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Modelling the interaction of an underground structure with the soil in a megalopolis

Modélisation de l'interaction d'une structure souterraine avec le sol dans une mégapole

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ABSTRACT: The paper presents an assessment of the interaction of the elements of the "soil-tunnel" system under conditions of changes in the stiffness of the structure when soil parameters change. The study was carried out using numerical modelling and field tests with cyclic loads typical for such structures. In megacities, large-diameter underground tunnels are being constructed; they are several kilometres long and pass-through soils with different properties. An example of such a facility is the construction of a 3.6 m diameter tunnel in Kyiv with a length of about 10 km. Its depth varies from 5 to 90 m. In some parts of the tunnel, due to long-standing erosion processes, the semi-hard clay surrounding the tunnel is replaced by much weaker flowable sandy loam, so there is a need to strengthen the weak foundation. To evaluate the effectiveness of different options for strengthening the foundation, field tests were carried out by injecting polymer mortars into the soil in different volumes and over different areas, followed by cyclic load tests. During the test of the weak base in its natural state, vertical displacements of 3.7 cm were recorded. These displacements are 2 times higher than in semi-hard clay. The volume of mortar used for the reinforced foundation was justified so that the displacements did not exceed the permissible operational requirements. Subsequently, numerical modelling of the interaction of natural and reinforced foundations with an underground structure at different stages of its life cycle was carried out in a physically nonlinear formulation.

RÉSUMÉ: L'article présente une évaluation de l'interaction des éléments du système "environnement du sol-tunnel" dans des conditions de changement de la rigidité de la structure lorsque les paramètres du sol changent. L'étude a été réalisée à l'aide d'une modélisation numérique et d'essais sur le terrain avec des charges cycliques typiques pour de telles structures. Dans les mégapoles, des tunnels souterrains de grand diamètre sont construits; ils mesurent plusieurs kilomètres de long et traversent des sols aux propriétés différentes. Un exemple de ce type d'installation est la construction d'un tunnel de 3,6 m de diamètre à Kiev, d'une longueur d'environ 10 km. Dans certaines parties du tunnel, en raison de processus d'érosion de longue date, l'argile semi-dure entourant le tunnel est remplacée par un limon sableux fluide beaucoup plus faible, d'où la nécessité de renforcer les fondations fragiles. Pour évaluer l'efficacité des différentes options de renforcement de la fondation, des essais sur le terrain ont été réalisés en injectant des mortiers polymères dans le sol en différents volumes et sur différentes zones, suivis d'essais de charge cyclique. Lors de l'essai de la base faible dans son état naturel, des déplacements verticaux de 3,7 cm ont été enregistrés. Ces déplacements sont 2 fois plus élevés que dans l'argile semi-dure. Le volume de mortier utilisé pour la fondation renforcée a été justifié de manière à ce que les déplacements ne dépassent pas les exigences opérationnelles admissibles. Par la suite, la modélisation numérique de l'interaction des fondations naturelles et renforcées avec une structure souterraine à différents stades de son cycle de vie a été réalisée dans une formulation physiquement non linéaire.

Keywords: Underground structure; numerical modelling.

1 INTRODUCTION

Modern cities face many complex geotechnical challenges. It is necessary to solve the issues of deep pits, design and construction of foundations of high-rise buildings under loads of various types in different geological conditions, taking account the presence of existing buildings when laying underground structures, and much more. The problem of insufficient territory in large cities is solved by using underground space (Broere, 2016). The work of many geotechnics shows the level of complexity and relevance of issues related to the use of underground space for the construction of buried engineering structures, such as subway tunnels in the historic environment (Burghignoli et al. 2013). The peculiarities of designing and experimental research of tunnel-type structures are devoted to the works of many scientists (Mair, 2008). The downside of human activity in cities is the pollution of the territory and the need to solve geo-environmental problems associated with the transport of household waste. For this purpose, large-diameter collectors are constructed, which are tunnels designed to transport household wastewater to the place of its treatment. These tunnels are several kilometers long and run through soils with different properties. The design and construction of such structures requires an integrated approach, including: initial analysis of the topographic and geological situation, surveys along the route of the structure, specification of soil parameters depending on the calculation methods used to assess the interaction between the soil environment and the structure, selection of construction technology, assessment of changes in soil parameters on the stress-strain state of the tunnel structures, improvement of soil properties in certain sections of the tunnel.

2 INTERACTION OF AN UNDERGROUND STRUCTURE WITH THE SOIL

The main purpose of this paper is to evaluate the interaction of the elements of the "soil environment-tunnel" system under conditions of changes in structural stiffness and soil parameters. The research was carried out both by means of numerical modelling and by conducting field tests of the tunnel elements with cyclic loads.

2.1 Tunnel construction

An example of such a complex geotechnical facility is the construction of a tunnel for a new main city sewer in Kyiv, which is about 10 km long. Its depth varies from 5 m to almost 90 m. The tunnel consists of an outer lining of 8 precast concrete segments forming a circle and an inner lining of reinforced concrete cylindrical fragments with a protective polymer coating inside. The tunnel for installing the collector was constructed using a 3,600 mm diameter tunnel boring machine with sectional installation of the outer segments to the ground and their wedging, after which the secondary lining was installed in the inner space of the primary lining, and the space between them was injected with cement mortar. In certain sections of the tunnel, temporary soil freezing, temporary water lowering and protective screens made of walls in the ground were used to protect it from the effects of active groundwater movement. At the stage of operation, the tunnel is a cylindrical structure with an internal diameter of 2760 mm. During operation, the internal walls of the tunnel structure are subjected to cyclic loading due to daily changes in its operation mode. The minimum pressure at the bottom of the collector is 10 kPa, and the maximum pressure is up to 30 kPa. The outer casing of the collector is under ground pressure, which varies depending on the depth of the deposit from 90 kPa to 450 kPa.

2.2 Geological conditions

For the vast majority of the tunnel's length, the geotechnical profile around the tunnel is represented by semi-hard, sometimes stiff, marl clay, which has the following physical and mechanical properties: density $\rho \approx 1.9$ t/m^3, cohesion c=70...95 kPa, friction angle $\varphi \approx 12°$, and modulus of deformation $E \approx 35$ MPa. This soil has low permeability properties, which provides additional protection for the tunnel. However, in some sections of the tunnel route, due to long-standing erosion and siltation processes, there is no clay, and the environment around the tunnel is represented by weak plastic sandy loam and flowable sandy loam. The main physical and mechanical properties of these sandy loams are: density $\rho \approx 1.8$ t/m^3, cohesion $c \approx 10$ kPa, friction angle $\varphi \approx 18°$ and modulus of deformation $E \approx 6$ MPa. These characteristics were further verified by testing the weak soil with a pressiometer.

2.3 Changes in soil properties

In order to avoid uneven deformations of more than 10 mm per 1 m of the buried structure length in areas with a sharp change in geological structure, it was proposed to strengthen weak sandy loam soils by injecting solutions into the soil. The following were considered as possible alternatives for injection: silicate, cement and cement-polymer mortars of different water-cement ratios (time to reach design strength is more than 1 day) and, as an alternative, rapidly hardening two-component polymer mortars (time to reach design strength is 15-20 minutes).

Analysing the possible technologies for strengthening the soil base, we can note the advantages and disadvantages of each. Cementation is a technology that can be used for most soils, but the disadvantage is that it takes several days to gain strength and has an average cost among other technologies. Silicification is used for hard sands and sandy loams, but is ineffective for water-saturated soils, which in this case are the main ones on the site of the buried structure. Silicification has the lowest cost per 1 m^3 of treated base compared to other technologies. When using polymer mixtures, the advantage is that in order to strengthen the soil base under existing buried structures, it is necessary to make technological holes for injectors of the smallest size (20 mm in diameter), while for other technologies the holes have a diameter of 50 mm. Another advantage of polymeric solutions is their fast curing (up to 30 minutes) and, as a result, the ability to ensure a fast pace of work. The disadvantage is the highest cost among other technologies. Based on the technical and economic comparisons and taking into account the factor of rapid gain of the required strength and formation of bonds with the surrounding soil, injections using a two-component polymer solution were chosen as the main option. An important aspect of the injection technology is the possible heterogeneity of the artificially fixed soil mass and, as a result, the need to select injection modes to obtain the required deformation parameters of the fixed mass. To select the injection modes and predict the deformations of the consolidated soil base, a series of field studies of the technology with different injection modes and subsequent testing of the base by loading the tunnel segments were carried out at the experimental sites in real soil conditions.

2.4 Full-scale testing of tunnel segments

By applying a series of gradually increasing loads to the tunnel fragments placed in the soil, a series of field tests of the soil base in its natural state were carried out and vertical displacements were recorded, which in the range of operating pressures ranged from 16 mm to 37 mm for weak sandy loam soils, respectively (Figure 1). These displacements are significantly higher than those recorded for the areas where the subsoil was made up of semi-hard clays. After that, a series of experimental injections of polymeric mortar into weak sandy loam soils was performed to select the mode of supply and volume of such mortar so that the reinforced base had deformation characteristics close to semi-hard clay. For the reinforced base, vertical deformations ranging from 8 mm to 21 mm were obtained after the initial loading. This is 2 times less than for the unfixed base, but more than for the neighbouring areas with semi-hard clays. The reinforced base was reloaded, which corresponds to the operating mode of the reservoir with cyclic loads. After reloading, the deformations ranged from 5 mm to 11 mm. Such deformation values ensure compliance with the requirements for the allowable difference in deformation for neighbouring parts of the collector located in different soil conditions.

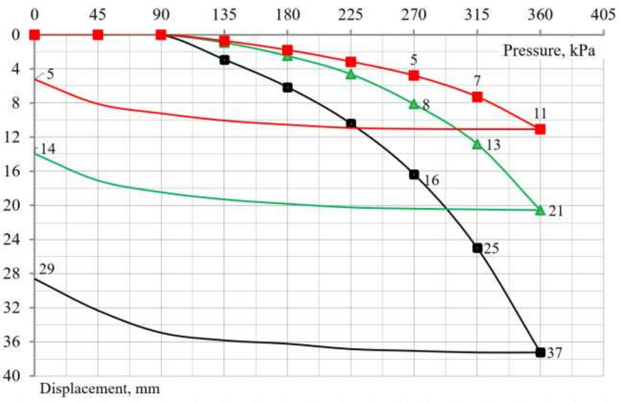

Figure 1. Dependence of displacements of the experimental tunnel section on the pressure on it at different properties of the base soil.

2.5 Numerical modelling of tunnel-soil interaction

To evaluate the effectiveness of various reinforcement options, numerical simulations of the stress-strain state of the soil medium-tunnel system at different stages of its life cycle were performed in a physically nonlinear formulation.

The soil model used in the numerical simulation allows to take into account changes in the deformation parameters of soils depending on the level of applied stresses and to describe the deformation processes of dispersed soils under complex loading/unloading trajectories.

To obtain correct results of numerical simulation, it is necessary to identify the model parameters in advance on the basis of laboratory soil tests or previously conducted field experiments.

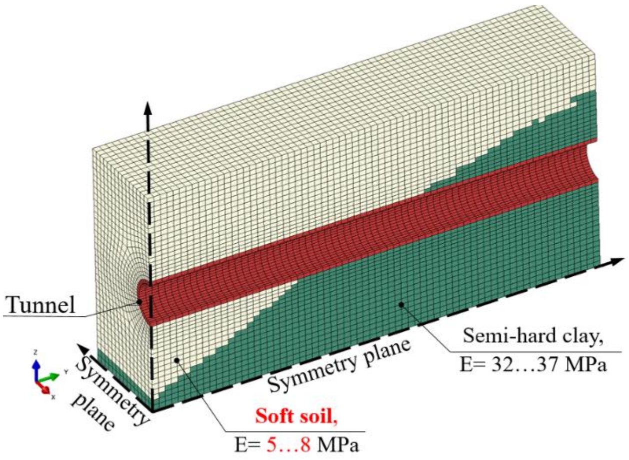

Figure 2. Finite element model of the "soil environment - tunnel" system.

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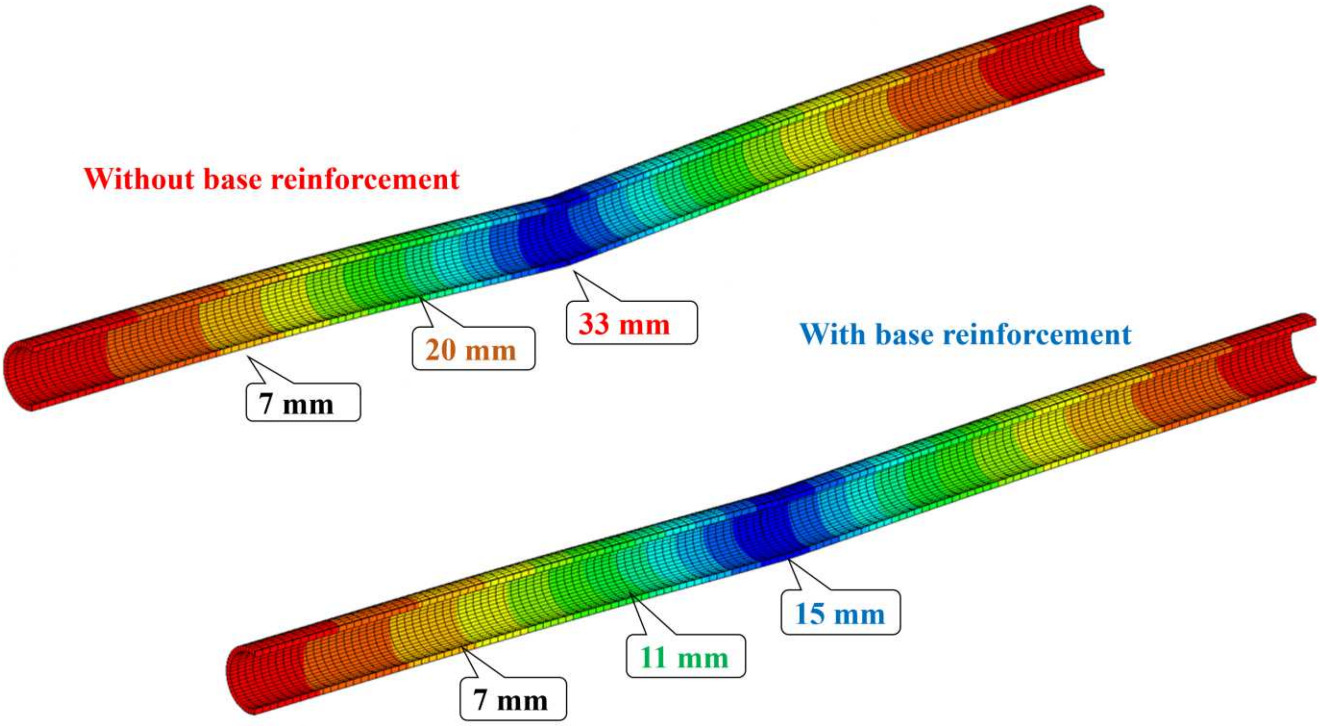

Figure 3. Comparison of displacements of the tunnel section obtained by numerical simulation for the variant without and with strengthening of the weak soil base.

According to the numerical modelling data, at the maximum pressure from the tunnel structures to the base during the operation of the reinforced base, the displacement reached to 13 mm, and the data of measurements of the structure displacement in the field experiment at the same pressure showed 11 mm.

The discrepancy between the numerical modelling and field experiments was up to 25% in the direction of overestimation of deformations in the modelling.

Three-dimensional numerical modelling of the tunnel-soil interaction in the transition zone from semi-hard clay to weak soils for two scenarios: the first, when the tunnel base was natural, and the second, with reinforced injection, showed a possible maximum difference in their displacements of 33 mm and 15 mm, respectively. Numerical modelling of the entire tunnel section in the zone of weak soils allowed us to select the effective number of weak base strengthening zones and the volume of polymeric mortar to strengthen and stabilize the weak soil and ensure safe operation of the tunnel.

3 CONCLUSIONS

The experimental results showed a decrease in the deformation of the fixed base under cyclic loads by up to 2 times compared to the unfastened base. On the basis of test injections with different volume of polymer mixture is established that in these soil conditions, the deformation of the fixed base depends on the injection mode and its volume.

A set of measures, including full-scale field tests and numerical modelling of the interaction between the foundation and the underground structure with the identification of foundation parameters, allowed us to substantiate an effective technology for strengthening a weak soil foundation and now we have experience of its safe operation. In the future, it is planned to extend this approach to the design of underground structures for sheltering people and energy facilities in Ukraine.

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