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CONSIDERATION OF THE RIGIDITY OF STRUCTURE IN THE CALCULATION OF SETTLEMENT OF THE FOUNDATION ACCORDING TO EUROCODE 7

1. Introduction

The Polish Committee for Standardization announced on March 31, 2010 the withdrawal of the 39 Polish Standards applicable to the design of buildings and structures and their replacement with Eurocodes. Eurocode 7 [1] which introduces five limited states of load capacity and serviceability limit state SLS for design in the geotechnical field. Guidelines were given for the estimation of serviceability limit state SLS for foundations which have replaced the previously guidelines used according to the standard approach PN-81/B-03020, including the popular „standard" method for the estimation of settlements, based on an oedometric test.

This paper presents a discussion on the manner in which the rigidity of the structure of a foundation is included in calculations for the settlement of subsoil carried out in accordance with Eurocode 7. Possibly the most accurate assessment for the value of the settlement of individual foundations and any differences between them is desirable for spatial structures and can be realized through the use of equations from the theory of elasticity and the huge potential of modern computer software systems.

Nevertheless, in many cases of practical engineering tasks (in Geotechnical Categories 1 and 2), approximate methods for the evaluation of the settlement of selected foundation points that are characterized by a particular rigidity and can be used, and furthermore the differences in the settlement between adjacent foundations can be determined.

For a typical task involving two foundations in the form of rectangular plates placed in a wide excavation, settlement estimation was conducted by two of the three calculation methods from Eurocode 7. Differences were indicated in the estimation of the settlement depending on: the state of distortion assumed in the calculation method; the impact of the adjacent foundation; and the manner in which the rigidity of its structure was included.

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2. Settlement according to Eurocode 7

The verification of serviceability limit states SLS in subsoil, structural elements or their combination should be performed according to the criteria given by the following inequality:

$$E_d \leq C_d \tag{1}$$

where:

E_d — the design value of the effect of actions
C_d — the limiting design value of the effect of an action

The values of partial factors for serviceability limit state are generally accepted as equal to 1.0.

According to annex "H" of PN-EN 1997-1, the following items subject to the displacement of the foundation are to be checked: settling, settling differences, rotation, tilt, relative deflection, relative rotation, horizontal displacement and amplitude of vibration. The National Annex [3] narrowed the range recommended for the analysis of the components of foundation displacement. Settlement limit states of structures are recommended to be verified on the basis of the measurement of displacements and deformations:

$s_{\max}$ — settlement,
$\Theta_{\max}$ — rotation,
$\Delta_{\max}$ — deflection,
$\omega_{\max}$ — tilt.

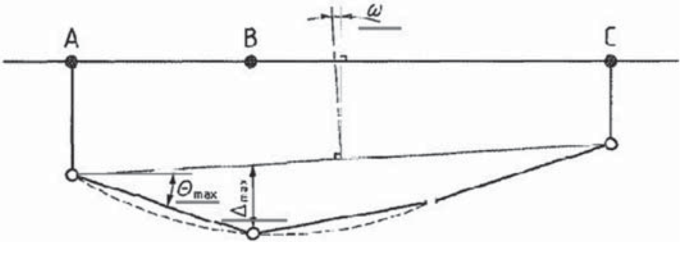

Fig. 1. Definitions of measures of foundation displacement

Total settlement is the sum of the following components:

$$s_{Ed} = s_0 + s_1 + s_2 \leq s_{Cd} \tag{2}$$

where:

s_0 — immediate settlement, in saturated soil resultant of distortion at constant volume, and in the unsaturated soil as a result of distortion and reduction of the volume,
s_1 — settlement caused by consolidation (so. filtration consolidation),
s_2 — settlement caused by soil creep of the subsoil (the effect of structural consolidation).

Annex “F” of that standard [1] lists and partially characterizes the following examples of methods for estimating the settlement:

- method of summation of subsoil deformations (stress-strain method),
- adjusted elasticity method,
- settlements caused by consolidation.

3. Method for assessing the average contact stresses to the foundation plate

The analytical evaluation of the value for structure settlement generally includes a number of simplifying calculation assumptions. The rigidity of the loaded surface is essential for stress distribution under the foundation base, which translates directly to the size of ground settlements at particular points of the foundation base. For rigid plates, average values of stress and then mean values of settlement are determined. The estimation of the average value of the vertical component of stress at the base of the foundation plate including the rigidity of its structure is shown below.

According to the method given by S. Pisarczyk in the publication [5], vertical stress in soil is calculated the same as uniform stress with the average value (integral) limited to the dimensions of the aggravated foundation plate.

In the case of a single rigid foundation (Fig. 2) the value for average stress at a depth of z* below the base is defined by the formula:

$$\sigma_{zs} = \frac{q}{L \cdot B} \cdot \int_{-\frac{L}{2}}^{+\frac{L}{2}} \int_{-\frac{B}{2}}^{+\frac{B}{2}} \eta_n\left(\frac{L}{B}, \frac{z^*}{B}\right) dxdy \tag{3}$$

where: η_n — influence factor for the vertical stress due to a corner point of rectangular elastic foundation according to the standard [2]

Figure 2 also shows the distributions of stresses at a depth of z* for the corresponding elastic foundation. Consideration of the influence of load on the adjacent foundation results in loss of the symmetry of stress distribution, as seen in Figure 3.

Adopting a similar assumption, as in the case of a single foundation for determining the average value of vertical stress with the inclusion of the influence of the neighbouring load as an average of the integral limited by the dimensions of the plate, is an assumption to the side of safety.

Including the influence of an adjacent foundation (Fig. 3) the value of stress at a depth of z^* below its base, assuming its rigidity, can be estimated using the formula:

$$\sigma^*_{zs} = \kappa \cdot \sigma^*_{zq} \tag{4}$$

where: κ — correction factor for the inclusion of foundation rigidity (its distribution shown in Figure 4) is given by:

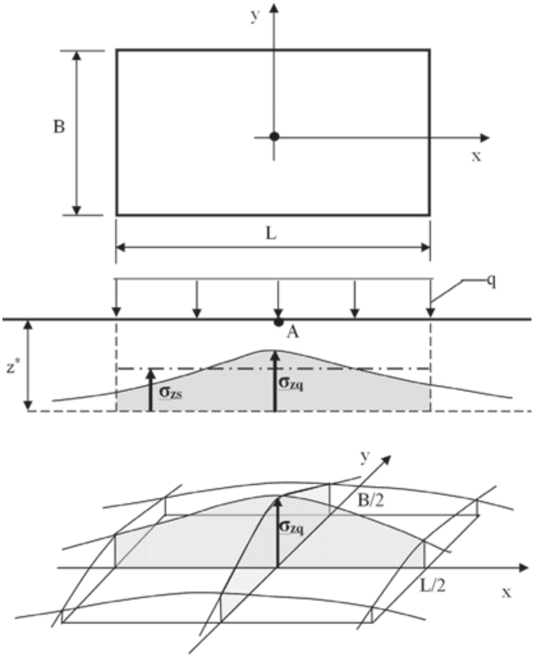

Fig. 2. The distribution of vertical stress at the midpoint of a single elastic foundation

$$\kappa = \frac{\eta_m\left(\frac{L}{B},\frac{z^*}{B}\right)}{\eta_S\left(\frac{L}{B},\frac{z^*}{B}\right)} \tag{5}$$

η_m — influence factor for the vertical stress due to a center-point of rectangular elastic foundation according to the standard [2],

η_s — influence factor for the vertical stress due to a center-point of rectangular rigid foundation according to the standard [2],

σ^*_{zq} — vertical stress for loads determined as elastic loads.

Figure 3 also shows the distribution of stresses at a depth of z^* for the system of two slender foundations.

4. An example of calculation of the settlement of a foundation plate

The analysis for the example was performed with two square foundations of the dimensions of L×B = 4×4 m which sit in a wide excavation with layered subsoil. An example illustrates the projection and cross section shown in Figure 5.

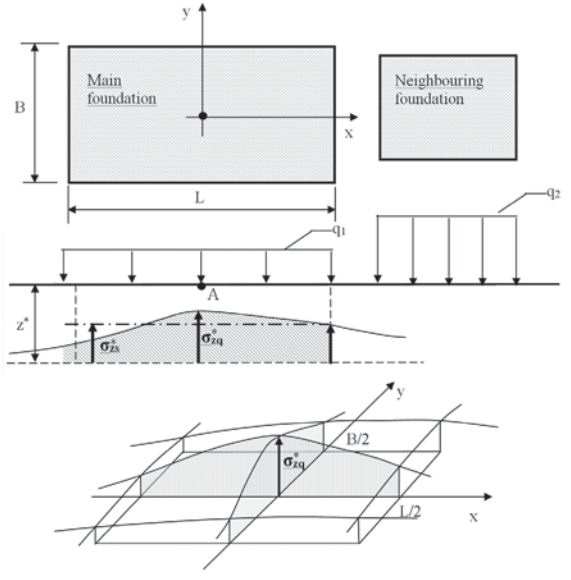

Fig. 3. The distribution of vertical stress at the midpoint of an elastic foundation including the neighbouring load

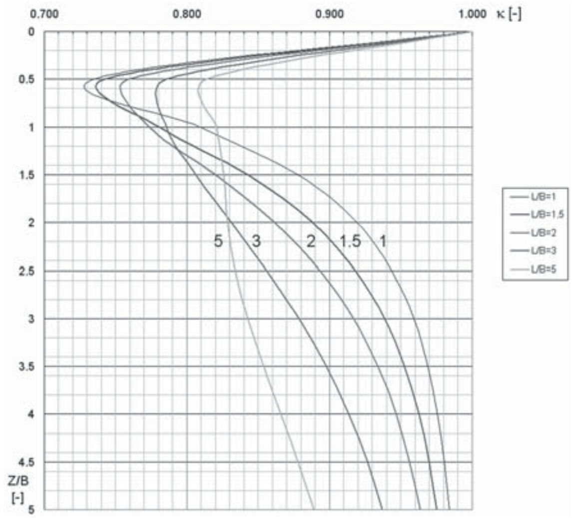

Fig. 4. The correction factor for including the foundation rigidity

Calculations were performed using two calculation methods specified by Eurocode 7 and using two methods which include the rigidity of the foundation.

The method for the calculations of substrate distortion (the uniaxial deformation method) settlement was performed according to PN-81/B-03020 (2), determining the extent of

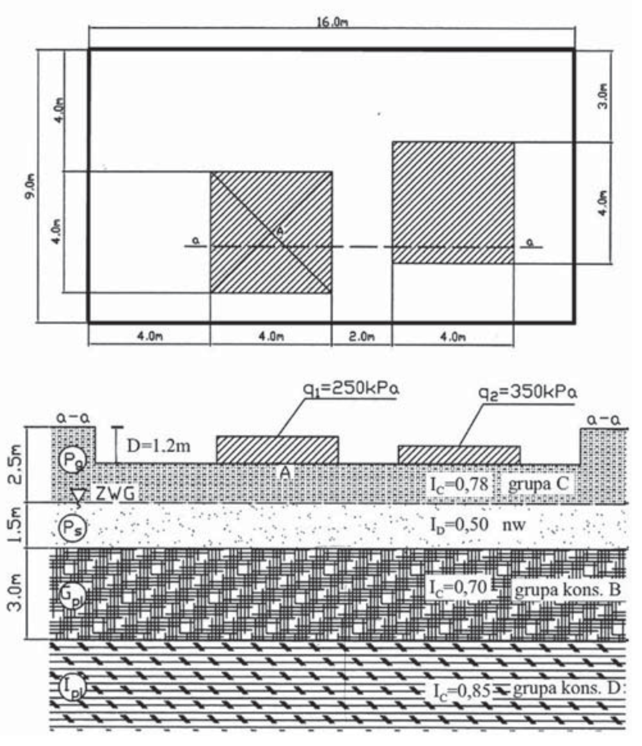

Fig. 5. Ground plan of the excavation for foundations of the calculated example with a vertical cross-section

the depth of the active subsoil, $z_{\max}$, according to a new criterion given in Eurocode 7 [1]. In cases where the rigidity of the foundation is taken into account, the previously described method for determining the average values of vertical stress with the aid of the coefficient κ is applied.

For comparison, the average settlement of the foundation for the given example was evaluated using the method specified by Z. Glazer in the monograph [4], which relies on calculating the corner settlement, s_n and the center $s_{śr}$ of the rectangular elastic foundation was used.

In this case, the average settlement of a rigid rectangular plate is:

$$s = \frac{1}{3} \cdot (2 \cdot s_{sr} + s_n) \tag{6}$$

In a simplified method for an elastic body (triaxial deformation method), the settlements of the individual calculated layers (to a depth of $z_{\max}$) are determined from the formula:

$$S_1 = \left(\frac{\sigma_{zsi}}{E_i} + \frac{\sigma_{zdi}}{E_0}\right) - B \cdot \Delta\omega_{zi} \cdot (1 - \nu_i^2) \tag{7}$$

where:

σ_{zdi}, σ_{zsi} — additional and secondary stress,

E_i, E_{0i}, ν — deformability parameters of soil,

$\Delta\omega_{zi}$ — difference in the impact factors for the sling and floor of the calculated layer.

The applied method for calculating the settlements with the use of the impact factors $\Delta\omega_{zi}$ presupposes the inclusion of foundation rigidity, because their values were determined for the ratio $\nu = 0.3$.

Figure 6 shows an example of vertical stress distribution which is specified in the method of summation of deformation in the elastic foundation under consideration, in which all the geotechnical parameters of soil layers adopted for the calculation are also shown.

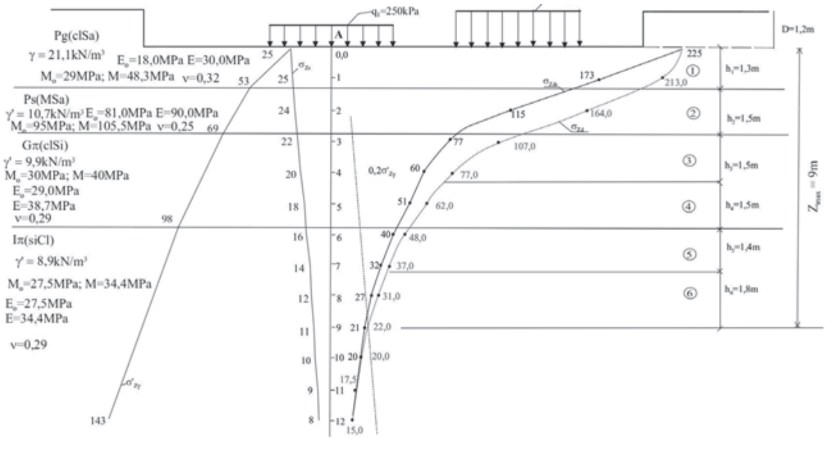

Fig. 6. Stress distribution in the method of summation of deformations for slender foundations

The results of the calculations for the final settlements of the center point A of the foundation are shown in Table 1.

TABLE 1

Summary of results for calculations of the settlements of the foundation at the point A

Calculation method	**Elastic load**	**Rigid load**
	s [cm]	s^* [cm]
The method of uniaxial deformation	2.79	2,40* 2,37**
The method of triaxial deformation		1,54

* — Settlement calculated on the authors proposal,

** — Settlement calculated according to the proposal given in [4].

5. Summary

In this article, calculations of typical foundation settlement in a deformable layered subsoil were calculated to compare the obtained rating with the methods expected by the Eurocode 7. In these assessments the rigidity of a foundation is taken into account.

There was a significant difference of around 50% in settlement ratings with the assumption of oedometric test and methods of triaxial deformation. While comparing the assessment of the elastic foundation settlement and the settlement of the foundation while including the rigidity of its structure, much smaller differences were obtained, amounting to about 15%.

The close values gained from the assessment of the "rigid" foundation settlement were obtained using a method proposed by the authors and a method from Z. Glazer. It is estimated, that a resulting error in the calculations for a perfectly rigid plate ($\nu = 0{,}0$) is 5% in either direction. It should also be noted that at a particular rigidity of the foundation structure and progressive consolidation of the subsoil, follows a change in loads, which leads to a reduction of differences in settlements of individual points in the foundation and points to well-know conclusions.

Analysis of the results of the calculations carried out underlines the importance of the choice of calculation method, which can lead to unreliable settlements results or a difference in settlements of foundations, which ultimately affects the design of the structure of the given foundation.

Finally it is important to add that in the case of checking the serviceability limit state SLS, it is no less important than the choice of the calculation method which gives the appropriate selection of subsoil deformability parameters.

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