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Construction of the Donetsk (Ukraine) Underground Railway on the undermined territories and tectonic faults

Construction du métropolitain de Donetsk (Ukraine) sur les teritoires des mines et les accidents tectoniques

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ABSTRACT

The actual problems of the Donetsk Underground Railway construction related to geomechanics, mechanics of the underground constructions and building structures have been examined. Preconditions for developing the structural measures for running tunnels protection against uneven deformations of the soil body have been set up. The technical solutions for protection against the undermining and tectonic faults to improve the construction serviceability with minimum costs have been offered and implemented.

RÉSUMÉ


Keywords: undermined territories, tectonic faults, the Underground Railway, construction protective measures

1 INTRODUCTION

Up to 50m deep lines of the Donetsk Underground Railway either run in close proximity to the tectonic fault planes which crop out the ground surface or are buried under overburden, or pass through such fault planes. Such faulting, as well as running of the lines over the previously undermined territories, possible mining activities with partial pillar (mining exclusion zone) recovery can lead, without relevant protective measures, to excessive deformation of the Underground structures.

2 GEOTECHNICAL CONDITIONS OF THE CONSTRUCTION

From the geomechanical point of view the construction of the Donetsk Underground railway is complicated by the following factors: the rock mass and ground surface frequently undermined at different depth levels; possible future influence of the mining works on the Underground structures; 17 geological faults over the Underground Railway lines (Fig. 1) - such faults, being a complicated factor by their own, in case of undermining them, become a prevailing factor; wide-scale closures of mines with partial or complete flooding of them which activates the rock mass displacement process and, consequently, the ground surface displacement.

The Underground Railway mainly runs through the zones of weathering the Carbon rocks. The depth of the bottom boundary of this zone increases with the growth of the rock metamorphism intensity. In the anthracite regions it reaches the depth of 35-40m, and within the areas of gas coal occurrence – up to 100-110m (Sverzhevskiy & Polozhai 1969). The rock mass in the area is structurally weakened and its strength properties are sharply decreased. The most weakened is claystone (clay slate) and siltstone (sandy slate), in a lesser degree – sandstone. The rocks found in this zone are characterized by natural fracturing and porosity if compared with deeper levels (Ksenda 1982). Due to the repeated mining works the fracturing intensity increases. Therefore, the rock mass can be treated as a discrete medium consisting of separate blocks of various size.

Figure 1. The Donetsk Underground lines overlapping the tectonic faults outcropping.

The rock mass has even more complicated structure within tectonic fault areas. The dominating type of such faulting in the Donbass region is thrust faults, which are always in a certain manner connected to separate folds or the whole folded areas and present, in the aggregate, the same type deformation – reduction of area size in a horizontal direction. Based on the results of the geodetic measurements carried out within the area of the French thrust fault, the compression of the ground surface with the average intensity of up to 20mm/year, stable subsidence – up to 3mm/year (Vereda et al 1978) have been recorded. The collected material about crossings of the Donbass faulted zones proves that the thrust faults are of a complicated...
structure. Figure 2 shows, as an example, a sketch of crossing the French thrust fault area with the mining works.

Figure 2. The scheme of crossing the French thrust fault zone with the mining works.

Separate small faults are intermittent with the undisturbed rock bedding. Within peripheral areas of the zone the faults are presented by single fault planes, located at the distance of up to 50m from each other. In the central area there are non-thick rock breaking zones and the distance between them is reduced to 20m (maximum). The rocks between separate faults are greatly diverse. Low-scale amplitude faults (having the amplitude less 10-15m) can be presented by a single fracture or a group of individual faults.

3 SPECIFIC FEATURES OF THE ROCK DEFORMATION WITHIN THE TECTONIC FAULT ZONES

Long-term observations have shown that in case of undermining a fault with mining works the abnormal distribution of displacements and deformations, if compared with the unbroken rock bedding, can be observed (Gavrilenko 1995). During investigations an emphasis is mainly put on the central section of the displacement trough. But taking into consideration that the Underground Railway structures are secured by a pillar we have examined the cases when the fault outcrops are located at the end section of the displacement trough.

If the faults crop out above the mining exclusion zones, the benches are not formed and the smoothed sign alternating deformations are recorded. Besides, there are cases when faults crop out outside the trough, formed by boundary angles.

Figure 3 shows the results of undermining the French thrust fault. They are interesting because the faults cross the area of mining work influence, reach the boundary section and run outside the displacement trough. Despite the fact that considerable concentrations of deformations have not been recorded, the allocation of displacement and deformations shows great difference from the unbroken rock bedding. Displacements extend far outside a typical trough and the settlement of rock of a hanging limb is less than expected. This leads to extended trough which results in less-than-expected inclinations. It should also be pointed that within the boundaries of the whole half-trough prevail the horizontal deformations of compression with two distinct areas of compression concentrations at the boundaries of a tectonic zone with the rocks of both hanging and lower limb.

Figure 4 shows the graph of settlements and deformations within A-B section (according to Figure 3) restricted by a displacement angle assumed when a mining exclusion zone is organized. Sign alternating deformations (both horizontal and vertical) are typical for this area where the benchmarks are placed at 5-10m spacing.

The above example allows to state the following: in case of mining works carried out outside the mining exclusion zones within the areas of the fault outcrops, the displacements are possible even outside a typical trough; displacements and deformations are of a clearly uneven nature; the process is characterized by gradual rising of parameters.

Figure 4. Distribution of displacements and deformations within the end section of the mining work influence area.

The tectonic faults and geodynamic structures are revealed within the rock mass by sharp changes of the rock properties, their stress and hydrogeological conditions which determine the anomaly of different physical fields above these zones.

Figure 5 shows the results of studies of the geodynamic zone activities within the area of the French and Coke thrust faults. As to the extent of the measured geophysical fields differentiation, the geodynamic zones are divided into 3 categories: I – is characterized by high amplitude activity of a
4 DESIGN PRECONDITIONS

Based on the above deformation principles and geological specific features of the rock mass the following preconditions for developing the structural protective measures for the running tunnels against uneven deformations of the rock mass have been set up:

- design values of the ground surface deformations are the following: outside tectonic fault zones – \( i_p = \pm 2.5 \text{mm/m} \); \( \varepsilon_p = \pm 2 \text{mm/m} \); \( R_\text{fp} = \pm 15 \text{km} \); inside tectonic fault zones – \( i_p = \pm 4 \text{mm/m} \); \( \varepsilon_p = \pm 3 \text{mm/m} \); \( R_\text{fp} = \pm 3.1 \text{km} \);
- the most dangerous from the point of deformation concentration at the fault area boundaries are the areas of “enter” and “exit”;
- within the fault areas the rock-hardness ratio and elastic resistance coefficient is 3-4 times and the elastic modulus is 3-5 times higher than outside these areas;
- large tectonic faults are characterized by a block structure. That is why, except of the distributed load, the concentrated loads from possible falls of separate rock blocks from the mining work area contours are to be considered;
- extruded - into- the rock (pressed/fastened down) lining is more effective in terms of avoiding displacement of blocks directly adjoining the mining work area contours and provocation of displacement of another blocks. This is a reason why application of drill and blast tunnelling method is rather dangerous;
- block structure of the tectonic zones can lead to deformation of the above layers consisting of the intermittent compression-tension zones. Therefore, the tunnel lining should structurally take up sign alternating vertical and horizontal deformations in both transverse and longitudinal direction. Because the size of individually shifting rock blocks is not known and can vary in a wide range, the length of rigid segments is to be taken as minimum as possible;
- block structure and poor reliability of tectonic zones require advance check drillings and improved accident prevention measures because falls of rock blocks are possible within these zones.

5 STRUCTURAL PROTECTIVE MEASURES

Implementation of some new preconditions in the design of the Donetsk Underground Railway allows to compensate, to some extent, the geotechnical complications of the construction site.

In particular, the Ukrainian standards provide “fan” separation (gapping) of the block rings (Fig. 6.a). Taking into consideration the above analysis of the geomechanical process within the predominantly compressed rock mass and restricted (constrained) behaviour of the block lining, the most possible type of its deformation is plane-parallel displacement of block rings with opening and closing the ring joints (Fig. 6.b).

The given preconditions have been implemented into the working design and construction of the running tunnels.

Over the whole route, inside or outside the tectonic fault areas, the reinforced concrete block lining Ø5.65m with cylindrical joints between blocks has been provided. In such a case, the running tunnel in a longitudinal direction consists of flexible (ductile) segments \( L_0 \) and deformation insertions \( L_0 \) between them (Fig. 7).

In the ductile (flexible) segments the connection-movement joints between the block rings ensure their one-way work – only in the horizontal tension strain at which the length of a rigid segment will be equal to the length of one block ring \( l_0 \) and, consequently, the required compensating capacity of a joint, even in case of the maximum value of \( i = \pm 12 \cdot 10^2 \), will be no more than \( |K| = \pm 12 \text{mm} \). In case of horizontal compression strain the block rings, shifting in a longitudinal direction, take up the mounting gap \( a_r \), lock into each other and form a rigid segment with the length equal to the sum of the block ring lengths within a ductile (flexible) segment. Furthermore, the length of a self-formed rigid segment in case of compressive force (~7200kN/linear meter) is restricted only by the design cement bearing strength \( R_{c,b} \) of the edge surfaces of the block rings.

Further displacement of a segment \( L_0 \) passes into a deformation insertion in which the movement joints (between block rings), working in both directions –compression and tension, are provided. In this case, the length of a rigid segment within a deformation insertion in any (out of two) direction of work is equal to the length of a block ring \( l_0 \) and the gaps \( a_3 \) between them are selected in such a manner that within the
deformation insertion their sum would be no less than the size of a movement (deformation) gap $\Delta$ between estimated segments $L_0$. It gives the possibility to use any quantity of block rings in a deformation insertion due to available tight seals with set compensating capacity.

Thus, a ductile (flexible) segment $L_0$ behaviour follows two patterns: as a single rigid segment with the length of $L_0$, in case of $-\varepsilon$, and as individual rigid segments each having the length of a block ring $L_0$ in case of $+\varepsilon$. Deformation insertion $L_0$ behaves as separate rigid segments $L_0$ in case of both $+\varepsilon$ and $-\varepsilon$.

Technical result of a new structural solution is that the compensation of considerable deformations of the soil body, affecting the tunnel, takes place with minimum gapping between block rings in a deformation insertion, filled with available elastic tight material.

The length of a ductile (flexible) segment and deformation insertions is determined on the basis of the following equation:

Length of a ductile (flexible) segment:

$$ L_0 = \frac{\eta \cdot R_{\text{comp}}}{\tau} $$

(1)

where $L_0=\Sigma L_0$; $\delta$ – depth of block section; $\eta$ – compensation factor of horizontal compression strain; $\eta=\varepsilon_0/\text{e}_0$; $k$ – a parameter of lining-earth contact surface, $\geq 2; \varepsilon_0 = \text{a}_m$; $\text{m}$ – a relative value of mounting gaps between block rings along ductile (flexible) segment, $\varepsilon_0=\text{a}_m/\text{h}_m$; $\text{m}$ – a mounting gap between block rings within a ductile (flexible) segment; $\tau$ – ultimate shear stress in the ground caused by horizontal compression strain.

Length of a deformation insertion:

$$ L_0 = \frac{\varepsilon}{ \frac{\text{a}_m}{ \text{e}_m} - \varepsilon } $$

(2)

where $\varepsilon$ – a relative value of movement (deformation) gaps between block rings along a deformation insertion, $\varepsilon=\text{a}_m/\text{h}_m$; $\text{m}$ – a movement (deformation) gap between block rings along a deformation insertion, $\Sigma \text{a}_m \geq \Delta$; $\Delta=L_0 + L_0$; $L_0=\Sigma L_0$.

The technical solution offered (Patent No.1061 UA) lead to the equal compensating capacity of the structure with gaps $a_0\leq 20$ mm between block rings within a deformation insertion.

For Line I of the Underground Railway the following was adopted: the ductile (flexible) segment – deformation insertion length, $L_0=60$ m; $L_0=60$ m; inside tectonic fault zones, the above ratio – 1:1, correspondingly $L_0=60$ m; in such a case, the gaps between block rings in deformation insertions are $a_0=5$-7 mm, within ductile (flexible) segments – $a_0=1$-3 mm.

It is obvious that the offered technical solution for the running tunnel reflects the strategy of its protection against the mining activities and tectonic faults and ensures its completely new working conditions, which allows to increase its serviceability at minimum costs.

The widely spread ideas about the interaction of the unevenly deformed soil body with lining are not exactly correct. The tests (Rozenvasser & Olmezov 1997) have shown that because of the arch effect within flexible lining, the initial values of the horizontal compression strain, as they are reaching mine working, are reducing to zero, change the sign, and, within the area of contact with lining - form the ram pressure from compression strain by 2-3 times lower than initial ones.

Within the undermined territories in-time putting of the lining into operation is of significant importance since in the block massif even the minimum delay of the lining construction from mine workings can provoke contour falling. In such a case, it is required, on the one hand – no-settling technologies to avoid this (Rozenvasser & Shamrin 1993), on the other hand –

authentic calculation models reflecting the above stated specific features of the disturbed soil ground and nonlinear effects in the behaviour of ground, materials and structures as a whole.

At present, boring of the main line tunnels for the first section of the Proletsarosko-Kievskiy Line (from the Proletarskaya Station to the Politechnical Institute Station) is underway. This section comprises 6 stations and 10 km double-track main line tunnels, electrical depot at the Proletarskaya Station, the culvert from archch closed reinforced concrete blocks, engineering facilities, etc.

Two thrust faults (Zaperavalny and Musketovskiy) have been passed through successfully that proves efficiency and competitiveness of the structural protection measures.

6 CONCLUSIONS

During design and construction of the Donets Underground Railway under complicated geotechnical conditions of Donbass, a number of challenges related to geomechanics, mechanics of underground and building structures have been faced.

The investigation results have shown some patterns of rock deformation within the tectonic fault zones, especially in case of their undermining. Within these areas was recorded the abnormal distribution of displacements and deformations, if compared with the undisturbed rock mass, in such a case, one-type deformations of the earth surface compression prevail.

The tectonic faults and geodynamic structures in the rock mass demonstrate sharp changes of rock properties, stress and hydrogeological conditions which determine the anomaly of different physical fields above these zones.

These investigations show the evidence of the unfavourable geomechanical situation within the areas where the running tunnels pass through the tectonic faults.

Design preconditions, the most important of which is the minimum length of a rigid segment with application of the extruded (pressed / fastened down) lining, have been developed.

A new structural solution for running tunnels has been developed, which provides alternation of the ductile (flexible) segments, outside the tectonic fault zones, and deformation inserts, inside such zones, with different patterns of the movement joint behaviour: one-way pattern for the ductile (flexible) segments – compression only, two-way pattern for the deformation inserts – tension-compression.

Complete studies of the problems allowed to ensure the serviceability of the Underground Railway structures and achieve substantial economic benefits.

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