Preliminary assessment of the earth's surface movement in the impact zone of a subway tunnel construction

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Abstract. Numerical modeling of the displacement of the earth's surface during the construction of deep tunnels is considered on the example of one of the Moscow metro lines. Based on the results of numerical simulation of the driving of one and two tunnels using several calculation schemes, the forecast parameters of the displacement trough, such as subsidence, slopes, curvature, horizontal deformations of the earth's surface, are determined. According to the criteria of deformations of the earth's surface, a tunnel influence zone is constructed. In the influence zone of tunnels, it is necessary to create observation stations for surveying (geodetic) monitoring of subsidence of buildings and the earth's surface, including using automated monitoring systems. According to monitoring data, the parameters of the calculation models are adjusted to increase the reliability of the simulation results. A technique is proposed for a preliminary assessment of the displacement of the earth's surface in the influence zone of the construction of subways tunnels.

1. Introduction

Deep underground tunnels are constructed by an enclosed (mining) method without opening the land surface, at a depth of not less than 15 m. Let us consider a preliminary assessment of the development of the process of shifting the soil mass and the earth's surface during the construction of deep underground tunnels using an example of one of the Moscow metro lines.

To assess the displacement of the soil mass and the earth's surface after driving one and two subway tunnels, numerical modeling by the finite element method in the Plaxis 2d program was performed. As the experience of using Plaxis shows, numerical modeling is very sensitive to the quality of the source data: minor changes in the physicomechanical properties of soils, tunnel attachment parameters, or groundwater level can quite strongly, sometimes multi-fold change the calculation results.

For example, in [1], the influence of soil type on the vertical displacements (subsidence) of the earth's surface was estimated when modeling in Plaxis for the U-8-Nord underground line under construction in Munich (Germany). The tunneling was simulated in various types of soils, the results of modeling by the criterion of the parameters of the tear plate are compared with full-scale surveying (geodetic) observations. Based on the calculated and actual data on monitoring the movement of the earth's surface, the soil parameters optimal for the calculation model were determined.

In [2], a geomechanical analysis of subsidence of the earth's surface during the construction of a deep underground station in St. Petersburg (Russia) was performed. To assess the reliability of the calculation model and the results of numerical modeling, we also used the method of comparing the...
calculated trough of displacement and the data of geodetic monitoring during the construction of pylon stations in similar engineering and geological conditions.

In [3], a study was made of the influence of the depth of the tunnel on the stress-strain state of the massif and the displacement of the earth's surface when driving a double-track haul subway tunnel in St. Petersburg. It is shown that for a soil mass composed of four layers of soil with different physical and mechanical properties, an increase in the depth of the tunnel from 20 m to 40 m causes an increase in subsidence of the earth's surface by about 1.2 times. In addition, the zone of influence of the tunnel is determined from the simulation results.

In [4], the monitoring results of the earth's surface movement during the construction of a number of metro stations in St. Petersburg were analyzed. According to field observations of the subsidence of the earth's surface, the slopes and curvature in the trough of displacement were additionally calculated. Typical strain distribution curves were obtained in the displacement trough for mining and geological conditions for the construction of escalator tunnels in St. Petersburg. The data obtained were used to predict displacements and deformations of the earth's surface during the construction of tunnels in similar conditions.

In [5], when modeling changes in the stress-strain state (SSS) of a soil massif, it was shown that the initial data on the physicomechanical properties of soils, in particular, the soil deformation modulus, significantly influence the modeling results.

Thus, one of the necessary conditions for obtaining reliable results of a preliminary assessment of the process of displacement of the earth's surface and soil mass during modeling in Plaxis are:

- the adequate set of source data, including the physicomechanical properties of the soil mass,
- the use in assessing not only the criterion of the earth's surface subsidence, but also others, such as slopes, curvature, horizontal strains of compression-tension of the earth's surface,
- comparison of simulation results with field monitoring data (geodetic, geotechnical) and adjustment, if necessary, of the initial data of the calculation models.

2. Research Methods

To draw up calculation schemes for numerical modeling, a conventional engineering-geological section has been used, on which three types of soils, called "Sand", "Clay", "Limestone", are represented.

Table 1 shows the physicomechanical properties of these types of soils adopted in the model, which are defined as average according to [6], as well as according to the data given in the publication [7]:

| Parameter / Designation / Unit | "Sand" | "Clay" | "Limestone" |
|-----------------------------|--------|--------|-------------|
| Specific gravity γ t/m³     | 1.7    | 2.0    | 2.6         |
| Deformation modulus E MPa  | 22     | 35     | 150         |
| Poisson's ratio ν           | 0.3    | 0.35   | 0.25        |
| Adhesion c kPa              | 2      | 30     | 3000        |
| Angle of internal friction ϕ° | 35    | 20     | 33          |

For numerical simulation, three design schemes have been compiled, differing in different depths of the tunnels:

- Scheme 1: the laying depth is 15 m, the tunnels lie in "Sand";
- Scheme 2: laying depth is 25 m, the axis of the tunnel passes through the contact "Sand"–"Clay";
- Scheme 3: laying depth is 35 m, the tunnels lie in "Limestone";
- distance between the axes of the tunnels in the plan: 13 m;
- diameter of the tunnel: 6.5 m;
• groundwater table: 10 m.

The dimensions of the calculation model are taken as 100 m along the horizontal axis X and 50 m along the vertical axis Y. The boundary conditions in the model are set as follows: horizontal movements are forbidden on the lateral boundaries, horizontal and vertical movements are forbidden on the lower boundary.

Figure 1 shows the calculated simulation scheme with a tunnel laying depth of 15 m:

![Figure 1](image1.png)

**Figure 1.** Settling scheme No. 1 (tunneling depth 15 m. Vertical axis (X) is the depth from the surface, m; horizontal axis (Y) are the distances in the plane perpendicular to the axis of the tunnels, m; “groundwater table” is the groundwater level; “Sand”, “Clay”, “Limestone” are conventional soil types accepted in the calculation model.

Modeling includes three stages:
Stage 1 – calculation of the initial (initial) stress-strain state (VAT) of the soil mass;
Stage 2 – change in the initial VAT of the soil mass after boring the 1st tunnel;
Stage 3 – changing the VAT of the soil mass after boring the 2nd tunnel.

The comparison of the simulation results of tunneling in various design schemes is presented in Table 2.

![Figure 2](image2.png)

**Figure 2.** Estimated vertical displacements of the soil massif (mm) after boring the first (a) and second (b) tunnels
Table 2. Comparison of the results of modeling tunneling in various design schemes according to the criteria of vertical and horizontal displacements of the soil mass

| Calculation scheme | Estimated vertical and horizontal displacements of the massif of soil [mm] | | | |
|---|---|---|---|---|
| | after boring 1st tunnel | after boring 2nd tunnel | displacement increment [mm] | displacement increment [times] |
| vertical displacements on surface | 14 | 21 | 7 | 1.5 |
| in whole massif | 24 | 28 | 4 | 1.2 |
| horizontal displacements on surface | 4 | 7 | 3 | 1.8 |
| in whole massif | 8 | 8 | - | - |
| **Scheme No. 1** (tunnels lie in "Sand", depth is 15 m) | | | | |
| vertical displacements on surface | 12 | 25 | 13 | 2.1 |
| in whole massif | 41 | 50 | 9 | 1.2 |
| horizontal displacements on surface | 4 | 9 | 5 | 2.3 |
| in whole massif | 14 | 19 | 5 | 1.4 |
| **Scheme No. 2** (axis of tunnel passes through contact of "Sand" and "Clay", depth is 25 m) | | | | |
| vertical displacements on surface | 4 | 9 | 5 | 2.3 |
| in whole massif | 18 | 22 | 4 | 1.2 |
| horizontal displacements on surface | 2 | 3 | 1 | 1.5 |
| in whole massif | 7 | 8 | 1 | 1.1 |
| **Scheme No. 3** (tunnels lie in "Limestone", depth is 35 m) | | | | |
| vertical displacements on surface | 4 | 9 | 5 | 2.3 |
| in whole massif | 18 | 22 | 4 | 1.2 |
| horizontal displacements on surface | 2 | 3 | 1 | 1.5 |
| in whole massif | 7 | 8 | 1 | 1.1 |

Based on the simulation results, we can conclude that the tunneling of the second tunnel causes an increase in vertical displacements of the earth's surface by an average of 1.5–2.3 times. Figure 2 shows the distribution of the estimated vertical displacements of the earth's surface after the first and second tunnels are drilled using the calculation scheme No. 1 as an example.

3. Brief analysis of the results of numerical simulation

The danger to buildings and structures on the earth's surface is not vertical movements (subsidence) as such, but their unevenness in the trough of displacement, which leads to the appearance of such types of deformations of the earth's surface as slopes, curvature, horizontal tensile/compression deformations.

In accordance with [8],

1. the boundary of the zone of influence of the underground structure or the boundary of the trough of displacement is the contour of the zone on the earth's surface, determined by the deformations:
   - inclinations \( i=0.5 \times 10^{-3} \),
   - horizontal tensile strains \( \varepsilon=0.5 \times 10^{-3} \), with interval lengths of 15–20 m.
2. the boundary of the zone of the dangerous influence of the underground structure is the contour of the zone on the earth's surface, determined by deformations:
   - inclinations \( i=4 \times 10^{-3} \),
   - curvature \( k=0.2 \times 10^{-3} \)
   - horizontal tensile strains \( \varepsilon=2 \times 10^{-3} \), with interval lengths of 15–20 m.
Let us analyze the calculated zone of the earth surface displacement trough for each of the calculation schemes according to the simulation results.

According to the results of numerical modeling, the values of the deformations, inclinations and curvature of the earth’s surface in the trough of displacement from the penetration of two tunnels with an interval of 2.5 m along the X axis are calculated, and the calculated zone of influence of the tunnels is determined. Figure 3 shows the calculated values of subsidence (a), slopes (b), curvature (c) and horizontal deformations (d) of the earth’s surface according to the simulation results (the influence zone of the tunnels is shown by the horizontal dashed line, the dashed-dotted vertical line shows the position of the axes of the left and right tunnels.

![Figure 3](image-url)

Figure 3. Calculated values of the subsidence (a), slopes (b), curvature (c) and horizontal strains (d) of the earth’s surface in the displacement trough from the penetration of two tunnels according to the simulation results

In [9], according to the results of modeling a large number of geomechanical situations with various technological parameters and properties of the soil mass, regression expressions were compiled to calculate the maximum subsidence of the earth’s surface $\eta_{\text{max}}$ along the center line of the trough of displacement above the axis of the tunnel:

$$
\eta_{\text{max}} = \frac{2 \cdot u}{1 + 0.42 \left( \frac{H}{D} \right)} \cdot (c \cdot E)^{-0.08}, \ m
$$

where $u$ is the construction gap in the arch of the tunnel lining, $H$ is the depth of the tunnel, $D$ is the diameter of the tunnel, $c$ and $E$ are the adhesion and soil deformation modulus.

In [8], the maximum subsidence of the earth’s surface is recommended to be determined by the formula:

$$
\eta_{\text{max}} = q_0 \cdot u \sqrt{\eta_1 \cdot \eta_2}
$$

where $q_0$ is the coefficient that takes into account the nature of the attenuation of displacements from the excavation to the earth’s surface, fluctuates for the conditions of the Moscow region in the range...
from 0.7 to 0.9 (the stronger the rocks, the less $q_0$); $u$ is the subsidence value of the roof; $n_1$ and $n_2$ are underworking coefficients, determined from the expressions:

$$n_1 = 0.9\sqrt{D_1/H}$$

$$n_2 = 0.9\sqrt{D_2/H}$$

where $D_1$ and $D_2$ are the transverse and longitudinal dimensions of the underground site; $H$ is the depth of the site. For values $n_1$ and $n_2 > 1$, $n_1$ and $n_2 = 1$ are accepted. Since in tunnels the longitudinal dimension $D_2$ is always very large, the coefficient $n_2 = 1$.

Figure 4 shows the curves of the maximum possible settlement of the earth's surface depending on the depth of the tunnels for the parameters of the calculation model adopted in this paper, constructed according to the methods of [8] and [9]:

![Figure 4](image)

**Figure 4.** Calculated curves of the maximum possible subsidence of the earth's surface depending on the depth of the tunnel by the methods [8] and [9].

According to the simulation results, the maximum subsidence of the earth's surface during the tunneling of two tunnels was 25 mm with a tunneling depth of 25 m, which does not exceed the maximum possible calculated values by the methods [8] and [9].

According to surveying observations of precipitation of buildings and structures in the zone of influence of the construction of metro tunnels similar in parameters, the maximum values of subsidence of deformation marks on buildings are in the range of 5–25 mm, which is in good agreement with the modeling results in Plaxis.

According to the simulation results, according to the criterion of slopes and horizontal deformations, the maximum size of the displacement trough (zones of influence of tunnels) on the earth's surface is determined to be about 80 m.

According to the calculated value of the zone of influence of tunnels, the boundaries of the zone of influence and the boundaries of the zone of dangerous influence, if any, are plotted on the general plan of the surface. For buildings and structures on the earth's surface falling within the zone of influence of tunnels, it is necessary to conduct surveying (geodesic) monitoring to monitor precipitation and banks. According to the monitoring data, the correspondence of the simulation results to the actually observable is determined, and adjustments are made to the calculated modeling schemes.

As a rule, based on the results of direct measurements of the displacements of deformation grades on buildings and structures, it is possible to evaluate the displacement of the soil mass only at a certain stage, when most of the deformations of the soil mass are already implemented. For more operational
control of the movement processes, along with direct surveying (geodetic) measurements, automated monitoring systems can be used.

Indeed, in [10], on the example of the construction of one of the metro lines in St. Petersburg, the use of an automated monitoring system is considered, which allows controlling the movement of the soil mass throughout the depth from the lining of the tunnel to the earth's surface at the initial stages, directly in the process tunnel penetration. In [11], an automated geotechnical monitoring system was described during the construction of the 1st stage of the IZMIR LRTS (Light Rapid Transit System) in Izmir (Turkey). An integrated system of geotechnical monitoring includes monitoring the movement of the earth's surface and the deformations of the structures of the tunnel itself.

In [12], emergency situations were considered during the construction of subways. An example of an emergency analysis caused by the removal of flooded sands into a tunnel and resulting in the deformation of a precast concrete waterproof lining of a tunnel shows the need for continuous automated monitoring of tunnel deformations.

4. Conclusion
In the event that the amount of data on the engineering and geological conditions of the construction site, physical and mechanical properties of soils, etc. is insufficient to build the correct calculation schemes for numerical modeling, or the available data need to be clarified when comparing the simulation results with field data, a preliminary assessment of the movement of the earth's surface in the zone of influence of the construction of subway tunnels can be performed according to the following method:

1) Engineering-geological sections are selected along the tunnel route, along which numerical modeling of changes in the stress-strain state of the soil mass after tunneling will be performed;
2) If there is a sufficient amount of data on the physicomechanical properties of soils from these sections, they are accepted as the source for numerical modeling;
3) In the absence of such data, or in case of insufficient volume, the physicomechanical properties of soils are accepted in the range “from ... to ...” according to the normative documentation for this type of soil (sands, clays, limestones, etc.), as well according to data for similar tunnel construction conditions;
4) A numerical simulation is performed, according to the results of which the calculated values of vertical and horizontal displacements of the soil mass, horizontal deformations of the earth's surface, slopes, curvature are determined;
5) Based on the simulation results, zones of influence and zones of hazardous effects of tunnel construction are determined;
6) The zones of influence are applied to the general plan of the surface, the buildings and structures falling into the zone of influence are determined;
7) For buildings and structures falling within the zone of influence of the construction of tunnels, special observation stations are created for surveying (geodetic) monitoring of deformations, including automated monitoring, including observations of subsidence, banks and horizontal deformations of buildings and structures;
8) The results of direct monitoring are correlated with the calculated data, and if necessary, the calculated models are adjusted to fully comply with the results of field observations.

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