Utilization of Underground Walls in Urban Areas

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Abstract. The paper deals with the solution of the problem of the buildings foundation in confined spaces of urban development. The most commonly used solutions are the underground walls, which provide space for the construction pit during the construction of underground parts of buildings. They must meet certain conditions in the urban development. The paper focuses on the analysis of the interaction of wall systems (mainly sheeting structures of building pits) and the surrounding earth massif. The distribution of the contact stress influences decisively the dimensioning of the foundation structure and the assessment of the foundation soil in terms of limit states. Similarly, other load-bearing structures ensuring the stability and usability of a building have been affected by an increase in the deformation load, which may cause a noticeable increase in internal forces and bending moments, which are not normally considered or assumed in static calculations of external loads, or their determination is based on false assumptions. If the magnitude of the deformation effects is incorrectly determined, the serviceability or loss of stability of the building structure may be limited. For this reason, to ensure a reliable and economical design, it is necessary to describe as closely as possible the interaction of the foundation structure with the subsoil. A prerequisite for a correct and economical solution to the problem is to capture the physical nature of the task at all stages of the solution. The use of the possibilities provided by the mathematical apparatus of the most versatile numerical method - finite element method (FEM) also contributes significantly to a more complex analysis of the problem. The practical lining wall model of the Eurovea shopping and entertainment center in Bratislava, Slovakia has been chosen as a practical example of the calculation. The main reason was the availability of the results of available inclinometric measurements. These have been compared with the results of the structural design model. The task was to create a model of the underground (lining) wall and compare the obtained results with the inclinometric measurements on realized objects. The obtained results have been presented in graphical form.

1. Introduction
The safe and reliable operation of a building during its entire lifetime (expected or actual) has been crucially influenced by its correct foundation, i.e. its installation in a natural subsoil environment.

When founding objects, there is an immediate contact of the foundation structure with the environment representing the subsoil. On the contact surface, at the level of the foundation gap located between the foundation structure and the subsoil, due to the change of equilibrium state (loading and unloading) the stress state changes, which is reflected in the upper structure and also in the land massif. This effect has been reflected in the interaction of the building structure with the subsoil, which depends on a number of different factors. From the point of view of the building structure, it is
mainly the stiffness of the system upper structure - foundation structure, stiffness of the foundation structure itself (its geometric shape, height, and material properties), load intensity. From the point of view of the subsoil, these are: strength and deformation properties, inhomogeneity, and anisotropy.

The design variables for the bearing structures have been based on the assumptions determining the interaction of the building structure with the subsoil. At present, still more and more complex structural systems have been designed and their final implementation is more influenced by the economic design criterion. Consideration of economic design while respecting the priority requirement of the safe and reliable foundation of the building has been the most important criteria.

When designing foundation structures and assessing the foundation soil in terms of limit states, we need to know the amount and distribution of contact stress. A number of different factors influence the distribution of the contact stress at the foundation gap level. It has been generally assumed that its distribution depends on the relative stiffness of the foundation with respect to the subsoil. The concept of relative stiffness includes several factors that to varying degrees affect the overall stiffness of the building structure at the foundation gap level.

2. The objective of the paper
The paper is focused on the analysis of the interaction of wall systems (mainly sheeting structures of foundation pits) and the surrounding earth massif. The distribution of the contact stress has a decisive influence on the dimensioning of the foundation structure and the assessment of the foundation soil in terms of limit states. Similarly, other load-bearing structures ensuring the stability and usability of a building are affected by an increase in the deformation load, which may cause a noticeable increase in internal forces and bending moments, which are not normally considered or assumed in static calculations due to external loads, or their determination is based on false assumptions. If the amount of the deformation effects is incorrectly determined, the structure serviceability may be limited or loss of stability of the building structure may occur. For this reason, it is necessary to describe the interaction of the foundation structure with the subsoil to enable a reliable and economical design. A prerequisite for a correct and economical solution to the problem is to capture the physical nature of the task in all stages of the solution. The use of the possibilities provided by the mathematical apparatus of the most universal numerical method - The Finite Element Method (FEM) also contributes significantly to a more complex analysis of the problem [1-3].

Based on quantitative and qualitative evaluation of individual calculation results, generally valid recommendations will be formulated for optimizing the design of planar foundation structures while respecting the relationship between the relative stiffness of the foundation - subsoil system. The conclusions and recommendations will also take into account the different boundary conditions, which determine the interaction of foundation structures with the subsoil and the static effect of subsoil response distribution and deformation of the foundation structure upon its assessment according to categories I and II of limit states.

3. Sheet structures
Geotechnical problems of sheeting structures with sealing function belong to serious problems of the foundation of buildings. They are closely related to several areas of soil mechanics – state of stress in the foundation soil, soil pressures on structures and water flow in soils. The main area with which the geotechnical problems of sheeting structures are associated is the theory of earth pressures.

In the design stage of the sheeting structure, we proceed from the analysis of engineering-geological conditions through an idealized geotechnical model to the creation of a computational model. The computational model incorporates the model of all applied loads and it is an idealization of the structure with boundary conditions. An appropriate calculation procedure has been then applied to
this calculation model. There is a choice of multiple approaches at each design step. The degree of idealization of the computational model must not reduce the physical aptness of the problem solved. The main criterion to be taken into account is the required safety of the design at maximum economical effectiveness [4, 5].

4. Underground walls
The model of a sheeting wall of the Eurovea shopping and entertainment center in Bratislava, Slovakia (Figure 1, Figure 2) has been chosen as a practical example of the calculation. The main reason was the availability of results of inclinometric measurements. These have been compared with the results of the structural design model.

Figure 1. Overall view of the construction site (view from the Apollo Bridge)

The construction site is situated on the left bank of the Danube River. Among the important buildings, the new building of the Slovak National Theater, the building of the Ministry of Interior of the Slovak Republic and the building of Slovenská sporiteľňa are located in its immediate vicinity.
Figure 2. Building pit and underground parts of the structure

In individual phases of construction, inclinometric measurements had been performed on the construction site. The process of these measurements has been presented by the photos in Figure 3.

Figure 3. Inclinometric measurements

4.1. Structural model of the underground wall
A 3D model of the sheeting wall structure was created in ANSYS software (Figure 4). The following elements from the ANSYS library had been used to create the model:

- SOLID45 – soil,
- SHELL63 a SHELL91 – reinforced concrete sheeting wall,
- TARGE170 a CONTA173 – contact elements,
- CONTAC52 – elastic support of a spacer frame.
Figure 4. 3D model and detail at the point of the spacer frame

The physical non-linearity of the material behavior had been taken into account in the SHELL91 layered elements by defining a parabolic-bilinear work diagram of reinforced concrete in the area under pressure, and a bilinear work diagram in the area of reinforced concrete under tension with the elimination of tension. The reinforcement work diagram was linear with strengthening. The SHELL91 layered shell element enabled us to consider nonlinearities. Contact elements TARGE170 and CONTA173 had been used for modeling of unilateral bonds between the underground wall and subsoil. Another non-linearity occurred at the elastic support of the wall using the spring element CONTAC52, where the initial deformation of the wall at the point of support by the spacer frame had been specified [6-8].

5. The results obtained
Following Figures 5 and 6 present the results obtained from the 3D structural model.

Figure 5. Horizontal deformations of the underground wall
Figure 6. Stresses in concrete layers, reinforcement of the underground wall

The observed differences between the measurements and the calculation models can be explained by the fact that the layered cross-section creates cracks and the concrete does not transmit tensile stresses. Such a cross-section has lower bending stiffness, resulting in a greater curvature of the displacement line.

6. Conclusions
In a practical example of comparing the computational model with inclinometric measurements, some differences in the results can be noted. These are mainly due to the way in which both the stiffness of the spacer frame, and its deformation during construction due to construction activities, have been introduced into the calculation.

In the presented work, the deformation of the sheeting structures in the calculations and in reality had been observed from the viewpoint of the material behavior of the sheeting structure itself. For reinforced concrete structures, this is the effect of the change in the bending stiffness of the structure caused by the formation of cracks in the cross-sectional areas under tension (reinforced concrete principle). The proper method of modeling the contact of the structure with the earth massif plays an important role, too.

In conclusion, it is possible to state that the horizontal displacements of the sheeting structure can be predicted sufficiently well by calculation using the Finite Element Method. However, the degree of approximation to reality will depend on the correct definition of the assumptions. In case of uncertain inputs, it is preferable to work not with one value but with a certain interval of possible values. In this way, it is possible to determine certain limits within which the values of expected real horizontal displacements will occur.
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