is simulated by springs, by small hydraulic jacks or by simple line load on the contact surface of the foundation. Considering this, it was decided to perform the experiment on the natural bedding, in real conditions *in situ*, with foundations – test specimens and corresponding load. Complexity of the whole problem required serious preparation and detailed planning.

2. EXPERIMENT SETUP

Basic concept of the preparation plan should encompass:
- selection of the appropriate site for the performing of the experiment,
- selection of the bedding under the foundation,
- number of the test specimens – foundations, their size, type, and quality of the material (concrete and reinforcement), way of manufacturing,
- perceiving of all parameters of the bedding and of the foundation that should be identified in advance, or measured during the experiment,
- analysis related to the way of the mode of foundation loading, selection of the loading equipment,
- selection of the equipment for measuring all scheduled parameters in the bedding and in the foundations,
- identification of the financing plan and providing the necessary financing resources, manpower, and necessary accessory and transport devices,
- approximate time needed for all phases during the experiment.

The scheme of the experiment is shown in Fig. 1. Adopted dimensions of all 12 test specimens - footings in floor plan were 85x85cm. The height of the foundations ranged between 12.5cm and 25cm. A steel test frame was constructed so as to receive the reactive force of the hydraulic jack used to load foundations [4]. A foundation pit with dimensions of 5x4m in floor plan and 3.0m in depth was excavated, and then the previously prepared steel frame was laid into the pit. The excavated material was substituted by the river aggregate whose granulometric composition was designed in the Laboratory for geotechnics of the GAF – Niš. The prepared mixture was inserted in layers of approximate depth of 30cm and compacted by plate vibrator. After completing the compacting, the compactness of every layer was controlled by circular plate test (Fig. 2). The average values of Modulus of compressibility (M_s) by layers ranged between 43,3 and 66,7MPa [5].
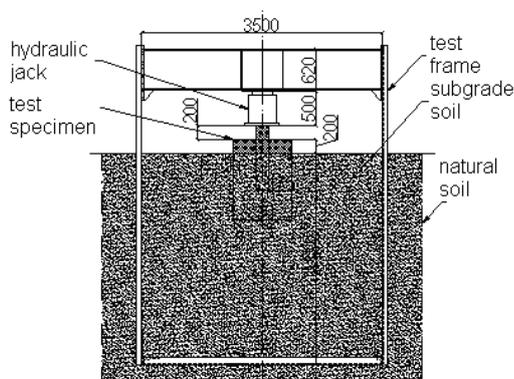
Fig. 1 Experiment scheme   Fig. 2 Layer compactness control

The remaining space between the soil and frame of about 0.9m was used to install the foundation footing, hydraulic jack and necessary equipment for measuring the applied force. For the scheduled measuring in the subgrade soil and in the footings, the following equipment was intended: for strains in the reinforcement and in concrete – appropriate strain gages, for registration of the contact pressures - measuring cells for soil pressure, for registration of the footing displacement - LVDT instrument, for footing loading - hydraulic jack, capacity 1000kN, and for registration of the applied force intensity - force pickup, capacity 1000kN.

3. A COMPARATIVE ANALYSIS OF MEASURED AND CALCULATED SETTLEMENTS

During the examination of each footing, strains in footing concrete and in reinforcement, deflection of the footing at corners and under the column, intensity of the applied force during loading, and contact pressures under the footing were measured. The measured deflections of the characteristic points of footing labeled TI - 3 are shown in Fig. 3. The curves are step-shaped because the applied force is increased gradually in steps of 50kN, queuing completing of increase of deflection for each load level.

A remarkable number of methods have been developed to estimate the settlement of shallow foundations on granular soil, yet consistent success in accurately predicting such has remained largely elusive [6]. These methods in general overestimate the expected settlement, and underestimate soil bearing capacity, which results in a conservative foundation design. Except for occasional happy coincidences, soil settlement computations are only best estimates of the deformation to expect when a load is applied [7].

In order to examine and avaluate some commonly-used methods and also some new approaches in estimating settlements, a comparative analysis of settlements measured during this experiment and those calculated using 4 different methods, was performed. The following is a brief review of methods that were used for comparative analysis in this paper.
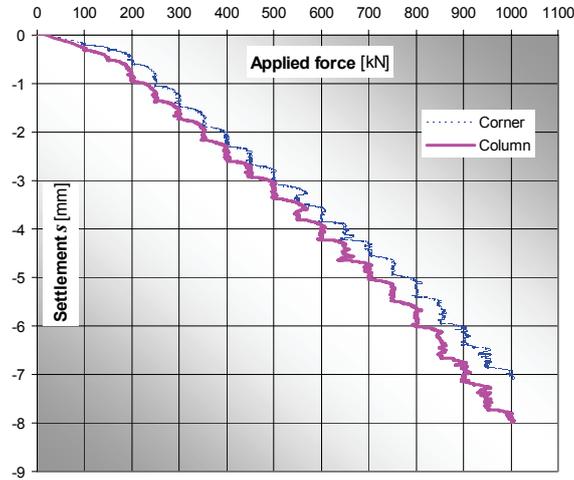
Fig. 3 Foundation T I – 3: Measured settlements

Many techniques are presented in the literature for predicting the settlement of shallow foundations on granular soil. Depending upon which method is used, this calculation can be a very simple one or it can be moderately complex, and the resulting predictions can differ greatly. Most of the methods can be placed within one of two categories: some are modeled after the Terzaghi and Peck (1948) bearing capacity and settlement–footing width relationship, and others are modeled after elasticity theory[8]. A few methods combine some aspects of both.

Terzaghi and Peck (1948) developed the first rational method for estimating the settlement of shallow foundations on sand. They carried out plate load tests (PLT) with 300 mm square plate on sands and related the settlement (s) of a B meter wide square footing to that of a square plate (s_p) by the equation:

$$s = s_p \cdot \left(\frac{2B}{B+0,3} \right)^2 \cdot \left(1 - \frac{D}{4B} \right) \tag{1}$$

where D is depth of embedment. This method was widely used in engineering practice over the past decades, but history has proven that its results are very conservative. That is why this method in practice gave way to newer solutions.

Soil is often treated as an elastic medium, linear or nonlinear, to which the elastic theory assumptions and principles of stress and strain are applied. Settlement computations of this form use the elastic properties of Poisson's ratio (v) and Young's modulus (E) to represent the soil. Here are two different calculation procedures:

a) Integration of vertical deformation of point on the surface of terrain (Strain Integration Method) settlement is calculated using the term:

$$s = \frac{q_n \cdot B \cdot (1-v^2) \cdot I}{E} \tag{2}$$

where q_n is the increase in effective vertical pressure at foundation level, I is influence factor which depends on the shape and rigidity of the foundation and on the position of the point whose settlement is calculated.

b) Otherwise, integration of vertical dilatation (ε_z) of soil points below the point whose settlement is calculated, where:

$$\varepsilon_z = [\sigma_z - \nu(\sigma_x + \sigma_z)]/E \tag{3}$$

In practice it usually ignores the horizontal deformation of soil ($\nu=0$), so:

$$\varepsilon_z = \sigma_z / E \tag{4}$$

Settlement is obtained integrating the stress in the soil:

$$s = \int_0^z \varepsilon_z dz = (1/E)\int_0^z \sigma_z dz \tag{5}$$

This procedure is therefore be called Stress Integration Method.

Schmertmann (1970) proposed a different approach to the use of Cone Penetration Test (CPT) results in the calculation of the settlement of footings on sands. He noted that the distribution of vertical strain under the centre of a footing on a uniform sand is not qualitatively similar to the distribution of the increase in vertical stress, the greatest vertical strain occuring at a depth of about $B/2$. Equation for calculating settlement is:

$$s = C_1 \cdot C_2 \cdot q_n \cdot \sum_0^{2B} \frac{I_z}{E_s} \Delta z \tag{6}$$

where q_n is the increase in effective vertical pressure at foundation level, Δz is the thickness of layer under consideration, C_1 is the depth embedment factor, C_2 is the empirical creep factor, E_s is the modulus of deformation, which is estimated from the cone resistance (q_c) from CPT. The variation of the strain influence factor (I_z) with depth is represented by the so-called "2B-0,6" diagram, where :

$$I_z = 0 \text{ at } z = 0$$
$$I_z = 0.6 \text{ at } z = 0.5B \tag{7}$$
$$I_z = 0 \text{ at } z = 2B$$

Schmertmann et al. (1978) made some modifications to the above method, giving new influence factors for strip footings and new relationship between q_c and I_z. However, additional complications are not justified expectation so that an older version often shows better agreement with the measurement of real objects, than a modified "more refined" procedure [9].

One of the recent approaches that appear to give better settlement predictions is method proposed by Mayne and Poulos (1999) [10], where elastic settlement of footings is calculated using displacement influence factors derived from elasticity continuum theory. It is assumed that the soil stiffness (modulus of deformation E_s) increases with depth, from a value of E_0 at footing level. Settlements are calculated from the equation:

$$s = \frac{q_n \cdot B' \cdot I_G \cdot I_F \cdot I_E \cdot (1 - v^2)}{E_0} \tag{8}$$

where B' is equivalent diameter of a rectangular footing, I_G is influence factor for the variation of E_s with depth, I_F is foundation rigidity correction factor, and I_E is foundation embedment correction factor. This procedure will give good results provided the modulus of deformation of soil is predicted reasonably well [11].

Methods used to calculate settlements for the purpose of comparative analysis are: Schmertmann (1970), Strain Integration Method, Stress Integration Method and Mayne & Poulos (1999). The results obtained using these methods were compared with deflections measured during above described experiment, but also with each other.

The starting point in analysis are the deflections that are measured during the examination of footing labeled TI-3. In this analysis are taken into account the settlements obtained for increasing force from 0 to 1000 kN. It is important to note that a force of 1000 kN significantly smaller than those that (at a later stage of the loading of this footing) led to the failure.

All necessary calculations are made within an Excel document "Footing TI-3: Settlement Calculation", created for that purpose. The settlements for values of applied force from 0 to 1000kN, using all the selected methods, are calculated. These calculations were done for 4 adopted values of v (0,25, 0,26, 0,27 and 0,30), that were within the recommended range of values for gravelly sand (Das, 1984) [12]. In Table 1 results obtained by measuring and calculating settlements of the foundation TI-3 for the highest applied force 1000kN, separately for each adopted value of Poisson´s ratio of soil (v), are summarized.

Table 1 Measured and calculated settlements (s) of footing TI-3

Applied force = 1000 kN		v			
		0.25	0.26	0.27	0.30
s [mm]	Schmertmann (1970)	11.627	11.856	12.108	13.044
	Mayne & Poulos	11.462	11.400	11.335	11.126
	Stress Integration Method	13.494			
	Strain Integration Method	15.058	15.270	15.506	16.396
	Measured	7.899			

It is obvious that only Stress Integration Method is insensitive to the change of v. As expected, all methods significantly overestimate settlements, and most of all Strain Integration Method. The settlements calculated using this method were 90% (for v=0,25) to 107% (for v=0,30) higher than the measured. Stress Integration Method overestimates settlements by 70%, Schmertmann 47% to 65%, and Mayne & Poulos "only" 40% to 45%. In Fig. 4 can be seen the impact of the adopted value of Poisson´s ratio on calculated settlements for applied force 1000kN, using each method. While with increasing value of v from 0,25 to 0,30 Mayne & Poulos Method is "slowly" approaching the measured settlement, Schmertmann and Strain Integration Method are "much faster" away, and

Stress Integration Method remains at the same distance from the measured settlements, because, as already mentioned, insensitive to the change of *v*.
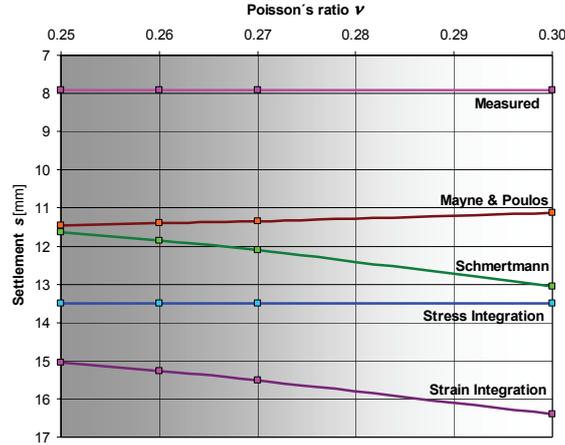

Fig. 4 The impact of the adopted value of Poisson´s ratio on calculated settlements

In Fig. 5 are presented graphically measured and calculated settlements using each method, for increasing force from 0 to 1000 kN, and for assumed *v*=0,27. It is evident that consistently (for all values of applied force) Mayne & Poulos Method gives the best results. Behind it were one after the other, the more or less equal distance, the other methods in this order: Schmertmann, Stress Integration and Strain Integration Method. In similar diagrams, drawn for *v*=0,25, *v*=0,26 and *v*=0,30, the order of methods in terms of accuracy remains the same, only changes a deviation from the curve of measured settlements.
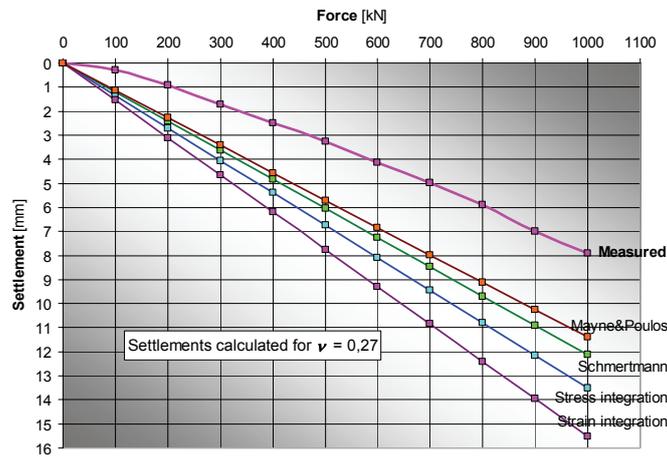

Fig. 5 Measured and calculated settlements (for adopted *v* = 0,27)

4. CONCLUSIONS

Previously described comparative analysis was carried out with the aim of testing and evaluation 3 commonly-used methods (such as Schmertmann, Stress Integration Method and Strain Integration Method) and also 1 new approach in estimating settlements, such as Mayne & Poulos Method (1999). The analysis, whose starting point is deflections that are measured during the examination of footing labeled TI-3, is generally confirmed well-known fact that all methods overestimate settlements. But it should be noted that of all the methods studied here, Mayne & Poulos gives the best results consistently. The analysis also confirmed that settlement predictions are more sensitive to the geotechnical parameters than to the method of analysis.

However, we should not ignore the fact that deterministic solutions, which are all described above, due to inherent variability of the soil properties, cannot provide information about the likely error of the prediction. In these conventional procedures analyses are based on the idealisation of the soil profile as a series of uniform soil layers, each soil layer being represented by a single characteristic value of the soil parameter. The use of conservative values of soil parameters is no longer acceptable because the measure of success is how close a prediction is to the observed performance. The shortcomings of using a deterministic approach led to the development of probabilistic methods. By incorporating probability into the prediction process, a clearer picture emerges about the likely range of settlements. This is very helpful in decision-making, thereby quantifying the risks inherent in the prediction. Despite the obvious advantages the probabilistic approach is still not sufficiently widely used in practice because of the statistical terminology and concepts that are not familiar to most geotechnical engineers.

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UPOREDNA TEORIJSKO-EKSPERIMENTALNA ANALIZA SLEGANJA PLITKIH TEMELJA NA KRUPNOZRNOM TLU

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U radu je dat kratak opis eksperimentalnog dela naučno-istraživačkog projekta ″Teorijska i eksperimentalna analiza interakcije plitkih armirano-betonskih temelja i tla za potrebe unapređenja domaće regulative i primene sistema Evrokodova″, u okviru koga je izvršeno eksperimentalno ispitivanje serije armirano-betonskih temelja, opterećivanjem do loma. Po pravilu, metode za proračun sleganja plitkih temelja na krupnozrnom tlu precenjuju očekivana sleganja, a potcenjuju nosivost tla, što dovodi do toga da je dimenzionisanje temelja konzervativno. U cilju provere tačnosti i pouzdanosti različitih metoda za proračun sleganja uizvršena je uporedna analiza sleganja sračunatih primenom ovih metoda i onih izmerenih tokom eksperimenta.

Ključne reči: *sleganja, plitki temelji, krupnozrno tlo, eksperiment, tačnost, pouzdanost, uporedna analiza.*