NUMERICAL MODELLING OF THE BEHAVIOUR OF FACE AND FOREPOLING ROCK SUPPORT IN TUNNELLING

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Abstract: The paper deals with the types of contour and pre-reinforced supports under use in tunnel engineering. The technique for simulation of pre-reinforced support and finite element model of the system “support-massif” have been developed. Model investigations on the interaction of protection pipe screens with ground massif have been conducted. Nomograph of relationship between earth surface settlement and the variant of technological solution has been plotted.

Keywords: Pre-reinforced, finite element model, system “support-massif”, surface settlement, technological solution.

1. THE STATE - OF - THE ART

In the practice of up-to-date tunnel engineering there have been widely used various types of pre-reinforced supports such as pipe screens, concrete vaults, ground screens, stabilized by artificial freezing, chemical grouting, jet cementation, etc. Pre-reinforced support is a preventing measure, ensuring safe tunnel excavation and stability of the surrounding ground massif.

Pre-reinforced support is mainly used at the sections of faulted rock, low stable and unstable soft water bearing soils, encountered with at the routes of rock, underwater and urban tunnels, being constructed by tunneling method. Selection of the right support type and the technology for its installation are defined by the extent of faulted zones, the kind and property of the soil to be excavated, the location of ground water, etc.

The technology under consideration is characterized by sufficient flexibility and adaptability to changing engineering and geological conditions. It reduces to minimum environment violation and has a number of advantages as compared with other methods for supporting excavations when tunnelling. Pre-reinforced supports have been used for
construction of many tunnels and urban underground structures in England, Germany, France, Italy, Russia, USA, Japan, Singapore and other countries [1].

Conduction of theoretical and experimental investigations on interaction of the support and soil massif at various stages of tunnel construction is required for reasoned design of pre-reinforced supports and specification of their rational structural and technological parameters.

The most precise stressed-strain state of the pre-reinforced support under tunnelling might be obtained by means of three dimensional calculation of stressed-strain state of the system “support – massif” at all the stages of tunnel construction.

To achieve the purpose, application of finite element method, which had been widely used for solution of geological and mechanical problems, has been considered as the most reasonable one [2].

As a rule, the calculation procedure proves to be complicated due to both step-by-step implementation of work and elastic and plastic deformations of the soil massif. Program packages «NASTRAN» and «COSMOS/M» might serve as the examples of finite element method realization for calculating stressed-strain state of random form elements. Packages «PLAXIS» and «Z-SOIL» are the examples of the design program packages, taking into consideration the peculiarities of construction of structures in ground massif.

II. THE TECHNIQUE FOR SIMULATION OF PRE-REINFORCED SUPPORT

Selection of dimensions of ground massif design fragment is considered to be the priority for simulation of tunnel engineering challenges.

From theoretical solutions of elasticity theory plane problems it is known that disturbances of stress-strain state, induced by excavation, are practically damped at the distance of approximately 2.5 R from the excavation, where R is a section reduced radius. In the case when zones of plastic deformations appear in the vicinity of excavation, the above mentioned distance may increase up to (3÷4) R. Hence it follows that the design fragment width shall be not less than 6 R; when using model symmetry – not less than 3 R in elastic problems and (7÷8) R in elastic and plastic ones. The bottom boundary of the fragment shall be located at the same distance as well. The distance might be decreased, if there appear firmer and stiffer soils in the excavation vicinity. The front and back boundaries of the fragment shall be located at the distance of not less than (3÷4) R from the face of the tunnel under construction.

Thus, in the finite element modeling the ground massif minimal dimensions are as follows: 6 R by the tunnel length and 6 R by the tunnel width (3R – for symmetrical problems), 4 R + H by the height, where H is the tunnel depth. For deep tunnels (H > 10 R) there may be adopted a fragment of 6 R height with uniform load on the upper bound, imitating the pressure of overlying grounds.

Simulation of tunnel construction process consists of step-by-step sequence in solution of
the following problems [3]:

1. Selection of ground massif design fragment and plotting “support-massif” design scheme. Ground is assumed as possessing idealized elastic and plastic properties.

2. Definition of initial stresses in undisturbed weight massif under ground dead weight and tectonic processes. To find out the values of acting stresses on the excavation contour, using the problem solution.

3. Inclusion of contour and/or pre-reinforced support into the design scheme.

4. Step-by-step loading of opening contour in weightless semi-plane or plane by initial stresses, taken with opposite sign, and check of plasticity conditions for each finite element and alteration of its properties if necessary.

5. Inclusion of the lining or temporary support into the design scheme at a prescribed step.

6. Continuation of step-by-step loading pursuant to clause 4 up to the last values of contour stresses under record.

7. Transition to the next phase of tunnel construction (arrangement of pre-reinforced support, excavation and installation of temporary support or lining).

A large system of linear equations, which might change in the process of calculation, shall be solved at each step of loading.

Deformation properties of materials, which the semi-plane consists of, are defined by deformation modulus $E$ and coefficient of cross expansion $\eta$, as well as by strength, characterized by bond $C$, and the angle of inner friction $\phi$. The construction is modeled by the system of elastic bars, which deformation properties are defined by deformation modulus $E_0$, cross section area $F$ and inertia moment $I$. The semi-plane material ceases resistance to shear under violation of Coulomb-Mohr strength conditions.

The side boundaries of the fragment are fixed against horizontal displacements, the bottom boundary - against vertical displacements and the upper one is under free deformation.

III. INVESTIGATION OF RELATIONS BETWEEN PROTECTING PIPE SCREENS AND GROUND MASSIF

Basing on the above stated concepts there has been developed three-dimensional finite element model, imitating the behaviour of the system “support-massif”, depending on model geometrical parameters, on strength and deformation properties of soils around the tunnel periphery and on technological factors at various stages of the tunnel construction.

The scientists of the chair on bridges and transportation tunnels of MADI together with Research Centre “Tunnels and Metro” of TsNIIS have undertaken the study with the aim of defining the interaction between protecting pipe screens and soil massif applicable for driving the highway tunnel of 15x8.5 m section and 35 m length under the railway embankment at the
depth of 4.5 m.

Figure 1 illustrates stress-strain state of ground massif after arrangement of pipe screen.

![Figure 1. Stress-strain state of the massif after installation of pipe screen](image)

Twenty seven series of calculations have been conducted on the three-dimensional model. Each series represented one of the tunnelling variants under consideration, specified according to the construction experience. Their averaged representative values have been prescribed as initial parameters. Surface settlement above the tunnel has been considered as the character under study and the indication of the efficiency of system technological variant.

The variants of technological solutions, subjected to the analysis, were combinations, composed from engineering and geological tunnelling conditions (in sands, clays and loam), screen constructions (use of 630 mm, 820 mm and 1020 mm diameter pipes) and tunnelling conditions (1 m, 2 m and 3 m step). Thus three factors, each of which had been prescribed at three levels, have been considered under simulation.

A numerical modeling of driving and its results analysis were considered to be an appropriate tool for establishment of the dependence of earth surface settlement on the accepted technological variant for tunneling. The trend to change of earth surface settlement was considered as the dependence to be determined. Any deviation from that trend was considered as random component, information “noise”, giving rise to a great number of poorly controllable factors (natural, technological, structural and others) as well as discrete nature, limited truth and insufficient initial data, obtained from the practice of construction tunnels, being unique structures.

Analysis of the capabilities of current methods for planning and processing of experiments results has made it possible to select rather simple and efficient method, taking into account the
given conditions and providing the possibilities for consideration of all the driving technological variants under study from united position and for representation of the dependence to be determined in visual form, convenient for designers. Trend analysis was used for specification of the dependence to be determined.

The variants of the indicated technological solutions were represented by empirical set, consisting of $3^3 = 27$ objects.

Direct application of quantitative mathematical methods to such objects proves to be impossible. Therefore at first the variants were rated depending on their efficiency – the value of resulted surface settlement. Then the empirical set was mapped onto numerical system with prescribed ratio.

For mapping the combinations of technological solutions (driving variants) onto numerical set there was used scaling – numerical values assignment to the variants. As a result there appeared the possibility for measurement of the variants, followed by plotting uniform discrete 27 - rating scale on the set of variants scale values, considering the rating as variant measurement unit.

Operating by scale values of variants has provided adequacy of objects of initial (empirical) and transformed (numerical) sets. Thus for each variant of technological solution there was uniquely defined its place on the axis of categories (X axis). Afterwards the nomograph of relations between settlement Y and value of variant X was plotted (fig 2). As the followed investigations showed the use of single-dimensional scale appeared to have been quite sufficient for solution of the problem under study.

![Fig 2. Nomograph for relation between settlement Y and variant category X](image-url)