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ОБЕСПЕЧЕНИЕ БЕЗОПАСНОСТИ ПРИ СТРОИТЕЛЬСТВЕ ДВУХПУТНОГО ТОННЕЛЯ МЕТРОПОЛИТЕНА В ЧЕТВЕРТИЧНЫХ ОТЛОЖЕНИЯХ

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Аннотация: Впервые в практике строительства метрополитенов на территории Российской Федерации осуществлено строительство двухпутного перегонного тоннеля. Проходка тоннеля выполнялась в пределах четвертичных отложений — водонасыщенных совершенно неустойчивых грунтах, а также в плотных протерозойских глинах. Проходка выполнялась при помощи тоннелепроходческого механизированного комплекса с грунтопригрузом. Трасса тоннеля пересекала транспортные развязки, железную дорогу, в зоне влияния строительства находились здания и сооружения. Для обеспечения безопасности строительства осуществлялся геотехнический мониторинг, одной из задач которого являлась корректировка технологических параметров ведения щита. Для возможности оперативного принятия решений в случае приближения контролируемыми параметрами напряженно-деформированного состояния системы «тоннель — грунтовый массив» к критериальным величинам, измерения выполнялись автоматизированными системами с контролем в режиме реального времени. Это позволяет не только качественно выполнить в случае необходимости противоаварийные мероприятия, но и осуществить оперативную корректировку технологического режима проходки, направленную на снижение деформаций окружающего грунтового массива.

Ключевые слова: метрополитен, двухпутный перегонный тоннель, четвертичные отложения, режим проходки, геотехнический мониторинг.

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Safety provision in the construction of a two-track subway tunnel in quaternary deposits

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Abstract: For the first time in the practice of construction of subways in the territory of the Russian Federation, a double-track running tunnel was built. Tunnelling excavation was carried out within the quaternary deposits — water-saturated completely unstable soils, as well as in dense Proterozoic clays. Tunnelling excavation was carried out using a tunnel-boring mechanized complex (TBMC) with earth pressure balance. The tunnel route crossed the traffic junctions, the railway; in the zone of influence of the construction there were buildings and structures. To ensure the safety of construction, geotechnical monitoring was carried out, one of the tasks of which was to adjust the technological parameters of the shield. For the possibility of prompt decision-making in the event that the controlled-parameters of the stress-strain state of the «tunnel-soil massif» system approach the criterion values, the measurements were performed by automated systems with real-time monitoring. This allows not only qualitatively to carry out emergency response in case of need, but also to make an operative correction of the technological mode of penetration, aimed at reducing deformations of the surrounding soil massif.

Key words: subway, double-track running tunnel, quaternary deposits, mode of penetration, geotechnical monitoring.

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Introduction

The subway construction in the city of Leningrad started at significant depths, approximately 60 metres under the ground, on average. The reason for such deep placement was the presence of a thick layer of quaternary deposits in the form of water-saturated unstable soils. Since the pick hammer served as the main tool for tunnelling up to the middle of the 20th century, the water tightness of the subway facilities could only be achieved within the aquilide of dense claystone-like Kotlin underclays of the quaternary deposits.

The development of the technologies and the international experience of their application for the construction of wide diameter subway tunnels [1, 2] allowed constructing a two-track tunnel in Saint-Petersburg. This, in turn, made it possible to apply modern engineering solutions when constructing subsurface stations [3].

The first two-track running tunnel was constructed with the help of an EPB TBMC along the Nevsko-Vasilievskaya line of the Saint-Petersburg subway.

A major part of the 3,800 metres long running tunnel is located in the completely unstable soils at the depth of 10,0 to 13,6 metres (measured at the height of the vault crown). The TBMC reaches the dismantle chamber at the depth of more than 50 metres.

In the subsurface sections the host rocks are boulder clays with gravel and pebbles inclusions constituting 10—15% of the rock, with sporadic low-plasticity and semisolid crystalline boulders; dense boulder clay sands with gravel and pebbles inclusions constituting 10—20% of the rock, with sporadic solid and lower-plasticity boulders; re-deposited solid clays and dislocated Lower Cambrian solid clays. The moraine may contain large boulders over 0,5 metres in size. In rare cases the boulders can reach up to 3—5 metres. The bottom of the tunnel is composed of semi-solid and solid clay soils.

In the deep level sections the tunnel excavation was done in the undisturbed Lower Cambrian clays and dense claystone-like solid Kotlin clays with the hardness coefficient of $f = 1.5$ by the Protodyakonov scale of hardness. The silica clays contain pressured water. The hydrostatic pressure in the silica clays ranges between 0,35 and 0,56 MPa depending on the depth of occurrence. By their strength and deformation properties clays are classified as half-rocks.

A tunnel measuring 9,4 m of diameter on the inside and 10,3 m on the outside was excavated with the help of a «Herrenknecht» TBMC with soil tightening weight in the bottom. The cross-section of the tunnel is presented in Fig. 1.

The zone of influence of the tunnel comprised the ring road, railroad tracks, buildings and structures, tramway tracks and motor roads.

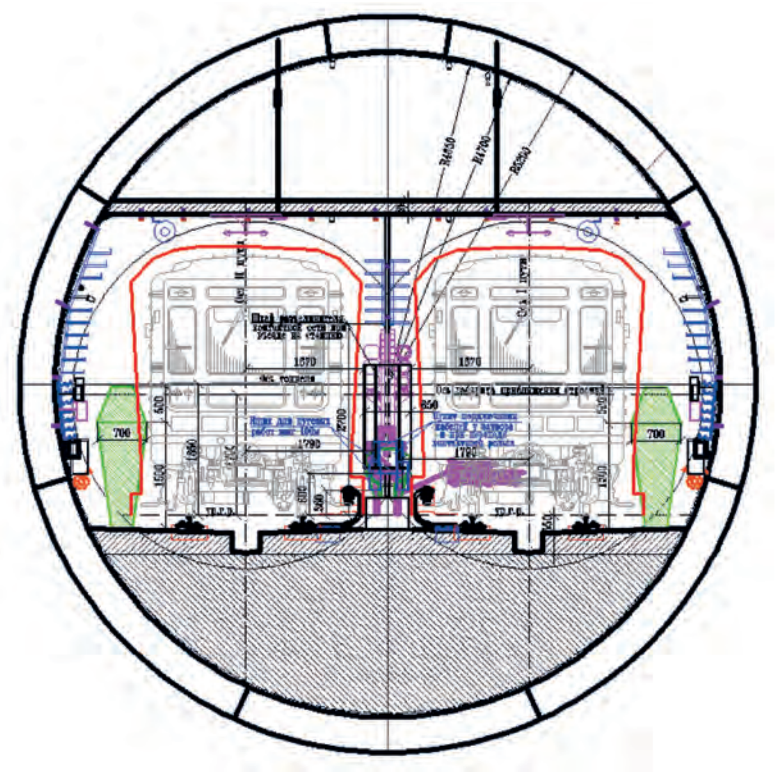

Fig. 1. Cross-section of the two-track tunnel

During excavation, the geotechnical monitoring was set up, aimed at reducing the negative impact of the anthropogenic processes involved in the construction of the tunnel on the environment and the safety of tunnel excavation. The geotechnical monitoring served to the following purposes:

- making engineering and geological, as well as hydrogeological forecast beyond the bottom;
- identification of the surface and the deep level soil massifs;
- visual and instrumental monitoring of the structures in the area of tunnel construction;
- controlling the quality of backfilling of the area beyond the tunnel lining;
- assessing the stress-strain behaviour of the tunnel lining.

The safety of conduction of tunnelling works depends to a large extent on the availability of ultimately reliable and up-to-date data on the stress-strain behaviour of the «tunnel — host rock mass» system, as well as of the daylight surface. This data can be obtained through geotechnical monitoring with the use of automated systems that assure the availability of up-to-date information received from all fixed control and measuring devices [4].

The purposes to which geotechnical monitoring serves are related to assessing the behaviour of the structures under construction, of the host rock mass, of the daylight surface and of the buildings situated in the zone of influence of the construction. The need to preserve the buildings and structures on the daylight surface explains the priority use of automated systems for locating soil massif strain, from the contour of the underground facilities to the surface of the ground. The results

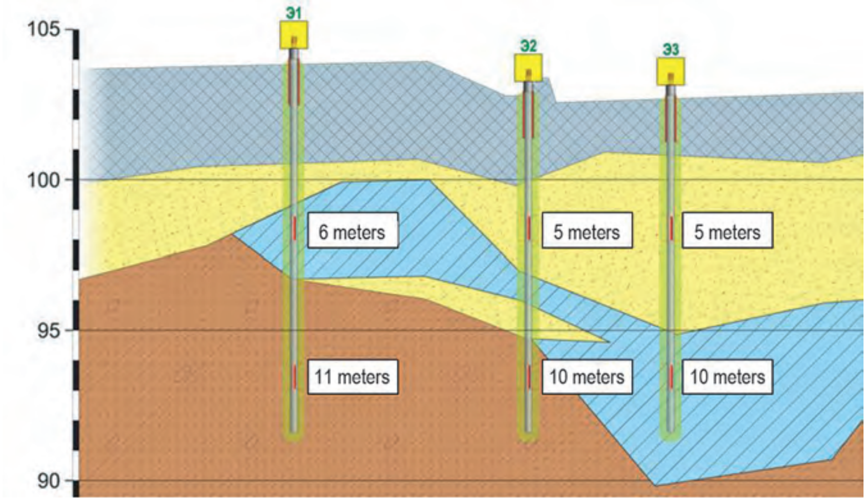

Fig. 2. Location of the extensometer wells above the subsurface section of the two-track running tunnel

of the monitoring allow adjusting in the process of construction the technological parameters of tunnelling, the mounting parameters and the technology of lining construction, as well as working out recommendations for reducing the negative impact on the environment.

Geotechnical monitoring

The major issue related to the construction of subsurface tunnels in soft soils is maintaining the daylight surface. The geodetic control of the strains fails to define specific technological parameters for guiding the TBMC that influence the strain formation of the host rock mass. In order to monitor these, extensometer wells have been placed all the way along the running tunnel route, at the subsurface level (Fig. 2), as well as at the deep level. The lower extensometers are located 1.5 metres above the 10,3 metres diameter tunnel lining. The measurements have been performed every 2 hours by an

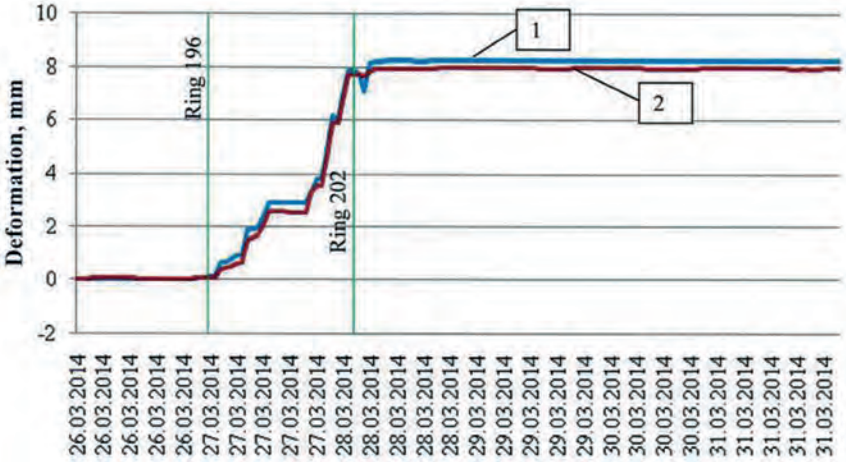

Fig. 3. Formation of strains in the soil massif as measured by two extensometers placed in the same well: 1 — 5 metres deep; 2 — 10 metres deep

automated system secured in a tamperproof cabinet, and the data was forwarded to a remote Internet portal. The results of the measurements at one of the tunnel sections are presented in Fig. 3.

Following the results obtained, a timeframe has been set up to establish correlation between strains and technological parameters of the TBMC guiding, and the velocity of the strain spread from the lining contour to the surface was calculated. The optimal pressure of the tightening weight of the bottom did not incur any strain of the soil massif either beyond the bottom or during the movement of the shield under the well. Ascent strain occurred only when delivering grouting mortar beyond the lining. Given the absence of the engineering communications in this section of the tunnel, it became possible to exceed the pressure of delivery of backfill compared to the estimated threshold of the surface rising (Fig. 4).


Fig. 4. Crack on the ground surface resulting from the backfill of the space beyond the lining

Besides, it was discovered that the 12 metres thick layer of soil above the tunnel almost does not get compressed, that is why the excessive pressure produced when backfilling the space beyond the tunnel lining was immediately transferred to the ground surface. Within 2 days from 26 March, 2014 till 28 March, 2014, the ground level ascended by 45 mm, though it had been estimated that it would sink by 20 mm.

Another result obtained during the study of the soil massif strain was indirect limitation of the «survival time» of the grouting mortar. The extensometer ascent strain lasts for more than 24 hours. Within this period, 6 ring sections of the lining were erected; the distance from the shield was about 10,8 metres. This is only possible when the pressure is applied from the contour of the tunnel, that is, through the pressure of the grouting mortar. The setting time of the mortar determine not only the surface strain, but also the stress-strain behaviour of the lining.

The adjustment of the technological parameters of the TBMC at the section analysed allowed the excavation the rest of the subsurface tunnel route with minimal surface strain, ranging from –5 mm (sinking) to +15 mm. As a rule, the areas that registered an ascent of the surface did not sink later on.

Altogether, 6 extensometer wells have been placed along the tunnel route in the subsurface area, and 2 wells in the deep level area.

In the deep level area the extensometers registered sinking strain of the near-lining zone by 0,5 mm. No surface strain has been observed following these sinking strains of the near-lining zone.

The control of the quality of filling of the space beyond the tunnel lining with grouting mortar is also essential, as for each technological pattern a specific composition of the mortar is determined, as well

Fig. 5. Location of the instrumental monitoring sensors on the façade of one of the buildings

as the parameters of its delivery into the space beyond the lining. Taking into the account the speed of the tunnel construction, it is important to consider the setting time of the grouting mortar in order to put the lining together with the soil massif into operation on time. The assessment of the quality of backfill beyond the lining has been performed with the help of geotechnical monitoring by ultrasound CT scanners and georadars; recommendations have been worked out for the further adjustment of the technological parameters of the backfill stipulated by the process regulations.

The visual and instrumental monitoring of the buildings plays a significant role in assessing the impact of the construction process on the pre-existing buildings and structures or the absence of such impact.

The zone of influence along the tunnel route comprised 4 residential and public buildings in the subsurface section and 2 residential buildings in the deep level section. One of the buildings was situated directly above the tunnel, while the others were at 4 to 10 metres from the tunnel lining.

In order to assess the stress-strain behaviour of the buildings, a fixed system for monitoring architectural structures was used. The measuring devices registered regularly the change in the crack openings, in the intensity of vibrations, in the tilt angle and the temperature in the points where the devices were installed; the data collected was further transferred through radio channel to a remote Internet portal. The high-precision tilt angle gauges (tilt meters) can measure the changes in the tilt and the sag of the structure of the building related to the vertical line (plumb line) in two directions; they are typically installed on the roofs of the buildings. The sensors register changes (Fig. 5) automatically and forward the data to a remote Internet portal.

The 2-year-long monitoring with the help of the control and measurement devices installed determined that the crack openings mostly depended on the changes in the temperature alone. The range of the crack opening and closing reached 2 mm. The cracks did not return to their previous state. The accumulated crack opening, not taking into account the temperature, amounted to 0,5 mm. At the same time, no crack opening resulting from the tunnel construction was observed on the façades of the buildings or on the inner structure.

Among safety measures for subsurface excavation, it is important to cite the respect of the admissible vibration impact on the pre-existing buildings and structures. The building situated directly above the tunnel was surveyed for this particular

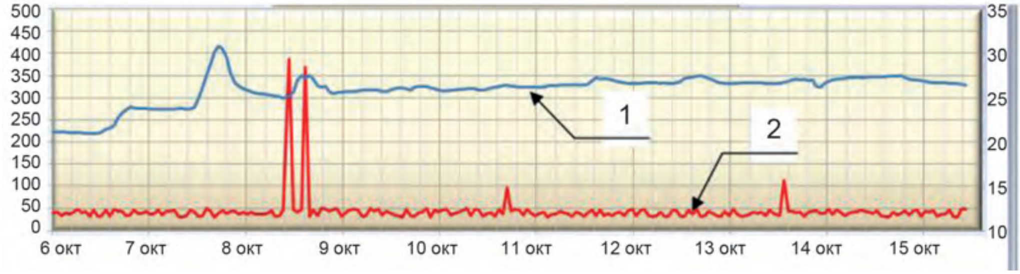

Fig. 6. Results of monitoring of the vibration impact on the building by the data of one of the vibration sensors installed on the load-bearing structure: 1 — temperature, 0C; 2 — vibrations μm/sec

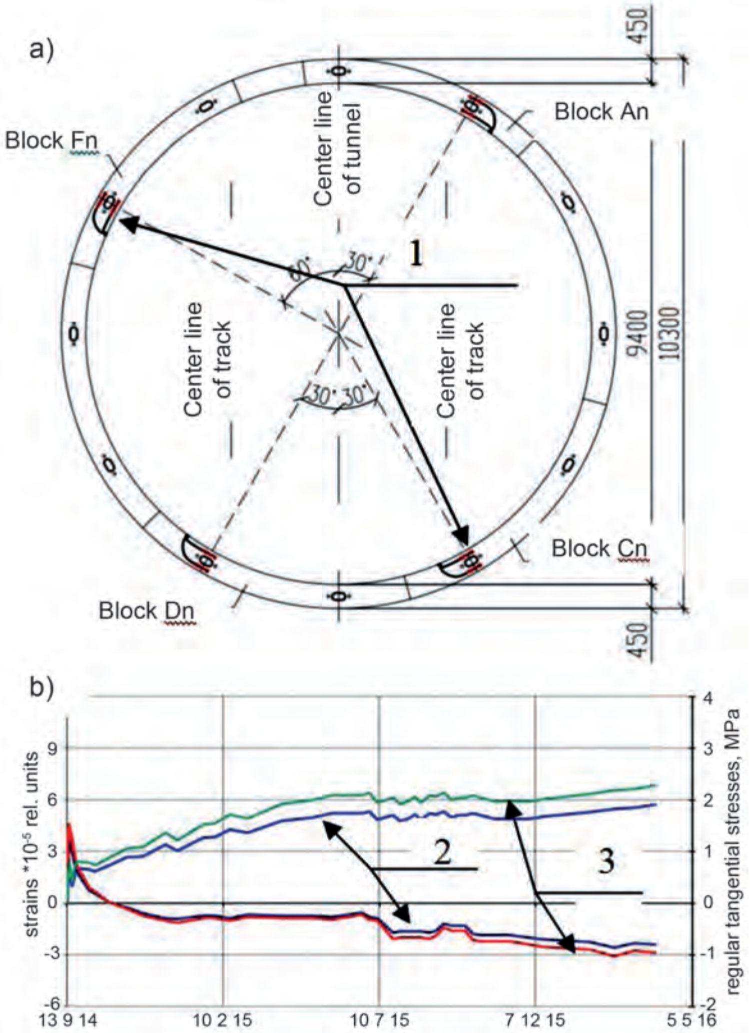

Fig. 7. Location of the sensors in the lining of the two-track running tunnel a) and typical diagram of pressure formation in the lining b): 1 — string sensors; 2 — relative strains in the inner and the outer contours $*10^{-5}$ rel. units; 3 — regular tangential stresses in the concrete of the inner and the outer contours, mPa

purpose. The soil layer between the tunnel lining and the daylight surface equalled 12 metres.

Vibration sensors were installed on the load-bearing structures of the building and connected to an automated data collection system with collection frequency at one collection per hour. Following the results of daily monitoring (Fig. 6) during the tunnel excavation underneath the building, it can be confirmed that the overall level of vibration of the architectural structure were below the threshold levels, and the registered sporadic shocks were due to the operation of the Youth Centre during the day and the tram circulation at the distance of 30 metres from the building. The leap in vibration registered between 8 and 9 October (Fig. 6) occurred when the TBMC was stalled for maintenance.

The stress-strain behaviour of the tunnel lining was assessed with the use of control and measurement devices installed in the blocks during their production. The lining was equipped with string strain meters — tensometers with 200 mm spacing. The registered local relative strains were used to calculate the regular tangential stresses. In concrete and reinforced concrete structures the stresses are calculated using a special method that takes into account the loading of the concrete at an early stage and concrete crawling.

The most extensive data on the formation of the stress-strain behaviour of the mounts and linings is provided by a combination of sensors (strain meters) inside the structure (Fig. 7, *a*) and measurement of the inner contour strain starting from the moment of construction.

Taking into account the construction technology, it is possible to control the qualitative and the quantitative changes in the stress-strain behaviour of the lining (Fig. 7, *b*) from the moment of the ring assembly to under the protection of the TBMC shield. The comparison of the stress in the lining with the strains in the inner lining for a specific cross-section allows assessing the load-bearing capacity of the other sections of the tunnels with fewer costs, limiting it to inner lining strain control only. For reliable and sufficient determining of the load-bearing capacity of the lining along the tunnel route using this method, the lining is equipped with sensors within all lithological varieties that the tunnel crosses. Along the route of the tunnel analysed, 18 rings were equipped with sensors.

The control of the stress-strain behaviour of the lining as concerns the duration and the change speed of the observed values allows assessing not only the absolute values determined through calculation, but also assessing indirectly the quality of backfill of the space beyond the tunnel lining and the time of setting of the grouting mortar.

Conclusion

The construction of a large cross-section running tunnel in the complex engineering and geological conditions of Saint-Petersburg confirms that the safety during construction is assured through the implementation of the modern technologies to complement the geotechnical monitoring.

The results of the studies allowed determining the main factors that influence the movement of the soil massif across the entire soil layer and working out recommendations for adjustment of the construction technology parameters, for reduction of the negative impact of the ground sinking and the related process of building deterioration within the shift trough, as well as for the reduction of the vibration impact on such building to the admissible level.

The use of modern automated geotechnical monitoring systems during tunnel excavation for different purposes, particularly in urban construction areas, constitutes an efficient element of the technological process allowing to mitigate considerably the risks of emergencies and to increase the efficiency of the measures adopted following the monitoring results.

The placement of the control and measuring devices within the lining for assessment of the stress-strain behaviour helps not only to control the pressure formation during the tunnel construction, but also to estimate the load-bearing capacity of the lining in order to assure safe operation of the transportation tunnels.

Generalizing the accumulated experience of geotechnical monitoring, it is important to recognize its role in the process of subterranean construction and to point out the following advantages of such monitoring:

- the research tasks allow formulating an overall understanding of the cooperation and joint functioning of the «tunnel — soil massif» system to be used for rapid decision-making related to the need of adjustment of the construction technical parameters;
- the aims of the monitoring complement each other and help avoiding possible mistakes in the interpretation of the data collected;
- the monitoring assists in reducing the negative impact of the tunnelling on the environment; it assures industrial safety during the construction phase.

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