Evolution of loading paths in a heterogeneous soil mass during the foundation pits’ construction

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Abstract. This article shows the construction of loading paths for the soil mass points using the example of a phased construction of the subway structure underground part. The solution to the problem was obtained by the finite element method using a PC PLAXIS 2D. The graphs of changes in the points’ stress state in coordinates $p'/q$ are shown.

1. Introduction

The Moscow metro construction history has almost a century-long history. The stations of the first stage were built mainly shallow in pits up to 12 m deep. Along with the subway construction underground space development, the theoretical and applied science of soil mechanics, which today is the main analysis tool in the new station complexes and running tunnels’ design, as well as other underground construction projects, has been developed.

At present, the formation and development of theories for describing the soils mechanical behavior mathematical models based on solutions of the theory of elasticity continues. The appearance of the CamClay mathematical soil model (the Cambridge clay model) in the 1950s made it possible to better predict the stress paths in comparison with the linear-elastic and elastic-plastic models Linear Elastic and Mohr-Columb. On its basis, a separate direction in the models’ development was identified with the introduction of an independent law of soils behavior during deformation, while the shear hardening region develops independently of volumetric deformations. Such models include the soil model of Zaretsky Yu.K. [1], as well as the elastic-plastic model with isotropic Hardening Soil and its modifications. Hardening Soil and Hardening Soil Small are often used options for designing pit barriers. The Hardening Soil model includes deviatoric loading, which induces shear hardening, and oedometric loading, which induces compressive hardening.

There are two main types of hardening: shear hardening and compression hardening. Shear hardening is used to model irreversible deformations resulting from primary deviatoric loading, while compression hardening is used to model the irreversible plastic deformations caused by primary compaction under oedometrique and isotropic loading. In the Hardening soil model, the shear strength is determined using a triaxial $E_{50}$ deformation modulus, compressive hardening - oedometrique $E_{oed}$. The soil mass behavior is processed during numerical modeling by constructing stress paths. For the behavior of the laboratory sample, the stress paths are shown in Figure 1 [8].
According to Figure 1, after the stage of anisotropic loading with vertical pressure exceeding the lateral pressure, the further path of stresses can change in three ways [8]:

1) with a decrease in lateral pressure with a constant vertical - the path deviates to the left;

2) with an increase in vertical pressure with a simultaneous decrease in lateral pressure with a constant ratio of them (constant shear stresses) - the vertical position of the line (an increase in the vertical load is equal to a double decrease in the horizontal load);

3) with an increase in only vertical pressure with a constant lateral pressure - the path deviates to the right.

2. Formulation of the problem

To determine the stress state for some points of the soil massif, a geotechnical calculation was carried out for a stage-by-stage construction of a pit for the assembly-shield chamber (ASC) construction using the PLAXIS 2D software package [11].

The main parameters of the design scheme (Figure 2) are: the enclosing structures of the pit for the construction of the assembly-shield chamber (ASC) are provided in the form of a monolithic reinforced concrete "wall in the ground" of a trench type 800 mm thick. The length of the "wall in soil" is 39.5 m. The depth of the pit is 25.6 m. The stability and spatial invariability of the pit fence is ensured by a spacer system consisting of 5 tiers of spacers and distribution belts. Spacer installation step is 4 m.

The geotechnical model of the foundation was adopted on the basis of analysis and generalization of the materials from engineering and geological surveys carried out at the construction site. In mathematical modeling, the Hardening Soil and Mohr-Coulomb model were used to describe the mechanical behavior of the soil. The base is represented by sandy soils with water-saturated layers. At the excavation stage for the 4th tier, dewatering works are carried out for further development of the soil.
Figure 2. Design scheme in PC PLAXIS 2D: a) at the stage of excavation development to the bottom with the installation of the 5th tier; b) at the stage of dismantling the 1st tier and backfilling

To study the stress state formation during step-by-step development with the installation of a spacer attachment and the erection of structures with the subsequent removal of the spacer system tiers, the most characteristic points that were within the collapse prism have been selected (Figure 3). The picture of the soil mass stress state is presented as follows (Figures 4-5.).

Figure 3. Characteristic points for studying stress paths.

In PC PLAXIS 2D the stress state is defined in the form of the following areas [11]:
1. **Failure points** (fracture point, red) - points of the Coulomb-Mohr strength condition violation, which is associated with the shear deformations development;
2. **Cap points** (hydrostatic reduction point, blue) – the points correspond to isotropic (hydrostatic) reduction.

3. **Hardening points** (hardening points, green) – the points correspond to shear hardening.

4. **Cap + Hardening points** (brown) – the points of hardening on the shear hardening envelope and on the hip-roofed surface.

![Figure 4](image)

**Figure 4.** Areas of stress state at the complete excavation stage.

![Figure 5](image)

**Figure 5.** Areas of stress state at the stage of dismantling the 1st tier of the spacer attachment and backfilling.

Further, the paths of stresses for the selected points were constructed with a description of the model behavior in space $p'-q$ (Figures 6-8). The beginning of each new phase is indicated by large markers.

The construction stages are presented in the following sequence:

- Stage 1 - Recess for the 1st tier of the spacer attachment;
- Stage 2 - 5 - Consecutive cuts for the spacer fastening tier followed by the foundation pit installation;
- Step 6 - Berm Development and Temporary Tray Design;
- Stage 7 - Dismantling of the temporary tray, pit excavation to the pit level with the installation of the 5th tier.
- Stages 8-12 - Consecutive erection of structures with the subsequent dismantling of the spacer fastening tiers

3. **Solution of the problem**

Figures 6 to 9 show the loading paths for the points A-D.
Figure 6. Loading paths of point A at the stages 1-12 in axes p'/q.

Figure 7. Theoretical construction of the loading path of point A at the stages 1-12.

At the stages 1-2, point A is characterized by an increase in vertical stresses and a slight increase in horizontal stresses, which leads to a deviation of the stress path to the right. At the stages 3-5, the lateral pressure decreases at a constant vertical pressure, which manifests itself in the form of a shift of the stress path to the left (since the point is at the level of the notch for the 3rd tier of the spacer). By stage 7, the stress path tends to the right with a decrease in the radii of Mohr’s circles, as the foundation is unloaded to the level of the pit. At the stages 8-12, with repeated loading, an increase in lateral pressure occurs with a slight increase in vertical - the stress path tends vertically up.

Point A at all stages corresponds to isotropic (hydrostatic) reduction. As shown in Figure 6, the path of isotropic compression is not a strictly horizontal line, which is associated with the influence of the cuts’ dimensions and shapes in the design model, the introduction of spacer fastening structures, as well as edge effects, boundary conditions. However, for point A, the displacement of the path to the right determines the type «Cap» in the stress state picture.
Figure 8. Load paths of point B at the stages 1-12 in axes $p'/q$.

Point B is notable for the path displacement to the left at the stages 1-6, as evidenced by the decrease in vertical pressure with increasing lateral pressure (with a phased unloading of the foundation). At the stage 7, a change in the stress path to a vertically directed downward (unloading of the base to the level of the pit) is observed with a decrease in the radii of Mohr’s circles. At the stage 8, the lateral pressure increases with a slight increase in the vertical pressure - the path deviates to the left. In general, for point B, the path displacement to the left at the stages of the forward stroke (stages 1-7) determines the type of “Hardening point” for it in the stress state picture, which corresponds to shear hardening. However, at the stages 9-12 with an increase in vertical and lateral pressures, the stress path deviates to the right, which determines the type of "Cap + Hardening point" for it in the stress state picture.
Figure 10. Trajectories of point C loading at the stages 1-12 in axes p'/q.

Figure 11. Theoretical construction of the point C loading path at the stages 1-12.

Point C, similar to point B, changes the stress state type during the forward and reverse stages. However, here there is a change from the type "Hardening point" (the path displacement to the left) to the type "Cap + Hardening point" (the path displacement to the left with the same ratio of increments of q and p') at the stage 3, and at the stages 8-12 there is a change to the type Cap (the path displacement to the right) due to repeated subgrade loading.

Point D (Figures 12-13) is characterized by a shift of the loading path to the left. At the stages 9-12, with an insignificant increase in vertical and lateral pressures, the stress path deviates to the right, but in the stress state picture at all stages it is characterized by the “Hardening point” type.

Figure 12. Loading paths of point D at the stages 1-12 in axes p'/q.
Figure 13. Theoretical construction of point B loading path at the stages 1-12.

4. Summary
As a result of numerical scheme modeling of the pit development stages with the installation of spacer tiers and the erection of structures for the underground part of the metro structure, the main loading paths for the points located in the collapse prism have been obtained. Analysis of the solution results shows that the stress state for the same point can be transformed at the stages 1-7 and 8-12, which illustrates the construction of loading paths.

Determination of the stress state fields at the soil mass points is necessary to assess the deformability of soil mass layers, to determine the effect on nearby buildings, underground structures and utilities [2].

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