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GEOTECHNICAL MONITORING

COMPREHENSIVE AUTOMATED GEOTECHNICAL MONITORING SYSTEM AND EXPERIENCE IN ITS APPLICATION IN THE CONSTRUCTION OF UNDERGROUND FACILITIES

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This article provides basic information about the automated system Monitron developed at the Research Center "Tonnelnaya assotsiatsiya" and "Sigma Tau" as well as integrated systems for measuring vibrations and the stress-strain state of structures. This article also presents application of Monitron in a sometypical tunneling facilities.

Monitron, the hydrostatic leveling system developed by the Research Center "Tonnelnaya assotsiatsiya" and "Sigma Tau," is used to trace the vertical displacements of buildings and structures during geotechnical monitoring [1-5] (Fig. 1).

The advantages of this system over optical levels and tacheometers (manual and automated) are the following:

– cyclical measurements (data are obtained from sensors once in a minute);

– independence of measurement results on weather conditions and human factors;

– absence of the direct line of sight between sensors;

– fixed measurement accuracy of 0.1 mm, regardless of the distance between the sensors and their number.

The monitoring cyclicity is especially relevant during the construction of tunnels using modern shield tunnel boring machines (TBM), for which the penetration rate can exceed 10 m/day. Furthermore, the constant control of the strain of the monitored objects enables rapid change of the penetration parameters, thus ensuring the safety of existing structures.

The system has the ability to perform self-diagnostic routines during operation, and the Internet service enables the configuration of the automatic generation of reports that are sent via SMS notifications when the maximum strains are reached.

The system software enables the integration of the information from almost any measuring instrument, for example:

– geodetic monitoring;

– control of the groundwater level using piezometers;

– control of the inclination of structures and the displacement of the soil mass using inclinometers;

– control of crack opening by an automated crack-meter or in manual mode (mechanical crack-meters or gypsum screeds with subsequent visual monitoring);

– vibration measurements (noise measurements, optional);

– video surveillance of objects.

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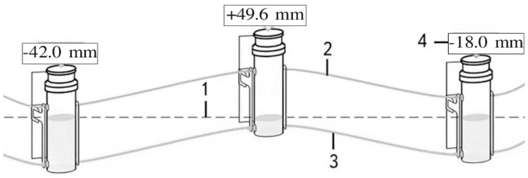

Fig. 1. The principle of operation of the hydrostatic leveling system: 1) the level of the working fluid in the hydraulic system, 2) airway line hose, 3) hydraulic line hose, 4) change in the high-altitude position of the measuring vessel from the baseline.

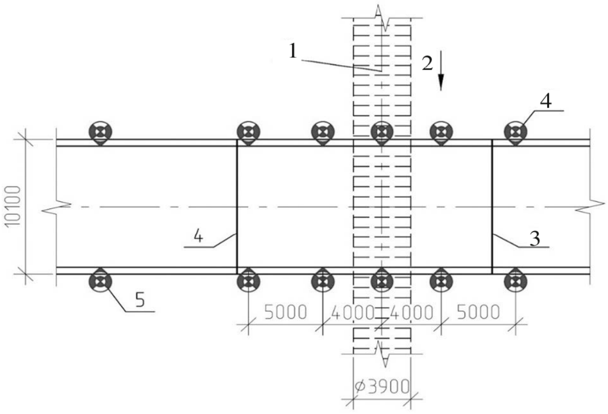

Fig. 2. Plan of the intersection of a tunnel under construction (1) with an existing metro structure (2), separated by expansion joints (3), and an indication of the location of hydrostatic levels (4), including support ones (5).

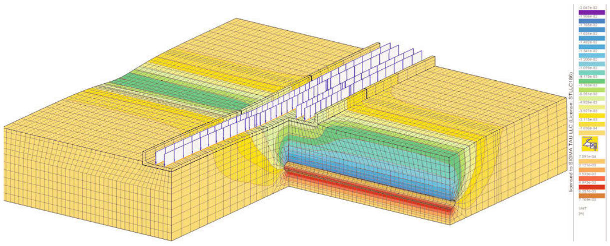

Fig. 3. Fragment of the digital twin at the time of the penetration completion.

One of the examples of the application of the Monitron is its use by Legion-Stroygroup, Moscow in the shield tunneling of the collector tunnel under the existing section of the Moscow metro between "Filatov lug" and "Salaryevo" stations of the Sokolnicheskaya line (Fig. 2).

Before the start of penetration, the digital twin created in the programming and computing suite (Z_Soil) (Fig. 3) enabled construction (by calculation for each of the hydrostatic leveling sensors) a graph of the dependence of the draft on the TBM position along with the predicted corridor boundaries (Fig. 4), the overrunning of which can be considered a signal for correcting the penetration parameters or the use of protective measures.

According to the project, the maximum design draft was 5.4 mm, and the maximum allowable was 14.0 mm. On June 23, 2020, at 22:00, the draft of the existing metro section was recorded, corresponding to the boundary of the predictive corridor (point 2), which represented the first alarm signal. Upon reach-

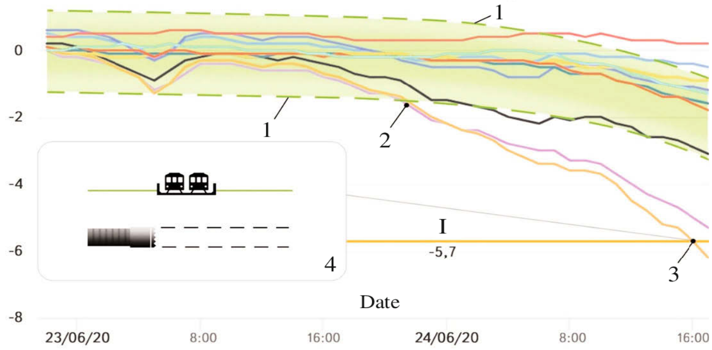

Fig. 4. Schedule of the vertical displacements of the operating metro section from 22:00 on June 22 to 17:00 on June 24, 2020: 1) boundaries of the predicted draft corridor, 2) the point where the actual draft leaves the predicted corridor, 3) maximum draft of 5.7 mm at 16:00 on June 24, 2020, 4) conditional position of the TBM relative to the metro construction at point 3, I) calculated design draft.

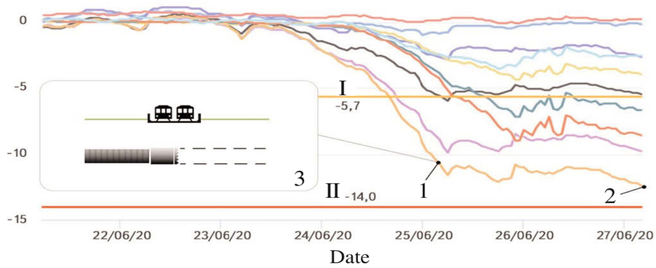

Fig. 5. Schedule of the vertical displacements of the existing metro section from 4:00 on June 21 to 4:00 on June 27, 2020: 1) maximum draft of 10.7 mm at 4:00 on June 25, 2020, 2) maximum draft of 12.4 mm at 4:00 on June 27, 2020, 3) conditional position of the TBM relative to the metro construction at point No. 1, I) calculated design draft, and II) ultimate draft.

ing the design draft of 5.7 mm (point 3), an instruction was received to increase the pressure of the earth pressure balance to 0.6 bar and to adjust the setting time of the curing compound to three hours.

Further penetration showed the insufficiency of the measures taken. With a draft of 10.7 mm, it was recommended to increase the pressure of the earth pressure balance to 1 bar, which led to a noticeable decrease in the intensity of the strain. (Fig. 5).

Considering the amount of draft, which by 4:00 on July 27, 2020 reached 12.4 mm (point 2) that corresponds to 87% of the limit value set by the operating organization, it was decided to perform works on controlled compensation grouting [6, 7] from the tunnel under construction to the base of the existing metro section.

The grouting work was stopped at a draft of 2.6 mm (point 2 in Fig. 6) at the sensor that previously recorded 12.4 mm. The subsequent process of relaxation of stress, shrinkage, and fluid loss of the solution led to the draft stabilization for 8 days to a maximum value of 8.6 mm (61% of the limit value).

An example of the effective integration of various types of monitoring into one service could be the connection of string strain gauges to the Internet portal https://monitron.xyz during the construction of a double line railway tunnel via mining a two-layer monolithic lining [8].

The monitoring program provided for the installation of four measuring sections in the primary sprayed concrete support and permanent lining in the lining areas with the highest stresses determined

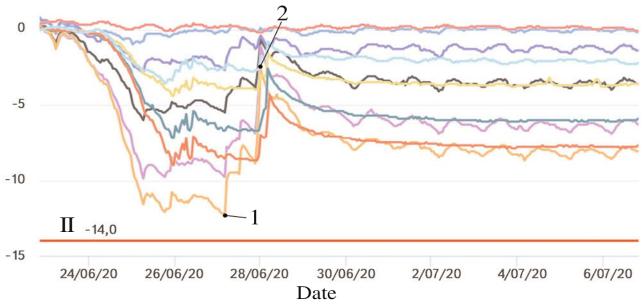

Fig. 6. The vertical displacements of the existing metro section for the entire monitoring period during tunneling: 1) commencement of work on compensation injection, maximum draft 12.4 mm at 4:00 on June 27, 2020, 2) compensated draft of 12.4-2.6 mm at 0:05 on June 28, 2020, II) ultimate draft.

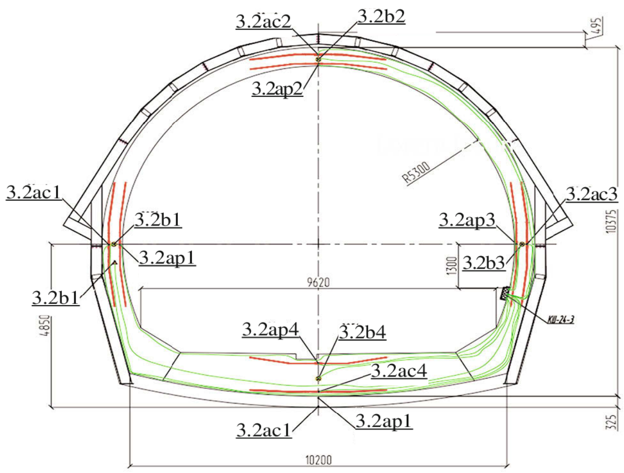

Fig. 7. Layout of the control and measuring equipment in the four measuring sections.

by the results of calculations for use of the control and measuring equipment (CME) developed by NIIES (RusHydro) (Fig. 7).

Remote reading of the CME was performed using an automated control system, which transfers the information (Fig. 8) to the central panel and automatically online to the web resource https://monitron.xyz for the entire monitoring period. This ensures efficient and trouble-free construction.

At many critical facilities and residential buildings in the zone of influence of underground construction, the levels of vibration and noise must be determined, and measures should be to keep these parameters within acceptable limits.

Considering the advantages of automated vibration monitoring systems compared with the traditional vibration monitoring methods (Table 1), the integration of this type of monitoring into the Monitron system has increased significantly the efficiency of its application.

Continuous monitoring of the natural vibration parameters of the structures for a long period enable its control to prevent emergency situations and immediately alerts when such situations arise (in accordance with the requirements [9, 10]).

Let us consider the characteristics of the automated vibration monitoring process using the example of tunneling for the Moscow metro under the structures of lock No. 9 in the Karamyshevsky alignment of the Moscow River [11].

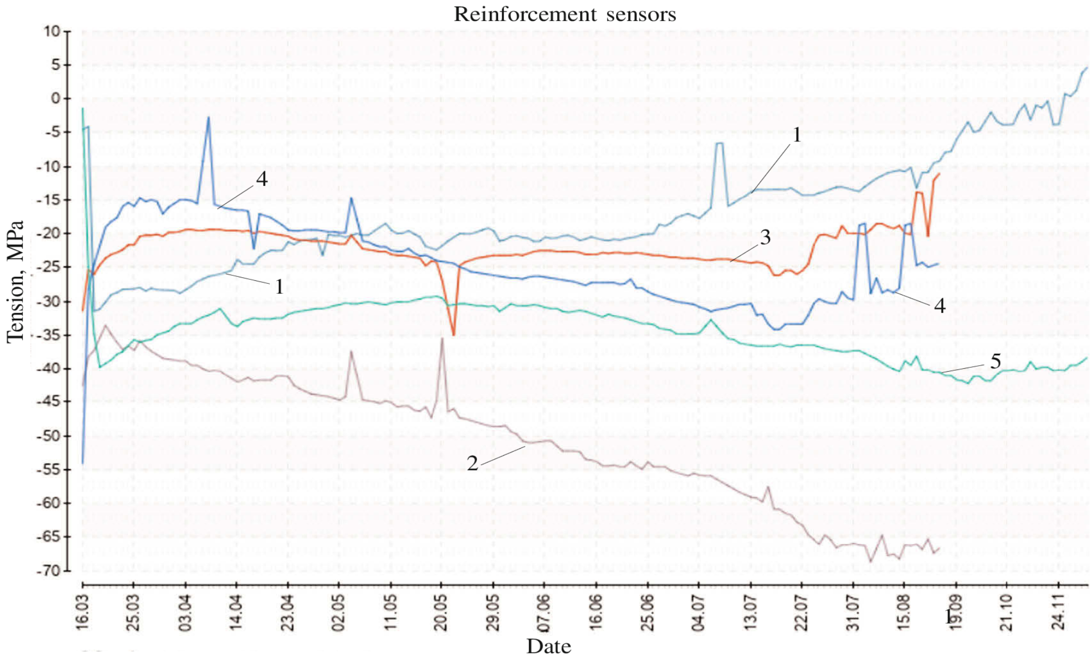

Fig. 8. Graphs of the stresses in the lining (according to monitoring data) at points (Fig. 7): 1) 3.2ap4, 2) 3.2ac1, 3) 3.2ac3, 4) 3.2ac3, and 5) 3.2ac4.

TABLE 1

Vibration monitoring method	Characteristics						
	Human factor	Measure-ment fre-quency	Data pro-cessing speed	Measure-ment accura-cy	Monitoring of structures inside the building	Cost of monitoring	Influence of weather conditions on the measurement accuracy
Manual	yes	low	low	medium	yes	medium	medium
Automated	no	high	high	high	yes	high	no

The possibility of tunneling under the lock without damaging its structures before the start of construction was highly questionable because of the identified defects that formed during operation and the reduced strength of concrete in certain sections of the lock. It was decided to use automated vibration monitoring systems during penetration based on four-channel SV 258 PRO stations (manufactured by SVAN-TEK, Poland) united by the Monitron system with automated monitoring of the high-altitude position (draft).

During the monitoring of vibrations of the lock structures, vibration velocities were measured at control points for three coordinate axes by two autonomous stations, one of which was installed on the northern bank of the lock, and the other of which was on the southern bank.

The stations ensured reliable registration and transfer of information both at positive and negative temperatures as well as during temporary power outages, continuously transmitting measurement data throughout the entire period of penetration. The graphs on the server were presented in an interactive form, which enabled control of the change in vibration velocity at the monitoring point at the appropriate time. In the event of exceeding the established limit values, appropriate e-mails containing a link to access additional information on the server were sent automatically to the users.

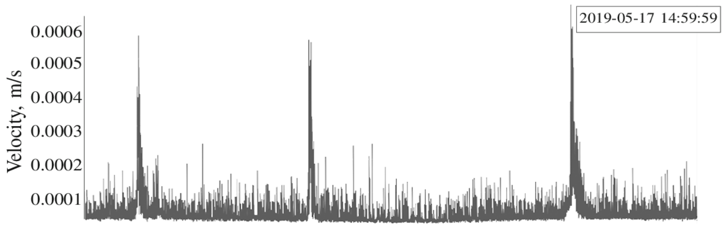

Fig. 9. An example of increased vibrations during locking (data from the northern station); vibration velocity along the Y axis ($V_{Y\max}$ = 0.662 mm/s).

The monitoring provided an exceptionally big data about the vibrations of the lock structures that enabled the possibility of obtaining vibration spectra, various samples, and statistics, as illustrated by the recording of horizontal vibrations of the lock wall during the water craft mooring in locking. The Figure 9 clearly presents bursts of vibrations when docking on the lock wall. The monitoring results can be used to determine the dynamic loads during water craft mooring in the lock, among other actions.

Automated Monitoring of "Sparing" Metro Tunneling Excavation under a Residential Building

The work aimed to ensure the preservation and safe operation of a five-story brick residential building constructed in Moscow in 1962 in the area of metro tunneling. Vibration monitoring was performed alongside the system for monitoring the high-altitude position of the building main load-bearing structures using the Monitron. An automatic vibration monitoring station was installed in the building basement above the metro tunnel construction. During the work, the resettlement of the tenants was not envisaged, and the parameters of displacement of the building structures were monitored. When the vibration velocities were beyond the permissible limits, it was assumed that the metro tunneling mode was to change.

According to the monitoring results, the maximum vibration velocities were recorded when the shield was moving directly under the building ($V_{X\max}$ = 1.479 mm/s, $V_{Y\max}$ = 0.582 mm/s, $V_{Z\max}$ = 0.596 mm/s). However, they did not exceed the maximum permissible values (3-10 mm/s, depending on the vibration frequency). Consequently, the operation of the tunneling shield did not have a negative impact on the state of the building structures.

In general, according to the construction practice, the use of automated vibration monitoring systems enables one to solve complex issues of operational monitoring of the state of building structures exposed to dynamic influences.

Conclusions

A Russian automated system of complex geotechnical monitoring was created that ensures constant monitoring and control over changes in the stress strain state of buildings and structures under construction or in operation during the development of an underground space based on the Monitron hydrostatic levels, software for the formation of digital twins and calculations, processing, and online transmission of data.

The Monitron system and its elements passed a full cycle of industrial tests and were validated at various construction sites. The application of the system is now instituted in the governing technical guidance documents of the Stroycomplex of the city of Moscow [12-14].

Combining various monitoring systems (including vibration monitoring of the dynamic parameters of structures) into the single automated complex, "Monitron" has enabled a qualitative increase in volume, efficiency, availability, continuity, and stability of monitoring under difficult conditions.

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