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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

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Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

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GEOPHYSICAL ASSESSMENT OF THE ENVIRONMENTAL CONDITION OF TECHNOGENICALLY DISTURBED TERRITORIES BASED ON ELECTRICAL RESISTIVITY TOMOGRAPHY

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Abstract. *Relevance.* The intensification of mining and industrial activities leads to the formation of technogenically disturbed territories characterized by structural transformation of the geological environment, altered hydrogeological conditions, and increased environmental risks. Conventional engineering-geological and geochemical methods are often time-consuming and costly, limiting their applicability for rapid environmental assessment. In this context, geophysical approaches offer an efficient alternative for obtaining subsurface information without invasive operations. *Objective.* To evaluate the effectiveness of geophysical methods, particularly electrical resistivity tomography, for identifying structural heterogeneities and assessing the ecological condition of technogenically disturbed territories. *Methods.* Field investigations were conducted using multichannel electrical resistivity equipment with Wenner–Schlumberger electrode configuration. Measurements were performed along several profiles, followed by data processing, inversion modeling, and interpretation of geoelectrical sections. The analysis focused on identifying resistivity anomalies associated with variations in lithology, moisture content, and technogenic impact. *Results and conclusions.* The study revealed a multilayered structure of the subsurface, with a near-surface technogenic soil layer characterized by low resistivity values (35–70 Ω·m) due to increased moisture and fine-grained composition. Beneath this layer, heterogeneous technogenic deposits mixed with natural sediments were identified, while deeper horizons correspond to relatively stable natural formations. Several local anomalies with very low resistivity (18–25 Ω·m) were detected, indicating water-saturated zones and potential pathways for contaminant migration. High-resistivity anomalies (up to 310 Ω·m) were associated with coarse technogenic materials and construction debris. The results confirm that electrical resistivity tomography is an effective, non-destructive tool for rapid environmental assessment. Its application enables reliable identification of subsurface heterogeneities, supports environmental monitoring, and contributes to sustainable management and risk mitigation in industrially impacted areas.

Keywords: technogenic territories, geophysical survey, electrical resistivity tomography, environmental monitoring, geological environment, anthropogenic impact

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ТЕХНОГЕНДІК БҰЗЫЛҒАН АУМАҚТАРДЫҢ ЭКОЛОГИЯЛЫҚ ЖАҒДАЙЫН ЭЛЕКТРЛІК КЕДЕРГІ ТОМОГРАФИЯСЫ НЕГІЗІНДЕ ГЕОФИЗИКАЛЫҚ БАҒАЛАУ

Рахимов Юнус — PhD, аға оқытушы, «Ташкент ирригация және ауыл шаруашылығын механикаландыру инженерлері институты» ұлттық зерттеу университеті, Ташкент, Өзбекстан,
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Аннотация. ***Өзектілігі***. Тау-кен және өнеркәсіптік қызметтің қарқынды дамуы геологиялық ортаның құрылымдық өзгеруімен, гидрогеологиялық жағдайлардың бұзылуымен және экологиялық қауіптердің артуымен сипатталатын техногендік бұзылған аумақтардың қалыптасуына әкеледі. Дәстүрлі инженерлік-геологиялық және геохимиялық әдістер көп уақыт пен қаржылық шығындарды талап етеді, бұл оларды жедел бағалау үшін шектейді. Осы жағдайда геофизикалық әдістер жер асты құрылымы туралы ақпаратты инвазивті жұмыстарсыз алуға мүмкіндік беретін тиімді балама болып табылады. ***Мақсаты***. Техногендік бұзылған аумақтардың құрылымдық ерекшеліктерін анықтау және олардың экологиялық жағдайын бағалау үшін геофизикалық әдістердің, әсіресе электрлік кедергі томографиясының тиімділігін зерттеу. ***Әдістері***. Далалық зерттеулер Веннер–Шлюмберже конфигурациясы қолданылған көпарналы геоэлектрлік жабдық арқылы жүргізілді. Бірнеше профиль бойынша өлшеулер орындалып, алынған деректер өңделіп, инверсияланып, геоэлектрлік қималар интерпретацияланды. Негізгі назар литология, ылғалдылық және техногендік әсерге байланысты электрлік кедергі аномалияларын анықтауға бағытталды. ***Нәтижелері және қорытындылар***. Зерттеу нәтижесінде геологиялық қиманың жоғарғы бөлігінде 35–70 Ом·м аралығындағы төмен кедергі мәндерімен сипатталатын техногендік қабат анықталды, бұл жоғары ылғалдылық пен ұсақ дисперсті құраммен байланысты. Оның астында табиғи жыныстармен араласқан әртекті техногендік шөгінділер орналасқан, ал терең қабаттар салыстырмалы тұрақты табиғи түзілімдерге сәйкес келеді. 18–25 Ом·м төмен кедергі мәндерімен сипатталатын локалдық аномалиялар анықталып, олар суға қаныққан аймақтарды және ластаушы заттардың миграция жолдарын көрсетуі мүмкін. 310 Ом·м дейінгі жоғары кедергі мәндері ірі түйірлі техногендік материалдар мен құрылыс қалдықтарына тән. Алынған нәтижелер электрлік кедергі томографиясының жедел және бұзбай зерттеу әдісі ретінде жоғары тиімділігін дәлелдейді және оны экологиялық мониторинг пен өнеркәсіптік аумақтарды басқаруда қолданудың маңыздылығын көрсетеді.

Түйін сөздер: техногендік бұзылған аумақтар, геофизикалық зерттеулер, электрлік кедергі томографиясы, экологиялық мониторинг, геологиялық орта, антропогендік әсер

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ГЕОФИЗИЧЕСКАЯ ОЦЕНКА ЭКОЛОГИЧЕСКОГО СОСТОЯНИЯ ТЕХНОГЕННО НАРУШЕННЫХ ТЕРРИТОРИЙ НА ОСНОВЕ ЭЛЕКТРОТОМОГРАФИЧЕСКИХ ИССЛЕДОВАНИЙ

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Аннотация. *Актуальность.* Интенсификация горнодобывающей и промышленной деятельности приводит к формированию техногенно нарушенных территорий, характеризующихся трансформацией геологической среды, изменением гидрогеологических условий и ростом экологических рисков. Традиционные инженерно-геологические и геохимические методы требуют значительных временных и финансовых затрат, что ограничивает их применение для оперативной оценки состояния территорий. В этих условиях геофизические методы представляют собой эффективную альтернативу, позволяя получать информацию о подповерхностной структуре без проведения инвазивных работ. ***Цель***. Оценить эффективность геофизических методов, в частности электротомографии, для выявления структурных неоднородностей и оценки экологического состояния техногенно нарушенных территорий. ***Методы***. Полевые исследования выполнены с использованием многоканальной аппаратуры электрического зондирования с применением установки Веннера - Шлюмберже. Проведены измерения по нескольким профилям с последующей обработкой данных, инверсией и интерпретацией геоэлектрических разрезов. Основное внимание уделено выявлению аномалий удельного электрического сопротивления, связанных с изменениями литологии, влажности и техногенного воздействия. ***Результаты и выводы.*** Установлено, что верхняя часть разреза представлена техногенным слоем с пониженными значениями удельного электрического сопротивления (35–70 Ом·м), обусловленными повышенной влажностью и мелкодисперсным составом. Ниже выделены неоднородные техногенные отложения, перемешанные с природными грунтами, тогда как более глубокие горизонты соответствуют относительно устойчивым естественным образованиям. Выявлены локальные аномалии с низкими значениями сопротивления (18–25 Ом·м), свидетельствующие о зонах водонасыщения и потенциальных путях миграции загрязняющих веществ. Высокие значения сопротивления, достигающие 310 Ом·м, связаны с грубообломочными техногенными материалами и строительным мусором. Полученные результаты подтверждают высокую эффективность электротомографии как неразрушающего метода экспресс-оценки, обеспечивающего выявление подповерхностных неоднородностей и способствующего экологическому мониторингу и управлению рисками на промышленных территориях.

Ключевые слова: техногенные территории, геофизические исследования, электротомография, экологический мониторинг, геологическая среда, антропогенное воздействие

Introduction. In the last 20–30 years, or more precisely, approximately from 1995 to 2025, when industrial growth rates in a number of regions reached 3.5–7.2% annually, the problem of man-made impact on the natural environment has finally gone beyond the scope of local studies and acquired a truly global scale, covering territories of tens and even hundreds of thousands of square kilometers (in certain industrial zones, up to 120,000–250,000 km²), since the accelerated development of industry, the mining sector, energy, and infrastructure projects, accompanied by an increase in the volume of mineral extraction to 10^6–10^8 tons per year and an increase in the man-made load on the geological environment by 1.8–2.6 times, inevitably leads to profound and often irreversible transformations of natural landscapes, including the formation of vast territories with disturbed geological and geoecological conditions, where the thickness of man-made layers can reach 1.2–2.0 m, and locally - up to 3.5 m, while such man-made transformed areas arise as a result of the extraction of raw materials, the construction of industrial facilities (sometimes with a building density of up to 60-75%), the storage of waste in volumes of up to 10^5-10^7 m³ and other economic operations, which, in turn, causes changes in the structure of the geological environment, the redistribution of soil masses (in some cases up to 40-60% of the original volume), the violation of hydrogeological conditions, including an increase in rock moisture and the formation of zones with a specific electrical resistance of only 35-70 Ohm m, and locally even 18-25 Ohm m, which indicates water saturation and potential migration of pollutants, and the formation of potential pollution zones, where concentrations of harmful components can exceed background values by 2-15 times, as a result of which serious environmental risks are formed at the global level associated with land degradation (up to 25-40% in industrial regions), pollution of soils and underground waters, as well as a decrease in the stability of natural ecosystems by 30–50% (Wibowo et al., 2025; Zaalishvili et al., 2024; Myrzakulov et al., 2024).

This problem is especially acute in regions with intensive development of the extractive and processing industries, where the scale of technogenic impact on the geological environment reaches maximum values (for example, the density of disturbed areas can be 0.6-0.8 of the total area of the industrial hub), while such areas, as shown by geophysical studies with a probing depth of 10-15 m and a resolution of about 0.5-1.0 m, are distinguished by an extremely complex internal structure, including heterogeneous technogenic deposits with a resistance of 70 to 160 Ohm m, zones of high humidity, local accumulations of pollutants 8-14 m wide, as well as areas of unstable soils, where the porosity coefficient can increase to 0.45-0.60, and a significant part of such objects continues to affect the environment even 5, 10, and sometimes 25 years after the cessation of economic activity, which is confirmed by the presence of persistent anomalies (for example, up to 310 Ohm m in construction waste zones or 18–25 Ohm m in water-saturated areas), and therefore the need to develop and implement effective methods for assessing the ecological state of such territories becomes obvious, including the identification of hidden processes occurring in the geological environment at depths of 2–5 m and more, where pollutant migration paths and secondary rock transformation zones are formed, which is of fundamental importance for environmental monitoring and risk management (Goltsev et al., 2020; Kulikova et al., 2023; Hasan et al., 2025).

Various approaches are used to address this issue, including geological, hydrogeological, geochemical, and remote sensing methods. Traditional geological and engineering-geological methods based on drilling and sampling provide reliable information on the composition and properties of rocks, but they are labor-intensive and have limited spatial information. Geochemical studies make it possible to identify contaminated zones and determine the concentrations of hazardous elements, but also require a significant number of samples and laboratory analysis (Podoprigora et.al., 2026; Fazylov et.al., 2026; Dzhemilev et.al., 2026; Zaurbekov et.al., 2026). Remote sensing and space monitoring methods provide information on the surface conditions of territories and landscape dynamics, but they are not effective enough to study deep processes and the internal structure of man-made structures (Filina et al., 2024; Malozyomov et al., 2024; Shabanov et al., 2023).

In this regard, geophysical research methods are increasingly used to obtain information on the structure of the geological environment without disturbing it. Geophysical methods are characterized by high speed, the ability to survey large areas, and the ability to identify heterogeneities in the structure of soils and man-made deposits. They can detect changes in the physical properties of rocks associated with waterlogging, the presence of voids, zones of softening, or localized accumulations of pollutants. Furthermore, the use of geophysical methods is particularly effective in man-made areas, where traditional research methods can be hampered by the complexity of the geological structure and the presence of artificial soils (Rachman et al., 2025; Sherov et al., 2024; Susanti et al., 2025; Mashekov et al., 2018).

Despite the significant potential of geophysical methods, their use for environmental assessment of man-made areas requires adapting research methods to the specific conditions of the sites and the characteristics of the man-made formations. Selecting the optimal set of geophysical methods is crucial, allowing us to identify the key structural features of the studied environment and assess the degree of its ecological transformation. In this context, conducting local studies aimed at refining the capabilities of geophysical methods and their practical application to address specific environmental issues is of significant scientific and applied interest (Arafat et al., 2025).

Thus, studying man-made areas using geophysical methods is a relevant area of modern geoecological research, allowing us to improve the efficiency of monitoring the state of the geological environment and ensure a more informed assessment of environmental risks. The objective of this study is to conduct a geophysical survey of a man-made area to identify the structural features of the geological environment and assess its ecological status.

Methods and Materials. In order to achieve the stated objective, which in the framework of this study was considered not in the abstract, but in a quite practical way - taking into account the depths of 10-15 m, characteristic ranges of specific electrical resistance from 18-25 to 260-310 Ohm m and areas of the order of 0.8-1.0 hectares, a set of experimental works was implemented, including not one or two stages, but a whole sequence of interconnected procedures (on average 3-5 field measurement cycles, 2-3 processing iterations and at least 4-6 interpretation sessions) aimed at assessing the ecological state of the man-made disturbed territory using geophysical methods, while the research program itself covered field geophysical observations (with a step of 2-5 m and a profile length of up to 80-120 m), primary processing of the obtained data with emission filtering at the level of 5-12% of the massif, as well as their subsequent geological and ecological interpretation, where both lithological differences were taken into account and humidity indicators capable of reducing resistance to 28–32 Ohm m, with the entire work focused on solving a fairly specific, but at the same time extremely illustrative task - identifying subsurface heterogeneities (including local anomalies 8–14 m wide) within the disturbed area and assessing the degree of transformation of the geological environment, where the thickness of the technogenic layer varies from 1.2 to 2.0 m, and in places reaches 3.0 m, and the chosen approach, in essence, served as a demonstration of how practical and effective it is to use geophysical methods for monitoring the environmental state of industrially affected areas, which, speaking without unnecessary pathos, has quite tangible significance for both industrial safety and rational land use, where errors can cost tens of millions of conventional units. Field studies were carried out within a locally disturbed area formed as a result of previous industrial activity (approximately over 5-15 years of active operation), and such territories, as practice shows, are typical for regions with developed mining and industrial infrastructure, where the density of man-made load can reach 60-80%, and often require a prompt assessment of the environmental condition - literally within a period of several days to 2-3 weeks - to identify potential risks associated with soil degradation (up to 30-45% deterioration of the structure), groundwater pollution at depths of 2-6 m and the formation of unstable soil zones, in which resistance can decrease to critical values of 18-25 Ohm m, and it is in this context that the use of non-destructive geophysical methods acquires particular value for industrial practice, since it allows obtaining fairly reliable information about the subsurface structure without drilling (to a depth of 10-20 m) and without large-scale excavation work of hundreds of cubic meters, which saves both time (up to 40–60%) and resources (up to 25–35% of the budget).

The main method used in this study was electrical sounding, or more precisely, the electrical resistivity tomography method, which is widely used to study near-surface geological structures (usually in the range of 0-15 m) and identify zones with contrasting physical properties, where resistance differences can reach 10-15-fold values (for example, from 20 to 300 Ohm m), while the measurements were carried out using a multichannel resistivity meter of the SKALA-48 type, developed by SKB Geophysics, which allows for highly accurate measurements of apparent specific electrical resistance with a resolution of up to 1-2 Ohm m and ensures stable signal recording at currents from 50 to 200 mA, which is especially important in conditions of heterogeneous soils, and during field work, a standard Wenner-Schlumberger electrode installation scheme was used, providing balanced sensitivity to both vertical and lateral changes in resistance, while the distance between the electrodes varied within 2–5 m (depending on the profile length of 80–120 m and the site characteristics), which made it possible to study the geological structure to a depth of about 10–15 m with a resolution of about 0.5–1.0 m, thereby providing a fairly detailed picture of the internal structure of the disturbed area and recording even relatively small anomalies associated with water saturation or man-made inclusions.

Measurements were carried out along several short geophysical profiles crossing the most representative parts of the disturbed territory. The average length of each profile ranged from 80 to 120 meters, which made it possible to cover the main geomorphological features of the site while maintaining high spatial resolution of the obtained data. Stainless steel electrodes were installed in the ground with uniform spacing, and current injection and potential measurements were performed automatically using the internal switching system of the resistivity meter. The measurement current ranged from 50 to 200 mA depending on ground resistivity conditions, while the acquisition time for each measurement cycle was approximately 1–2 seconds (Figure 1). Such measurement parameters ensured stable signal registration and reliable determination of apparent resistivity values.

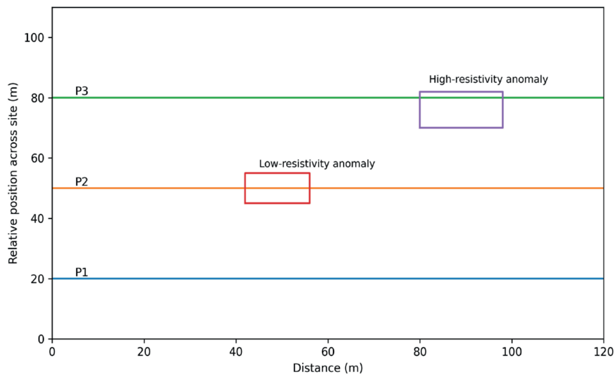

Fig. 1. Layout of geophysical profiles within the investigated technogenically disturbed area showing the positions of profiles P1–P3 and the location of the main resistivity anomaly zones identified during the survey.

Primary data processing was performed using the Res2DInv software package, which applies iterative inversion algorithms to convert apparent resistivity measurements into two-dimensional geoelectrical models of the subsurface. The inversion process included removal of outliers, smoothing of resistivity contrasts, and calculation of the most probable distribution of true resistivity values within the investigated section. The obtained resistivity models were then interpreted in terms of lithological composition, moisture content, and possible zones of technogenic disturbance.

Particular attention during interpretation was paid to identifying areas characterized by anomalously low or high resistivity values, which may indicate zones of increased moisture, accumulation of industrial waste materials, or areas of disturbed soil structure. Such anomalies are of direct interest for environmental monitoring and have important industrial implications, as they may indicate potential pathways for contaminant migration or areas of reduced ground stability.

Thus, the applied methodological approach demonstrates the practical efficiency of electrical geophysical investigations for assessing the ecological condition of technogenically disturbed territories. The obtained results provide valuable information for environmental control and industrial land management, highlighting the significant industrial importance of geophysical monitoring in regions affected by anthropogenic activity.

Results. The field geophysical survey carried out within the technogenically disturbed territory made it possible to obtain a detailed representation of the near-surface structure of the geological environment and to identify several zones characterized by contrasting physical properties. Electrical resistivity tomography profiles provided information about the distribution of electrical resistivity within the upper 10–15 m of the geological section, which is the most important depth interval for assessing environmental conditions and potential industrial risks associated with disturbed soils. The processed and inverted geophysical data demonstrated that the investigated area is characterized by significant spatial heterogeneity of the subsurface environment, which reflects both natural geological variability and the effects of anthropogenic transformation of the terrain.

The obtained resistivity models revealed that the uppermost layer of the geological section is represented by a relatively thin horizon with electrical resistivity values ranging from 35 to 70 Ω·m and thickness varying between 0.8 and 1.6 m. This layer corresponds to a mixture of technogenic soils formed during previous industrial activities and partially reclaimed surface sediments (Table 1). The relatively low resistivity values indicate an increased moisture content and the presence of fine-grained material such as silty and clayey particles. In several segments of the geophysical profiles, the resistivity of this horizon decreased to 28–32 Ω·m, which may indicate zones of increased water accumulation or localized infiltration of surface runoff. Such conditions are particularly important for environmental monitoring because these zones can potentially act as pathways for the migration of dissolved pollutants.

Table 1. Electrical resistivity characteristics of the main geoelectrical layers identified within the technogenically disturbed area.

Geoelectrical layer	**Depth interval (m)**	**Resistivity range (Ω·m)**	**Average resistivity (Ω·m)**	**Estimated thickness (m)**	**Interpretation of material composition**
Surface technogenic soil	0.0 – 0.8	35 – 70	52	0.8	Mixed disturbed soil with silty and clayey components
Moist technogenic sediments	0.8 – 1.6	28 – 60	44	0.8	Water-saturated fine sediments with increased porosity
Compacted sandy loam	1.6 – 3.5	90 – 140	112	1.9	Sandy loam mixed with technogenic fragments
Mixed technogenic deposits	3.5 – 5.0	70 – 160	118	1.5	Heterogeneous anthropogenic sediments
Coarse artificial materials	4.0 – 7.0	200 – 310	245	2.0 – 3.0	Coarse sand and construction debris
Natural sandy deposits	7.0 – 10.0	150 – 220	184	3.0	Relatively undisturbed natural sediments
Sandy-gravel basement	10.0 – 15.0	180 – 260	215	>4.0	Dense natural deposits forming geological base

Below the specified near-surface layer, the thickness of which averaged about 1.2–2.0 m (and locally reached 2.3–2.6 m with a change in humidity to 25–35%), the geoelectric sections demonstrated a much more complex and heterogeneous picture, where in most profiles (at least in 3 out of 3, and in individual segments – in 5–7 sections 10–20 m long each) a layer with a specific electrical resistance in the range of approximately 90 to 160 Ohm m was recorded, lying at depths of about 1.5–5.0 m, and the average values within this horizon were most often around 110–125 Ohm m, which is quite consistent with the characteristics of compacted sandy loams and sandy deposits mixed with technogenic inclusions – debris of building materials, fragments of artificial soils and disturbed natural rocks, where the share :The content of technogenic components could reach 15–40%, and the thickness of this layer varied from 2.5 to 4.0 m (with deviations of ±0.3–0.7 m depending on the position along a profile 80–120 m long). In the zones of the most intense technogenic impact formed during industrial activity (approximately over 8–12 years of site operation), the resistance values within this horizon decreased to 70–80 Ohm m, and sometimes even to 65 Ohm m, indicating an increase in the content of finely dispersed fraction (up to 35–50%) and an increase in the degree of water saturation (humidity could reach 30–45%). Such changes, if we look at them not formally, but in essence, quite clearly reflect the influence of anthropogenic processes on the physical parameters of the geological environment, changing it not only vertically, but also laterally. In addition to the relatively regular layered structure, along the studied profiles (P1–P3, with a total length of about 240–300 m), quite pronounced geophysical anomalies were also identified, and not just single ones, but several (at least 5–7 local zones), among which one of the most noticeable was the anomaly recorded in the central part of the studied area along profile P2, at a distance of approximately 42–56 m from the starting point (with an error of about ±1.5–2.0 m), where within a depth interval of 2–4 m, the values of specific electrical resistance sharply decreased to 18–25 Ohm m (which is almost 4–6 times lower than the background values of 90–140 Ohm m), while the length of this anomalous zone was about 14 m, and its vertical thickness reached 1.5–2.0 m, which, taking into account increased humidity and the probable content of finely dispersed man-made sediments may indicate the formation of a localized water-saturated area, potentially acting as a channel for the migration of pollutants, especially in conditions of a heterogeneous soil structure and the presence of man-made inclusions of various fractions.

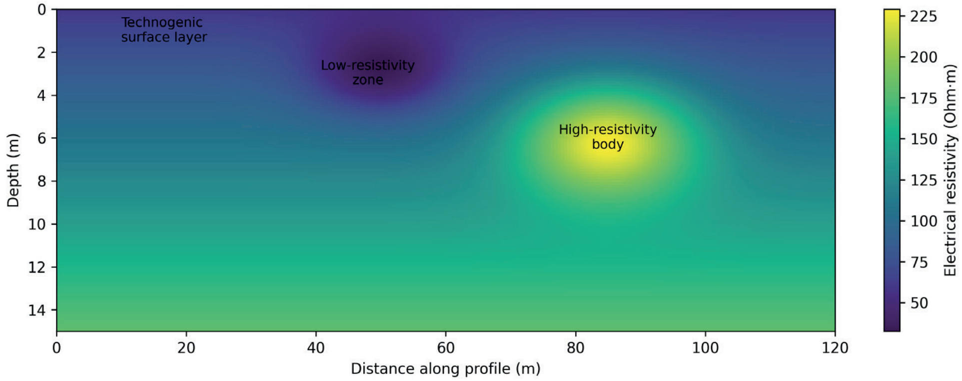

Fig. 2. Example geoelectrical resistivity section of a technogenically disturbed area showing the technogenic surface layer, a low-resistivity water-saturated zone, and a high-resistivity body associated with coarse technogenic materials.

The lateral extent of this anomaly reached about 14 m. Such low resistivity values significantly differ from the background resistivity of surrounding sediments and most likely indicate the presence of a localized zone of strongly water-saturated soils. Considering the industrial history of the site, this anomaly may also be associated with the accumulation of technogenic materials or fine-grained waste sediments that retain moisture (Table 2).

Table 2. Quantitative parameters of resistivity anomalies detected along geophysical profiles.

Profile	**Distance along profile (m)**	**Depth interval (m)**	**Resistivity (Ω·m)**	**Width of anomaly (m)**	**Probable geological interpretation**	**Environmental significance**
P1	18 – 28	1.5 – 3.0	40 – 55	10	Moist disturbed soils	Potential infiltration zone
P1	52 – 60	2.0 – 4.5	65 – 80	8	Clay-rich technogenic sediments	Possible accumulation of contaminants

Profile	Distance along profile (m)	Depth interval (m)	Resistivity (Ω·m)	Width of anomaly (m)	Probable geological interpretation	Environmental significance
P2	42 – 56	2.0 – 4.0	18 – 25	14	Highly water-saturated soils	Potential pollutant migration pathway
P2	68 – 78	3.0 – 5.5	75 – 95	10	Mixed sandy loam with debris	Technogenic ground disturbance
P3	20 – 34	4.0 – 7.0	260 – 310	14	Coarse technogenic material	Artificial subsurface body
P3	48 – 60	5.0 – 8.0	210 – 270	12	Dry sandy deposits	Stable ground zone
P3	72 – 85	3.5 – 6.0	95 – 130	13	Sandy sediments with moisture	Transitional geological zone

Another anomaly, quite contrasting in its physical parameters (and this was visible literally immediately after the data inversion, where the spread of values exceeded 200 Ohm m), was recorded along the P3 profile, where within the depths of approximately 4 to 7 m, that is, in an interval of about 3 m vertically, the values of specific electrical resistance sharply increased to 260–310 Ohm m (at some points reaching 295–305 Ohm m, which is almost 10–12 times higher than the minimum values of 18–25 Ohm m noted earlier), while the width of this high-resistivity body was about 18 m (with variations of ±1–2 m along the edges), and such elevated values, as a rule, are characteristic of coarse-grained sediments, dry sand masses with low moisture content (less than 8–12%), or zones containing construction waste and compacted man-made materials, where the proportion of large fractions can exceed 50-65%, and the very presence of such an anomaly quite convincingly indicates that during the period of industrial operation (possibly over 6-10 years of active use of the site) there was local storage or redistribution of coarse materials, resulting in the formation of an artificial subsurface body, noticeably different in its properties from the surrounding rocks, and this difference is manifested not only in resistance, but also in density, structure and water permeability. At the same time, the geophysical data showed not only sharp anomalies, but also a number of areas where the resistance changes occurred more smoothly, without jumps, but rather gradually - for example, along the P1 profile, a consistent increase in values was observed from approximately 60 Ohm m in the near-surface zone (depths up to 1.0-1.5 m) to about 170-180 Ohm m at depths above 8 m, where the change step could be 10-20 Ohm m per meter, and such a picture, if you look at it carefully, indicates relatively weakly disturbed natural deposits underlying a man-made layer with a thickness of about 1.2-2.0 m, and these deeper horizons are most likely represented by compacted sandy or sandy-gravel rocks with stable physical characteristics (average density of 1.8-2.1 g / cm^3, low porosity of about 15-25%), forming a natural The geological foundation of the study area, and the stability of the resistivity within this level (a spread of no more than ±10–15 Ohm m) suggests that the anthropogenic impact was mainly limited to the upper part of the section, not penetrating deeper than 6–8 m.

If we move on to a quantitative assessment, the analysis of the obtained geoelectric models made it possible to quite clearly distribute the various zones within the studied area (an area of about 0.9 hectares, i.e. approximately 9,000 m²), and it turned out that about 34% of the entire section is characterized by resistivity values below 60 Ohm m, which indicates increased humidity (up to 30–45%) and potentially high permeability for pollutants, about 46% falls in the range of 60–160 Ohm m, typical of moderately compacted soils and mixed technogenic deposits with an artificial component content of 20–40%, while the remaining 20% demonstrate values above 160 Ohm m, which, as a rule, it corresponds either to stable sand formations or to zones with coarse-grained man-made materials, where humidity can decrease to 5–10%, and density increases to 2.2 g/cm³, and such a distribution very clearly reflects the heterogeneity of the environment.

From the point of view of environmental monitoring, special attention is naturally drawn to zones with low resistivity values - it is precisely these areas, where 18-25 Ohm m or even 28-40 Ohm m are recorded, that can act as a kind of "channels" through which pollutants generated during industrial activity (in volumes of up to tens of tons per year) are capable of migrating deep into the geological environment. Moreover, the identification of these zones using geophysical methods gives specialists not just an abstract idea, but very specific guidelines - where exactly (with an accuracy of 2-5 m) it is necessary to conduct additional hydrogeological or geochemical studies, including sampling and laboratory analysis. In real production conditions, such information becomes critically important for planning remediation measures (with budgets from 10^5 to 10^7 conventional units) and preventing the further spread of pollution to depths greater than 10-12 m.

It is worth noting separately that the obtained results quite clearly demonstrate that even relatively small-scale geophysical surveys (in this case, an area of about 0.9 hectares, 3 profiles of 80-120 m, about 500-800 measurements) are capable of providing a very significant amount of information about the state of disturbed areas, revealing features that cannot be noticed during a normal visual inspection of the surface, and this, without further ado, emphasizes the effectiveness of geophysical methods as a rapid assessment tool, allowing one to obtain a detailed picture of the subsurface structure in a short time (sometimes in 2-5 days of field work). The practical significance of such studies is particularly high for the mining industry, where huge volumes of overburden and waste (up to 10^6–10^8 m³) are stored on the surface or in shallow excavations, and over time (over the course of 3–15 years), these materials undergo physicochemical changes—from compaction to secondary wetting and even chemical transformation, which can lead to environmental risks. Geophysical surveys, however, allow for the early identification of unstable zones, areas of water accumulation, and potential pollutant migration pathways, providing enterprises with sufficiently reliable information to make decisions aimed at improving environmental management and reducing long-term risks that could otherwise accumulate over years and lead to serious consequences.

In addition to the mining sector, the results of similar investigations are highly relevant for the oil and gas industry, where drilling sites, storage areas, and waste pits may create localized zones of disturbed ground conditions. Electrical resistivity methods are capable of detecting variations in soil moisture and composition that may be associated with leaks of drilling fluids or other industrial substances. Early identification of such anomalies is extremely important for maintaining environmental safety and preventing contamination of groundwater resources.

Another important field of application is the construction and infrastructure sector. Industrial sites that were previously used for production or storage activities are often redeveloped for new facilities. Before construction begins, it is necessary to evaluate the stability and environmental condition of the subsurface. Geophysical investigations provide essential information about the distribution of disturbed soils, voids, or zones with abnormal moisture content. The results obtained in this study demonstrate that even simple electrical resistivity surveys can significantly improve the reliability of such assessments.

The interpretation of the obtained geophysical data indicates that the investigated technogenically disturbed territory remains affected by processes associated with the redistribution of moisture and the presence of heterogeneous technogenic materials. Although no extremely large anomalies were detected, several localized zones with significantly altered physical properties were identified. These zones require additional attention because they may influence both environmental conditions and the mechanical stability of the ground.

The results also show that the thickness of the technogenic layer within the study site varies between 1.2 and 2.0 m, with an average value of approximately 1.5 m. Beneath this layer the geological environment gradually transitions into more stable natural sediments. This observation suggests that the main anthropogenic transformation of the geological medium occurred within the shallowest part of the section, which is consistent with the nature of industrial activities previously conducted in the area.

Overall, the conducted research confirms that electrical geophysical methods provide a reliable and efficient tool for studying technogenically disturbed territories. The obtained results demonstrate the ability of resistivity tomography to detect subsurface heterogeneities associated with both environmental and engineering factors. From an industrial perspective, such information is extremely valuable because it allows companies operating in the mining, oil and gas, and construction sectors to make informed decisions regarding land management, environmental protection, and the safe operation of industrial facilities.

Thus, the analysis of the geophysical data obtained during this study indicates that the investigated territory contains several zones of altered physical properties that reflect the influence of past industrial activity. The identification and characterization of these zones provide an important basis for further environmental assessment and for the development of appropriate monitoring strategies. The practical applicability of the proposed approach confirms the significant industrial importance of geophysical methods for evaluating the ecological condition of technogenically disturbed territories.

Conclusions. The study, if considered not in general terms, but with reference to specific numerical parameters (probing depths of 10–15 m, resistance ranges from a minimum of 18–25 Ohm m to a maximum of 260–310 Ohm m, a site area of about 0.9 hectares and a volume of measurements of up to 500–800 points), quite clearly demonstrates the high efficiency of geophysical methods in the study of man-made disturbed areas and the assessment of their ecological state, since the use of electrical resistivity tomography made it possible to obtain detailed information on the structure of the near-surface part of the geological environment (with a resolution of about 0.5–1.0 m in depth and 2–5 m laterally), and also to identify zones with contrasting physical properties directly related to anthropogenic transformation of relief and soils, where resistance differences can reach 8–12-fold values, and the results themselves, speaking without unnecessary formality, confirm that geophysical approaches provide sufficient A reliable, non-destructive, and relatively fast (fieldwork typically takes 2-5 days, with processing taking another 1-3 days) method for studying subsurface conditions in areas subject to industrial impact. The use of electrical resistivity measurements enables specialists to detect hidden inhomogeneities in soils and man-made deposits (including localized zones 8-18 m wide and 2-7 m deep) that cannot be detected by visual inspection or limited drilling (e.g., 1-2 boreholes per hectare). This ultimately significantly increases the reliability of environmental assessments (by 25-40% compared to traditional methods) and increases the effectiveness of monitoring programs for disturbed areas.

Geophysical survey showed that within the study area a multi-layer structure of the geological section is formed, where the upper part is represented by a man-made soil horizon with a thickness of about 1.2–2.0 m (in places up to 2.3 m), characterized by relatively low resistance values in the range of 35–70 Ohm m, caused by high humidity (up to 30–45%) and the presence of finely dispersed components (the content of clay and silt fractions can reach 40–60%), below which heterogeneous man-made deposits mixed with natural sediments are recorded, and in this interval (depths of approximately 1.5–5.0 m) the resistance values fluctuate within the range of 70–160 Ohm m, reflecting the complex history of industrial impact on the territory associated with the movement of soil masses with a volume of up to tens of thousands of cubic meters, and even deeper, starting from about 7–8 m and up to 10–15 m, there are more stable natural sand and sand-gravel deposits (with a resistance of 150–220 Ohm m and higher), which form the natural geological base of the site, which indicates that the main anthropogenic transformation is concentrated in the upper part of the section and only partially affects deeper horizons.

Geophysical anomalies of direct environmental significance identified during the survey certainly deserve special attention, since zones with significantly reduced resistivity values (18–25 Ohm m, sometimes up to 28–32 Ohm m) indicate increased humidity and possible accumulation of finely dispersed man-made materials, which can act as unique channels for the migration of pollutants to depths of 2–4 m or more, while anomalies with high values (260–310 Ohm m) correspond to bodies formed from coarse man-made materials or compacted construction waste generated during previous industrial activity, and the identification of such features, in practical terms, provides very valuable information for assessing potential environmental risks (including the likelihood of groundwater contamination at a level of 20–35% within local zones) and allows for a fairly accurate (with an error of 2–5 m) determination of areas where additional hydrogeological or geochemical studies, including detailed sampling and laboratory analysis, which ultimately makes such geophysical methods not just an auxiliary tool, but a completely independent and effective basis for decision-making in the field of environmental monitoring and management of disturbed areas.

Overall, the results of the study confirm that electrical resistivity tomography is an effective tool for environmental assessment of technogenically disturbed areas. The obtained data allow identification of zones of increased moisture, heterogeneous technogenic deposits, and stable natural formations, which is essential for environmental monitoring, land management, and planning of remediation measures. The proposed methodological approach can be successfully applied in regions with intensive industrial development, including mining, oil and gas production, and construction, where reliable information about the subsurface structure is necessary for ensuring environmental safety and sustainable land use.

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