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Article

Methodology for determining the extent of soil compaction deformation zones beneath foundations

Assel Mukhamejanova*

Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
*Correspondence: assel.84@list.ru

Abstract. The article is dedicated to a methodology for determining the actual dimensions of the zone of long-term compressed soils under existing foundations from their previous loading. Although construction norms provide conditional criteria for this, they do not always accurately reflect the real distribution of soil deformations at the depth of the foundation. The article presents a methodology for determining the actual dimensions of the compacted soil zone under the foundations. This methodology is based on both empirical and theoretical approaches, taking into account both the strength and deformation characteristics of the soil. The application of this methodology allows obtaining more accurate results and more reliably determining the dimensions of the compacted zone, which can be useful for conducting additional research for object reconstruction or determining the permissible distance between closely located foundations. During experimental and theoretical studies, regularities in the changes of soil compaction at the depth of the foundation and its deformations over time under constant loading were identified. The developed methodology enables a more precise determination of the actual dimensions of the compacted zone, which is of great significance for ensuring the safety and reliability of building structures.

Keywords: consolidated zone, soil, foundations, deformation, settlement.

1. Introduction

The formation of the consolidated zone of soils beneath foundations depends on several factors, such as soil type, foundation load, depth of placement, and foundation laying method. Practical methods based on the theory of linearly deformable bodies do not accurately predict the actual dimensions of the active foundation zone since they are designed for calculating assumptions about idealized soil conditions. Consequently, these methods often yield inflated values for the parameters of the consolidated foundation zone. Thus, there is a need to seek a new approach to assess the actual dimensions of the deformable zone beneath building and structure foundations. It is well-known that when calculating foundation settlements, the main task is to determine the ground displacements resulting from the action of vertical stress components σ_z. However, in reality, the foundation settlement occurs due to the volumetric compression of the soil within a limited zone under the combined effect of all stress components. This is confirmed by the results of numerous experiments – the actual dimensions of the soil compaction zone beneath foundations significantly exceed the boundaries of the isobar $\sigma_z = \sigma_{str}$ (where σ_{str} is the compressive strength of the soil) for both plane and spatial problems [1].

In the context of designing buildings within existing urban developments, including additions or extensions with consideration for potential future inundation of foundations, it is crucial to determine the actual dimensions of the long-term soil consolidation zone beneath existing foundations from their previous loading. The deformation of the foundation within a confined zone results primarily from structural consolidation deformations, leading to settlement of the foundation. These deformations cause significant changes in the inherent compressibility, strength, and other properties of the natural soils. Numerous studies have been conducted by researchers on the formation of the deformation and consolidation zone beneath loaded foundations and real buildings and structures. The results of these experimental studies have shown that the settlement of the foundation is caused by deformation within a confined zone, where structural consolidation deformations predominantly develop. As a consequence of these deformations, there is a substantial alteration in the original characteristics of the soils, including their compressibility, strength, and other properties associated with the natural soil compression process over time. During the compression of clayey soils, consolidation deformations predominantly occur, leading to changes in the soil structure. This is manifested by a reduction in porosity, more densely packed solid particles, and an increase in the contact area between them. Consequently, soil strengthening occurs through increased interlocking forces between the solid particles, primarily driven by structural and textural changes [2–4]. Various methods, such as optical, X-ray diffraction, and electron microscopy techniques, are employed to investigate changes in the texture of soils during their deformation. These methods enable the determination of the orientation of structural elements, such as particles and aggregates, before and after compaction or shearing. The utilization of such methods allows for a more detailed examination of the internal soil structure and understanding of the mechanisms that lead to its strengthening. This is crucial for comprehending the soil properties and developing appropriate models and methods to predict its behavior under loading and deformation. The analysis of soil texture using different methods during its deformation plays a significant role in understanding the mechanisms of soil compaction and consolidation [5].

The post-genetic changes in the properties of soils subjected to compaction beneath building foundations cannot be fully explained solely by the process of soil compaction. In the soil mass of urbanized areas, more complex phenomena occur, which involve not only soil compaction but also soil strengthening with alterations in the initial strength properties. Prolonged soil compaction can induce additional processes, such as water dissipation and an increase in interlocking forces between solid soil particles. As a result of these processes, structural and textural changes in the soil take place, leading to its strengthening. Soil strengthening due to prolonged compaction can be accompanied by modifications in its strength properties, including an increase in the coefficient of internal friction and cohesion, elevation of the angle of internal friction, and a reduction in compressional deformation [6]. The accurate assessment of the actual dimensions of the deformable zone beneath building and structure foundations holds significant importance from both scientific and practical perspectives in the field of construction. These parameters play a crucial role in solving numerous tasks related to engineering surveys and design. It is particularly important to consider these parameters when refining methods for calculating foundation settlements, taking into account local changes in soil properties within the active foundation zone during the building's service life [7].

The calculation of foundation settlements should take into account the factor of soil compaction, especially when dealing with extensions of existing structures, completion of unfinished preserved objects, and considering the impact of potential foundation inundation in operational buildings. Determining the optimal thickness of the reinforced load-bearing soil layer during the construction of artificial foundations, defining the required depth of dewatering, and establishing the maximum allowable distance between neighboring foundations also necessitate a reliable assessment of the dimensions of the deformable foundation zone. Additionally, evaluating the sizes of settlement funnels that may occur around constructed objects during the stabilization of foundation soil deformations is crucial in the design of vertical planning for developed areas [8].

During the survey of foundations for reconstructed structures, it is also essential to consider the actual dimensions of the deformable zone to determine the optimal scheme for the horizontal and vertical positioning of sampling points. This includes the use of trenches, boreholes, and conducting field tests on soils, such as plate load tests, static and dynamic probing, and other methods. Hence, the accurate determination of the actual dimensions of the deformable foundation zone plays a crucial role in solving various tasks in the field of engineering surveys and design. It ensures the reliability and safety of construction and helps develop effective solutions for specific construction challenges [9]. The investigation of existing theoretical and experimental methods for determining the dimensions of the consolidated zone beneath foundations is currently insufficiently developed. The existing analytical methods only yield approximate results [10]. There is currently no methodology for assessing similar parameters in the case of unconnected soils that lack cohesion. This creates difficulties in solving important practical tasks related to engineering surveys and the design of buildings and structures, especially when constructing on urbanized territories subject to various post-construction anthropogenic impacts. In light of the aforementioned, the aim of this research is to develop a methodology for determining the dimensions of the soil compaction deformation zone beneath foundations, taking into account both the strength and deformation characteristics of the soils.

2. Methods

To determine the dimensions of the soil compaction zone beneath strip footings, the method of isobars of maximum principal normal stresses is commonly employed, assuming that these isobars have a circular shape [11]. The calculations are based on the following condition:

$$\sigma_1 = \sigma_{str} \tag{1}$$

The extension of the foundation's compaction zone beyond the loaded area with a width of b is determined by the following equations:

$$l_a = (B_a - b)/2; \quad l_a/b = 0{,}5\left(\frac{B_a}{b} - 1\right) \tag{2}$$

Based on the literature review and statistical analysis of field test results conducted in various soil conditions and carried out according to a standardized procedure using large square-shaped stamp plates (with a base area of at least 0.5 m²), correlation dependencies have been obtained. These correlations include $B_a/b = f(H_a/b)$; $l_a/b = f(H_a/b)$ and $H_a/b = f(\sigma_{str})$. However, for construction practice, the most significant interest lies in the methodology for determining the dimensions of the deformable foundation zone, taking into account the deformational properties (E_o, m_o) and the strength properties (c, φ) the soils, obtained through geotechnical investigations. The analysis of field test results, during which measurements of the foundation's compaction zone dimensions were combined with the determination of soil deformation moduli, has allowed us to establish a highly significant correlation relationship $H_a/b = f(E_o)$ with a correlation coefficient of $\eta = 0{,}9$ (Figure 1).

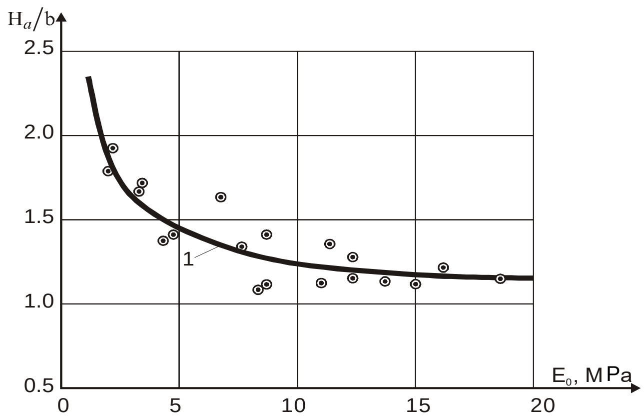


Figure 1 – The dependence of the relative depth of the foundation's compaction deformation zone for square footings on the value of the soil's deformation modulus: ⊙ – The experimental data points (correlation field); 1 – The curve obtained from the empirical equation

Based on the obtained regularities, it appears feasible to determine the dimensions of the soil compaction zone beneath square footings using the following correlation equations:

$$B_a/b = 0{,}14 + 1{,}13H_a/b, \tag{3}$$

$$l_a/b = - 0{,}43 + 0{,}565H_a/b, \tag{4}$$
$$H_a/b = 0{,}596 + 0{,}046/\sigma_{str}, \tag{5}$$
$$H_a/b = 1{,}05 + 1{,}95/E_o, \tag{6}$$

Where: 0.046 is a coefficient with the dimension of MPa^{-1}; E_o is the soil's modulus of deformation in MPa; σ_{str} is the compressive strength of the soil's structural bonds in MPa.

The proposed equations are applicable to foundations with a circular footprint as well, provided that the relationship $b = D/1.13$ is introduced, where D represents the diameter of the circular footing and 1.13 is the transition coefficient. The value of σ_{str} in Eq. (5) is recommended to be determined using Eqs. (7) and (8), which are derived from the condition of natural soil structure failure during compaction.

For cohesive soils, the exponent can be determined using the following equation:

$$\sigma_{str} = \frac{\xi_0 - \xi_a}{\xi_a} \cdot \sigma_{nat}, \tag{7}$$

For cohesive soils possessing cohesion, according to the equation:

$$\sigma_{стр} = \frac{1}{\xi_a}\left[(\xi_0 - \xi_a) \cdot \sigma_{быт} + 2C\sqrt{\xi_a}\right]. \tag{8}$$

Where: ξ_0 is a coefficient of lateral earth pressure for soil in a state of rest is determined by the equation:

$$\xi_0 = \frac{\mu}{1-\mu}, \tag{9}$$

where μ – is the coefficient of lateral earth pressure. The maximum principal normal stress at the considered point M is equal to the natural pressure of the soil σ_{nat}:

$$\sigma_1 = \sigma_1^g = \gamma \cdot h_1;\ \sigma_1^l = \sigma_1^g = \sigma_{nat} \tag{10}$$

Where: γ - specific gravity of soil; h_1 – thickness of the soil strata; ξ_a is a coefficient determined depending on the angle of internal friction, determined by the equation:

$$\xi_a = tg^2(45^o - \frac{\phi}{2}) = 1 \tag{11}$$

These dependencies can also be applied for approximate estimation of the size of the actual soil compaction zone under strip foundations, if correction factors are introduced into Eqs. (5) and (6), which take into account the difference of the stress state for the cases of spatial and planar problems.

For this purpose, it is proposed to use the transition coefficient:

$$K_\sigma^c = F_\sigma^{fl} / F_\sigma^{sp}, \tag{12}$$

Where: F_σ^{fl} and F_σ^{sp} are the areas of influence coefficient curves K_z (curves 1 and 2 in Figure 2) corresponding to the flat and spatial problems used to determine the distribution of normal stresses $(\sigma_z = \sigma_1)$, occurring under the center of the foundation footing from the action of load P_0.

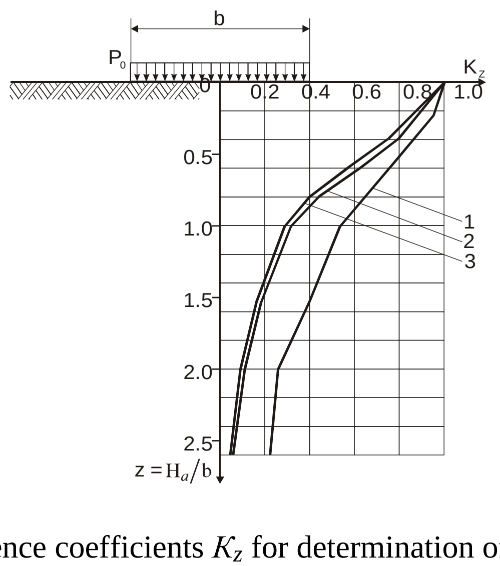


Figure 2 – Curves of influence coefficients K_z for determination of normal stresses under the center of the foundation footing from the action of the load P_0: 1 – for the case of a plane problem

(for strip foundations); 2 and 3 – for the case of a spatial problem (respectively, for square and circular foundations)

At the same time, the transition coefficient K_σ^c should be determined for the values of H_a/b, calculated by Eqs. (5) and (6). For example, at given values of $H_a/b = 1.0; 1.5; 2.0; 2.5$, the following values of the transition coefficient $K_\sigma^c = 1.17; 1.27; 1.36; 1.45$ are calculated by Eq. (12). For intermediate values of H_a/b, the corresponding values of the coefficient K_σ^c are recommended to be determined by linear interpolation.

In such a case, the actual compaction depth of the strip foundations can be determined according to the equations:

$$H_a^{fl}/b = K_\sigma^c \cdot (0.596 + 0.046/\sigma_{str}) \quad (13)$$

$$H_a^{fl}/b = K_\sigma^c\ (1.05 + 1.95/E_0) \quad (14)$$

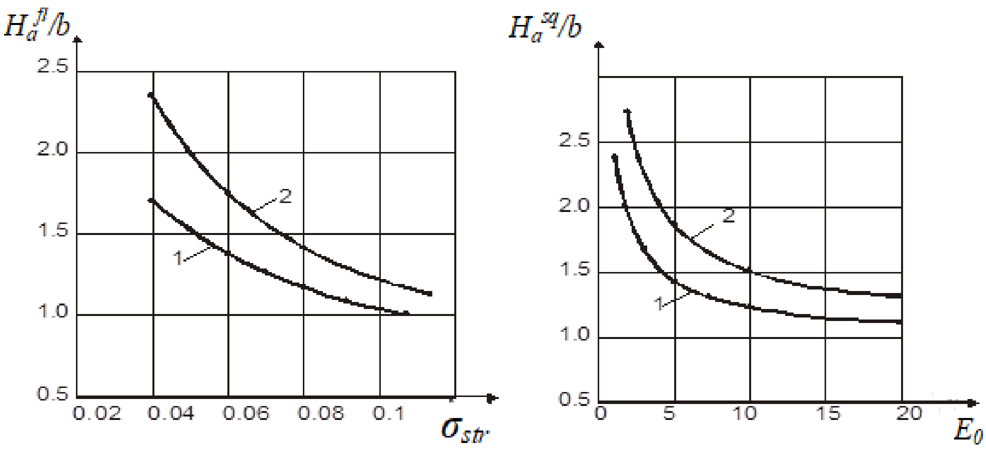
3. Results and Discussion

The boundary of the soil compaction deformation zone beneath foundation footings is a line that represents the geometric locus of points where the action of compressive normal stresses is balanced by the strength of the soil's structural bonds.

The settlement of the foundation footing is mainly influenced by the deformation resulting from the compaction of soils within a specific volume, which is commonly referred to as the foundation compaction deformation zone.

Figure 3 a and b show the graphs of dependence $H_a^{sq}/b = f(\sigma_{str})$; $H_a^{sq}/b = f(E_{0.})$ obtained by Eqs. (5) and (6) for square foundations (curves 1), as well as the graphs $H_a^{fl}/b = f(\sigma_{str})$ and $H_a^{fl}/b = f(E_{0.})$ plotted by Eqs. (13) and (14) for strip foundations (curves 2).

The width (B_a^{fl}) or extension (l_a^{fl} of the compaction zone of the strip foundations should be taken according to the dimensions of the isobars of the largest main normal stresses σ_1 at the given values $Z = H_a^{fl}/b$, determined from Eqs. (13) and (14).



a) b)

Figure 3 – The graph shows the relationship of the relative depth of the compaction deformation zone beneath foundation footings to the strength and deformation properties of the soil: a) The graph illustrates the dependency of the actual depth of the foundation compaction zone on the compressive strength of the soil's structural bonds; b) The graph depicts the relationship of the actual depth of the foundation compaction zone on the soil's deformation modulus

Figure 4 shows the graphs of dependence of l_a (or B_a) on H_a in relative coordinates, obtained from experimental data (graph 1) using Eqs. (3) and (4) and from theory - graphs 2, 2' and 3, plotted according to isobar dimensions σ_z (for square and strip foundations) and σ_1 at values $Z = H_a/b = 1; 1.5; 2.0; 2.5$, respectively.

As can be seen from the comparison of graphs 1 and 3, our proposal to estimate the width (or removal) of the soil compaction zone under strip foundations by the size of isobars σ1 has experimental confirmation, since these graphs within the most probable values of $H_a = 1b…2b$ converge.

At the same time, the known recommendations [12] on determining the dimensions of the deformed zone of the foundation base by constructing isobars of vertical normal stresses σ_z (for square - curve 2 and for strip foundations – curve 2') are not confirmed by the results of experimental investigations - graphs 1 and 2, 2' diverge.

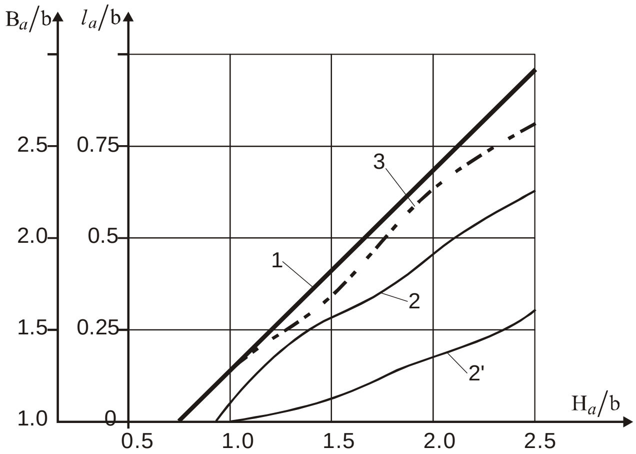


Figure 4 – Graphs depicting the relationship of the width and extension of the soil compaction zone beneath foundation footings to its depth in relative coordinates: 1 – Experimental graph obtained from the empirical equation; 2 and 2' – Theoretical graphs constructed based on the sizes of the σ_z isobars (for square and strip footings) at values of $z=H_a/b=1; 1.5; 2.0$ and 2.5; 3 – Theoretical graph obtained from the sizes of the σ1 isobar at values of $z=H_a/b=1; 1.5; 2.0$ and 2.5

This engineering method for estimating the dimensions of the deformable zone beneath the foundation can also be applied to rectangular footings, if the transition coefficient according to Eq. (13) is determined considering the aspect ratio of their base. In this case, the influence coefficient curve, K_z will lie between curves 1 and 2 (Figure 2). The calculation is then conducted similar to a strip footing using Eqs. (13) and (14), but with the consideration of the transition coefficient, K_σ^c, calculated for the rectangular footing.

4. Conclusions

The analysis of the research results has led to the following conclusions:

1. The proposed methodology for determining the actual dimensions of the soil compaction deformation zone beneath various types of foundations, including square, circular, strip, and rectangular footings, has demonstrated high accuracy and reliability of the results. This signifies a significant contribution of the study to the field of geotechnical engineering.

2. The experimental data have confirmed the theoretical assumptions regarding the influence of the soil's structural bond strength on the size of the foundation's deformation compaction zone. Understanding these interconnections is an essential aspect in developing the methodology and applying the results in practical projects.

3. The importance of considering the deformation characteristics of the soil during the process of determining the dimensions of the compacted zone has been validated by the research findings. This enables a more accurate representation of soil compaction processes and their impact on construction structures.

4. The studies have shown that the sizes of the deformation compaction zone can significantly vary for different types of soils and foundations. This highlights the importance of accounting for the specific characteristics of the soil foundation during the design and construction of various structures.

5. The developed empirical and theoretical methods have a wide range of potential applications in engineering projects. They can be used for determining safe design parameters, calculating foundation settlements under various conditions, and optimizing construction solutions.

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Information about author:

Assel Mukhamejanova – PhD, Senior Lecturer, Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, assel.84@list.ru

Author Contributions:

Assel Mukhamejanova – concept, methodology, resources, data collection, testing, modeling, analysis, visualization, interpretation, drafting, editing, funding acquisition.

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