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THE METHOD OF DETERMINING THE RATIONAL TUNNEL FACE PRESSURE BASED ON PREDICTION OF STRESS-STRAIN STATE OF "SOIL-LINING" SYSTEM IN THE BOTTOMHOLE ZONE OF THE TUNNEL DURING THE TUNNELING OPERATION USING TBMC

Anatoliy Grigoryevich Protosenya, Nikita Andreevich Belyakov, Petr Alekseevich Demenkov

Saint-Petersburg Mining University, Russia, 199106,
Saint-Petersburg, Vasilevskiy Island, 21-st line, 2

ABSTRACT

In this paper the technique of determination of rational values of tunnel face pressure in the bottom of the tunnel in a massif of soft soils based on the analysis of the geomechanical processes occurring in the bottom part of the tunnel during the tunneling with the use of tunnel-boring mechanized complex (TBMC) with active tunnel face pressure (TFP) is described. The technique is based on the use of multivariate numerical simulation for solving complex problems of mechanics of underground structures in a spatial setting based on the interaction schemes with the use of elastic and inelastic mechanical behavior of soils.

The paper presents an implementation of the proposed method for determining the rational TFP during the construction of tunnels in engineering-geological conditions of the section between stations "Lesnaya" and "Ploschad Muzhestva" and between the stations "South" and "Danube" of Saint-Petersburg metro. An attempt of verification of the proposed computational method on the results of in-field observations of land subsidence has been performed.

Key words: tunnel, metro, TBMC, subsidence, strain, TFP, tunnel face, the lining.

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1. INTRODUCTION

During the construction of underground structures in complex geological and hydrogeological conditions, especially in dense urban areas, the tunnel-boring mechanized complexes (TBMC) with different types of tunnel face pressure (TFP) are generally used [1; 2; 3].

The tunneling using TBMC machines with TFP allows to obtain a high rate of tunelling during construction in difficult engineering-geological conditions due to the high degree of mechanization of labor drifters.

Another clear advantage of this construction technology is the ability to avoid the loss of stability of the bottom hole during tunneling due to its constant pressurization force of TFP, which can be created in various ways (earth pressure balance, hydro-pressure balance, foaming pressure balance and others). With proper selection of the TFP it is possible to achieve full compensation of displacements of the bottom plane inside the mined-out space. This latter allows to avoid subsidence of the surface, i.e. it will allow to create almost subsidence-free construction technology.

The objectives of the study of geomechanical processes occurring in the soil massif in the area of the bottom part of the tunnel during the tunneling operation with the use of TBMC with an active TFP was a subject of many scientific works, and the main part of the ideas is reported in the papers [4-24].

Conventionally, the whole mass of techniques of prediction of rational values TFP in scientific work can be divided into four groups on the basis of the approach to the prediction of dimensions of significant inelastic (i.e., plastic and/or rheology) deformations in the host soil:

- the group of analytical methods, where prediction of the size of zone of significant inelastic deformation is carried out analytically, usually without taking into account the restraining effect of the TFP, and the TFP is considered as a load which has to prevent the collapsing the volume of soil within the zone of significant inelastic deformations;
- the group of empirical methods, where the calculation of the rational TFP is performed on the basis of the empirical relationships which are based on the analysis of a large volume of results of in-field observations;
- experimental techniques, where the calculation of rational TFP is performed on the basis of the empirical relationships which are based on the physical modeling of the development of the tunnel by TBMC with active TFP
- group of numerical methods, where the prediction of a significant inelastic deformations is performed on the basis of numerical simulations using the finite element method (FEM), method of individual elements (DEM), or any other method that allows to perform a forecast of changes in the size of this zone with respect to the reinforcing action of the TFP.

Analytical methods are largely based on the concept of loss of stability of the soil mass in front of the tunnel face, formulated by Horn (Horn 1961). They possess the important property of universal solutions, and, therefore, the complexity of their practical implementation is the smallest. However, at the same time these methods do not take into account a number of important features of the technology of tunnel construction, and therefore they should only be used for the calculations in the first approximation, and for verification.

Empirical methods are simple in practical use, but they give reliable results only in specific geological and technological conditions of the tunnel construction, for which they were developed. In many ways, this group of techniques developed in the works of Broms and Bennermark [11]. The development of such techniques is extremely labor-cost because it deals with the necessity of accumulation of a large amount of data of in-field observations, and without them the obtained empirical formulas will not be representative.

Experimental methods are based on the results of physical modeling with the application of basic dependencies of the theory of similarity. To implement this approach, a complicated and expensive laboratory equipment (e.g. centrifuge) is required and obviously, the solution obtained on the basis of physical modeling is not an universal one. The great advantage of this approach is a possibility to simulate an emergency situation in the tunnel, accompanied by the loss of stability of the tunnel face and to observe the process of deformation of the soil mass in the area of the bottom part of the tunnel after the collapse of the rock exposure.

Numerical methods are based on the usage of the results of mathematical modeling using various computational methods. This approach allows to obtain the solution of the problem of prediction of stress-strain state of the soil massif in the area of the bottom part of the tunnel during its tunneling with the use of TBMC with an active TFP on the basis of the scheme of interaction. Then sequentially performing multivariate numerical simulation at different TFP load values it is possible to find a rational value of the pressure of TFP necessary for the preservation of the tunnel face in a steady state to prevent the filtering of groundwater in mined-out space, and to minimize land subsidence upon a need.

The methodology proposed in this paper should be attributed to the group of numeric data because it involves the use of multivariate numerical simulation using the finite element method.

2. METHODS

During the tunnel construction in difficult engineering-geological conditions with the use of TBMC with TFP the main objective of the EPB load is ensuring the stability of the tunnel face, preventing groundwater filtering (if any) in the mined-out space in the bottom part of the tunnel and reduction (or in ideal case the full compensation) of land subsidence due to the development of the tunnel.

In this article the technique of calculation of the required in the tunnel during its development using TBMC is proposed. The proposed method is based on multivariate numerical modeling of geomechanical processes occurring in the soil massif hosting the tunnel, particularly in its bottom part during the tunelling. Multivariate modeling is a sequential change of the value of TFP, while examining the sustainability of the tunnel face and magnitude of land subsidence. In addition, the obvious interest concerns the relationship of stress-strain state of elements of the tunnel lining from the parameters active TFP machines. The multiple-choice questions devoted to numerical simulations [25; 26; 27].

It should be noted that multivariate numerical simulation should be performed in the spatial formulation using elastic-plastic or visco-elasto-plastic geomechanical models of the behavior of the enclosing soil massif. This is due to the fact that in the massif of soft soils, especially in the bottom part of the tunnel, a significant contribution to the resulting deformation processes make it non-elastic (plastic or rheological) strain and defiance in the behavior of soil leads to significant inaccuracies in the prediction of stress-strain state of the massif.

In general, the proposed technique can be represented as the following sequence:

- Analysis of the results of laboratory tests of the soil from the site of tunnel construction and selection of appropriate geomechanical behaviour of soil with subsequent determination of the model parameters on the basis of test results.
- Development of a numerical model of tunnel construction with the use of TBMC with active TFP.
- Implementation of multivariate simulation in the framework of the developed numerical model of tunnel construction using TBMC, based on the sequential change of the value of TFP within a certain range, accompanied by tracking changes in the condition of stability of the tunnel face and land subsidence.
- Processing and analysis of multivariate modeling leading to the preparation of graphic dependence of land subsidence and longitudinal relative to the axis of the tunnel, displacement of the tunnel face on the magnitude of TFP.

By using this dependence one can find the most suitable TFP value in terms of stability of the tunnel face and to minimize land subsidence, which is essentially a solution of the targeting problem.

It should be noted that since as a primary design approach of the proposed methodology assumes the use of numerical simulation, the results are essentially the solution of the problem on the interaction mechanics of underground structures in spatial statement. This means that what is happening in the area of the bottom part of the tunnel in soil inelastic deformation processes is largely dependent on the magnitude of TFP and parameters of the lining of the tunnel. This approach is more reliable than analytical approaches described above, which consider the thesis of independence of the deformation parameters of TFP and the magnitude of TFP is only considered as active pressure, designed to retain sediment from collapsing within the prism of sliding in front of the tunnel face.

3. RESULTS

We used the proposed methodology to determine required value of TFP at the bottom of the tunnel in engineering geological conditions of the construction of the running tunnels between the stations "Lesnaya" and "Ploschad Muzhestva" and between the stations "South" and "Danube" metro of Saint-Petersburg.

The first phase of the outlined above tunnels has a particular interest because theses running tunnels route is crossed by an ancient riverbed, which is currently filled with quicksand. The Geology of this area was the reason for the appearance in 1974 of a serious accident, namely, the breakthrough quicksand, the construction of the first pair of tunnels, and by 1995, these open-line tunnels of the first phase on the stretch of quicksand critically dipped and this led to the decision about the necessity of their flooding. Running tunnels of the second stage were built with the use of TBMC with hydro pressure balance and the development was accompanied with many difficulties, however, in 2004, the tunnels were put into operation [28].

Obviously, the engineering-geological conditions of the development of tunnels in thearea of quicksand can be attributed to the complex ones. At the same time, construction of tunnels of the second stage was accompanied by the implementation of a significant volume of in-field studies in order to overcome the plot of quicksand, which is good from the point of view of verification of the computational method proposed in this work. In this regard, this section of the Metropolitan of St. Petersburg was selected for present study.

In order to study the influence of TFP load on the stress-strain state of a massif, we have performed a finite element modeling of the underground rock mass containing dead-end mined out space of circular shape fixed by concrete supports and at the head supported by the shell of TBMC. The lag of the supports from the bottom of tunnel was 1 m. For modeling the diameter of the mined out space of the tunnel was taken equal to 7.1 m, whereas the depth of its inception was 50 m. Unfixed mined out space in the plane of the bottom of tunnel were either freely deforming or subjected to TFP processing with different force.

The TFP was modeled with uniformly distributed load applied directly to the plane of the bottom of tunnel and to the walls of the tunnel in the area between this plane and the shell of TBMC. It should be noted that fundamentally TFP should be simulated with the load distributed on the tunnel face, gradually increasing the height of the tunnel, i.e. taking into account the self-weight of the material of TFP.

A separate issue arising in the modeling of the tunnel construction with the use of TBMC is the investigation of the formation of the stress-strain state of lining of the tunnel. It is obvious that the parameters of TFP not only affect the displacement of the rock contour of the tunnel and subsidence of the earth's surface, but also on the stress state of the elements of the tunnel lining.

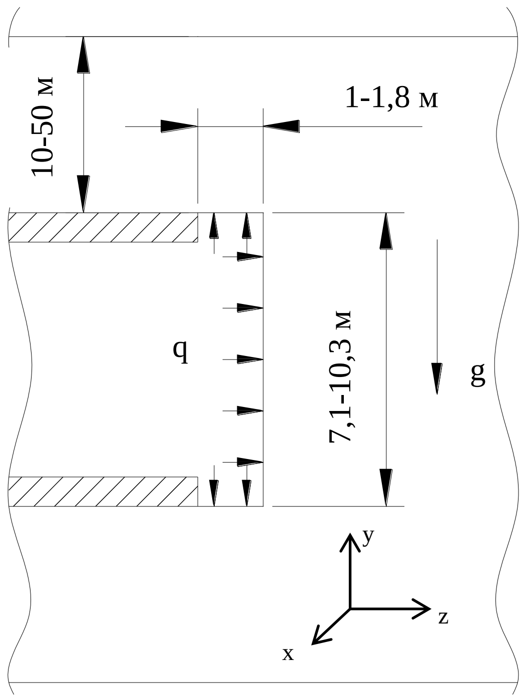

Figure 1 Fundamental design scheme

To investigate this issue we have chosen the construction site of the tunnel of the metro of Saint Petersburg that is located between the stations "South" and "the Danube". This area is distinguished by the fact that this running tunnel was built with the use of double-track TBMC with a diameter of 10.3 m. The depth of greater part of the tunnel is about 10 m, and the gap of the lining from the bottom of tunnel is 1.8 m.

A fundamental design scheme is presented in Figure 1. According to the design scheme, in the model we created non-uniformed initial stress field under the action of its own weight of a rock mass.

The problem was solved with the use of elastic and elastic-plastic models behavior of the soil mass in condition of plasticity of Coulomb-Mohr. To account the influence of strength and deformation properties of rocks composing the massif, and the parameters of TFP when carrying out work on displacement of massif, the problem was solving in two stages:

- in the first stage, we calculated the initial stress field and historical displacements in intact massif under its own weight with the boundary conditions given above.

in a second step, the model of the array of stress and strain as defined in the first phase, was attenuated by output of circular shape. In the result to determine the displacements produced as a result of the tunnel, from full field displacement was deducted its historical component, found in the first stage.

Strength and deformation characteristics of the soil mass that were used in the simulation are presented in table 1.

Table 1 Strength and deformation characteristics of the soil mass

Sample N	Indicator	Unit	Value
1	Unit weight	kN/m^3	23,54
2	Modulus of total deformation	MPa	50
3	The coefficient of transverse deformation		0,35
4	Angle of internal friction	degrees	9
5	Grip of massif	MPa	0,05

When performing mathematical modeling of the magnitude of the TFP q was varied from 100 kPa to 1 MPa; it is represented in parts by γH (where γ – weighted average unit weight of soil, kN/m3; H – depth of workings, m).

The results of multivariate mathematical modeling for the section of the tunnel between the stations "Lesnaya" and "Ploschad Muzhestva" led to a number of graphical dependencies of the distribution of the longitudinal displacements of the rock mass directly behind the plane of tunneling and the highest vertical land subsidence for different values of the TFP. The graphical analysis of these dependencies allows to execute them in a single graph of longitudinal displacement and vertical settlement processes directly from the magnitude of the TFP machines shown in Figure 2.

By using the data presented in the graph and using the given valid values of vertical surface subsidence it is possible to determine the magnitude of the longitudinal displacement of the plane of the bottom inside of the tunnel and to determine the necessary value of TFP.

It can be seen from the diagram that the magnitude of the vertical subsidence of the surface less than the service limit is achieved only when magnitudes of TFP machines are in the order of 0.35 γH. The magnitude of the longitudinal displacement of the plane of the bottom inside of the tunnel is not more than 0.18 m.

The achievement of a fully subsidence-free technology is possible when the value of the TFP load is in the order of 0.38 to 0.4 γH. However, note that at zero vertical displacement on the earth's surface, longitudinal displacement of the tunnel face will take place and it will be about 100 mm.

When the values of the TFP load is more than 0,42 γH, there will be a rise (lifting) of the soil on the surface, and it is a highly undesirable process.

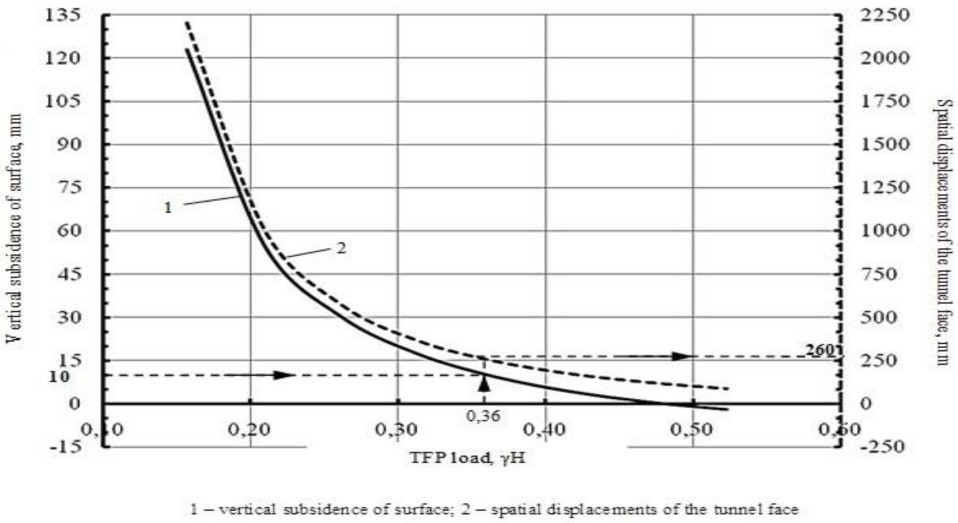

Figure 2 Diagram of dependence of spatial displacements along the axis of the tunnel behind the forehead of tunneling and vertical displacements of earth surface as a function of the TFP value.

Numerical simulation of multivariant of the section of the tunnel between stations "South" and "Danube" of the Metropolitan of St. Petersburg was carried out to analyze the influence of the parameters of TFP on the stress-strain state of lining of the tunnel. The resulting simulation graphs of the formation of the largest compressive stresses at the top of the arch of the tunnel lining as moved to the bottom of the tunnel for the first variant of the mixed tunneling is presented in Figure 3.

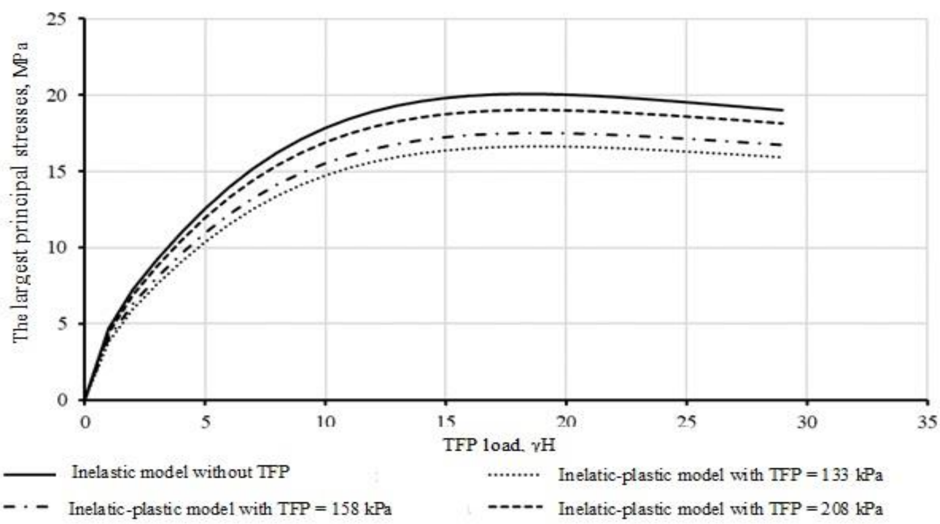

Figure 3 Graphics of dependences of the largest principal stresses in the arch of the tunnel lining from the value TFP of tunnel face.

The magnitude of the greatest compressive stresses depends on the pressure of TFP. The greater the TFP pressure is used in tunnel development, the larger the stress values are in the lining at constant other conditions. This is caused by a fact that high pressure of TFP can better keep an massif from the displacement, and then as a result, the majority of the potential displacements of the tunnel contour is realized in the form of additional load on the tunnel lining.

4. DISCUSSION

One of the main objectives of this study was to perform a verification of the proposed computational method. Such verification can only be done on the basis of the comparison of the modeling results with the results of in-field observations of the predicted geomechanical processes occurring in the soil mass in the development of tunnels.

To check the reliability of the methods of prediction of movement in the construction of tunnels in complex geological and hydrogeological conditions we used the results of in-field observations in the construction of running tunnels between the stations "Lesnaya" and "Ploschad Muzhestva" (the so-called area of "Washout") of the Metropolitan of St. Petersburg.

Tunnels through "Washout" with a total length of about 1600 m completed mechanized ALPINE POLYSHIELD PDS 740-09/RM (TBMC) with an outer diameter of the front 7385 mm and outer tunnel lining 7100 mm.

The development of tunnels on the section between the stations "Lesnaya" and "Ploschad Muzhestva" was accompanied by considerable difficulties and a separate long stops of TBMC (2 to 4 months). This circumstance has predetermined the features of the process displacement of the earth's surface.

In Figure 4 the plots of in-field observations of land subsidence on the profile lines are shown [29]. After crossing the first tunnel by data lines, the subsidence on its axis was 9-10 mm.

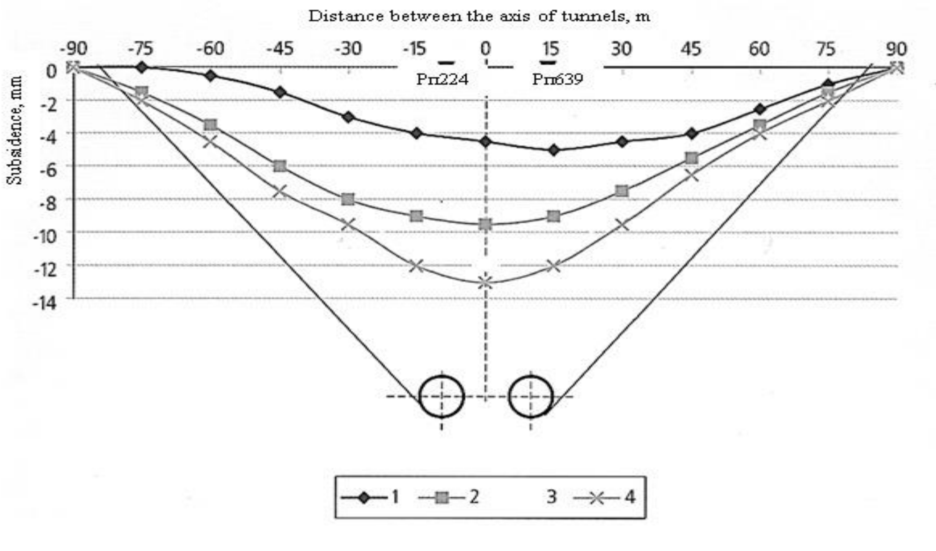

Figure 4 Dynamics of the earth surface subsidence along the profiles of soil baselines in areas of long stop of tunneling in the mud (profile line 2) and the “Washout” zone (profile line 6): 1 - After excavation of first tunnel under profile lines 2 and 6; 2- After excavation of second tunnel under profiles lines 2 and 6 in December 2004 (after finishing of the construction of the tunnels)

Development of the second tunnel under the same profile lines caused a further increase in subsidence up to 16-18 mm. After the end of the tunnel construction in 2004, it has increased by 2-4 mm. Measurements in December 2004 recorded the subsidence of 22-24 mm, which corresponds to an increase of 2 mm. The maximum values of deformations of the earth's surface that were calculated on the basis of the data presented above surface, were as follows: bevel of 0.5 mm/m, the curvature of $0{,}2x10^4$ 1/m (the radius of curvature R=50 km).

According to the results shown in Figure 2 the estimated relative value of the TFP load required for obtaining the land subsidence in the order of 9-10 mm is about (0,35-0,4) γH, which corresponds to the absolute value of pressure in the order of 4-4,5 bar, and it coincides with the pressure value of the TFP used in the area of overcoming quicksand during the construction of running tunnels between the stations "Lesnaya" and "Ploschad Muzhestva". Thus, it is possible to conclude that the good coherence of the results obtained on the basis of multivariate numerical modeling and in-field observation.

Note that for full testing of the methods proposed in the present work, it should be repeatedly checked under different conditions, including conditions when the construction of the tunnel with TBMC is performed in the massif of soils with distinct rheological properties, i.e. in the case when describing the mechanical behaviour of the soil we will have to use a viscoelastic or visco-elasto-plastic geomechanical model. This seems as the one of the most promising directions of further development and generalization of the proposed design methodology.

5. CONCLUSIONS

The construction of urban underground transport in dense areas is often faced with the necessity of construction of tunnels at relatively shallow depths and in the complex engineering-geological conditions (weak soft soils or silt, and/or large water inflows). It is not enough just to provide the stability of rock outcrops in the tunnel during the construction period. Here it is necessary to provide (if possible) either low subsidence or subsidence-free tunneling. This latter is possible only through the use of TBMC with active TFP machines, the type of TFP and pressure of TFP have to be justified with reference to the engineering-geological conditions of construction and depth. In this regard, a task which was proposed in the framework of this scientific article is extremely relevant to urban underground construction.

The methodology developed in this article was tested for the calculation of the parameters of TFP in the construction of tunnels between the stations "Lesnaya" and "Ploschad Muzhestva" and between the stations "South" and "Danube" of metro of Saint-Petersburg. The comparison of the simulation results with the results of in-field studies showed a good convergence for the pressure of TFP and vertical land subsidence. Thus, the proposed methodology showed its effectiveness when using the elastoplastic model with the condition of plasticity Coulomb-Mohr to describe the mechanical behaviour of the soil massif.

The development of the proposed method would be in the performance of its verification for the conditions of the construction of tunnels with application TBMC with the active TFP machines in the soil that is tend to significant rheological properties, i.e. in the case where the mechanical behavior of the soil in the simulation should describe the viscoelastic or visco-elasto-plastic models. In addition, the certain interest represents the study of geomechanical processes in the host soil in the construction of several tunnels with the use of TBMC with the active TFP in the zone of mutual influence.

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