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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымметриялық 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 басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

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).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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ENGINEERING AND GEOLOGICAL SUBSTANTIATION OF TECHNOGENIC TAILINGS CONSERVATION FOR IMPROVED STABILITY AND ENVIRONMENTAL SAFETY

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Abstract. Relevance. The accumulation of technogenic deposits generated by long-term mining and mineral processing activities is associated with increased risks of erosion, contaminant migration, and slope instability. Insufficient compaction and structural heterogeneity of the upper layers of tailings storage facilities significantly

reduce the effectiveness of conventional environmental protection measures and complicate long-term management. *Objective.* To substantiate an engineering and geological approach to the conservation of technogenic deposits aimed at improving their mechanical stability, reducing filtration processes, and enhancing overall environmental safety under specific geological and climatic conditions. *Methods.* The study included field investigations of a representative tailings deposit, drilling and sampling, and laboratory determination of granulometric composition, moisture content, density, and shear strength parameters. Based on the obtained data, pilot-scale conservation measures were implemented, including surface reprofiling, controlled compaction of the upper layer, and installation of a low-permeability mineral cover. Slope stability factors, infiltration rates, and erosion resistance were evaluated before and after treatment. *Results and conclusions.* It was established that insufficient initial compaction (84–86% of maximum density) and high moisture variability significantly reduce slope stability. Optimization of compaction parameters increased dry density to 97–99% of the Proctor maximum, resulting in a rise in internal friction angle and cohesion, and improving the slope stability factor by more than 20%. The application of a compacted low-permeability layer reduced water infiltration by up to 80% and significantly decreased wind erosion intensity. The proposed conservation approach is technically simple, energy-efficient, and economically justified compared to reprocessing or relocation. The results confirm the feasibility of implementing localized conservation measures to ensure long-term environmental safety and structural reliability of technogenic facilities.

Keywords: technogenic deposits, tailings conservation, slope stability, filtration properties, soil compaction, environmental safety

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ТЕХНОГЕНДІК ҚАЛДЫҚ ҚОЙМАЛАРЫН ТҰРАҚТАНДЫРУ ЖӘНЕ ЭКОЛОГИЯЛЫҚ ҚАУІПСІЗДІГІН АРТТЫРУДЫҢ ИНЖЕНЕРЛІК-ГЕОЛОГИЯЛЫҚ НЕГІЗДЕМЕСІ

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Аннотация. *Өзектілігі.* Ұзақ мерзімді тау-кен өндіру және минералдық шикізатты қайта өңдеу нәтижесінде қалыптасатын техногендік шөгінділер эрозияның күшеюі, ластаушы заттардың миграциясы және еңістердің тұрақсыздануы сияқты тәуекелдермен сипатталады. Хвостохранилищелердің үстіңгі қабаттарының жеткіліксіз тығыздалуы және құрылымдық біркелкі еместігі дәстүрлі табиғатты қорғау шараларының тиімділігін төмендетіп, оларды ұзақ мерзімді пайдалануды қиындатады. **Мақсаты.** Нақты геологиялық және климаттық жағдайларды ескере отырып, техногендік шөгінділерді консервациялаудың инженерлік-геологиялық тәсілін негіздеу, олардың механикалық тұрақтылығын арттыру, сүзгілену үдерістерін азайту және экологиялық қауіпсіздігін қамтамасыз ету. **Әдістері.** Зерттеу барысында

техногендік объектіде далалық жұмыстар жүргізіліп, бұрғылау және сынама алу орындалды, сондай-ақ гранулометриялық құрамы, ылғалдылығы, тығыздығы және беріктік сипаттамалары зертханалық жағдайда анықталды. Алынған нәтижелер негізінде беткі қабатты қайта профильдеу, жоғарғы қабатты бақыланатын түрде тығыздау және төмен өткізгішті қорғаныш қабатын орнату бойынша пилоттық шаралар жүзеге асырылды. Өндеуге дейін және кейін еңіс тұрақтылығы коэффициенті, инфильтрация қарқындылығы және эрозияға төзімділік бағаланды. **Нәтижелері мен қорытындылары.** Бастапқы материалдың жеткіліксіз тығыздалуы (максималды тығыздықтың 84–86%-ы) және ылғалдылықтың жоғары өзгергіштігі еңістердің тұрақтылығын төмендететіні анықталды. Тығыздау параметрлерін оңтайландыру нәтижесінде құрғақ тығыздық Проктор бойынша 97–99%-ға дейін артты, бұл ішкі үйкеліс бұрышы мен ілінісу күшінің өсуін және тұрақтылық коэффициентінің 20%-дан астам жоғарылауын қамтамасыз етті. Төмен өткізгішті қорғаныш қабатын қолдану су инфильтрациясын 80%-ға дейін төмендетіп, жел эрозиясын айтарлықтай азайтты. Ұсынылған тәсіл технологиялық тұрғыдан қарапайым, энергия тиімді және экономикалық жағынан негізделген. Зерттеу нәтижелері техногендік нысандардың ұзақ мерзімді экологиялық қауіпсіздігін қамтамасыз ету үшін жергілікті консервациялық шараларды енгізудің тиімділігін дәлелдейді.

Түйін сөздер: техногендік шөгінділер, қалдық қоймаларын консервациялау, еңіс тұрақтылығы, сүзгілік қасиеттер, топырақты тығыздау, экологиялық қауіпсіздік

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**ИНЖЕНЕРНО-ГЕОЛОГИЧЕСКОЕ ОБОСНОВАНИЕ КОНСЕРВАЦИИ
ТЕХНОГЕННЫХ ХВОСТОХРАНИЛИЩ ДЛЯ ПОВЫШЕНИЯ
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Аннотация. *Актуальность.* Накопление техногенных отложений, образующихся в результате длительной горнодобывающей и перерабатывающей деятельности, сопровождается повышенными рисками эрозии, миграции загрязняющих веществ и нарушения устойчивости склонов. Недостаточная уплотненность и структурная неоднородность верхних слоев хвостохранилищ существенно снижают эффективность традиционных природоохранных мероприятий и усложняют их долгосрочную эксплуатацию. **Цель.** Обосновать инженерно-геологический подход к консервации техногенных отложений, направленный на повышение их механической устойчивости, снижение фильтрационных процессов и обеспечение экологической безопасности с учетом конкретных геологических и климатических условий. **Методы.** Проведены полевые обследования техногенного объекта, бурение и отбор проб, лабораторное определение гранулометрического состава, влажности, плотности и прочностных характеристик. На основе полученных данных реализованы опытно-промышленные мероприятия, включающие репрофилирование поверхности, контролируемое уплотнение верхнего слоя и устройство малопроницаемого защитного покрытия. Выполнена оценка коэффициента устойчивости склонов, интенсивности инфильтрации и устойчивости к эрозии до и после обработки. **Результаты и выводы.** Установлено, что недостаточная степень уплотнения исходного материала (84–86% от максимальной плотности) и высокая изменчивость влажности приводят к снижению устойчивости склонов. Оптимизация параметров уплотнения позволила увеличить плотность до 97–99% от максимума по Проктору, что обеспечило рост угла внутреннего трения и сцепления, а также повышение коэффициента устойчивости более чем на 20%. Применение защитного малопроницаемого слоя снизило инфильтрацию воды до 80% и существенно уменьшило ветровую эрозию. Предложенный подход является технологически простым, энергоэффективным и экономически оправданным

по сравнению с переработкой или перемещением отходов. Результаты подтверждают целесообразность локальных мероприятий по обеспечению долговременной экологической безопасности техногенных объектов.

Ключевые слова: техногенные отложения, консервация хвостохранилищ, устойчивость склонов, фильтрационные свойства, уплотнение грунта, экологическая безопасность

Introduction. The accumulation of man-made mineral formations, formed as a result of long-term mining and processing activities, often lasting not 5-10, but 30-70 years, and in a number of industrial regions even over 100 years, today represents not just an abstract problem, but a very tangible, multi-layered - environmental, technological and even socio-economic - challenge of a global scale, since, according to various studies, the total volume of such accumulations reaches tens of billions of tons (in some countries - more than 10-15 billion tons), including waste rock dumps, tailings ponds with an area of 10-50 to 500-1000 hectares and other anthropogenic massifs formed over decades (Rachman Asmar et al., 2025; Wibowo et al., 2025; Myrzakulov et al., 2024), while these formations themselves, despite the presence of residual valuable components (sometimes up to 0.2–1.5% of metals in tailings) simultaneously create a whole range of risks - from wind erosion with losses of up to 0.42 kg/m² in 20 minutes at a wind speed of 12–15 m/s to water infiltration with coefficients of about 3.2×10^{-6} m/s, the formation of acid drainage, dust formation and migration of toxic elements into soils and groundwater, where concentrations can exceed background values by 2–5 times or more, especially in arid and semi-arid zones with an annual precipitation of about 200–300 mm and sharp seasonal fluctuations in humidity (from 6.5% to 14.2%), where the stability of such man-made bodies becomes a critical parameter directly affecting environmental safety, land use structure and the quality of life of the population (Malozymov et al., 2024; Sherov et al., 2021; Tananykhin et al., 2026).

In global practice, if we look beyond the surface and take into account the accumulated engineering experience over the past 20–30 years, quite a number of approaches to solving the problem of man-made deposits have been proposed and implemented. Among these, one of the most discussed areas remains their processing with the extraction of residual useful components using modern enrichment technologies (Fazylov et al., 2026). This allows for the partial recovery of up to 10–40% of the remaining metals and a reduction in waste volumes. However, it requires significant capital investment (often 20–30 USD/m² and higher), stable market conditions, and developed infrastructure. In reality, however, especially with low content (less than 0.3–0.5%) or small volumes, such processing proves economically unjustifiable. another way - the complete removal or relocation of man-made masses with subsequent reclamation of territories - at first glance seems radically effective, but is accompanied by high transportation costs, additional land disturbance (sometimes up to +15-25% of the area) and the creation of new storage facilities (Kulikova et al., 2023; Mashekov et al., 2018; Aldini et al., 2025), therefore, against this background, an alternative logic based on the conservation

of such formations directly on site is becoming increasingly noticeable, where due to relatively simple, but technologically proven measures - re-profiling the surface to slopes of about 15-16°, controlled compaction of the upper layers to 97-99% of the maximum Proctor density (instead of the original 84-86%), the installation of protective low-permeability screens with a thickness of about 0.15-0.30 m with a filtration coefficient of about 10^{-7} m/s - it is possible to reduce water infiltration to 80%, increase the slope stability coefficient by more than 20% (from ~1.18 to 1.30–1.42) and reduce wind erosion several times, while maintaining a reasonable balance between costs (about 4–6 USD/m²), technological feasibility and long-term environmental efficiency, which is especially important for regions with a high concentration of mining enterprises and accumulated tailings storage facilities.

An alternative and increasingly relevant direction is the conservation of technogenic deposits in situ, aimed at ensuring their long-term physical and chemical stability while minimizing environmental impact. Conservation measures may include surface profiling, compaction, installation of protective covers, drainage systems to control infiltration, and the application of binding or insulating materials. Compared to large-scale reprocessing or relocation, conservation requires relatively moderate investments and can be implemented step by step, taking into account local geological, hydrogeological, and climatic conditions. Nevertheless, the effectiveness of conservation depends on a correct assessment of the stability of technogenic bodies, the prediction of possible degradation processes, and the selection of technically justified protective solutions. Insufficiently substantiated measures may lead to continued pollutant migration or structural instability of the deposit body (Khoirunnisak et al., 2025; Arafat et al., 2025; Shabanov et al., 2023).

The relevance of conservation as a practical solution is increasing in the context of sustainable development and the transition to more responsible subsoil use. Many countries are faced with legacy mining sites where the original operators no longer exist or where economic conditions do not allow for profitable reprocessing. In such cases, ensuring environmental safety through rational conservation becomes not only an ecological task but also a socio-economic priority. For regions with a high concentration of mining enterprises, including Central Asia, the development of scientifically grounded, technically simple, and economically feasible conservation approaches is particularly important. The solution of relatively small, site-specific tasks—such as the assessment of slope stability, the optimization of surface protection layers, or the evaluation of water infiltration regimes—can significantly improve the overall reliability of technogenic formations and reduce long-term environmental risks (Filina et al., 2024; Sherov et al., 2024; Toshov et al., 2023).

In this context, the present study is aimed at substantiating and evaluating a technically feasible method for the conservation of technogenic deposits under specific geological and climatic conditions, with an emphasis on ensuring their structural stability and minimizing adverse environmental impact. The work focuses on solving a limited but practically significant task related to improving the reliability of conservation measures for technogenic formations.

Methods and Materials. The experimental work in question was not carried out spontaneously, but within the framework of a fairly clearly structured, essentially multi-stage program, including, on the one hand, detailed field surveys of the selected man-made object, on the other - a laboratory study of the composition of the material (with the determination of a whole set of parameters, from granulometry to strength), as well as pilot industrial tests of the conservation option aimed at increasing the stability of the surface and simultaneously reducing water infiltration, and the study itself, although it solved a local problem, at first glance limited (in fact, it was a question of refining the upper protective layer with a thickness of about 0.3 m with a total sampling depth of up to 1.0 m), nevertheless had quite practical significance, since real geological and climatic conditions were considered with characteristic variations in humidity from ~ 6.5% to 14.2% and a density of about 1.42 t / m³ in a natural state, and all stages, without exception, were carried out by the authors on a typical site of the tailings storage facility, Where signs of erosion (cracks up to 12 mm wide and up to 80 mm deep) and seasonal waterlogging were already recorded, the massif itself consisted of loose, finely dispersed material with a predominance of particles smaller than 0.1 mm (up to 62–68%), moderate slopes of approximately 17.8° (locally up to 21–23°), and pronounced structural heterogeneity.

During the first stage, which occupied a significant portion of the fieldwork, measurements of the geometric characteristics of the object were taken—from slope angles to microrelief assessment. Slopes were recorded using a digital inclinometer (accuracy up to 0.1–0.2°), and the thickness of the loose layer was determined through a combination of probing and selective opening followed by sampling. The samples of man-made material themselves were extracted from various depths, down to 1.0 m, using a hand auger, after which, in parallel, density measurements were carried out using the sand displacement method (which made it possible to fairly reliably estimate the actual degree of compaction, which, as calculations showed, was only about 84-86% of the maximum), and all of these seemingly routine procedures had direct practical significance, since it is the combination of density and slope geometry (with a stability coefficient of about 1.05-1.18 under unfavorable conditions) that determines whether an object will retain its shape for decades or begin to degrade after 2-3 seasons.

The next stage involved laboratory testing, where the material was “taken apart”: the particle size distribution was determined using a vibrating sieve analyzer with a frequency of 50 Hz (the duration of one cycle was about 10 minutes), moisture content was determined by drying at a temperature of 105°C to a constant weight (with a deviation of no more than 0.1–0.2%), density and strength characteristics were determined through a series of tests, including a direct cut under normal loads from 50 to 200 kPa (which corresponds to the real stresses in the upper layers), while the angle of internal friction of the original material was about 19–22°, and adhesion was 14–18 kPa, and additionally, compaction tests were performed according to the Proctor standard, which made it possible to determine the optimal

moisture content of about 12.8% and the maximum dry density of up to 1.68 t/m³, which together made it possible to quantitatively, rather than “by eye”, evaluate how the material reacts to compaction. and what parameters need to be set to form a truly effective protective layer.

Based on these data, a pilot conservation option was implemented on a test site of approximately 100 m²: the upper 0.3 m of the material were first reprofiled (leveling the slopes to ~15–16°), then compacted with a vibrating plate at a frequency of 60 Hz and a specific pressure of about 15 kPa, while the moisture content was brought to optimal values (12–13%) through controlled wetting, and then an additional protective layer of local loam with a thickness of about 0.15 m, with reduced permeability (a coefficient of about 1.6×10^{-7} m/s versus the original 4.8×10^{-6} m/s), which was also compacted, and then, using a double ring infiltrometer, the filtration capacity was assessed, showing a decrease in the infiltration rate of approximately 3.2×10^{-6} to 6.5×10^{-7} m/s, or almost 80%, which, when recalculated to annual volumes (with precipitation of about 250 mm), means a reduction in water inflow from ~6,300 to less than 1,400 m³ per hectare.

It is important to note that the methodology itself was not initially conceived as a large-scale, expensive project, but as a limited-in-scope, yet realistically approach, where a combination of field observations, laboratory calculations, and pilot implementation made it possible to obtain a fairly comprehensive, yet economically reasonable picture of efficiency (with costs of about 4–6 USD/m² versus 20–30 USD/m² for alternative options). The results obtained under these conditions have very specific significance for industry, as they demonstrate that even without complex technologies,

Results. Field studies conducted at the selected man-made site have shown quite convincingly, without any reservations, that the massif in question is characterized by insufficient stability of the surface zone and pronounced heterogeneity of the upper layer, and it is this combination of factors - uneven structure plus weak compaction - that directly, without intermediate assumptions, affects its behavior in the long term (not for months, but for 5-10-20 years), while the average slope angle within the surveyed area was about 17.8°, however, locally zones with slopes of 21–23° were recorded, which is already beyond the recommended values for the stable storage of fine tailings in comparable climatic conditions, and visual observations carried out during dry periods (at a humidity of about 6.5–7.0%) revealed a developed network of cracks up to 10–12 mm wide and up to 60–80 mm deep, indicating shrinkage processes associated with seasonal humidity fluctuations (up to 14–14.2% after precipitation), and such defects cannot be considered “cosmetic”, since they form channels for accelerated infiltration of atmospheric moisture (at speeds of about 3.2×10^{-6} m/s) and subsequent migration of dissolved components deep into the massif and further into underground horizons, which is critical for industrial mining facilities.

Granulometric analysis performed using vibrating sieve equipment (50 Hz, 10 minutes per sample) showed that the material of technogenic origin consists almost

entirely of fine fractions: the proportion of particles less than 0.1 mm reaches 62–68% by weight, and the clay component (<0.01 mm) is about 24%, which, on the one hand, explains the susceptibility of the surface to wind erosion (especially at wind speeds of 12–15 m/s, when losses can reach 0.42 kg/m² in 20 minutes), and on the other hand, enhances the dependence of strength characteristics on moisture, while the natural moisture content of the upper half-meter layer varies over a fairly wide range (6.5–14.2%), the average density in natural occurrence is about 1.42 t/m³, while the laboratory-established maximum dry density reaches 1.68 t/m³ with an optimal moisture content of 12.8%, and this discrepancy is clearly This shows that the actual state of the massif corresponds to only 84–86% of the potential compaction level, which, frankly, is insufficient for reliable and long-term preservation without additional measures.

Shear tests conducted in the normal stress range of 50–200 kPa demonstrated that the internal friction angle of the uncompacted material is within 19–22°, and the adhesion is 14–18 kPa. Moreover, with an increase in moisture content to 14–15%, adhesion decreases by approximately 20–25%, which significantly degrades slope stability during periods of moisture. If we use limit equilibrium calculations, the stability factor for the steepest sections at a near-saturated state barely reaches 1.18 (sometimes decreasing to 1.05–1.10), that is, it is practically at the limit of the permissible level. This, without exaggeration, confirms the need for targeted engineering solutions rather than formal monitoring of degradation processes. After re-profiling and compaction of the top layer with a thickness of about 0.3 m on the test site, the results were, let's say, quite indicative: the achieved dry density increased to 1.63–1.66 t/m³ (that is, up to 97–99% of the laboratory maximum), the humidity during the work was maintained in the range of 12–13% (which ensured optimal energy transfer from the vibratory plate with a frequency of 60 Hz and a pressure of about 15 kPa), and repeated density measurements across the site showed uniform compaction with deviations of no more than 2–3%, while the strength characteristics significantly improved - the angle of internal friction increased to 26–28 °, adhesion reached 22–25 kPa, and, as a result, the stability coefficient increased to 1.42 in a dry state and did not fall below 1.30 even when simulating almost saturated conditions, which already forms a safety margin that allows to significantly reduce the risk of local landslides, subsidence and erosional washouts.

An additional effect was obtained by installing a protective layer of low-permeability loam about 0.15 m thick, which after compaction showed a filtration coefficient of about 1.6×10^{-7} m/s (versus the original 4.8×10^{-6} m/s for the man-made material), and field tests using a double ring infiltrometer recorded a decrease in the steady-state infiltration rate from 3.2×10^{-6} to 6.5×10^{-7} m/s, that is, by about 75–80%, and if this is converted into annual volumes with an average rainfall of about 250 mm, then infiltration decreases from approximately 6,300 m³ to less than 1,400 m³ per hectare, which already has quite tangible practical meaning, especially for mining and uranium industries, where control of pollutant migration

substances is not a formality, but a matter of preventing groundwater pollution and the associated environmental and economic consequences.

Table 1. Comparative geotechnical, hydraulic and erosion parameters of the technogenic deposit before and after conservation treatment.

Parameter	Unit	Untreated condition (average)	After compaction	After compaction + protective layer	Relative change (%)
Natural moisture content	%	6.5–14.2	12–13 (controlled)	11–13 (stabilized)	Stabilized regime
In situ dry density	t/m ³	1.42	1.63	1.66	+16.9
Degree of compaction	% of Proctor max	84–86	97	99	+15
Internal friction angle	degrees	19–22	26	28	+32 (avg.)
Cohesion	kPa	14–18	22	25	+47 (avg.)
Calculated safety factor (dry)	–	1.18	1.36	1.42	+20
Calculated safety factor (near saturation)	–	1.05–1.10	1.25	1.30	+19
Filtration coefficient	m/s	4.8×10^{-6}	2.1×10^{-6}	6.5×10^{-7}	–86
Steady-state infiltration rate	m/s	3.2×10^{-6}	1.4×10^{-6}	6.5×10^{-7}	–80
Estimated annual infiltrated water (per ha)	m ³ /year	~6300	~2800	<1400	–78
Wind erosion mass loss (15 m/s, 20 min)	kg/m ²	0.42	0.18	0.09	–79
Surface runoff coefficient	%	35	49	58	+66
Surface crack width (max observed)	mm	12	3–4	not observed	Significant reduction
Microdepression coverage	% of area	18	4	<1	–94

In addition to purely mechanical stabilization, which, of course, had its effect (an increase in density to 1.63-1.66 t/m³ and an increase in the degree of compaction to 97-99%), an additional, at first glance less noticeable, but in practice extremely important role was played by the re-profiling of the surface, thanks to which it was possible to smooth out the microrelief and eliminate those very local irregularities where water had previously accumulated, since before the start of the work, microdepressions with a depth of 5 to 12 cm (sometimes up to 0.12 m) were recorded on approximately 18% of the surveyed area, acting as a kind of “traps” for moisture, whereas after the planning operations the slope of the surface was brought to more stable values of about 15-16°, and the depressions themselves actually disappeared, and this, in combination with controlled tests of artificial sprinkling (the water supply intensity was about 60 mm/h with an exposure duration of 30 minutes, which is equivalent to about 30 mm of precipitation in half an hour), allowed us to record a very clear result: the share of surface runoff increased from 35% to 58%, that is, almost 1.65 times, which directly indicates more efficient removal of moisture from the dump body, and therefore a decrease in infiltration

(previously reaching 3.2×10^{-6} m/s) and a decrease in the risk of leaching of dissolved components deep into the massif, which is especially critical for arid and semi-arid mining regions with an annual rainfall of about 200–250 mm, where even short-term but intense rains can trigger a chain of processes - from local erosion to the transfer of pollutants over significant distances.

No less indicative was the combined effect of compaction together with the installation of a protective layer on the material's resistance to wind exposure: if before the measures were taken, at air flow speeds of 12–15 m/s (which is a typical value for many regions during windy periods), mass losses of up to 0.42 kg/m² were recorded in a wind tunnel after just 20 minutes of exposure, accompanied by active dust formation, then after the implementation of a set of measures (compaction + a coating about 0.15 m thick with a filtration coefficient of 1.6×10^{-7} m/s), these losses decreased to 0.09 kg/m² under the same conditions, that is, almost 4.5–5 times, and such a difference is not just figures for the sake of reporting, but a quite noticeable reduction in dust emissions, which could otherwise be carried for kilometers (sometimes 1–3 km or more) and settle in adjacent areas, which is of direct importance for non-ferrous metallurgy enterprises, rare metal processing and other industries working with finely dispersed tailings, since reducing emissions simultaneously reduces both the environmental burden (less air pollution) and material losses, which, when calculated for large areas (tens and hundreds of hectares), can reach very significant amounts within a single season.



Fig. 1. Results of wind erosion simulation for the technogenic deposit: (a) untreated surface under airflow of 12–15 m/s, demonstrating intensive dust emission and material loss; (b) conserved surface after compaction and protective layer installation, showing significantly reduced dust generation and improved resistance to wind erosion.

From a technological point of view, the implemented conservation option proved itself, to put it mildly, to be quite viable and even, in a sense, “down-to-earth”, since all operations were carried out using standard construction and mining equipment – without complex installations, without multi-stage technological lines, without capital-intensive complexes – and the energy consumption for compaction, performed by a vibratory plate with an operating frequency of about 60 Hz and a specific pressure of about 15 kPa, amounted to only about 0.8–1.1 kW h for every 10 m² of processed surface (which, if recalculated per hectare, gives approximately 800–1100 kW h/ha), that is, an order of magnitude lower than in the processing of tailings, where specific energy costs can reach 8–15 kW h/m² or more, while the cost assessment carried out for a pilot site of about 100 m² showed that the complex of proposed measures (repurposing, compaction of a 0.3 m thick layer, installation of a 0.15 m thick protective coating) costs approximately 4-6 USD/m², varying depending on the availability of local materials and logistics, while alternative scenarios - partial processing or movement of man-made masses - under comparable conditions require 20-30 USD/m², and sometimes even more (up to 35-40 USD/m² with an increase in the transportation distance to 5-10 km), and such a difference, which is not 10-20%, but 4-6 times, quite clearly demonstrates that the proposed approach makes not only engineering, but also quite tangible economic sense for enterprises forced to seek a balance between costs and environmental requirements.

The results of subsequent monitoring, which was carried out for approximately 6 months (i.e., about 180 days, including both dry periods and episodes with precipitation of up to 20-30 mm in a short period of time), were no less indicative: no new cracks were observed to form on the treated surface (either with a width of 10-12 mm, or even with minimal values of 2-3 mm), no signs of erosion or localized erosion were recorded, while the adjacent, untreated areas continued to demonstrate the usual picture - seasonal cracking, the development of microdepressions with a depth of 5-10 cm and focal gullies after rains, while measurements of moisture at a depth of about 0.5 m under the protective layer showed fairly stable values in the range of 9-11% (with variations of no more than $\pm 1\%$), while in the untreated areas this parameter “wandered” much wider - from 7% in dry periods to 15–16% after precipitation, and it is precisely this stabilization of the water regime, although not obvious at first glance, that plays a key role in maintaining the constancy of the mechanical properties of the material (the angle of internal friction is 26–28°, adhesion is 22–25 kPa) and, as a result, reduces the risk of uneven settlement, subsidence and gradual degradation of the massif, which in the long term (1–3–5 years or more) becomes a critical factor in the reliability of man-made objects.



Fig. 2. Visual comparison of the technogenic deposit surface condition: (a) untreated area characterized by cracking and erosion features; (b) conserved area after six months of monitoring, demonstrating improved surface integrity, absence of visible cracks, and enhanced stability.

The obtained results, if considered not in fragments, but in the aggregate of all measurements, tests and observations (including a density of 1.63–1.66 t/m³, a degree of compaction of 97–99%, filtration coefficients of about 6.5×10^{-7} m/s after treatment and initial values up to 4.8×10^{-6} m/s, as well as a decrease in infiltration by almost 80% and a decrease in wind losses from 0.42 to 0.09 kg/m² in 20 minutes at speeds of 12–15 m/s), quite confidently confirm that even relatively limited in scale, local in nature measures (conditionally - work on an area of 100 m², a layer 0.3 m thick plus a covering of 0.15 m) are capable of significantly, and not symbolically, improving both the mechanical stability of man-made massifs (an increase in the stability coefficient from ~1.18 to 1.30–1.42), as well as their hydrological characteristics, and for industries such as mining, metallurgy and uranium mining, where there may be dozens, and sometimes hundreds, of similar facilities with areas from 10 to 500 hectares and a service life of decades (20–30–50 years or more), the recorded changes—whether it be a reduction in infiltration from thousands of cubic meters per hectare (~6,300 m³/year) to levels less than 1,400 m³/year, or stabilization of humidity in the range of 9–11% instead of jumps of 7–16%—are not of theoretical, but of quite practical significance, since they directly affect the risks of pollution, slope stability and operational reliability, and, what is especially indicative, the study clearly demonstrates that the solution to a relatively small engineering problem (in fact, the optimization of the upper protective layer several tens of centimeters thick) is capable of producing a measurable effect in several directions at once—from environmental safety to a reduction operational risks.

In a broader sense, the data obtained allow us to make a generalization that may

sound simple, but behind it lies a rather impressive set of figures and observations: rationally organized compaction (bringing up to 97-99% of the maximum according to Proctor with an optimal moisture content of about 12-13%) in combination with the installation of a low-permeability protective layer (with a thickness of about 0.15 m and a filtration coefficient of 10^{-7} m/s) forms a technologically simple, but at the same time a really working mechanism for the conservation of man-made formations, and the achieved quantitative improvements - an increase in the angle of internal friction from 19-22° to 26-28°, an increase in adhesion from 14-18 to 22-25 kPa, a decrease in filtration rate by 5-7 times and a decrease in erosion losses by almost 4-5 times - convincingly demonstrate that such solutions can be scaled up and transferred to other objects with similar engineering-geological and climatic conditions. (precipitation of about 200-300 mm/year, seasonal fluctuations in humidity, predominance of fine fractions of 60-70%), and for industrial enterprises, especially those operating in the segment of extraction and processing of minerals, such targeted conservation strategies look like a completely reasonable compromise, where environmental responsibility (reduced dust, limited migration of pollutants, stabilization of the massif) is combined with economic feasibility (costs of 4-6 USD/m² versus 20-30 USD/m² for alternatives), allowing problems to be solved not “in theory”, but in real operating conditions over a horizon of many years.

Conclusions. The study, if we consider it not formally, but through the prism of all the accumulated numerical indicators (density of 1.42 t/m³ in the initial state versus 1.63–1.66 t/m³ after treatment, degree of compaction of 84–86% versus 97–99%, filtration coefficients from 4.8×10^{-6} to 6.5×10^{-7} m/s, reduction of infiltration by approximately 75–80%, reduction of wind losses from 0.42 to 0.09 kg/m² at a flow velocity of 12–15 m/s, as well as stabilization of humidity in the range of 9–11% instead of fluctuations of 7–16%), quite clearly demonstrated that the long-term sustainability and environmental safety of man-made massifs can be significantly — and this is not an exaggeration — increased due to relatively simple from an engineering point of view, but competently selected and economically justified measures, focused primarily on optimizing the upper protective layer with a thickness of approximately 0.15–0.30 m, while the obtained results clearly confirm that factors such as insufficient compaction (below 90% of the maximum), pronounced structural heterogeneity and uncontrolled moisture penetration (with an intensity of up to 3.2×10^{-6} m/s) are the key reasons for the decrease in the reliability of such objects and the increase in the risks of erosion, dust formation and migration of pollutants, and the combination of field observations (slopes of 17.8–23°), laboratory tests (loads of 50–200 kPa, friction angle of 19–22°) and experimental implementation made it possible to obtain a fairly comprehensive understanding of the behavior of the material in real, rather than “laboratory” geological and climatic conditions.

If we formulate a general conclusion without excessive academic ponderousness, it comes down to a rather practical idea: rational compaction, brought to 97-99% of the maximum Proctor density at an optimal moisture content of about 12-

13%, in combination with the installation of a low-permeability mineral coating (approximately 0.15 m thick and a filtration coefficient of about 10^{-7} m/s), can be considered as a completely viable alternative to expensive operations of processing or moving man-made masses, the cost of which reaches 20-30 USD/m² and higher, while the proposed approach fits within 4-6 USD/m², providing not only savings, but also a noticeable improvement in operational characteristics, and, importantly, such an approach allows us to find a balance between environmental requirements and industrial feasibility, since even relatively local interventions (at the level of tens or hundreds of square meters) lead to an increase in the slope stability coefficient above 1.30 (up to 1.42 in a dry state), Stabilization of the moisture regime, a significant reduction in infiltration, and a decrease in wind erosion by almost 4-5 times, which is especially relevant for mining, metallurgy, and uranium industries operating in arid and semi-arid regions with precipitation of approximately 200-300 mm/year and frequent winds of 10-15 m/s, where degradation processes occur more rapidly than usual.

More specifically, an increase in dry density to 97-99% of the maximum value (1.68 t/m³) directly led to an increase in strength parameters: the angle of internal friction increased from 19-22° to 26-28°, adhesion—from 14-18 to 22-25 kPa. As a result, the slope stability coefficient at a near-saturated state exceeded 1.30, forming not a marginal, but a completely reliable stability margin; The installation of a compacted loam screen allowed us to reduce the filtration coefficient by more than an order of magnitude (from 10^{-6} to 10^{-7} m/s) and reduce vertical infiltration by approximately 80% (from ~6300 to <1400 m³/ha per year with precipitation of about 250 mm), thereby limiting the transfer of polluting components, while an increase in resistance to wind exposure by almost 5 times (0.42 → 0.09 kg/m²) turned out to be critically important in terms of reducing dust and associated environmental consequences, which, for large areas (tens of hectares), can already acquire a regional scale.

In general, to sum it up without being too dry, the obtained results quite confidently confirm that the targeted treatment of the surface of man-made massifs – even if limited in volume and carried out by standard equipment with energy consumption of about 0.8–1.1 kW h per 10 m² – is not only technically accessible, but also an energy-efficient conservation strategy, and the proposed methodology, based on very specific numerical parameters and tested in real conditions, can be adapted for other objects with similar engineering and geological characteristics (fine-dispersed composition of 60–70%, humidity of 6–14%, slopes up to 20°), and in the future is quite capable of becoming the basis for the development of regulatory and production recommendations aimed at sustainable, rather than formal, management of accumulated mining legacy objects.

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