Deformations of soil in deep excavations: comparing calculation results with in-situ measurements

Déformation de fondation des fouilles profondes: la comparaison des méthodes diverses du compte aux les données des in-situ observations

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ABSTRACT
The paper deals with the issue of realism, such as may or may not be displayed by various models and calculation methods when used to calculate retaining structures of deep excavations. This issue is crucial for development of underground construction in areas of soft soils distribution and congested urban areas. Based on a series of large scale in-situ testing in deep excavations St. Petersburg geotechnical engineers have drawn certain conclusions on applicability and usefulness of deformation and settlement prediction methods used to assess movement of cofferdams and existing buildings. The paper describes one of the several test pits in St. Petersburg, where a series of in-situ monitoring was carried out.

RÉSUMÉ
Dans l'article on examine la question de la conformité de réalité des modèle divers et des mèthodes du compte des structures des soutènement des fouilles profondes. Cette question est extraordinairement actuelle pour développement de la construction souterraine dans les conditions des terrain meuble et en dense urbaine milieu. À la base des copieux in-situ observations du travail des fouilles profondes accomplis par ingénieurs géotechniques de Pétersbourg on fait les conclusions en ce qui concerne l'utilité des méthodes du pronostic des déformations de batardeau et des tassements des bâtiments voisins. Dans l'article on examine une de quelques aire d'essai à Pétersbourg, sur qui on faisait le complexe des in-situ observations.

Keywords : deep excavations, shear deformations of clay, visco-elasto-plastic soil model

1 INTRODUCTION

In the congested conditions of modern cities the issue of building underground structures that can be used for parking, shopping arcades, or motorway junctions becomes more and more important. Conditions for underground construction in such maritime cities as Amsterdam, Stockholm, or St. Petersburg are not favourable. In St. Petersburg typical soil profile consists of 15-20 m deep layer of soft plastic and liquid soils. These soils have low strength and high density, which justifies for higher pressure values onto retaining structures.

The analysis of failures in underground construction demonstrates the scope of research in the sphere of subsoil behaviour during excavation works to be insufficient. The shortage of such studies is readily illustrated by the work of Schweiger (2002). Besides, the existing calculation methods for cofferdams focus mainly on their strength and stability (in this case the calculations are based on the ultimate limit states).

In congested urban areas it is important to limit permissible deformations of the adjacent buildings, and consequently of the cofferdam. Thus the calculations based on the serviceability limit states become crucial. Apart from the deformations of subsoil caused by excavation works there are also deformations conditioned by construction method. Technology-related settlements can cause unacceptable deformation of the adjacent buildings.

Emergency situations may appear when the experience of construction of excavations on a site not surrounded by adjacent buildings is used for construction in congested urban areas. When existing buildings are situated in the close proximity to the site, the loads onto the cofferdam increase considerably while permissible settlements of historical buildings are as a rule limited to 2-3 cm according to St. Petersburg Codes.

To facilitate development of underground construction in difficult geological conditions of St. Petersburg it is required to carry out complex research of soil behaviour that would include instrumented monitoring of cofferdam and soil displacements both in the ground and on the surface.

In 2006 authors initiated big-scaled instrumental studies of cofferdam and subsoil behaviour at several deep excavations in St. Petersburg. Instrumented measurements of cofferdam displacements during construction of deep underground structures in soft soils were also performed by other specialized companies. The present paper contains the monitoring data from the test pit located in the central part of St. Petersburg.

2 REVIEW OF THE MAIN APPROACHES TOWARDS CALCULATIONS OF DEEP EXCAVATION COFFERDAMS

Most of the existing methods of cofferdam calculation are focused on assessment of cofferdam strength and stability. The simplest analytic calculation methods assume full realization of active and passive pressures.

To reduce the flexibility of the cofferdam in congested urban areas it is required to apply such technologies as would allow minimizing its displacements. In such circumstances the assumption as to full realization of both active and passive pressures becomes not exactly correct.

Under these conditions the approach using coefficients of subgrade reaction is widely applied to calculations. Therefore we will refer to it as a subgrade reaction method. In this case certain nonlinear dependence between pressure of the soil on the cofferdam and cofferdam displacement is replaced by piecewise-linear dependence, with a slope of the line in the pre-limit state determined by a coefficient of subgrade reaction. The

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main disadvantage of this approach is the uncertainty of values of the subgrade reaction coefficient K_h. Determination of coefficients encounters difficulties, in this connection a range of empirical formulae exists. In particular, Schmitt formula can be used (Schmitt, 1995):

$$K_h = 2.1 \frac{E_{oed}^{4/3}}{EI^{1/3}} \quad (1)$$

where E_{oed} is the constrained deformation modulus, E – Young modulus, I – moment of inertia.

Another drawback of the subgrade reaction method is the lack of possibility to predict the movement of subsoil.

To overcome the shortcomings of this method of calculation it is possible to use an elasto-plastic model with a strength criterion, described by Mohr-Coulomb equation. This model was also realized in many local and international software products.

Application of this model may sometimes lead to erroneous results. In this model soil behaviour both at the stage of loading and unloading is described by the same deformation modulus, which does not correspond to the real soil behaviour. When modelling excavations in soft soils, the model predicts abnormal uplift of the excavation bottom which leads to a distortion of the overall deformation picture. Instead of ground settlement outside the excavation within a considerable area, it shows uplift of the surface (see Fig. 6, 7).

When modelling the movements of the subsoil of the underground structure the most important thing is to define soil deformations during the unloading phase and deformations of form change that occur when stress deviator increases. Hence, in compression test results closer attention should be paid to unloading curve. In case of clay soils with a low seepage ratio it would be prudent to carry out undrained triaxial test, because the time of excavation is not enough for consolidation to occur. The soil model should be able to describe soil behaviour during the unloading phase and non-linear behaviour of the soil when the stress deviator increases. To meet these requirements it is necessary to use more complicated soil models, accounting for soil form change deformations.

In reality deformations of cofferdam and of soil mass develop over a time (see Fig. 8). When excavation for underground structures is carried out in stages, the deformations often are not stabilised during the undergoing works of each stage. To give the actual values of movements the model should take into account a possibility of incomplete deformation realization on each stage. The model should include rheological parameters that describe the development of deformations in time. In many models the delay in time of deformations of form change is either not described at all (the deformation of form change is considered to be instantaneous), or is connected to consolidation and volume creep through the effect of dilatancy or contraction. Shear creep of soil should be taken into account

In Russia geotechnical researchers traditionally give prominence to the issue of shear creep (Maslov, 1977, Vyalov, 1978). To describe the deformation of clay soils a visco-elasto-plastic model was proposed (Shashkin et al., 2005, 2007) which accounts for deformation development in time in terms of shear creep.

3 DEFINITION OF THE PARAMETERS OF THE VISCO-ELASTO-PLASTIC MODEL

Majority of the parameters of the model may be determined through results of standard oedometric and triaxial tests.

The biggest challenge is to set rheological parameters of the soil. Clay soils that are typical for St. Petersburg demonstrate clearly pronounced thixotropic properties. When their natural structure is disturbed they can transform from solid to liquid state. And as the result the soil viscosity considerably decreases (by several orders of magnitude). In the process of coring the natural structure of the samples is disturbed to a certain degree. Hence, during the laboratory tests considerable deformations of the samples develop within several minutes. In reality deformations of structures appear within rather a long period (ranging from several days to several months or years).

To test in-situ properties of soils, samples were taken while excavating the test pits. The samples were directly placed in the rings for corresponding tests which ensured the minimal disturbance of their natural structure. During the triaxial tests the samples of liquid consistency exhibited a brittle failure pattern at vertical deformation of 5-7%, (the samples from boreholes exhibited yield without failure till the value of deformations of about 15%). Creep tests with low stress demonstrated rather prolonged development of deformations in time (Fig. 1). In this manner laboratory data prove the presence of considerable viscosity in natural undisturbed soils, the fact that should be taken into consideration at calculations.

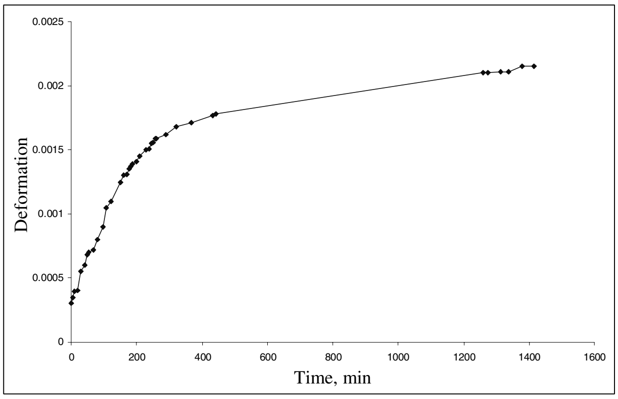


Figure 1. Unconfined creep test of the undisturbed sample of liquid loam at constant vertical normal stress of 5.4 kPa.

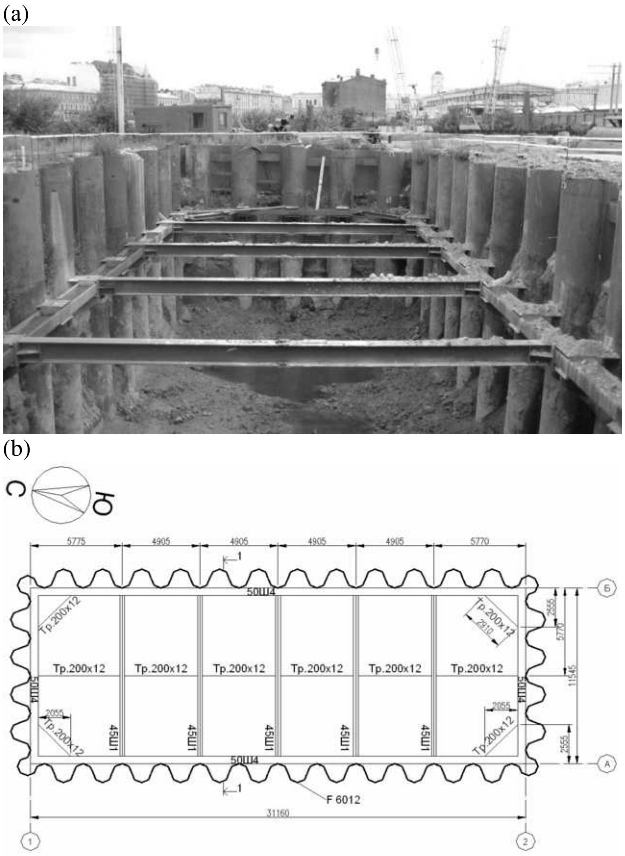
To derive rheological parameters for deformation of form change back analysis of the monitoring data of deformations of buildings and structures was used. The first information about the viscosity values local soils was obtained from the monitoring of deformations of the dyke structures. It was then adjusted based on the collected data of monitoring of the settlements of 15 buildings in St. Petersburg (Shashkin et al., 2007). Subsequent adjustment was made based on monitoring of underground works at the test pit.

4 COMPARISON OF THE CALCULATION RESULTS WITH THE DATA OF INSTRUMENTED MONITORING AT THE TEST PIT

The test pit has dimensions of 31m × 11.5m. The wailings of the strutting system were manufactured of H-beams, while H-beams of another type were used as cross bracings. The cofferdam was constructed of sheet piles type cut out of tubes with the diameter 1208 mm and thickness of 12 mm. The layout of the test pit is presented at Fig. 2, 3.

Fig 4 shows soil profile as revealed by site investigation. Prior to installation of sheet piles at the test pit, trenches of 1.5 - 2 m deep were excavated. When sheet piling was completed the internal volume of soil within the cofferdam was excavated down to -4m from the ground surface following which the struts were installed and the test pit gaps were backfilled. Thus, accompanying monitoring at the test pit started at the second stage of excavation, at the reference level of –4 m and down to the level of the bottom of excavation at –8.5 m (See Fig. 5).

(a)



(b)

Figure 2. Overview (a) and (b) layout of sheet piles and beams at the level of -3.5 m from the sheet piles top at the test pit.

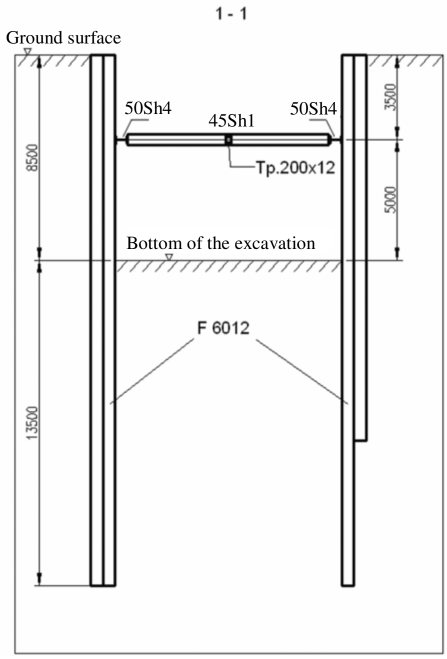


Figure 3. Cross-section of the excavation at the test pit.

Analysis of the monitoring readings evidences that the sheet pile wall generated displacement up to 5 cm, and the settlement of non-loaded soil surface at the distance of 15-20 m totalled 18-30 mm as of the moment when the monitoring was completed. In this manner it was proved that the technical solution of the cofferdam and struts system that was used at the test pit does not limit additional settlement of the adjacent buildings to the permissible values (2 cm for buildings of the third category of technical condition in St. Petersburg).

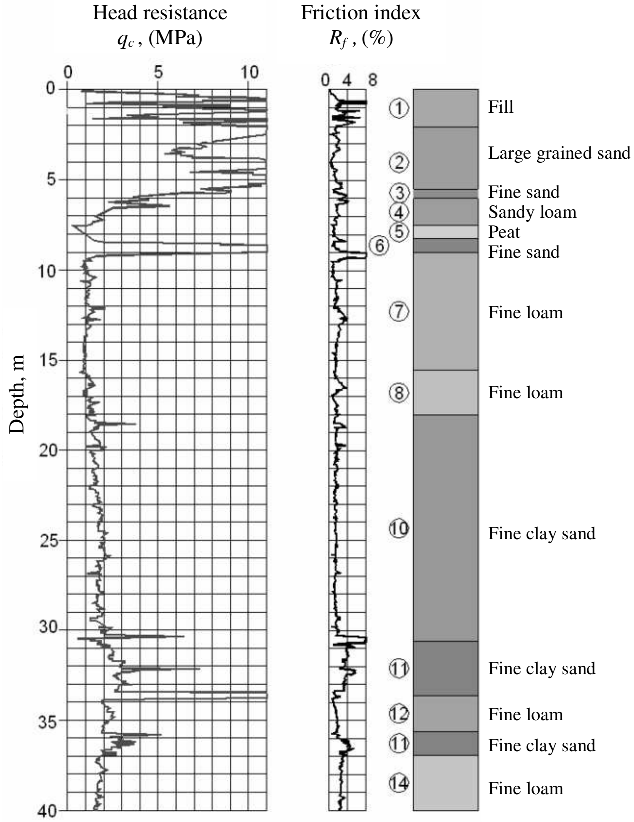


Figure 4. Geotechnical profile and results of SPT test carried out at the test pit.

Monitoring equipment was installed on the side of the pit where the sheet pile wall was completed down to the depth of 22 m (See Fig. 6). On the opposite side the pile toes had alternating levels of 16 - 22 m.

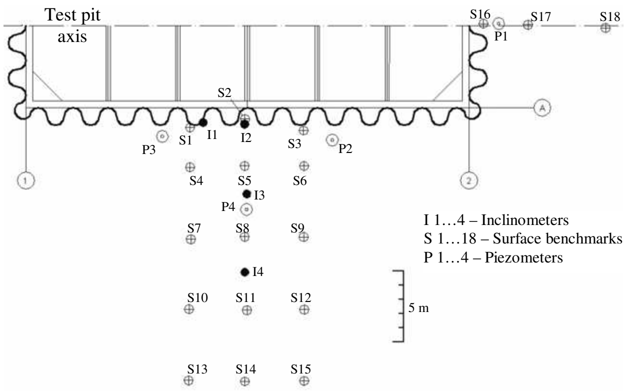


Figure 5. Position of monitoring equipment near the test pit.

Three various approaches were used to calculate the test pit in question: subgrade reaction method, Mohr-Coulomb and the visco-elasto-plastic model. Fig. 6 shows that the subgrade reaction method allows to accurately predict deformations of the sheet pile wall. In Mohr-Coulomb model standard soil properties were used. Fig. 6, 7 demonstrate that in general this model describes the behaviour of the soil incorrectly, which can be explained by the above-mentioned shortcomings of the model itself. When visco-elasto-plastic model was applied with the parameters based on the results of oedometric and triaxial tests, the resulting prediction was close to the monitoring data. Therefore, the model allows to describe correctly soil behaviour in time (Fig. 6).

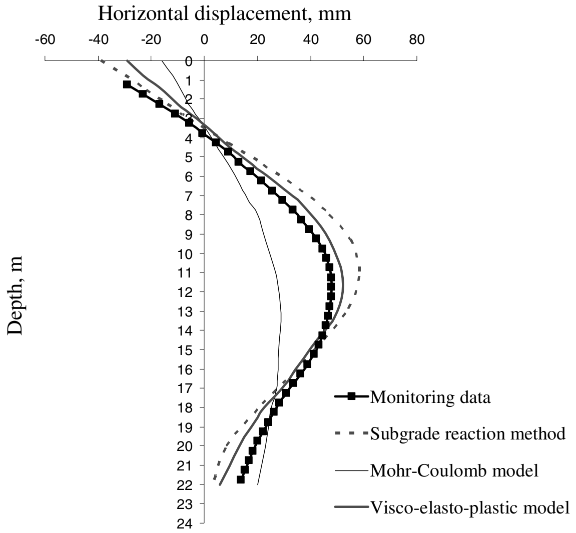


Figure 6. Comparison of the monitoring data of the cofferdam movements with the calculations based on various models.

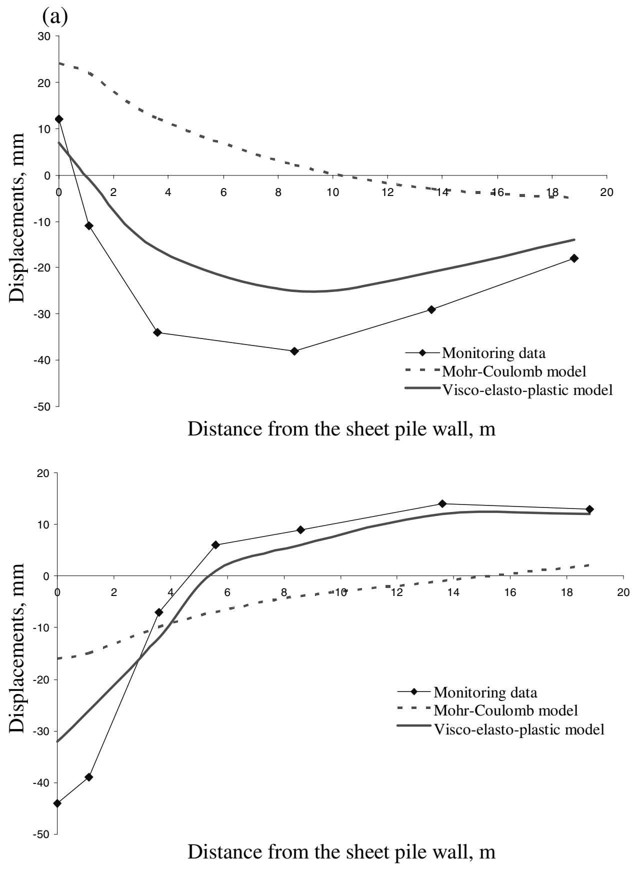


Figure 7. Comparison of vertical (a) and horizontal (b) displacement of the benchmarks as obtained during monitoring and as was predicted by calculations using different models.

5 CONCLUSIONS

In-situ tests on deep excavations conducted in St. Petersburg provided unique material for scholarly analyses as well as a chance of developing a most realistic calculation methodology for underground structures. Here we studied the observation data and the calculation results obtained from one of the test pits in downtown St. Petersburg. The observations obtained from that project proved typical for other sites also.

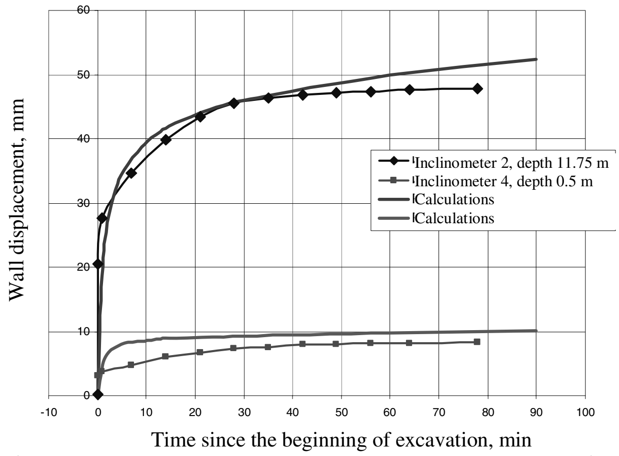


Figure 8. Comparison of the deformations development in various locations of the soil with the calculations made with the Visco-elasto-plastic model.

When developing calculation methodologies for deep pits cofferdams two approaches are possible. These approaches are radically different: (1) development of simple empirical methods, which would allow one to approach most closely the results of in-situ measurements and (2) development of computation methods based on analyses of physical regularities observed in silty clay soils' behaviour.

The advantage of the first approach is simplicity of calculation method. However, in that case possibilities of accurate soil deformation predictions are limited. Based on the observations of the test pits, as an example of the first approach one may recommend the half-analytical method defining coefficient of subgrade reaction based on formula (1).

The advantage of the second approach is considerable universality of the computation methodology.

When assigning standard soil behaviour parameters, the simplest elasto-plastic model with a limited Mohr-Coulomb surface does not provide an adequate definition of subsoil behaviour. To achieve a correct representation of soil behaviour it is necessary to use models depicting a difference in soil behaviour during loading and unloading, as well as non-linear character of soil response under form change deformations in triaxial tests. Additionally, for computation of underground structures it is highly important to work with realistic values of subsoil deformation rate. As demonstrated by comparison of calculations and the in-situ measurements the visco-elasto-plastic model of soil behaviour produces a good accuracy of prediction, including time-dependant deformations. This allows to recommend the presented approach for calculating retaining structures in soft soils and congested urban conditions.

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