Geomechanical and Geophysical Investigations in Repaired Underground Structures

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ABSTRACT: A new approach provides increased economic efficiency of the design decisions and their subsequent implementation in repaired underground structures. The key element of the approach is the geomechanical and geophysical investigations during geological survey in the period of the design works on underground structures' reconstruction. In particular, geomechanical and geophysical investigations allow assessing the quality of interaction between the rock massif and existing supporting structures, as well as the condition of the existing lining which should be dismantled. Another part of the proposed approach is to take into account the modern idea of the equilibrium state of rock mass which is formed during the long-term operation process of underground structures.

KEYWORDS: Reconstruction, Railway tunnel, Equilibrium state, Stress-strain state, Field measurements, Mining and environmental (geotechnical) monitoring, Support, Lining, «Underground structure - enclosing massif» system; Geotechnical calculation; Safe exploitation

1. INTRODUCTION

According to a technical survey made in 2003, many of Russia's railway tunnels had various violations, the most common ones being water cut of varying degrees and structural deformation. During the inspection, defects were reported such a significant decrease in the lining strength, cracks and outfalls in outdated masonry, including through ones with deformations of the earth's surface above the tunnels.

About half of all the Russian railway tunnels in operation by 2003 did not meet the safety margins for structures, the limiting transverse perpendicular axis of the track, a shape into which, in addition to rolling stock, no parts of structures and devices should be included, except for devices that are designed for direct interaction with rolling stock established by the state standard. The service life of a number of existing railway tunnels exceeds standard indicators - these are structures that have been in operation for more than 100 years.

Currently, the number of railway tunnels that do not meet modern requirements has been reduced due to the large volume of work on overhaul and reconstruction of structures built in the late XIX - early XX centuries, as well as the construction of new tunnels parallel to the old ones. Examples are the reconstruction of the Khingan tunnels on the Far Eastern Railway (2009-2013), tunnels in the North Caucasus (1998-2014), the Tomusinsky Tunnel on the West Siberian Railway (2018), and a number of tunnels on the Krasnoyarsk Railway (2006-2018), as well as the construction of new railway tunnels for the Olympic Games in Sochi and others. This trend continues as new tunnels are being designed in the Caucasus, Siberia and the Far East, the modernization of the Baikal-Amur Railway Mainline (BAM) continues with the construction of new tunnels and the reconstruction of existing ones.

The choice of the method of calculating the supports and lining during the reconstruction of transport tunnels, which would reflect the actual construction and operational loads for specific engineering and geological conditions, seems to be an extremely urgent and promising task.

2. RECONSTRUCTION OF TUNNELS

During operation, all underground structures are subject to natural physical deterioration: under the influence of cyclic loads, external mechanical influences in an aggressive environment, the physical properties of structural elements and the host soil mass change their properties. Degradation of the properties of materials over time, and other negative effects cause a change in the stress-strain state (SSS) of structures. At the same time, it follows from the practice of operating underground structures that in some cases the tunnel is unsuitable for further operation still having a sufficient bearing capacity of the lining due to the "moral aging" of the object [Limanov, 1976].

In this regard, during the design of reconstruction of railway tunnels, along with recommendations to strengthen the existing lining by grouting voids behind the lining, making a reinforced concrete coating, etc., a decision may be made on the feasibility of partial or complete replacement of the old tunnel lining with a new one with a change in safety margins.

According to the experience of such works, serious problems arise in unstable soils, as well as in tunnel open cuts, where the load from a full column of soil is realized. The practice of overhauls of tunnels in unstable soils, performed with the completion of the old section of the tunnel along the arch, shows that soils above the old lining are weakened everywhere. Piles of soil are formed on the tunnel lining. When developing the old lining without additional measures to strengthen the lining space, large outfalls are possible even with sinkholes appearing on the surface. Therefore, when reconstructing tunnels with the complete replacement of the old tunnel lining, a very important point is the determination of the loads that will affect the newly erected supporting structure.

The initial data for the calculations are the data provided by updated engineering-geological and hydrogeological survey carried out according to a special technical task and program, taking into account the features of the structure. Currently, calculations of the supporting structures of transport tunnels are performed by numerical methods using the widely used software systems ABAQUS, FLAC, PLAXIS, MIDAS GTS, Z-soil, etc.

In the conditions of reconstruction of an underground structure with complete dismantling of the lining due to the lack of the ability to verify the calculation results, currently existing calculation methods among which analytical and numerical methods that work, including those with rheological properties of the rock massif, present significant difficulties. This is a probable reason for requirement according to the existing regulatory documentation to 30% increase the normative rock pressure load on the tunnel during tunnel reconstruction with a complete lining replacement. But is such an increase always necessary?

Taking into account the features and fundamental differences of geomechanical processes during reconstruction work on underground structures from similar processes in new construction can result in a significant reduction in the consumption of building materials, the cost of which during the construction of tunnels is 20-40% of the total cost of construction. For example, according to [Kaufman et.al., 2010], the works associated with the construction of advancing anchor supports made of concrete and reinforced concrete accounted for 47% of the base cost of building a tunnel with a length of 3.7 km, the remaining 53% of the base cost was assigned for the types of work associated with the construction site, portals, tunnel boring, drilling of exploratory wells, grouting and other expenses.

3. FORMATION OF A NEW EQUILIBRIUM STATE

It was noted that the formation of a load on the lining of tunnels under reconstruction is of a two-stage nature [Limanov, 1976; Budaeva, 1972]. At the first stage of formation of rock pressure, the loads on the newly erected lining are determined by the weight of the rocks exfoliated from the rock mass during the initial construction of the tunnel. Repeated violation of the equilibrium state during overhaul or reconstruction leads to an increase in the collapse zone and an increase in load by approximately 1.3–1.4 times at the second stage of formation of rock pressure in comparison with the actual value noted before the start of reconstruction, i.e. at the initial stage [Limanov, 1976].
Thus, the final load from the rock pressure acting on the newly constructed lining during the reconstruction of the tunnels is presented in [Limanov, 1976] in a general form as:

$$q = q_1 + q_d k_p \qquad (1)$$

where q_1 is the load at the first stage of formation of rock pressure, i.e. established during the initial operation of the tunnel before its reconstruction;
q_d - additional load caused by the increase in the radius of the zone of inelastic deformation during the reconstruction of the tunnel in the case of the maximum possible displacements of the mine working outline;
k_p - factor accounting for the magnitude of the displacements of the mine working outline, ranging 0 to 1.
After a series of transformations and the introduction of an empirical dependence, taking into account the module of relative fracturing of the rock mass, the formula for determining the final rock pressure load during the reconstruction of tunnels takes the following form [Limanov, 1976]:

$$q = q_1 + 1/3\ \gamma L_1 r k_p\ (L_2/L_1 0.755 n^{0.178} - 1) \qquad (2)$$

where γ is the volumetric weight (density);
L_1 - span of the mine before reconstruction of the tunnel;
L_2 - span generation during reconstruction of the tunnel;
n - relative fracture modulus;
r - the relative radius of the zone of inelastic deformation, defined as:

$$r = R/R_0 \qquad (3)$$

where R is the radius of the zone of inelastic deformation, m;
R_0 - radius or half-span of development, m.

The absence of studies that can reliably accept the values of the parameters included in (2) and (3) lead to the need for a peremptory increase in load by 30% in accordance with the requirement of SP 122.13330.2012: “When reconstructing a tunnel with a complete replacement of the lining, the normative rock pressure load on a tunnel shall be increase 1.3 times, but it should not exceed the load of a full column of soil.” Even in cases of strong, non-weathering, dry and stable rocks of the enclosing massif, when the same normative document (SP 122.13330.2012) is allowed to leave mine workings of tunnels without any supports or lining.
In [Limanov, 1976], other components of the total load acting on the tunnel lining are also indicated - the weight of the structure, as a factor associated with the inconsistency of bulk materials weights, and mainly with the presence of bumps during sinking, distorting the design geometry of the output, and significant impact caused by injection of various solutions under pressure into the backfill space. However, neither in [Limanov, 1976] nor in modern works on the reconstruction of underground structures, the issues of the complex nature of the interaction of the tunnel lining with the host rock massif in time are considered in sufficient detail. Consideration, if any, is only made in the form of an analysis of the risks and reasons causing the need to replace and strengthen the lining.
Nevertheless, this factor is very significant, as practice shows, the process of redistributing the SSS of the «underground structure - enclosing massif» system over time may tend to decay until the rock massif is weakened by the development of a stable equilibrium state. For example, in [Lebedev, Romanevich, 2019] examples of geotechnical situations during operation and reconstruction of underground structures are briefly considered. As a result of improper operation of the railway tunnel for a long service life (the tunnel has been operated for more than 100 years), due to various processes at the contact of the lining with the enclosing massif, cavities and voids with a thickness of 0.2 to 2.4 m have been identified over almost the entire structure contour (Fig. 1).

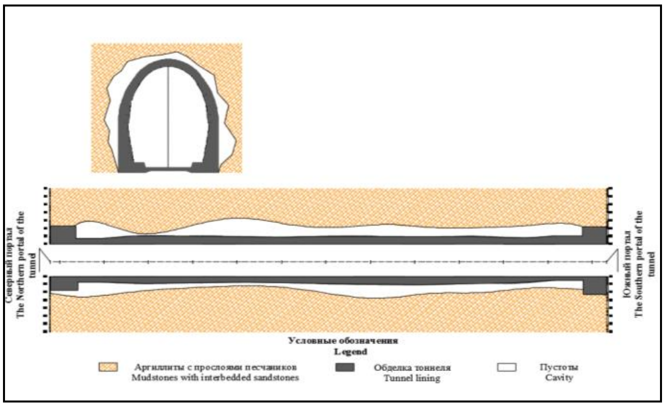

Figure 1 - Tunnel cross-section and longitudinal engineering-geological section of a rock massif containing a tunnel according to GPR data, drilling, well-examination and visual inspection

Such cavities behind the tunnel lining layer, especially in the absence of industrial interference, can be unambiguously detected during engineering-geophysical studies using modern standard geophysical equipment. The task of searching for voids, cavities, and dislocations is most often solved using various variants of seismic-acoustic methods [McCann et. al., 2001; Sloan et. al., 2015], using georadar [Nigel et. al., 2011; Lalague et. al., 2016], as well as combinations of various geophysical methods [Tu-guan et. al, 2015; Ding et. al., 2016].
If such a negative geotechnical situation is identified, associated with the detection of significant volumes of voids behind the lining in the case of ongoing and major repairs of tunnels, it is necessary to fill the lining space by pumping the appropriate solutions for tunnel lining. This is required to create joint work of the structure with the enclosing rock massif and to exclude conditions under which concentrated loads will be transferred to the lining.
On the other hand, the physical possibility of the existence of a powerful lining without contact with the enclosing massif along the perimeter of the tunnel for a long period of time may indicate the emergence of a stable form and condition of the rock mass. This fact indirectly reinforces the hypothesis of the formation of a new equilibrium state of the massif during the long-term operation of the underground structure, confirmed by direct geomechanical observations of the behaviour of the stress-strain state of the newly erected lining during reconstruction.
In [Lebedev, Romanevich, 2019], other confirmations of the formation of a new equilibrium state of the “underground structure - enclosing massif” system during the long-term operation of transport tunnels using examples of tunnels of the Circum-Baikal Railway, Gimrinsky Tunnel in the Republic of Dagestan, and Bosruck Railway Tunnel in Austria were also considered [Kohlbock et. al., 2019].
Another example, indicating the formation of a new equilibrium state in the absence of full contact of the lining with the enclosing massif, is a tunnel 89.4 meters long, built in 1907 [Dandurov, 1962]. The mountain massif cut through the tunnel is characterized by a wide variety of rocks (very dense and strong sandstones and

limestones, clay shales, marls and, finally, quartzites in the form of rods and veins cutting through dense limestones and schists).

After almost two decades in 1924, during the repair of a track on the side of the tunnel under the ballast layer, a cave with a width of 7.2 m was discovered (Fig. 2), and the eastern wall of the lining turned out to be a weight on this extension.

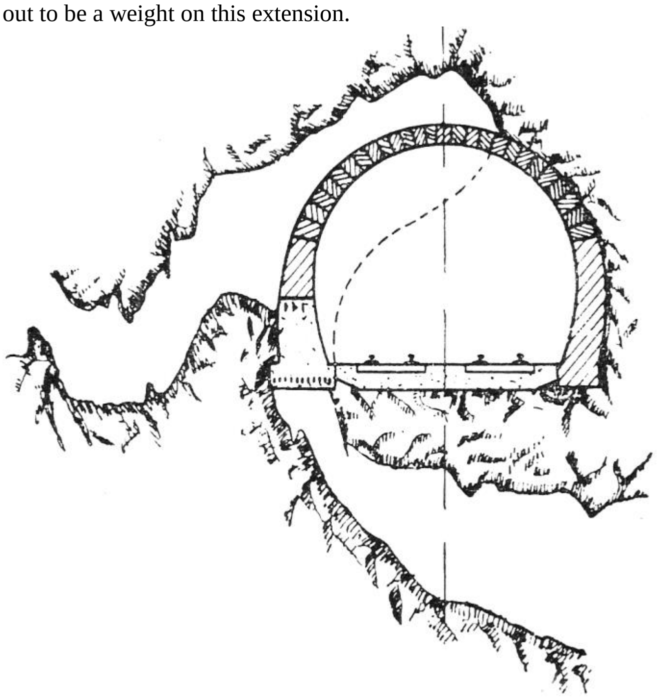

Figure 2 - Cross-section of the double track tunnel with a part of the enclosing massif with a cave [Dandurov, 1962]

With its single branch, the cave goes around more than half of the lining perimeter, then goes down a little, and then, turning abruptly upwards, extends far into the mountain. The lower branch of the cave gently drops below the base of the tunnel, and its bottom is vertically 8.5 m from the rail head. Continuing to descend, the cave passes under a large river and deepens into the neighboring mountains.

To ensure the stability of the lining, a reinforced concrete beam of 10.67 m long, 1.64 m wide and 2.06 m high, reinforced with rails, was brought under the wall. Outside, lining the entire height of the cave and over its entire width put a concrete guard wall.

Ancient confirmation of the legality of the assumption of the formation of a new stable equilibrium state near a mine working that can remain for a long time without additional increase in the bearing capacity of the roof supports is the ancient *kyariz* - traditional underground hydraulic systems in the cities and villages of Azerbaijan, Central Asia and Iran, combining a water supply system and an irrigation system. One of the oldest kyariz in the world in Gonabad was built between 700 and 500 BC; this system is more than 33 kilometers long at depths of up to several hundred meters and is still partially operational. Similar underground water systems are known in Istanbul (construction of the IV-VI century) and Madrid (construction of the X-XI century) [Pidal, 2019].

The processes of stabilization and achievement of stable equilibrium develop faster in rocky rocks that do not have creep properties. There are also known facts of the long-term stability of tunnels, the route of which runs through rocks of medium strength, represented by mudstones, shales, limestones and sandstones of various strengths [Lebedev, Romanevich, 2019].

Thus, under certain geotechnical conditions, at a certain stage of the existence of an underground structure, the enclosing massif can receive a new equilibrium state, in which, in the case of reconstruction, the stress-strain state in the newly constructed lining is not more, but less than in previously existing structures. Accordingly, the final load from rock pressure acting on the newly constructed lining during the reconstruction of the tunnel may be less than the load established at the stage of the initial operation of the tunnel:

$$q \le q_1 \qquad (4)$$

In this regard, the question arises of the advisability of increasing the normative rock pressure load on the lining by 30%, regulated by regulatory documentation in all cases of tunnel reconstruction with a complete replacement of the lining.

More reasonable is the way of a detailed study of the technical condition of existing structures and enclosing rocks in the backfill space of an underground structure, and the subsequent optimization of the parameters of newly constructed supporting structures of supports and lining at each specific site of the reconstructed object.

It was shown in [Dandurov, 1962] that the interaction of the underground structure with the surrounding massif is so complex and diverse that it cannot be expressed by laws generalizing the phenomena that occur. The issue is often even more complicated in connection with changes in soil properties and the general geological and hydrogeological situation over time.

Confidently judging the work of new load-bearing structures erected both after sinking during new construction and after dismantling the old tunnel lining during reconstruction, it seems possible only on the basis of full-scale studies of SSS, which give the most reliable results. Such complex observations in transport tunnels and other underground structures during their construction and operation, as well as during the reconstruction period, are widespread. The requirements for the observing system are summarized in the "Methodological Guide for Integrated Mountain-Ecological Monitoring in the Construction and Operation of Transport Tunnels", agreed by the Federal Service for Ecological, Technological and Atomic Supervision of the Russian Federation and approved by the Russian Tunnel Association.

4. NATURAL MEASUREMENTS OF THE SSS BY GEOTECHNICAL MONITORING OF TRANSPORT TUNNELS

Taking into account the theoretical concepts shown above about the formation of the load on the tunnel lining of underground structures, the NIPII Lenmetrogiprotrans OJSC Institute systematizes and accumulates the results of field measurements of strains, deformations and displacements in the structural elements of underground structures. To this end, comprehensive observations are carried out at various stages of construction and operation in transport tunnels and artificial structures of subways, including during the reconstruction period. These data allow a rational approach to the choice of design schemes, materials and parameters of lining, tunneling and re-tunneling technologies, as well as to methods for studying the SSS of supports and lining during subsequent reconstructions of underground structures. Such information, of course, will be in demand when resolving similar issues in the future.

The main source of new geotechnical information is the scientific and technical support for the design, construction and reconstruction of underground structures in the form of integrated mining and environmental (geotechnical) monitoring. In accordance with the developed methodology, the geological and technical measures include a system of observations, analysis and forecasting of the current geodynamic state of the geological environment, carried out within the framework of a given regulation, as well as an assessment of the negative impact of mining operations on the environment and safety during the construction and operation of transport tunnels.

One of the first tunnels, during the reconstruction of which in some sections did not have the carrying capacity of the temporary lining and required the construction of additional load-bearing elements, is the Big Loop Tunnel (BLT) of the Armavir-Tuapse section of the North Caucasus Railway [Lebedev, Balykin, 2006].

The Big Loop Tunnel is located 1,855 km between Goyth and Indyuk stations and runs under the top of one of the spurs of the Goyth Pass with a maximum elevation of 328 m. The length of the

tunnel is 986.6 m. The maximum laying depth is 125 m. The tunnel was built in 1910-1914 during the construction of the Armavir-Tuapse line in size for one normal gauge track of 1,524 mm, in the profile it is single-track with Imax = 14.7 ‰ in the direction of s. Indyuk, in the plan - on the portal areas on the R320 and R300 m curves and in the middle of the tunnel on a straight length of 296 m.
The conditions for tracing the railway on this stage are extremely difficult. To descend from the pass, in the presence of a strongly crossed mountainous terrain, on a steep slope, the railroad track was developed in the form of a spiral (loop) with a length of 3,700 m and a diameter of 940 m. Almost half of its length is made up of three loop railway tunnels: Big Loop tunnel (BLT), The Middle Loop Tunnel (MLT) and the Small Loop Tunnel (SLT) (Fig. 3).

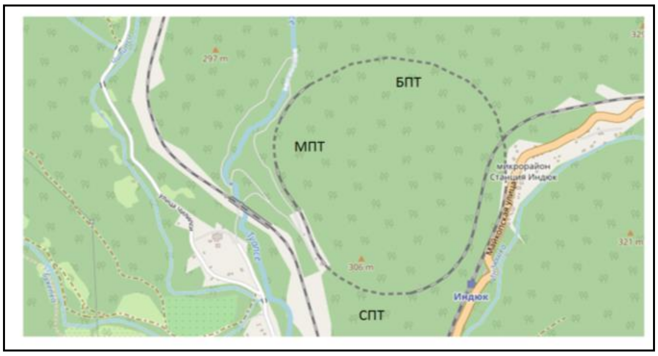

Figure 3 - Loop railroad track

Quaternary and Middle Jurassic deposits take part in the geological structure of the region. In general, the engineering and geological conditions of construction are complex.
Based on the results of the survey of the tunnel in 2001 and analysis of available observational data from previous years, the following conclusions about the state of the tunnel were made by the Tunnel inspection station of the Central of the Ministry of Railways of the Russian Federation:
- the internal outline of the tunnel, which does not meet the requirements for the safety margin, significantly limits the ability to pass oversized cargo and does not allow the passage of cargo foreseen in the future;
- the lining masonry has a number of defects in the form of empty joints, falling out of individual stones, delamination, throughout fallouts, which significantly reduce its bearing capacity;
- up to 35% of the lining is water-encroached: on 23 rings there is dripping, including in the zone of the contact wire. The largest number of lining defects occurred precisely in water-encroached areas.
A decision was made to reconstruct the Big Loop Tunnel. The reconstruction was carried out in the period 2003-2006 on a project by NIPII Lenmetrogiprotrans JSC.
The reconstruction project provided for the construction of a parallel tunnel over most of the length of the tunnel (790 m). In the northern section with a length of 120 m, where during the construction of a parallel tunnel the track comes to the surface in an extremely unfavourable place, a major overhaul of the tunnel was envisaged, while maintaining the existing planned and high-altitude track position. To connect the repaired section while maintaining the existing axis of the tunnel, with a section that runs parallel to the existing tunnel, it was planned to construct an interlinkage with a length of 98 m.
On the site where the project envisaged the preservation of the existing planned and high-altitude position of the track, the “old” lining was dismantled along the entire perimeter with the erection of a temporary “arch-concrete” lining and monolithic reinforced concrete lining. Here, measures were provided to ensure the stability of the roof when finalizing the section of the tunnel (grouting the space behind the existing lining, ahead of anchor fastening).

During the geological and technical measures carried out by the NIPII Lenmetrogiprotrans JSC institute the following tasks were fulfilled:
- the SSS of rocks, supports and lining of the existing and constructed tunnels was determined in natural conditions according to the displacements of the output contour and stresses in the structures, especially in the areas of their mutual influence;
- lining calculations were carried out with the determination of changes in the displacements of the output contour in time and their maximum values, taking into account the loading of concrete at an early age;
- the seismic effect of technogenic explosions on the lining of the existing tunnel was estimated during the drilling and blasting operations in the newly constructed area;
- the stability of the massif in the face zones of the tunnel under construction was assessed;
- an engineering-geological and hydrogeological forecast was carried out ahead of the faces of the tunnel under construction;
- observations were made of precipitation of the day surface above the tunnel route.
The most voluminous material according to the monitoring results was collected while determine the SSS of the supports. The SSS of the supports was determined in the experimental sections of the tunnel under construction along the new railway and along the existing tunnel railway. Determination of the SSS of the supports was carried out in two ways - stress measuring by installing string sensors and displacements of the internal contour of the supports. In this work, we consider four experimental sites located in similar mining conditions (Fig. 4).

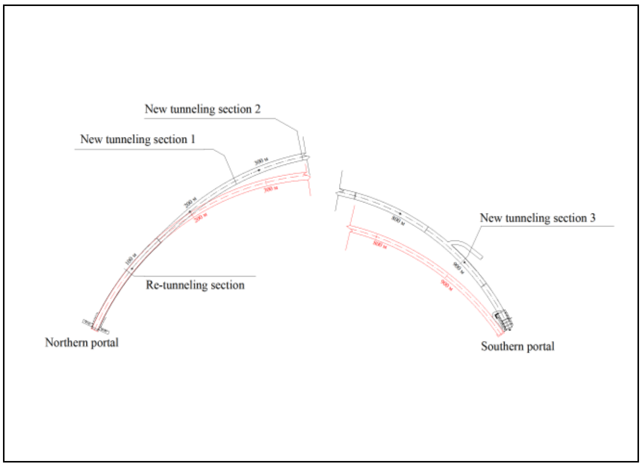

Figure 4 - The layout of the experimental sites in the Big Loop Tunnel

1) The re-tunneling section is located on the side of the Northern portal when the tunnel is being rebuilt. Observations on this experimental site were carried out under the conditions of lining bulkhead - the existing tunnel lining was replaced by a new supporting structure. Four knots of a steel I-beam arch construction, two string sensors in each, with subsequent concreting of the interframe space, were equipped with measuring sensors.
2) The new driving section n.1 is located on the side of the Northern Portal. String sensors were also installed on a steel I-beam.
3) The new tunneling section n.2 is located in the tunnel during the penetration from the North Portal. String sensors were installed in the reinforcing arch. The sensors were installed in the centre of the cross-section of the reinforcing cage before spraying concrete works.
4) The new tunneling section n.3 is located in the tunnel during the penetration from the South portal. String sensors were installed on a steel I-beam.
The arrangement of sensors on steel I-beams and in reinforcing arches is shown in Figure 5.

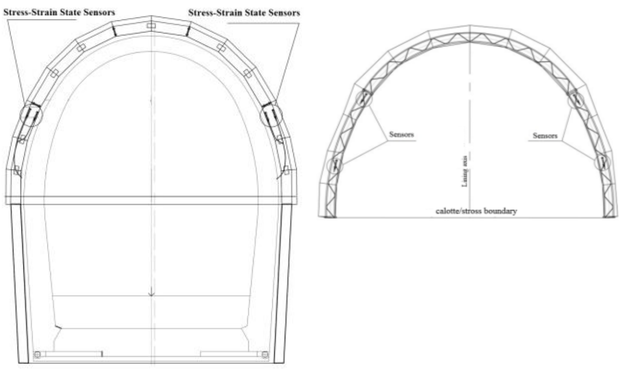

Figure 5 - Schematic diagram of the arrangement of sensors in the calotte part on the steel I-beam (left) and in the reinforcing arch (right)

All experimental sites under consideration were equipped with PLDS-400 string sensors (Fig. 6).

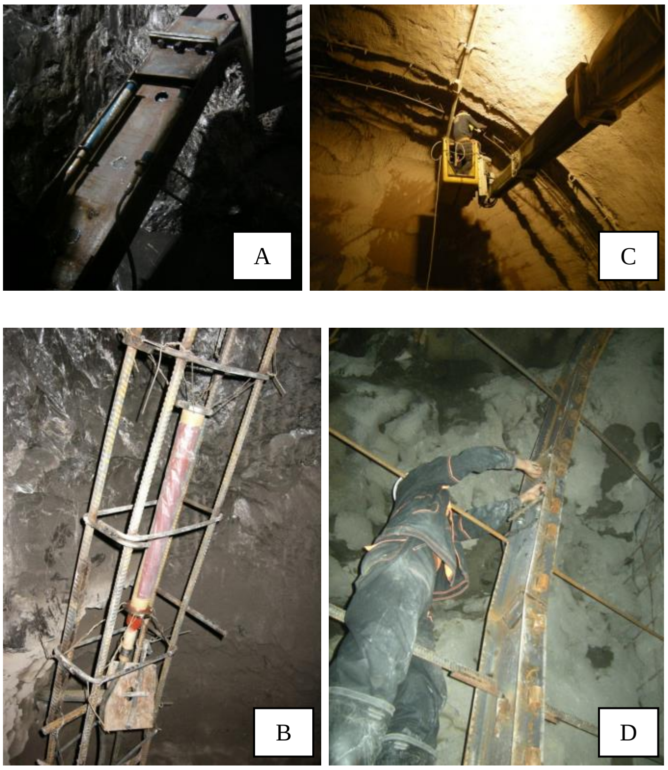

Figure 6 - Sensors PLDS-400 installed on a steel I-beam (A) and sensors PLDS-400 installed in a reinforcing arch (B). The process of installing sensors in a reinforcing arch (C), the process of installing sensors on a steel I-beam (D) before concreting

Based on the results of field studies, the normal tangential stresses in the lining were determined taking into account the creep of the lining material during early loading of concrete.

5. ANALYSIS OF THE STRESS-STRAIN STATE

The results of determining the normal tangential stresses in the experimental sections for the tunnel calotte part are shown in Figure 7.

In the area of new tunneling n.1, the maximum value of compressive stresses before putting into operation amounted to 15.5 MPa from the side of the existing tunnel and 6.5 MPa from the opposite side. Subsequently, stresses increased with a tendency to stabilize at the end of observations.

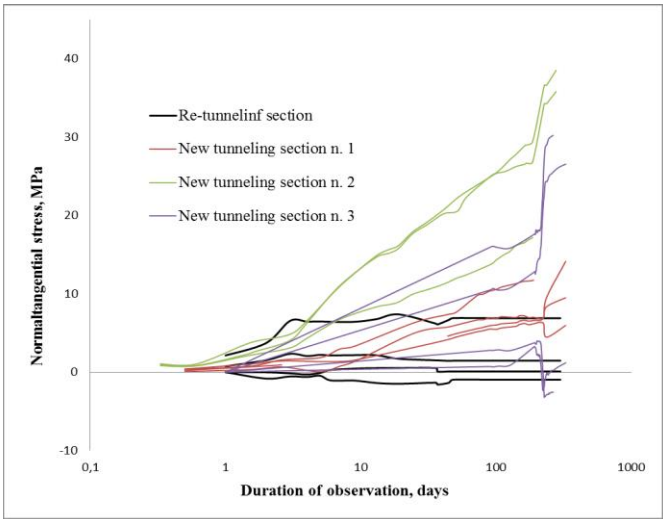

Figure 7 - The results of determining the normal tangential stresses in the experimental sections for the calotte part of the tunnel

Before the commissioning of the new section n.2, the maximum stress values along the perimeter of the arch were: in the arch - 38 MPa, in the lower part of the calotte - 20 MPa.

According to the results of observations in the temporary lining (by the time the constant lining was made), the mode of deformation was stabilized in the new tunneling section n.3. The maximum stresses in the calotte reached 30 MPa.

In the stross part of the tunnel in all experimental sections, the SSS values are approximately 2 times lower than in the calotte part.

The experimental section in which re-tunneling with the construction of a new tunnel lining was carried out is of the greatest interest within the framework of this work. After removing the old lining on this section of the route, structures similar to those constructed on complex sections of the tunnel were erected (near-portal zones, sections in the area of mates of mine workings, sections with a depth of up to 40 m, and also a section of tectonic disturbance). Heavy frame supports made of n.35 I-beams were used with concrete filling of the interframe space. Re-tunneling works were performed in the "window" with a complete stop of the traffic in this section. After the construction of a new lining, traffic along the old railway was restored. In parallel, work was underway to build a tunnel along the new railway.

In the re-tunneling section, the maximum recorded stresses in the structural elements are 4.8 MPa along the arch and 2.1 MPa along the lower part of the calotte.

In accordance with the observations made at the re-tunneling section, there was no significant change in the SSS of support. Compression and tensile stresses tended to decrease.

The construction of a permanent lining did not affect the change in SSS support.

Further observations did not reveal a significant change in the SSS support - during operation of this section of the tunnel, the stress-strain state remained unchanged.

Studies of the SSS of the temporary lining structure at the re-tunneling section showed that quantitatively these parameters were significantly less than for the same lining erected on the new tunnel route during the entire period of the tunnel construction and at the initial stage of its operation. The results of experimental observations show that the process of redistribution of the SSS of the "underground structure - enclosing massif" system stabilizes over time until a stable equilibrium state is reached.

6. CONCLUSIONS

1. The theoretical concept on establishing a new equilibrium state during the long-term operation of a railway tunnel is confirmed by

the results of the field studies. During the experiment, under the conditions of reconstruction of the tunnel, the old lining was replaced with a new supporting structure. In the construction of the temporary lining and in the new lining, insignificant changes in the stress-strain state (SSS) occurred and were rapidly stabilized. In the same tunnel, under the same engineering-geological, hydrogeological and mining conditions, but in the areas of new tunneling in the untouched massif, temporary lining structures recorded an increase in SSS even after the construction of a permanent lining.

2. Stresses in monolithic reinforced concrete lining of the first constructed tunnels increase with the beginning of their operation. So when monitoring the Olympic tunnels in Sochi, in addition to the influence of temperature gradients, which affect the change in stresses during the year to 1.5 MPa, there is a clear trend of an increase in compressive stresses in the lining, which increase by 2.5-3.0 MPa over 4 years. Moreover, with a high degree of probability, the preservation of the growth rate of stresses in the coming year is forecasted. Thus, the determination of the SSS of supports and lining using direct methods (installing sensors in load-bearing structures during erection) makes it possible to judge the efforts generated throughout the life of the tunnel from the moment of loading the supports (lining) in the face, and then during operation.

3. The system of mining and environmental (geotechnical) monitoring of tunnels at the stages of construction, operation, during repairs and reconstructions allows ensuring the safety of tunnels and predicting the state of the «underground structure - enclosing massif» system, as well as to obtain new scientific information that can change idea about the formation of stress-strain state in various engineering and geological conditions and for various technological schemes for underground structures construction.

Such knowledge makes it possible to verify the methods used for calculating supports and lining, thereby optimizing their design with safe operation.

7. REFERENCES

Bezrodny K.P., Lebedev M.O. (2009). “Guidelines for integrated mining and environmental monitoring in the construction and operation of transport tunnels”. URAN IPKON RAS, Lenmetrohyprotrans, Moscow. (In Russian).

Bernhard Kohlbock, Wolfgang Weinmar, Karl Hartleitner (2018). “Design and construction challenges of the refurbishment of the 110-year-old Bosruck rail tunnel, Austria”. Paper Proceedings ITA - AITES World Tunnel Congress, Dubai, UAE, 2018, pp. 1144—1157.

Budaeva A.Kh. (1972). “Study of the conditions of the static work of the lining, erected during the reconstruction of tunnels with relocation of the arch”. LIIZHT. Leningrad. (In Russian).

Dandurov M.I., Korolkov N.M. (1962). “Maintenance and reconstruction of tunnels”. All-Union Publishing and Printing Association of the Ministry of Railways. Moscow. (In Russian).

Haihong Ding, Weiwei Jiang (2016). “Application of Geophysical Methods in Tunnel Exploration”. Proceedings of the 5th International Conference on Civil, Architectural and Hydraulic Engineering (ICCAHE 2016), pp. 188–192.

Ignacio Menendez Pidal (2019). “Los viajes de agua en Madrid. Historical approach, reconstruction and conservation”. Materials of the Conference Underground space development as a means of preservation of historical environment, St.-Petersburg, Russia.

Kaufman L. L., Lysikov B. A., Zapolova K. I., Sirachev I. Zh. (2010). “Underground risk assessment experience. Science and transport progress”. Bulletin of the Dnipropetrovsk National University of Railway Transport, №32, pp. 55-60. (In Russian).

Lalague A., Lebens M. A., Hoff I., et al. (2016). “Detection of Rockfall on a Tunnel Concrete Lining with Ground-Penetrating Radar (GPR)”. Rock Mechanics & Rock Engineering, No 49(7), pp. 2811–2823.

Lebedev M.O., Romanevich K.V. (2019). “Engineering-geophysical studies in the reconstruction of underground structures”. Mountain News and Analysis Bulletin, № 5, pp. 97-110. (In Russian).

Lebedev M.O., Balykin V.V. (2006). “Mountain-ecological monitoring on the example of the Big Loop Tunnel”. Metro and tunnels, No 6. - pp. 27-29. (In Russian).

Limanov Yu.A., Podchekaev V.A., Korolkov N.M., Merinov I.I. (1976). “Maintenance and reconstruction of tunnels”. Transport, Moscow. (In Russian).

McCann D.M., Forde M.C. (2001). “Review of NDT methods in the assessment of concrete and masonry structures”. NDT&E. International, Vol. 34, pp. 71-84.

Nigel J. Cassidy, Rod Eddies, Sam Dods (2011). “Void detection beneath reinforced concrete sections: The practical application of ground-penetrating radar and ultrasonic techniques”. Journal of Applied Geophysics, Vol. 74, pp. 263-276.

Sloan S.D., Peterie S.L., Miller R.D., Ivanov J., Schwenk J. T., McKenna J.R. (2015). “Detecting clandestine tunnels using near-surface seismic techniques”. Geophysics, Vol. 80 (5), pp. 127-135.

Qin Tu-guan, Feng Yi (2015). “The Application of 2 Geophysical Exploration Methods to Guanyiyan Tunnel Construction”. Yunnan Geology, No.34(3), pp. 444-448.