TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

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Original Empirical Research

Justification of Criteria and Assessment of Environmental Safety during the Operation of Metro Facilities

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Abstract

Introduction. In today's world, with the increasing pace of urbanization, environmental safety plays a crucial role in urban planning and management. Subway operations, as an important part of urban infrastructure, contribute to population mobility, but they can also cause significant environmental problems. Such scientists as Kulikova E.Yu., Konyukhov D.S., Potapova E.V., Balovtsev S.V., Chunyuk D.Yu., etc have studied these issues. However, their research mostly ignores the fact that one of the major threats to environmental safety is the degradation of tunnel linings due to hydrogeological processes. This not only increases the risk of accidents but also increases the likelihood of negative impacts on groundwater and the environment. Therefore, the study of the nature of the development of defects in tunnel linings and their dynamics over time is of both scientific and practical interest, and is the aim of this research. To achieve this objective, it is necessary to analyze the relationship between the condition of the tunnel lining and environmental safety based on data about defects in subway tunnel structures and their impact on the environment.

Materials and Methods. For this study, we used defective sections of the subway tunnel linings from several lines of the Moscow Metro as materials. We conducted field studies of the lining's condition and geodetic surveys of the tunnels, which revealed significant changes in the indicators compared to the normative values as a result of the interaction between the human-made environment and the surrounding nature. Additionally, we employed seismoacoustic inspection methods to inspect the tunnel linings using shock excitation.

Results. Data on the dependence of defect development on changes in groundwater level has been obtained. Defects in tunnel linings contribute to the leakage of chemically active substances into soil and groundwater, which threatens biodiversity and reduces water quality used by the population.

Discussion and Conclusion. Field surveys have shown that defects in tunnel linings, such as cracks, concrete leaching, and waterproofing violations, have a direct impact on environmental safety. Therefore, maintaining the integrity of these structures is a key element in ensuring environmental safety in urban areas. The results of this research will form the basis for developing comprehensive proposals to improve monitoring techniques and ensure the structural integrity of tunnel structures.

Keywords: metro, environmental safety, sustainable development, urban transport system, environmental standards, innovative technologies

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Оригинальное эмпирическое исследование

Обоснование критериев и оценка экологической безопасности при эксплуатации объектов метрополитена

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Аннотация

Введение. В современном мире, где темпы урбанизации неуклонно растут, экологическая безопасность выступает в качестве критического аспекта городского планирования и управления. Эксплуатация метрополитенов, будучи важной частью городской инфраструктуры, вносит свой вклад в мобильность населения, но также может стать источником значительных экологических проблем. Данная тема исследована в трудах таких ученых, как Е.Ю. Куликова, Д.С. Конюхов, Е.В. Потапова, С.В. Баловцев, Д.Ю. Чунюк и др. Однако в их работах практически не учитывается тот факт, что одной из основных угроз экологической безопасности является ухудшение состояния тоннельной обделки под воздействием гидрогеологических процессов, которые не только усиливают риск аварийных ситуаций, но и повышают вероятность негативного воздействия на подземные воды и окружающую среду в целом. Поэтому исследование характера развития дефектов в тоннельных обделках и их динамики представляет научно-практический интерес и является целью данной работы. Для реализации поставленной цели необходимо проанализировать связи между состоянием тоннельной обделки и экологической безопасностью, основываясь на данных о дефектах конструкций тоннелей метрополитена и их влиянии на окружающую среду.

Материалы и методы. Материалами для данного исследования послужили дефектные участки обделки перегонных тоннелей некоторых линий Московского метрополитена. Проведены натурные исследования состояния обделки и геодезическая съемка туннеля, которые продемонстрировали значительные изменения показателей, по сравнению с нормативными, в результате взаимодействия техногенной среды с окружающей природой. При проведении исследования использованы также методы сейсмоакустического обследования обделки тоннеля с помощью ударного возбуждения.

Результаты исследования. Получены данные о зависимости развития дефектов от изменения уровня грунтовых вод. Дефекты тоннельной обделки способствуют утечке химически активных веществ в грунт и подземные воды, что угрожает биоразнообразию и снижает качество воды, используемой населением.

Обсуждение и заключение. Проведенные натурные изыскания показали, что дефекты тоннельной обделки, такие как трещины, выщелачивание бетона и нарушение гидроизоляции, оказывают прямое влияние на экологическую безопасность. Таким образом, поддержание целостности тоннельной обделки является ключевым элементом обеспечения экологической безопасности в городских условиях. Результаты проведенных исследований будут служить фундаментом для разработки комплексных предложений по улучшению методов мониторинга и обеспечения структурной целостности тоннельных конструкций.

Ключевые слова: метрополитен, экологическая безопасность, устойчивое развитие, городская транспортная система, экологические стандарты, инновационные технологии, риски

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Introduction. The construction and operation of subways are accompanied by increased environmental risks [1] associated with geological and geochemical hazards, noise, vibration, biological influences, etc. [2]. At the same time, the main criteria that must be taken into account when managing environmental risks at metro facilities include:

– *technical criteria*, which aim to minimize potential accidents and emergency situations (minimizing the ingress of hazardous and harmful substances used in the technological process into the biosphere components);

– *economic criteria*, which are designed to minimize investment risks in the operation of a particular metro facility;

– *regulatory and legal criteria,* which aim to geo-ecological, technological, and operational safety of metro facilities;

– *resource criteria*, which regulate the intensity of natural resource use in metro operations;

– *landscape and geographical criteria,* which aim to reduce undesirable environmental impacts on geographical components of natural and technical geosteme.

Monitoring of the above criteria can only be effective with the combined use of geotechnical and geoecological monitoring.

It should be noted that one of the main factors leading to decreased environmental safety in metro tunnels [3] is geological risk [4]. Moreover, it is the hydrogeological component of the geological risk that determines the nature of the decrease in reliability and durability of underground metro facilities [5]. At the same time, defects such as leaks, fractures, ellipticity, etc., can quickly develop in tunnels due to concomitant occurrences of quicksand breakthroughs, water intrusion, and the accumulation of loose aggregate in the space between the tunnel lining and the rock [6]. The aim of this paper was to analyze the development of defects in metro tunnels, study their dynamics and assess the impact of tunnel lining conditions on the environment.

Materials and Methods. The material for this study was the results of a survey of the metro tunnel lining. It was conducted using geodetic surveying, including seismic and acoustic methods using shock excitation.

The operational regime of metro facilities is largely determined by the nature of changes in the stress-strain state of the rock mass that houses the underground facility and the hydrogeological conditions in the area where it is located. Variability in hydrogeological situation over time often leads to the development of deformation processes [7], which can cause wear of tunnel linings and reduce the operational performance of the facility [8]. This is especially important to take into account when working with unstable loose soils, as changes in their structure can lead to defects in tunnel linings, as well as the movement of loose aggregates and large volumes of water into the developed spaces [9].

Fluctuations in hydrostatic pressure in such soils can lead to the rapid development of emergencies associated with weakening of strength characteristics of the lining, changes in the structure of the overlying soils and, accordingly, subsidence of earth's surface. This can cause deformation and destruction of underground utilities, buildings, and structures on the surface. Decreased tightness of tunnel lining indicates decreased hydrostatic pressure in the rock mass, which can lead to emergencies.

Classical monitoring of hydrological situation in metro tunnels [10] is an integral part of ensuring the environmental safety of operation of its facilities [11]. Figures 1–4 show photographic materials from the monitoring of an interstation tunnel on one of the Moscow Metro lines.

Fig. 1. Leaching and wet spot in the inter-ring and inter-block joint of the lining active leakage

Fig. 2. Soil washout into the area of the contact rail

Fig. 3. Bolt malfunction

Fig. 4. Leaching and wet spot in the inter-ring and inter-block joint of the lining, active leak. A crack in the back of the tubing

The examination of defective sections formed as a result of an accident allowed us to systematize the main violations in the block, their possible causes, and consequences of their development in accordance with GOST R 57208–2016[1] (Table 1).

Table 1

Classification of defects

No.	Type of defect	Potential causes	Potential consequences
1	Concrete spalling in wall blocks and roof slabs, including areas with exposed reinforcement	Mechanical impact	Reduction in bearing capacity of the lining
2	Leaching on wall blocks and roof slabs of the running tunnel. Wet spots on wall blocks. Dripping. Active leakages	Waterproofing violations	Destruction of concrete in structures, corrosion of metal and reinforcement. Reducing the operational characteristics of facilities
3	Steps at the joints of the roof slabs in the running tunnel up to 30 mm	Manufacturing and installation errors	The degree of reduction in load-bearing capacity is determined by calculation
4	Cracks in roof slabs with an aperture width of up to 0.2 mm	Shrinkage due to the heat and moisture treatment of the concrete mix, properties of the cement, etc.	No effect on load-bearing capacity. May reduce durability
5	Disruption of joint sealing in wall blocks and roof slabs	Tunnel and metro operations (including vibrations from moving trains)	Increased water infiltration and reduced operational performance of the structure

[1] GOST R 57208–2016. *Tunnels and Subways. Rules of Inspection and Elimination of Defects and Damages under Operation*. Moscow: Standartinform; 2019. 16 p. (In Russ.)

Research Results. The study of geological sections at emergency sites revealed changes in the level of aquifers over time and structural transformations of soils [12]. Additionally, changes in the geometry of the tunnel lining structure were observed.

During geodetic surveying of the defective sections of running tunnels, measurements of the actual dimensions of the structures were carried out using a manual laser rangefinder Leica DISTO D2. Measurement accuracy: ± 1.5 mm. Significant dimensional irregularities were discovered:

– on KP0167 + 09 – KP0167 + 23 (up to 303 mm) along track I;

– on KP0166 + 73 – KP0167 + 23 (up to 355 mm) along track II.

The results of measuring the actual geometric dimensions of the structures of the existing metro facilities in the problem areas under consideration are presented in summary Tables 2 and 3. Figures 5–18 provide the values of deformations at characteristic points of the lining and a graphical representation of the dependence of deformations on kilometer posts, indicating dangerous areas along tracks I and II according to the results of geodetic survey. The position of the characteristic points along tracks I and II is shown in Figure 19.

Table 2

Values of lining deformations of track I

KP	track1					rail level	
	point 1	point 2	point 3	point 4	point 5	point 6	point 7
165+53.40	–86	47	30	76	61	–35	18
165+63.40	–38	47	31	21	–65	–24	6
165+73.30	–44	2	13	22	–4	–11	–3
165+83.30	8	12	23	0	35	1	–1
165+93.30	2	10	3	–34	32	–2	1
166+3.40	18	–1	–73	–40	–44	–9	–11
166+13.40	–19	–54	1	–41	3	–11	–15
166+23.40	18	34	32	–95	–40	–3	–1
166+33.30	86	24	–15	–50	–38	–10	–12
166+34.40	98	75	–25	–98	–103	–7	–8
166+39.40	128	69	–90	–111	–105	–6	–7
166+50.40	100	31	–86	–68	–58	–14	–15
166+56.40	70	25	–56	–53	–49	–20	–22
166+62.40	84	75	–1	–44	–42	–9	–12
166+68.40	91	45	19	–21	–69	–11	–14
166+80.40	53	89	–43	–123	–43	–11	–12
166+89.50	96	20	–67	–75	–63	–22	–23
166+97.50	150	47	–113	–109	–60	–31	–32
167+0.50	144	67	–89	–108	–77	–22	–23
167+3.50	135	51	–76	–89	–81	–28	–27
167+6.45	110	48	–76	–84	–56	–24	–25
167+7.45	99	49	–78	–78	–49	–24	–23
167+8.45	117	45	–85	–81	–51	–22	–21
167+9.45	–172	–23	–187	–182	–352	–21	–21
167+18.30	–150	–59	–303	–351	–322	–10	–9
167+23.55	–188	–137	–138	–224	–351	–4	–5

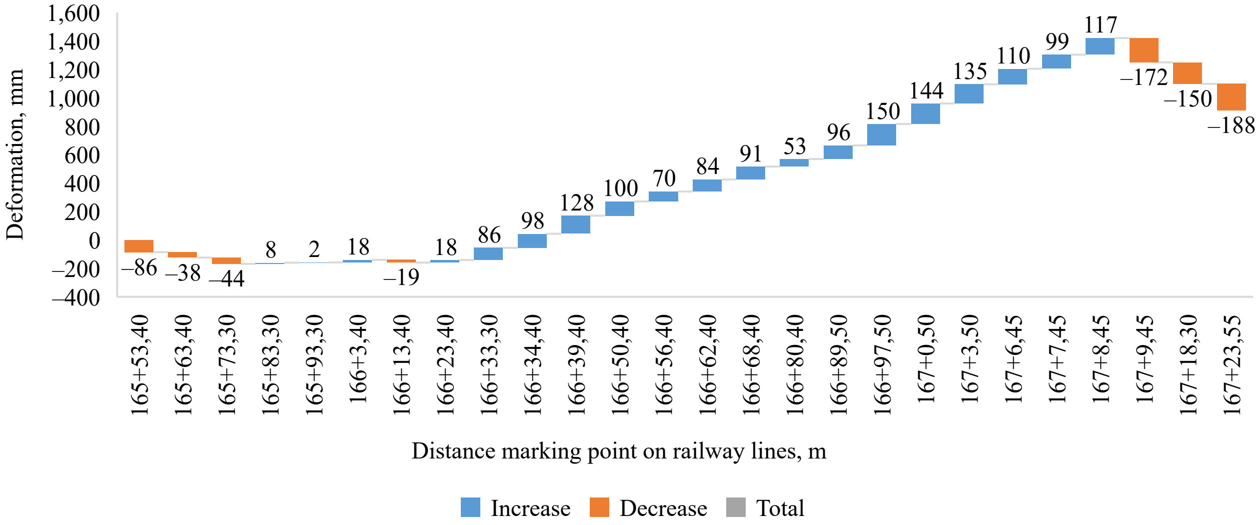

Fig. 5. Graph of lining deformation of track I point 1

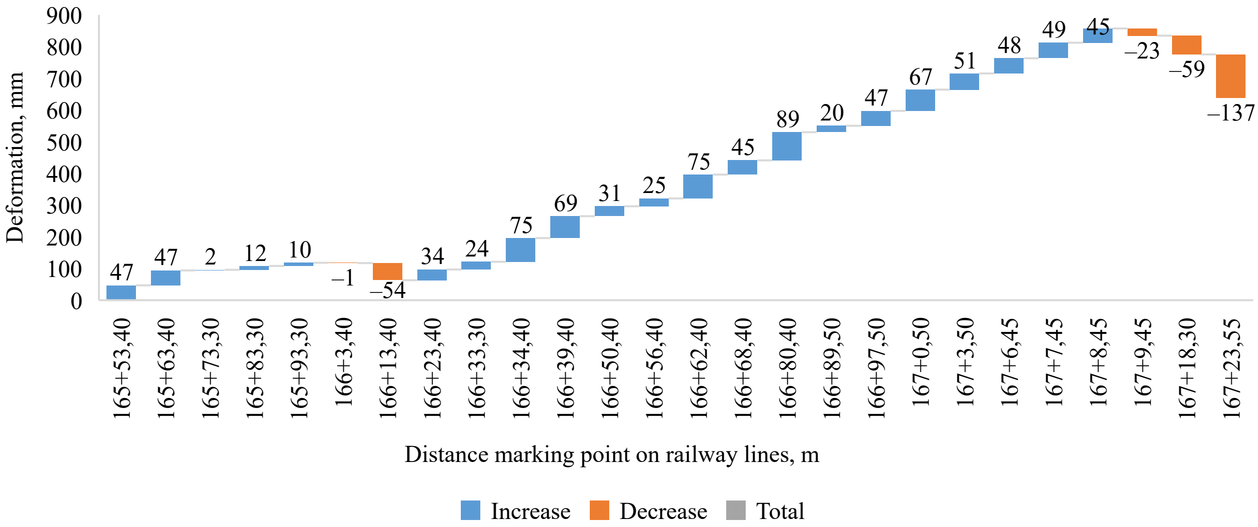

Fig. 6. Graph of lining deformation of track I point 2

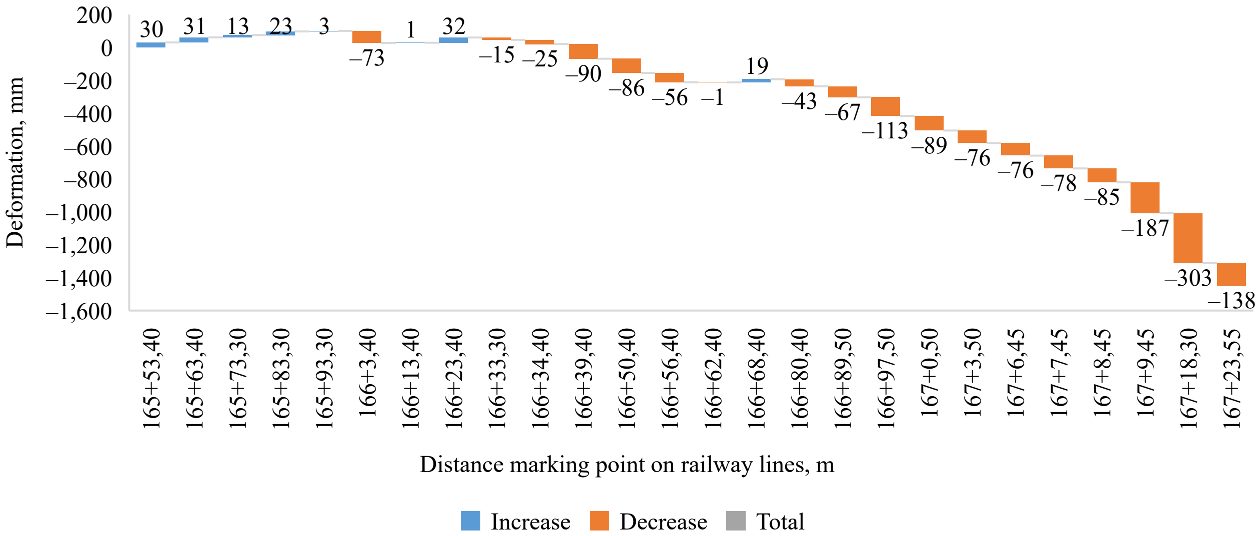

Fig. 7. Graph of lining deformation of track I point 3

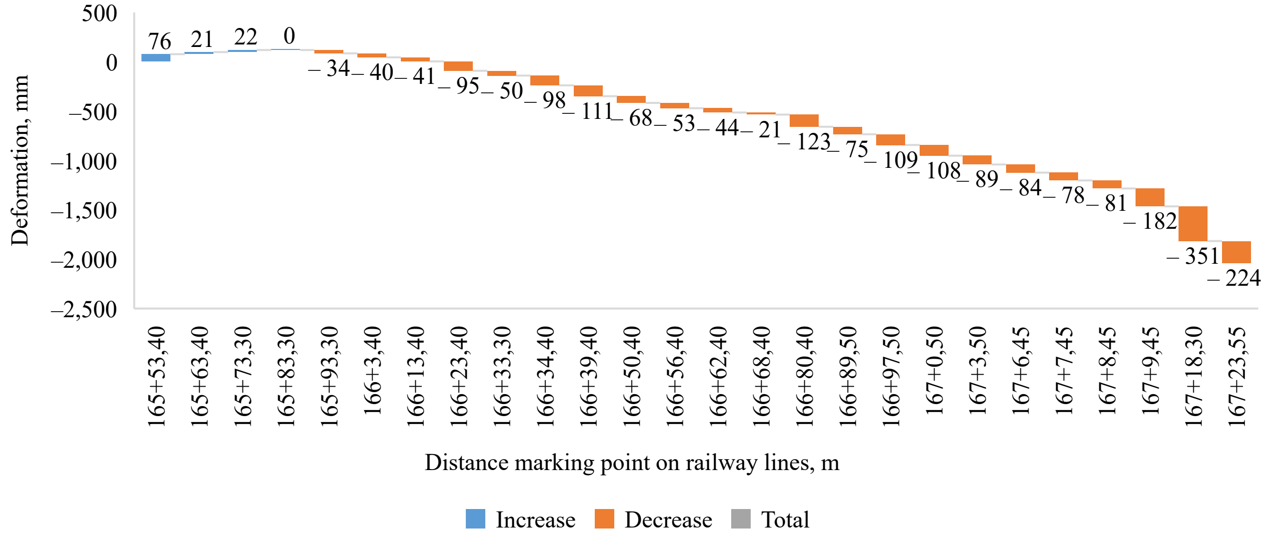

Fig. 8. Graph of lining deformation of track I point 4

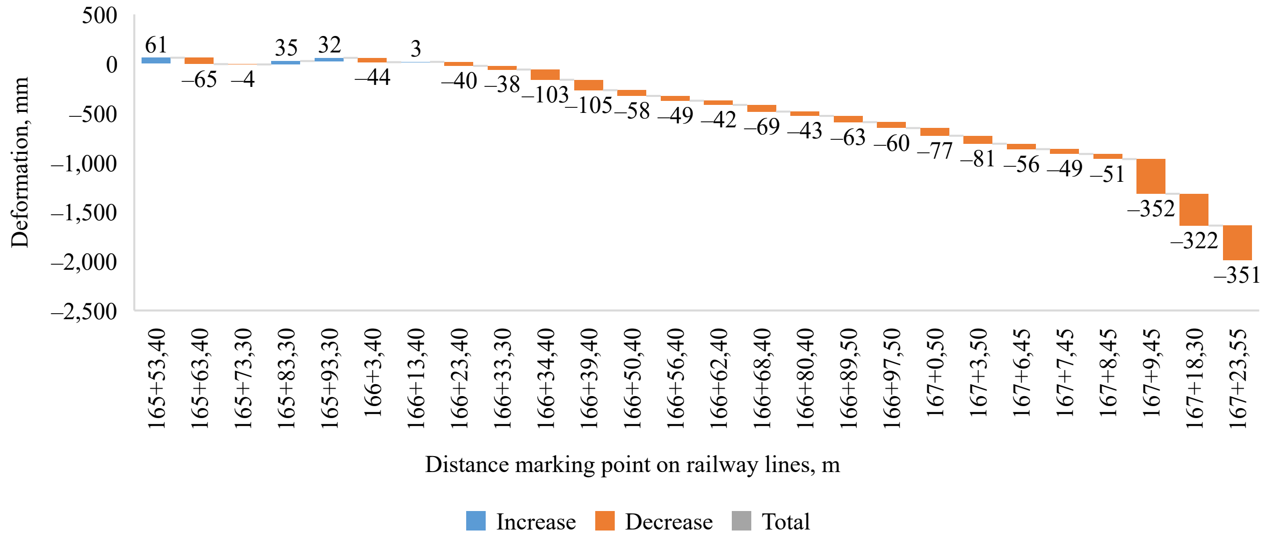

Fig. 9. Graph of lining deformation of track I point 5

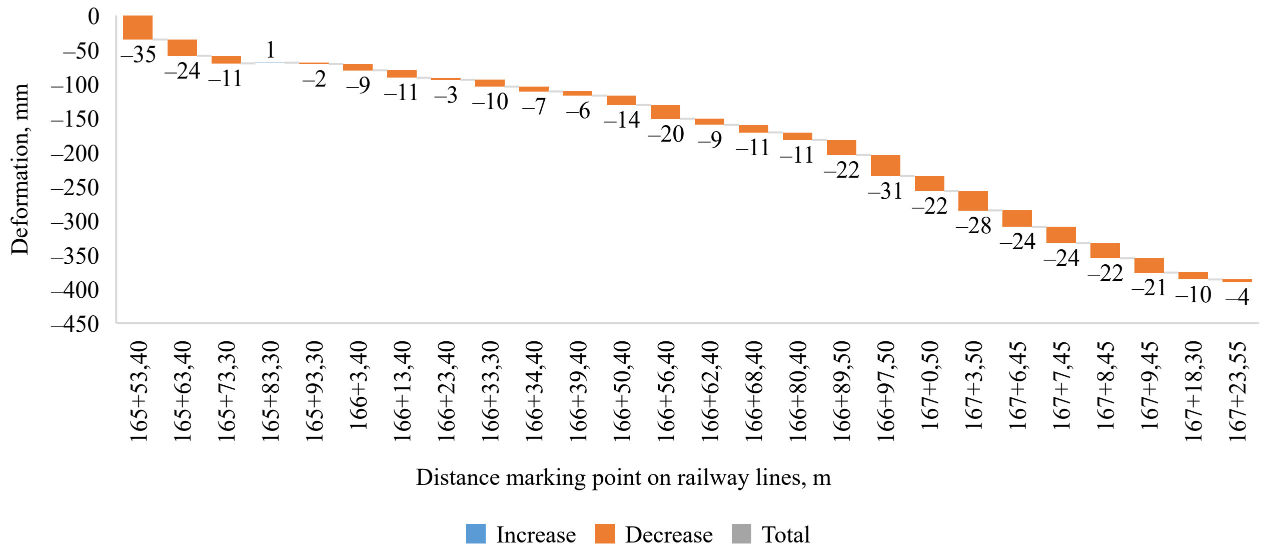

Fig. 10. Graph of lining deformation of track I point 6

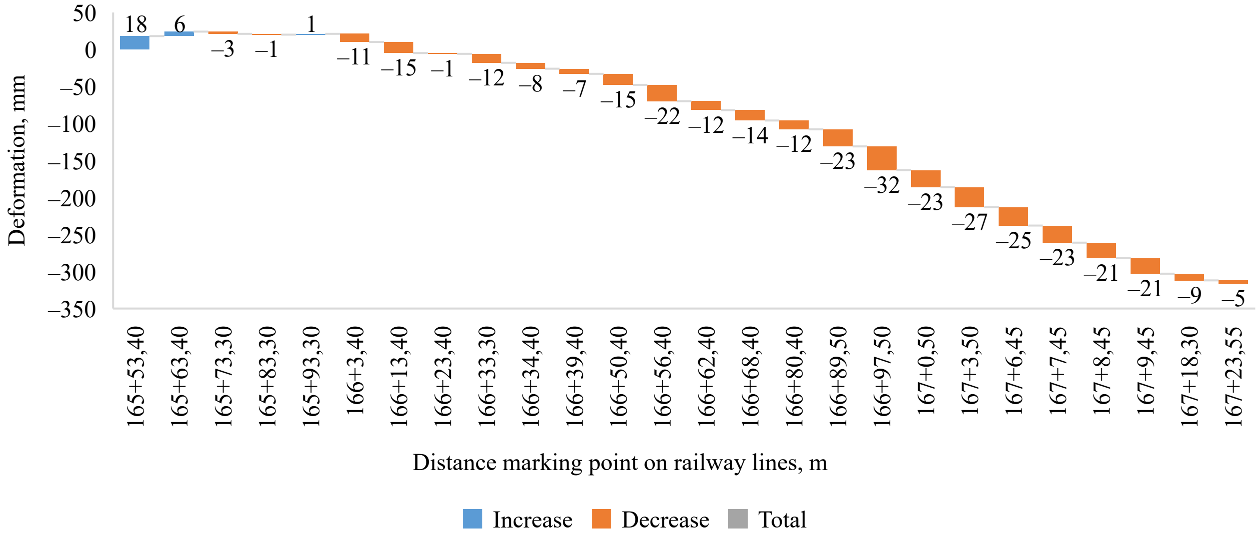

Fig. 11. Graph of lining deformation of track I point 7

Table 3

Values of lining deformations of track II

KP	track 2					rail level	
	point 1	point 2	point 3	point 4	point 5	point 6	point 7
165+69.10	–85	–71	–55	62	95	–19	–2
165+79.10	5	–8	2	17	26	–7	–5
165+89.10	–36	0	–45	–37	–30	–8	–5
165+99.20	–37	43	–32	–40	0	–6	–5
166+19.30	–38	11	58	33	0	–9	–10
166+29.30	–40	–18	16	39	38	–10	–11
166+39.30	45	14	–85	12	39	–19	–18
166+49.30	40	14	–163	–102	0	–21	–20
166+59.30	60	55	–86	–146	–80	–18	–19
166+69.30	150	47	–77	–1	–119	–5	–4
166+79.30	167	21	–129	–154	–119	–21	–19
166+99.40	194	–66	–271	–209	–95	–111	–105
167+4.40	166	–80	–268	–185	–84	–125	–127
167+7.40	261	11	–267	–284	–197	–127	–127
167+9.40	142	–66	–270	–227	–61	–131	–127
167+10.40	210	7	–273	–291	–170	–120	–120
167+13.40	231	14	–287	–301	–209	–114	–113
167+14.50	181	–92	–301	–242	–83	–77	–75
167+16.40	255	8	–332	–210	–185	–95	–93
167+17.40	210	–3	–334	–235	–181	–87	–85
167+18.40	295	–3	–355	–251	–148	–77	–75
167+19.40	214	–78	–270	–254	–55	–71	–72
167+22.40	209	37	–275	–194	–189	–44	–47
167+23.50	169	46	–261	–235	–120	–39	–42

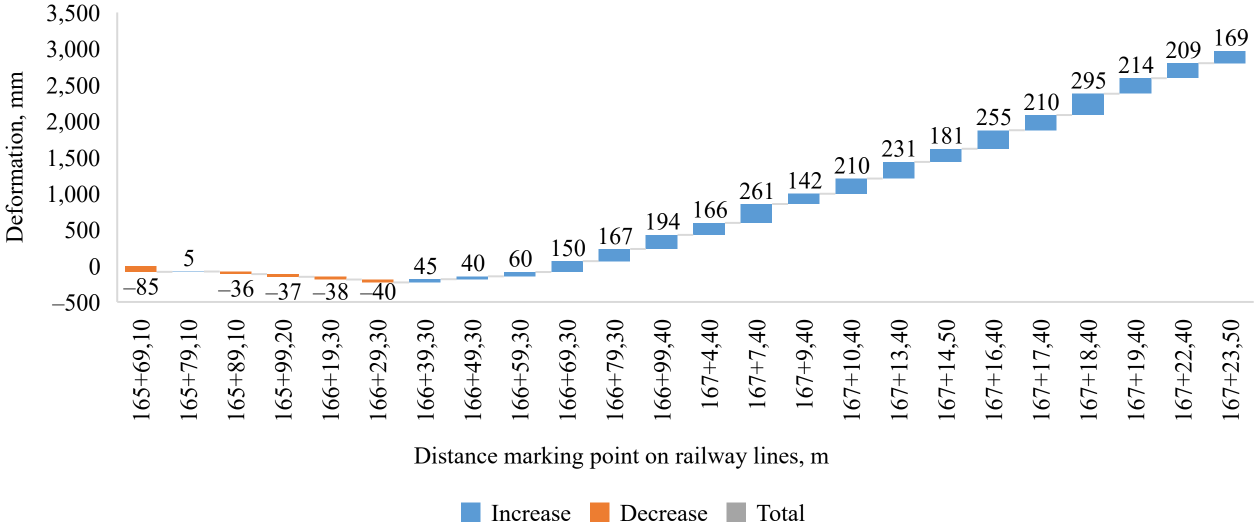

Fig. 12. Graph of lining deformation of track II point 1

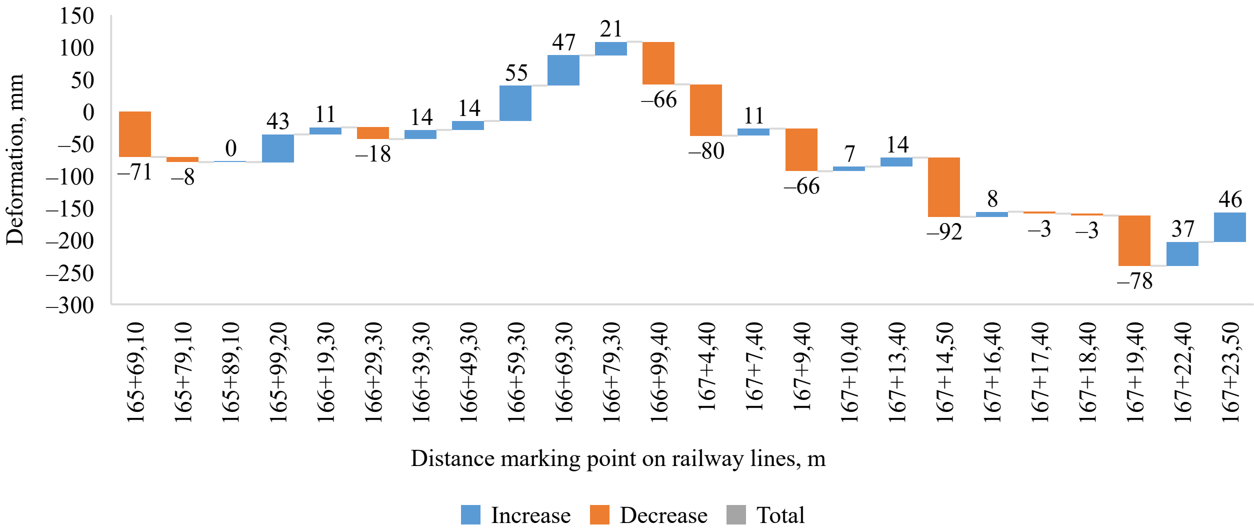

Fig. 13. Graph of lining deformation of track II point 2

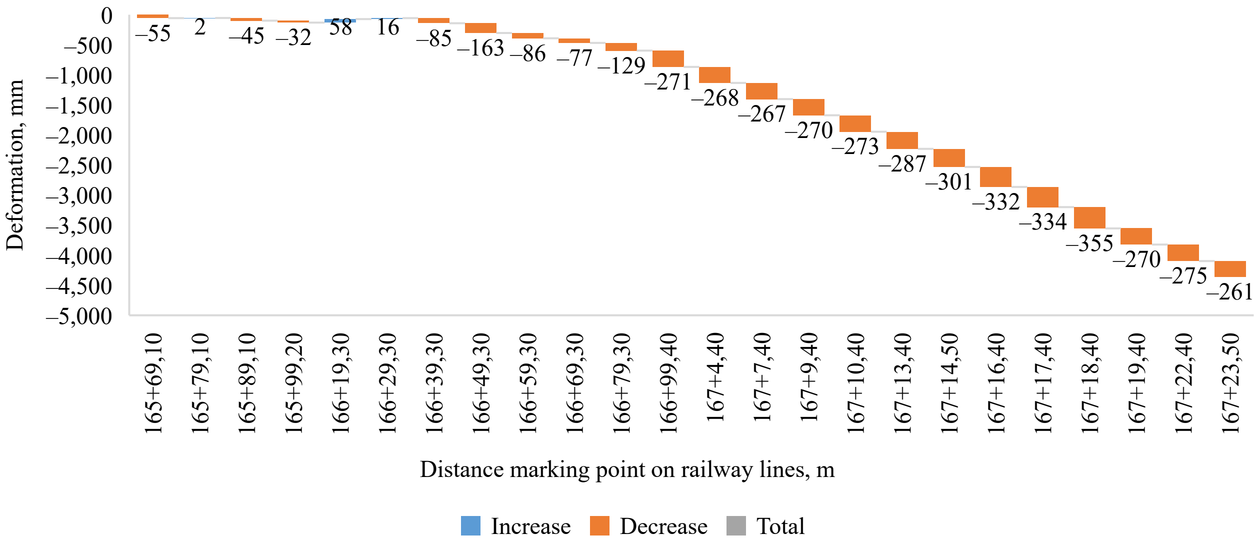

Fig. 14. Graph of lining deformation of track II point 3

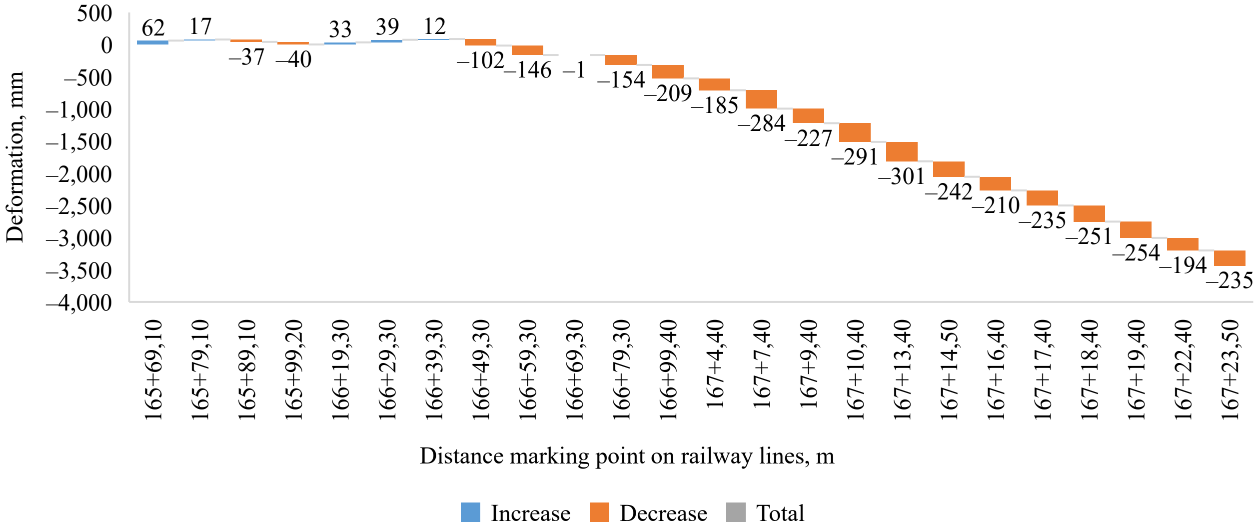

Fig. 15. Graph of lining deformation of track II point 4

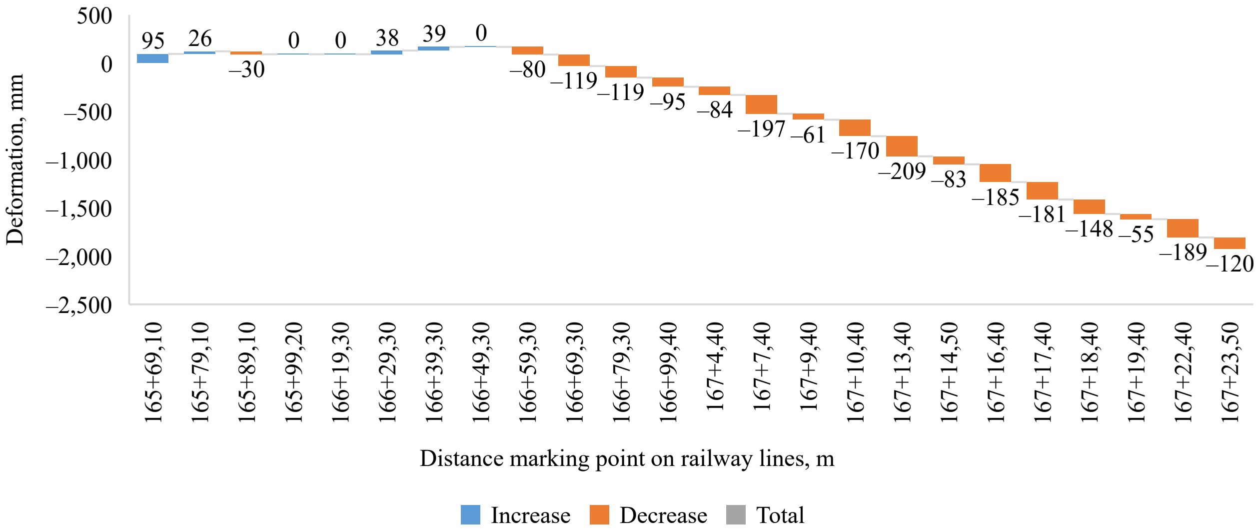

Fig. 16. Graph of lining deformation of track II point 5

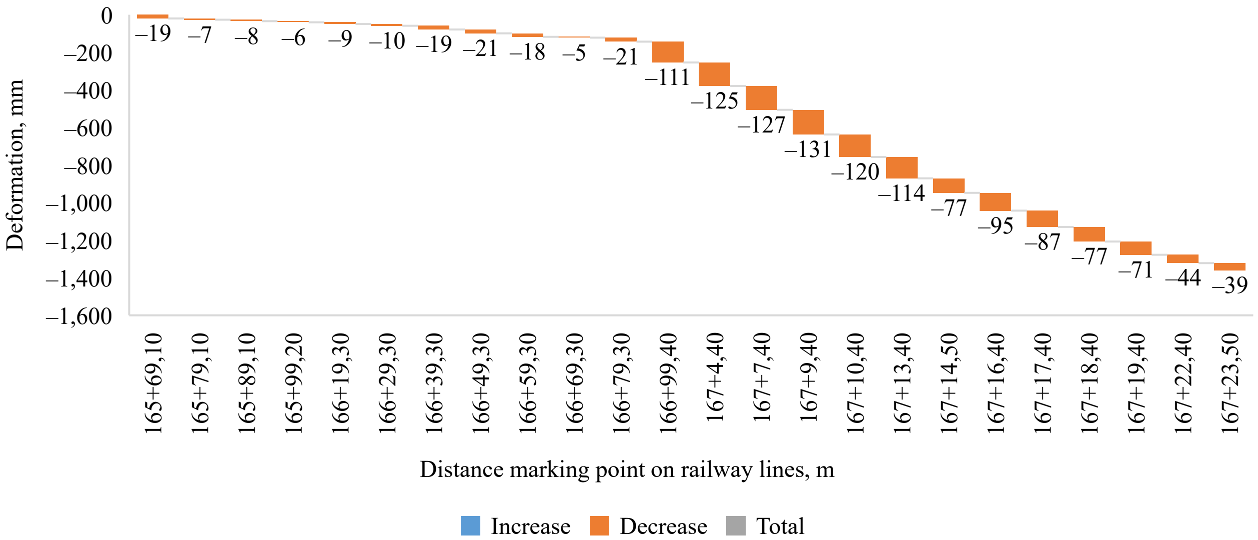

Fig. 17. Graph of lining deformation of track II point 6

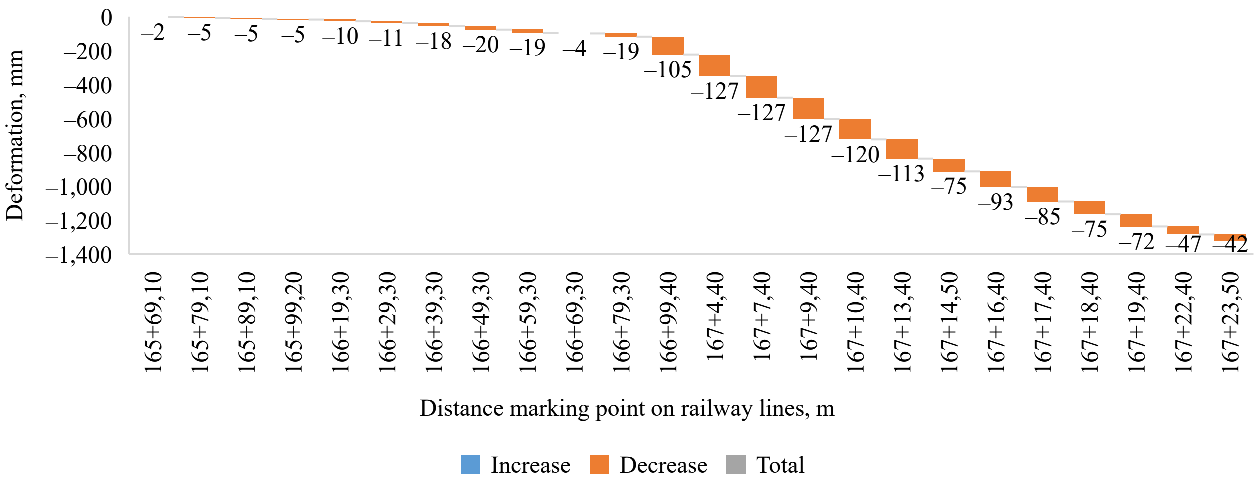

Fig. 18. Graph of lining deformation of track II point 7

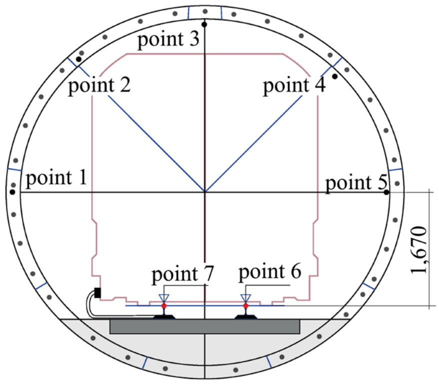

Fig. 19. Position of characteristic points

Based on Tables 2 and 3, it could be concluded that deformation processes had a negative impact on the condition of the tunnel lining, leading to its destruction [13]. An increase in groundwater inflow to the tunnel lining resulted in loss of anticorrosive and strength properties, which allowed water masses to infiltrate the space between the lining and rock through leaks and soil washout, reaching the track sections. This can be seen in the defect map created by the author (Fig. 20).

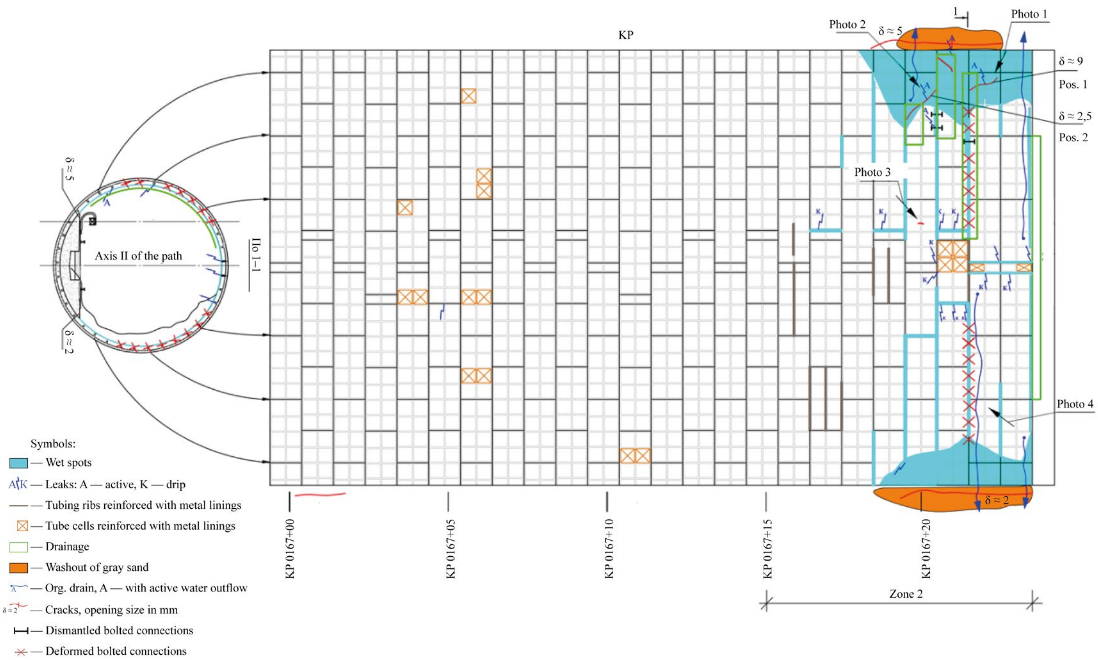

Fig. 20. Map of defects in the lining, compiled from field surveys

When using the method of seismoacoustic survey of the tunnel lining [14] using shock excitation (also called vibroacoustic, or seismoacoustic, method), zones of weakened contact “lining — soil body” were found. An electrodynamic sensor was mounted on the surface of the tubing on a special rod and pressed tightly against it. At some distance from the seismic sensor, the lining was excited using a striker mounted on another support rod. An elastic wave appeared, which was recorded when a certain threshold was exceeded. An archive of signals and responses was stored in the buffer of the device, which made it possible to record the full length of the lining response. Figure 21 provides the results of the survey.

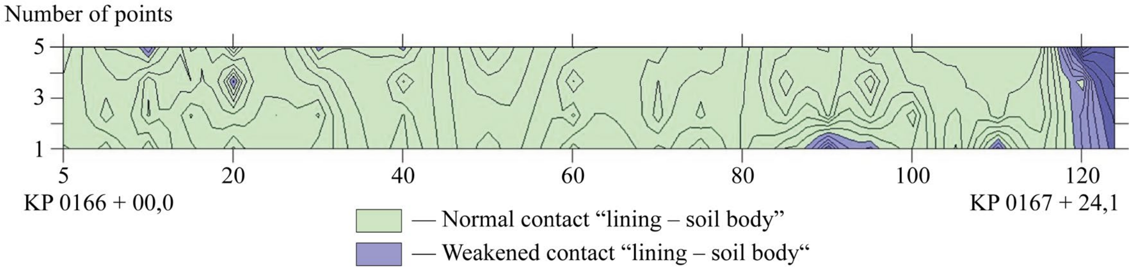

Рис. 21. Результаты сейсмоакустического контроля

A geophysical survey of the tunnels space allowed us to identify areas with weakened contact “lining — soil body”:

– on KP0166 + 10.0 in the gutter area on the left side of the running tunnel;

– on KP0166 + 20.0 at the level of the horizontal diameter on the left side of the running tunnel;

– on KP0166 + 30.0 in the gutter area on the left side of the running tunnel;

– on KP0166 + 40.0 in the gutter area on the left side of the running tunnel;

– from KP0166 + 87.0 to KP0166 + 96.0 below the horizontal diameter level in the right part of the running tunnel;

– on KP0167 + 10.0 in the gutter area on the right side of the running tunnel;

– from KP0167 + 19.0 to KP167 + 24.1 along the entire section of the tunnel.

There were less than 3% of the areas with weakened contact “lining — soil body” along track II in the space between lining and rock of the right running tunnel in the section from KP0166 + 00.0 to KP0167 + 24.1.

Discussion and Conclusion. Field surveys have shown that defects in tunnel lining (cracks, concrete leaching and waterproofing violations) have a direct impact on the level of environmental safety. These defects contribute to the leakage of polluted waters and chemically active substances into the soil, which threatens biodiversity and the quality of water used by the population. Thus, maintaining the integrity of the tunnel lining is a key element of ensuring environmental safety in urban environments.

The obtained results of this study are planned to be used as a basis for the development of proposals to improve the quality of monitoring and maintain the structural integrity of tunnel structures, which will minimize environmental risks and increase the safety level of urban underground transport.

References

1. Kulikova EYu, Balovtsev SV, Skopintseva OV. Complex Estimation of Geotechnical Risks in Mine and Underground Construction. *Sustainable development of mountain territories.* 2023;15(1):7–16. (In Russ.) http://doi.org/10.21177/1998-4502-2023-15-1-7-16

2. Kulikova EYu. Safety and Risk Management in Underground Construction as a Complex Information. *Mining informational and analytical bulletin (scientific and technical journal).* 2021;2(1):134–143. (In Russ.) http://doi.org/10.25018/0236-1493-2021-21-0-134-143

3. Xi-Cun He, Ye-Shuang Xu, Shui-Long Shen, An-Nan Zhou. Geological Environment Problems during Metro Shield Tunnelling in Shenzhen, China. *Arabian Journal of Geosciences.* 2020;13(2):87. http://doi.org/10.1007/s12517-020-5071-z

4. Ye-Shuang Xu, Jack Shuilong Shen, An-Nan Zhou, Arul Arulrajah. Geological and Hydrogeological Environment with Geohazards during Underground Construction in Hangzhou: A Review. *Arabian Journal of Geosciences.* 2018;11:544. http://doi.org/10.1007/s12517-018-3894-7

5. Xing-Tao Lin, Ren-Peng Chen, Huai-Na Wu, Hong-Zhan Cheng. Deformation Behaviors of Existing Tunnels Caused by Shield Tunneling Undercrossing with Oblique Angle. *Tunneling and Underground Space Technology.* 2019;89:78–90. http://doi.org/10.1016/j.tust.2019.03.021

6. Merisalu J, Sundell J, Rosén L. Probabilistic Cost-Benefit Analysis for Mitigating Hydrogeological Risks in Underground Construction. *Tunnelling and Underground Space Technology.* 2023;131:104815. http://doi.org/10.1016/j.tust.2022.104815

7. Konyukhov DS. Criteria Analysis of Modern Technologies of Underground Construction. *Geotechnics.* 2021;1:40–55. (In Russ.)

8. Konyukhov DS. Analysis of Mechanized Tunneling Parameters to Determine the Overcutting Characteristics. *Mining Science and Technology (Russia).* 2022;7(1):49–56 http://doi.org/10.17073/2500-0632-2022-1-49-56

9. Lebedev MO. Choosing a Calculation Method for Stress-Strain of Supports and Lining of Transport Tunnels. In: *16th World Conference of the Associated Research Centers for the Urban Underground Space (ACUUS 2018)*. Hong Kong; 2018, P. 678–687.

10. Garber VA. Non-Standard Situations in Underground Transport Facilities. *Underground Horizons*. 2018;16:20–25. (In Russ.)

11. Kulikova EYu. Methodical Principles for Improving the Ecological and Technological Reliability of Urban Underground Structures. *Mining informational and analytical bulletin (scientific and technical journal).* 2020;6(1): 176–185. (In Russ.) http://doi.org/10.25018/0236-1493-2020-61-0-176-185

12. Kulikova EYu, Balovtsev SV. Risk Control System for the Construction of Urban Underground Structures. *IOP Conference Series: Materials Science and Engineering.* 2020;962(4):042020. http://doi.org/10.1088/1757-899X/962/4/042020

13. Potapova EV. Typology of Metro Structures for the Tasks of Geotechnical Risk Classification. *Mining Science and Technology (Russia).* 2021;6(1):52–60. (In Russ.) http://doi.org/10.17073/2500-0632-2021-1-52-60

14. Kuepferle J, Röttger A, Theisen W, Alber M. Wear Prediction for Soft-Ground Tunneling Tools — A New Approach Regarding the Dominant Influencing Factors in the Tribological System of Tunneling Tools. In: *Proceeding of the World Tunnel Congress 2017 — Surface challenges — Underground solutions.* Bergen, Norway; 2017.

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