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# METHOD OF PREDICTING EARTH SURFACE SUBSIDENCE DURING THE CONSTRUCTION OF TUNNELS USING TBM WITH FACE CANTLEDGE ON THE BASIS OF MULTIVARIATE MODELING

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## ABSTRACT

*The paper analyzes the scientific literature on the construction of tunnels in complex engineering and geological conditions using tunnel boring machines (TBMs), on the basis of which a classification has been proposed for methods for predicting earth surface subsidence and rational values of face cant ledge. The method of predicting earth surface subsidence based on the analysis of geo mechanical processes occurring near the tunnel face during its tunneling with the use of TBM with active face cant ledge are presented, as well as the flowchart of its implementation. The method is based on the use of multivariate numerical modeling to solve the complex problem of the mechanics of underground structures in a spatial formulation based on the interaction scheme using inelastic geo mechanical models of soil behavior and allows determining rational parameters of the tunnel construction technology from the point of view of ensuring geo mechanical safety.*

**Keywords:** Subsidence, Displacement, TBM, Method, Face Cant ledge, Soil Mass, Tunnel, Underground

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## 1. INTRODUCTION

During the construction of underground structures in complex mining and geological and hydro geological conditions, especially in dense urban areas, currently, tunnel boring machines (TBMs) with various types of face cant ledge are usually used [1-3].

Tunneling using a TBM with face cant ledge allows obtaining high tunneling rates during construction in complex engineering and geological conditions due to the high degree of mechanization of tuneless' work. Another obvious advantage of such a construction technology is the ability to avoid loss of stability of the face in the process of tunneling due to its constant back pressure by means of cant ledge, which can be created in various ways (soil load, hydro-cant ledge, foam cant ledge, etc.).

With the right choice of the type and pressure of the face, it is possible to achieve full compensation for the displacement of the plane of the face inside the excavation, thus avoiding earth surface subsidence, which will allow creating a construction technology with practically no subsidence, provided there is a sufficiently rigid bracing system for the extended part of a tunnel.

In connection with the obvious advantages of using construction technologies with low risk of subsidence in the conditions of dense urban development, the relevance of the chosen research topic becomes clear.

## 2. METHODS

### 2.1. The main factors that should be considered when predicting earth surface subsidence

A large number of scientific works are devoted to the tasks of studying geo mechanical processes in a soil mass near the tunnel face when tunneling using a TBM with active face cant ledge, and the main part of the ideas, included in these works, is formulated in the works [4-15].

Conventionally, all the methods for predicting earth surface subsidence and rational values of face cant ledge in scientific works can be divided into four groups according to the sign of the approach used to predict the size of the zone of significant inelastic (that is, plastic and/or rheological) deformations in the surrounding soil mass:

- a group of analytical methods – prediction of the size of the zone of significant inelastic deformations is performed analytically, usually without taking into account the restraining influence of the cant ledge pressure, and face cant ledge is considered as a load that should keep the soil volume from collapsing within the zone of significant inelastic deformations;
- a group of empirical methods – the calculation of earth surface subsidence and rational pressure value of the face cant ledge is performed on the basis of empirical dependencies, which are derived based on the analysis of a large amount of field observations;
- a group of experimental methods – the calculation of the earth surface subsidence and the rational pressure value of the face cant ledge is carried out on the basis of empirical dependencies, which are derived based on the physical modeling of tunneling using a TBM with active face cant ledge;
- a group of numerical methods – the size of the zone of significant inelastic deformations is predicted on the basis of numerical modeling using the finite element

method (FEM), discrete element method (DEM) or any other, which allows predicting changes in the size of this zone and earth surface subsidence taking into account the strengthening action of the cant ledge pressure.

Analytical methods are largely based on the concept of loss of stability of the soil mass in the front of the tunnel face, as formulated in Horn's work [13]. They have an important property of the universality of solutions, and therefore the labor intensity of their practical implementation is at the lowest level, but at the same time, they do not take into account many important features of the tunnel construction technology, and therefore they should be used only for calculations for the first approximation, as well as for checking.

Empirical methods are simple in practical use, but give reliable results only in specific engineering and geological and technological conditions in the conditions of tunnel construction, for which they were developed. In many ways, this group of methods was developed in the works by Broms and Bennermark [11]. Creating such techniques is extremely time-consuming, since it is associated with the need to accumulate large amount of field observations, without which the resulting formulas will not be representative.

Experimental methods are based on using the results of physical modeling with the application of the basic dependencies of the similarity theory. To implement this approach, rather complicated and expensive laboratory equipment (for example, centrifuges) is required, and the solutions obtained on the basis of physical modeling are obviously not universal. A great advantage of this approach is the principal opportunity to simulate an emergency situation in a tunnel, accompanied by a loss of stability of the front of the face, and to visually observe the processes of soil mass deformation near the tunnel face after the collapse of the rocky outcrop.

Numerical methods are based on the use of the results of mathematical modeling using various numerical methods. This approach allows obtaining a solution to the problem of predicting the stress-strain state of soil mass near the tunnel face when tunneling using a TBM with an active face cant ledge based on the interaction scheme.

The method of predicting the earth surface subsidence during the tunnel construction with TBMs with face cant ledge, proposed in this work, is based on the use of multivariate numerical modeling based on the finite element method, i.e. it can be attributed to a group of numerical methods.

Multivariate modeling is performed to identify the basic laws of the formation of the stress-strain state of the "soil mass – lining – shield shell" system, taking into account the main technological features. By consistently changing the main influencing technological factors on the models, it is possible to establish generalized patterns of their influence on the parameters of the stress-strain state of this system, including the vertical subsidence of earth surface within the area of under working.

As a result of the analysis of emergencies arising during the tunnel construction with TBMs with active face cant ledge in various engineering and geological conditions, the main technological factors have been identified that have decisive influence on the formation of earth surface subsidence trough in the area of undermining a tunnel. These factors include:

- Injection pressure of cement slurry, which is injected over the ring of the tunnel lining, converging with the tail shell of the shield complex to the rock contour. This pressure creates resistance to the free displacement of the rock contour within the gap between the rock contour and the outer contour of the tunnel lining;
- The pressure of the active face cant ledge of the tunnel. This pressure creates resistance to free displacements of the plane of the tunnel face in the direction of the

undermined space and prevents the loss of stability of the front of the tunnel face. Depending on the type of cant ledge, the model can be represented in the form of a uniformly distributed (uniform pressure over the face area) or in the form of an unevenly distributed load;

- a decrease in the tunnel volume led by a decrease in its cross-sectional area due to free displacements of the rock contour within the gap between the cutting diameter of the executive body of TBM and the outer diameter of its tail shell (i.e. due to the actual taper of the shield shape).

The formation of a significant trough of earth surface subsidence is also possible due to the destruction of the tunnel lining rings, as well as due to possible technological errors made during the direct conducting of tunneling works, and the manifestation of unpredictable natural phenomena (the presence of various irregularities in the array of surrounding rocks in a tunnel route, quicksand's, confined groundwater, tectonic disturbances, etc.), which were not identified during the engineering and geological and hydro geological examinations. However, these factors do not seem appropriate to be considered while predicting trough of earth surface subsidence, since their appearance is related not to regular situations, but to the erroneous design decisions made at earlier stages of the project development and construction technology violations due to insufficient qualification of direct contractors of tunneling works or force majeure circumstances.

Multivariate numerical modeling should be performed in a spatial formulation using elastoplastic and visco-elastoplastic geo mechanical models to describe the mechanical behavior of soil mass. If there is anisotropy of deformation and strength properties in the soil mass, it should be taken into account by using appropriate anisotropic media models [16, 17].

The actual change in the deformation and strength properties of the soil mass in depth should be taken into account directly while modeling, specifying their change in the form of the functional dependences of the deformation and strength characteristics of the environmental model on the laying depth. The main parameters of these functional dependencies should be determined on the basis of a study of the results of laboratory tests of soil samples under various types of stress conditions and field observations of exploration wells.

If there is confined or unconfined groundwater, it should be taken into account when making predictions of the parameters of the trough of earth surface subsidence by means of appropriate mathematical models, which are available in the software package used for multivariate numerical modeling. One should take into account water buoyancy, its excess pressure if available, the inclination to filter groundwater when extracting an array within the contour of a tunnel under construction into the excavated space and features of water extraction from the soil interstices under the mechanical influence (drained and untrained behavior). The mechanical behavior of wet and water-saturated soil, as well as its physical and mechanical properties, is studied on the basis of laboratory tests, and the parameters of groundwater, on the basis of hydro geological surveys and multivariate modeling, are set in correspondence to those obtained as a result of conducting such a set of studies.

In the case of significantly varying topography within the studied area of the earth surface, which is subjected to additional work during the tunnel construction, especially in terms of significant variations in elevation, the real geometry of the earth surface obtained from the results of a topographical survey of the terrain should be used in the modelling. This makes it possible to correctly predict the parameters of the natural stress state and subsequently describe more correctly the distribution of vertical subsidence during the tunnel construction, especially at relatively shallow laying depths.

## 3. RESULTS

As an example of implementing the proposed methodology for predicting earth surface subsidence when it is undermined by a tunnel, conducted using a TBM with active face cant ledge, the authors propose to consider the case when a typical five-story residential building is located in the area of undermining.

The calculations provided for the possibility of undermining the building with a tunnel led directly under the building, as well as with a shift from its vertical axis at a distance (1.5-6.5) D (D = 10 m – the diameter of the tunnel). In addition, with multivariate modeling, the possibility of different spatial orientations of the tunnel with respect to the building was considered, namely, across the building (the longitudinal axis of the tunnel was oriented across the extended side of the building) at an angle of 45° (the longitudinal axis of the tunnel was inclined to the extended side of the building at an angle of 45°) and along the building (the longitudinal axis of the tunnel was oriented across the extended side of the building).

The task has been set as follows. On the soil, it is prohibited to shift the lateral faces of the model in the direction of the X-axis (see Figure 1), the lower face of the model should not be shifted in the direction of the Y-axis, and the end faces of the model should not be shifted in the direction of the Z-axis. The upper face of the model is left freely deformable. The field of natural stresses in the model is formed under the action of its own weight of geological differences presented in the model, in the vertical direction, and in the horizontal directions, the stresses are formed due to the effect of horizontal thrust.

The building and the soil mass interact through hard contact, and the building is put into operation on the model after the completion of the formation phase of the natural stress state in the soil mass. The tunneling on the model was conducted against the direction of the Z-axis.

The physical and mechanical characteristics of the surrounding soil mass used in the modeling are listed in Table 1.

**Table 1.** Estimated physical and mechanical characteristics of the soil mass

| Material | Specific gravity, $MN/m^3$ | Compressive strength of rock masses, MPa | Deformation modulus of rock masses, MPa | Poisson's ratio | Angle of internal friction, deg. | Tenacity, kPa |
|---|---|---|---|---|---|---|
| Sand | 0.019 | - | 30 | 0.37 | 30 | 1 |
| Clay | 0.021 | - | 15 | 0.33 | 20 | 25 |

Figure 1 shows the isochromes of the vertical subsidence of the soil mass and the structural elements of a residential building during under working by a tunnel, conducted with the use of a TBM with active face cant ledge, with different spatial orientation of the building for the variant when the tunnel is put at a distance of 1.5D from the vertical axis of the building.

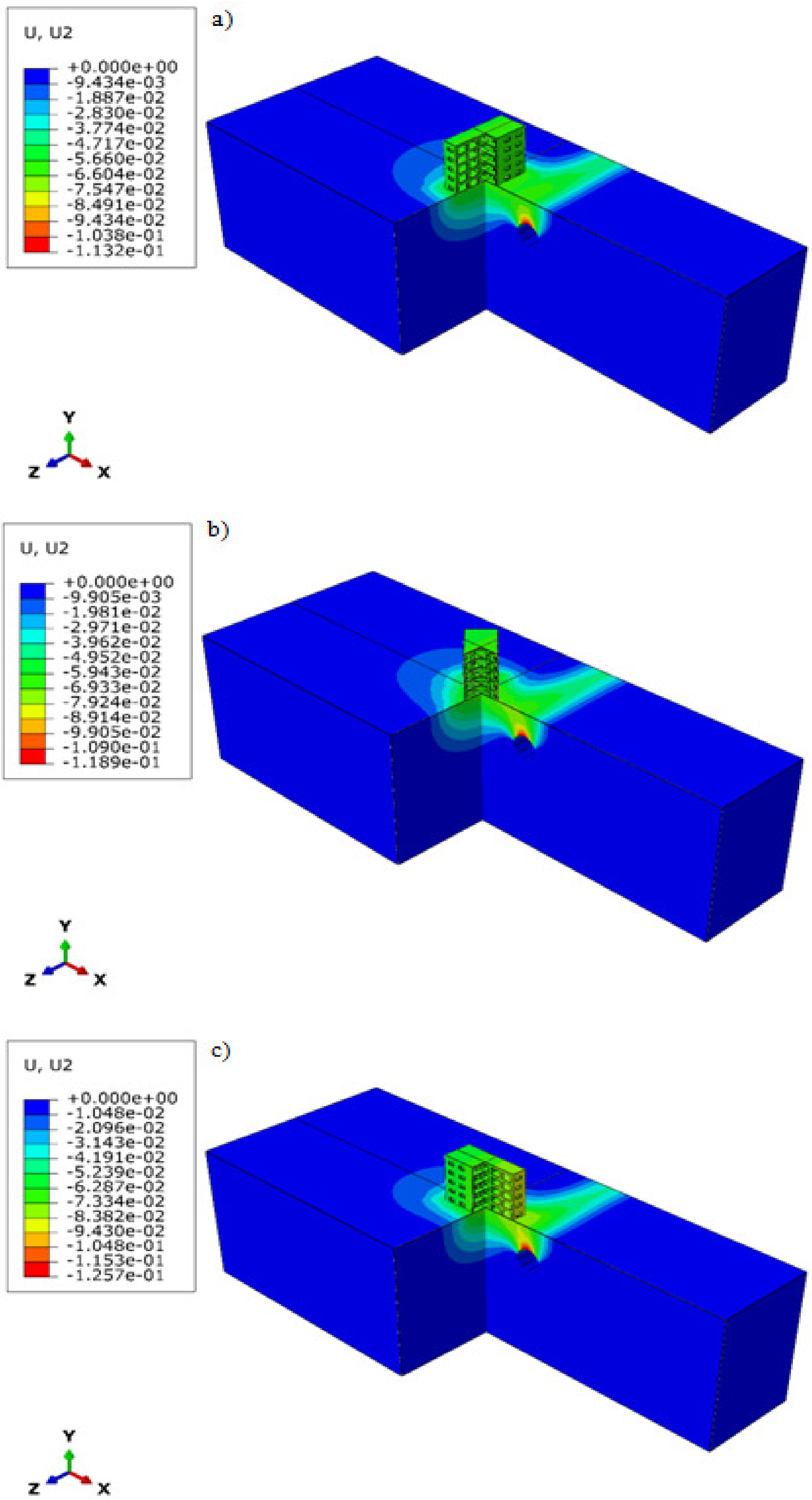


**Figure 1.**Isochromes of vertical subsidence of earth surface with different orientation of the tunnel towards the building, m. a) along the building; b) at an angle of 45°; c) along the building

Figure 2 shows the development curves of the largest principal stresses in the lower part of the building wall as the tunnel face moves in relation to the vertical axis of the building. The figure shows a variant when the tunnel is oriented at an angle of 45° towards the building; however, it should be noted that, with different orientations, the patterns of stress development in the lower part of the building wall are generally similar.

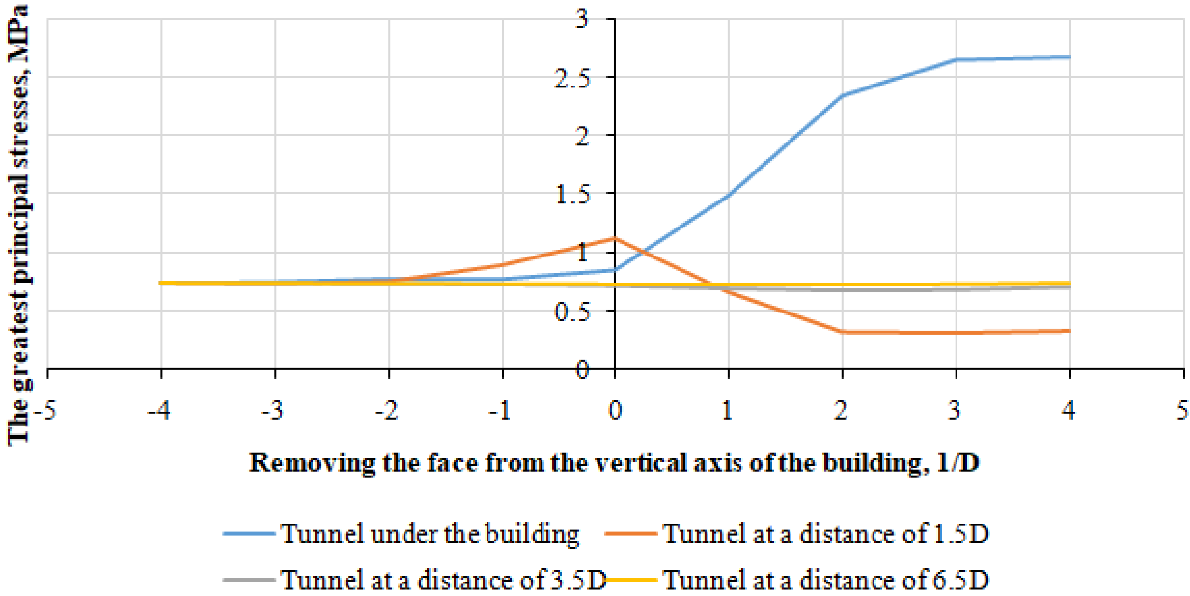


**Figure 2.** Development curves of the largest main stresses in the lower part of the building wall as the tunnel face moves

The assessment of the development of the largest principal stresses in the lower part of the building wall allows judging that the tunnel has an effect on the stress state of the supporting structures of the building up to a distance of 3.5D from the vertical axis of the building. The analysis of the resulting isochromes of the vertical subsidence of the soil mass and building structures leads to the same conclusions. This effect may be different depending on the actual distance at which the tunnel is undermined, but it is always expressed in its final form in the asymmetry of the distribution of stresses in the supporting structures.

The analysis of the stress state development in the supporting structures of the building, conducted on the basis of the results of multivariate modeling, allows concluding that the under working of the building mainly leads to an increase in stresses in most of the supporting structures, the areas of stress reduction are local in nature.

## 4. DISCUSSION

To implement the proposed methodology for predicting earth surface subsidence with the use of a TBM with active face cant ledge on the basis of numerical modeling, the following stages should be followed:

1. Study of earth surface topography within the under working area.
2. Study of geological cut within the tunnel route, which is constructed with the use of TBM.
3. Examination of the results of laboratory studies of the soil mass.
4. Study of the results of hydro geological examinations.
5. Study of the technical passport of the TBM with active face cant ledge and its passport engineering design.
6. Development of the geometry of the basic numerical model for multivariate modeling. The outer dimensions of the model should be chosen in such a way that the boundary

conditions applied to the lateral faces of the model do not affect the parameters of the earth surface subsidence trough. The greater is the width of the subsidence trough in the cross-section of the tunnel, the bigger are the own diameter and the laying depth of the tunnel. In general, the following recommendations can be followed:

- when the tunnel depth is up to 3D (D is the diameter of the tunnel in tunneling), the model dimensions should be at least 7D×7D in the cross-sectional plane of the tunnel;
- when the tunnel depth is more than 3D, the model dimensions should be at least (1.5-2)H×(1.5-2)H (H is the tunnel depth) in the cross-sectional plane of the tunnel.

In the direction of the longitudinal axis of the tunnel, the size of the model should be taken depending on the number of stages of tunneling, which are supposed to be modeled.

7. The basic parameters of geo mechanical models of soils and other materials that will be used in modeling are prescribed in the numerical model, the parameters of hydrogeology are prescribed, and in the first approximation technological parameters are set that determine the main factors influencing the formation of earth surface subsidence trough (cement slurry pressure, the pressure of face cant ledge and the loss of the tunnel volume), the boundary conditions are set, and the field of natural stresses is formed.
8. A trial calculation is performed with predetermined technological parameters, earth surface subsidence trough is built, and an analysis of the obtained results is performed.
9. Out of the three main technological factors, two are fixed on the same value, and one consistently changes in the operating range of the used TBM to reveal its influence on the change in the parameters of the resulting earth surface subsidence trough. Thus, it is necessary to determine the differential influence of each of the three technological factors and the results of such an analysis should be presented in the form of the diagrams.
10. Based on the constructed generalized diagrams of the differentiated influence of the main technological factors, one should either set the necessary values of the relevant technological parameters to ensure the required values of the vertical subsidence of the earth surface, or determine the resulting vertical subsidence of the earth surface, which is formed while constructing a tunnel.

In general, the proposed method in the form of the main stages and their results can be represented in the form of a flowchart shown in Figure 3.

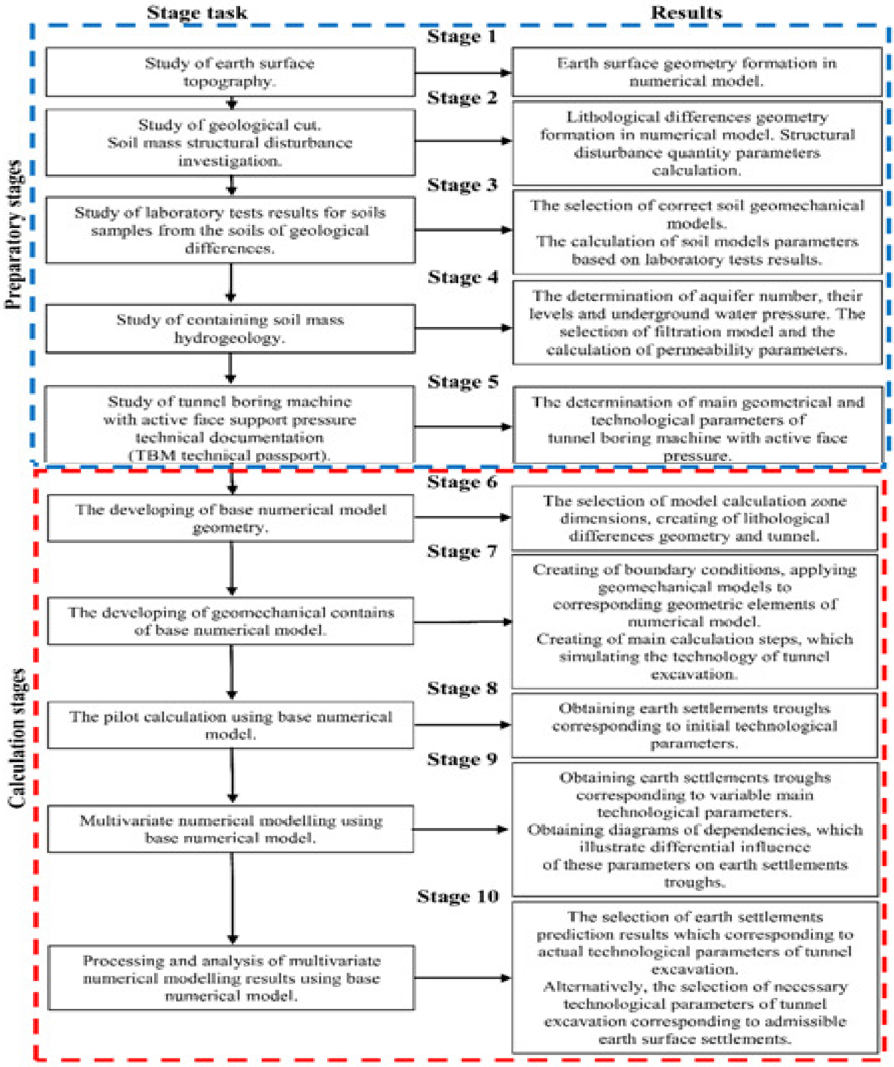


**Figure3.**A flowchart of the method of predicting earth surface subsidence

## 5. CONCLUSION

The article attempts to formulate the main approaches to predicting the earth surface subsidence during the construction of tunnels with the use of TBM with active face cant ledge. The proposed method has broad opportunities for adaptation for specific conditions of tasks being solved and is characterized by using numerical methods for solving problems of mechanics of underground structures, which makes it possible to take into account the main technological, geo mechanical and hydro geological factors that largely determine potential earth surface subsidence.

The proposed method allows determining the rational parameters of the tunnel construction technology from the point of view of ensuring geo mechanical safety, which makes it possible to adjust the corresponding design decisions.

## 6. ACKNOWLEDGEMENTS

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