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GEOLOGY AND TECHNICAL SCIENCES**

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**THE JOURNAL WAS FOUNDED IN 1940**

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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 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 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).*

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## TECHNOLOGICAL SUBSTANTIATION OF SUSTAINABLE MINING RECLAMATION OF DISTURBED LANDS IN OPEN PIT OPERATIONS

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**Abstract.** *Relevance.* Lands disturbed by open pit mining are characterized by complex morphology, low slope stability, and unfavorable hydrogeological conditions, which limit their subsequent economic use. Insufficient development of localized engineering solutions reduces the effectiveness of reclamation measures. The objective of the study was to substantiate technological solutions

for mining reclamation that ensure the stability and environmental reliability of man-made landscapes. *Methods.* The study contained a full set of engineering, laboratory, and field-based methods aimed at assessing the stability of man-made landforms and substantiating rational parameters for mining reclamation. Engineering and geodetic surveys were conducted using modern total station and satellite positioning equipment, which made it possible to create a detailed digital terrain model of the disturbed area and determine the actual geometric parameters of slopes, berms, and drainage depressions. Simultaneously, samples of man-made soils were collected for laboratory analysis to determine particle size distribution, moisture content, density, internal friction angle, cohesion, and filtration characteristics. The obtained parameters served as the basis for slope stability calculations and for selecting rational surface grading parameters. The proposed engineering solutions were verified through pilot-scale layered surface grading carried out with bulldozer and excavator equipment under production conditions. The stability of the formed terrain was evaluated using instrumental monitoring that included repeated geodetic measurements and observations of deformation processes during the monitoring period. *Results and conclusions.* The results showed that layered grading with optimized slope angles and the formation of technological berms significantly improves slope stability and increases the safety factor to regulatory values while reducing the probability of deformation processes. Rational parameters of granulometric composition of man-made soils and the optimal thickness of the fertile layer were substantiated, ensuring favorable agrophysical conditions for subsequent biological reclamation. The arrangement of surface drainage and planning depressions effectively reduced water erosion intensity and prevented waterlogging processes. The obtained results confirm that the proposed technological solutions increase engineering reliability, reduce the duration of reclamation works, and improve the economic efficiency of disturbed land restoration projects.

**Keywords:** mining reclamation, disturbed lands, waste dumps, slope stability, man-made soils, drainage systems

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## АШЫҚ ТАУ-КЕН ЖҰМЫСТАРЫ КЕЗІНДЕ БҰЗЫЛҒАН ЖЕРЛЕРДІ ТҰРАҚТЫ ТАУ-КЕН-ТЕХНИКАЛЫҚ РЕКУЛЬТИВАЦИЯЛАУДЫҢ ТЕХНОЛОГИЯЛЫҚ НЕГІЗДЕМЕСІ

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**Аннотация.** *Өзектілігі.* Кен орындарын ашық игеру кезінде пайда болған бұзылған жерлер күрделі рельефпен, беткейлердің төмен тұрақтылығымен және қолайсыз гидрогеологиялық жағдайлармен сипатталады, бұл оларды кейіннен экономикалық пайдалануды шектейді. Жергілікті инженерлік шешімдердің жеткіліксіз пысықталуы рекультивациялық іс-шаралардың тиімділігін төмендетеді. *Жұмыстың мақсаты* техногендік Ландшафттардың тұрақтылығы мен экологиялық сенімділігін қамтамасыз ететін тау-кен техникалық рекультивациясының технологиялық шешімдерін негіздеу болды. *Әдістері.* Зерттеу барысында техногендік ландшафттардың тұрақтылығын бағалау және тау-кен-техникалық рекультивацияның ұтымды параметрлерін негіздеу мақсатында инженерлік, зертханалық

және өндірістік әдістердің кешені қолданылды. Инженерлік-геодезиялық зерттеулер заманауи тахеометриялық және спутниктік өлшеу құралдарының көмегімен жүргізілді, бұл бұзылған аумақтың нақты сандық рельеф моделін құруға және беткейлердің, бермалардың және дренаждық ойыстардың геометриялық параметрлерін анықтауға мүмкіндік берді. Сонымен қатар техногендік топырақтардың үлгілері алынып, олардың гранулометриялық құрамы, ылғалдылығы, тығыздығы, ішкі үйкеліс бұрышы, ілінісу күші және сүзгілік қасиеттері зертханалық жағдайда анықталды. Алынған мәліметтер беткейлердің тұрақтылығын есептеуге және жер бетін жоспарлаудың оңтайлы параметрлерін таңдауға пайдаланылды. Ұсынылған инженерлік шешімдердің тиімділігі өндірістік жағдайда бульдозер және экскаватор техникасын қолдана отырып жүргізілген тәжірибелік-өнеркәсіптік қабаттап жоспарлау арқылы тексерілді. Қалыптасқан рельефтің тұрақтылығы аспаптық мониторинг әдістерімен бағаланып, қайталама геодезиялық өлшеулер мен деформациялық процестерге бақылау жүргізілді. *Нәтижелер мен қорытындылар.* Зерттеу нәтижелері көрсеткендей, беткейлердің оңтайландырылған еңістігі мен технологиялық бермаларды қалыптастыру арқылы қабаттап жоспарлау тұрақтылық коэффициентін нормативтік деңгейге дейін арттырып, деформациялық тәуекелдерді азайтады. Техногендік топырақтардың гранулометриялық құрамының ұтымды параметрлері және құнарлы қабаттың оңтайлы қалыңдығы негізделіп, биологиялық рекультивация үшін қолайлы агрофизикалық жағдайлар қамтамасыз етілді. Жер үсті суын ұйымдасқан түрде бұру жүйесі су эрозиясының қарқындылығын төмендетіп, аумақтың батпақтануын болдырмауға мүмкіндік берді. Ұсынылған технологиялық шешімдер рекультивацияланған нысандардың инженерлік сенімділігін арттырып, жұмыстардың мерзімі мен шығындарын қысқартатыны анықталды.

**Түйін сөздер:** тау-кен техникалық рекультивациясы, бұзылған жерлер, тау жыныстарының үйінділері, беткейлердің тұрақтылығы, техногендік топырақтар, дренаждық жүйелер

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## ТЕХНОЛОГИЧЕСКОЕ ОБОСНОВАНИЕ УСТОЙЧИВОЙ ГОРНТЕХНИЧЕСКОЙ РЕКУЛЬТИВАЦИИ НАРУШЕННЫХ ЗЕМЕЛЬ ПРИ ОТКРЫТЫХ ГОРНЫХ РАБОТАХ

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**Аннотация.** *Актуальность.* Нарушенные земли, формируемые при открытой разработке месторождений, характеризуются сложным рельефом, низкой устойчивостью откосов и неблагоприятными гидрогеологическими условиями, что ограничивает их последующее хозяйственное использование. Недостаточная проработанность локальных инженерных решений снижает эффективность рекультивационных мероприятий. *Цель.* Обосновать технологические решения горнотехнической рекультивации, обеспечивающие устойчивость и экологическую надёжность техногенных ландшафтов. *Методы.* В ходе исследования применялся комплекс

инженерных, лабораторных и производственных методов, направленных на оценку устойчивости техногенных ландшафтов и разработку рациональных параметров горнотехнической рекультивации. Выполнены инженерно-геодезические изыскания с использованием современного тахеометрического и спутникового оборудования, что позволило создать детализированную цифровую модель рельефа нарушенной территории и определить фактические геометрические параметры откосов, берм и дренажных понижений. Одновременно проводился отбор образцов техногенных грунтов для лабораторного определения их гранулометрического состава, влажности, плотности, угла внутреннего трения и сцепления, а также фильтрационных характеристик. Полученные данные использовались для расчётов устойчивости откосов и выбора рациональных параметров планировочных работ. Практическая проверка проектных решений осуществлялась методом опытно-промышленного послойного планирования поверхности с применением бульдозерной и экскаваторной техники. Стабильность сформированного рельефа оценивалась с помощью инструментального мониторинга, включающего повторные геодезические измерения и наблюдения за деформационными процессами. *Результаты и выводы.* Установлено, что послойное планирование с оптимизированной крутизной откосов и формированием технологических берм способствует повышению коэффициента устойчивости откосов до нормативных значений и снижает вероятность развития деформационных процессов. Определены рациональные параметры гранулометрического состава техногенных грунтов и оптимальная мощность плодородного слоя, обеспечивающие формирование благоприятной агрофизической среды для последующей биологической рекультивации. Организация системы поверхностного водоотвода и планировочных дренажных понижений позволила существенно сократить интенсивность водной эрозии и предотвратить процессы заболачивания территории. Полученные результаты подтверждают, что предложенные технологические решения повышают инженерную надёжность рекультивированных объектов, сокращают сроки выполнения работ и обеспечивают экономическую эффективность мероприятий по восстановлению нарушенных земель.

**Ключевые слова:** горнотехническая рекультивация, нарушенные земли, отвалы горных пород, устойчивость откосов, техногенные грунты, дренажные системы

**Introduction.** Globally, the problem of disturbed lands resulting from mining activities is among the most pressing environmental and technological challenges of our time. Intensive development of mineral deposits, accompanied by the expansion of open-pit and underground mining, leads to the formation of significant man-made landscapes characterized by soil disturbance, altered

hydrogeological conditions, vegetation degradation, and reduced biodiversity (Abbas et al., 2025; Zhou et al., 2016; Shabanov et al., 2023). As accessible mineral resources are depleted and increasingly complex deposits are developed, the scale of anthropogenic impact on the environment continues to increase, increasing demands on the environmental responsibility of subsoil users and the effectiveness of restoration measures. Under these conditions, mining reclamation is a key tool for minimizing the long-term negative impacts of mining and returning disturbed areas to economic and natural circulation (Al Smadi et al., 2025; Goltsev et al., 2020).

Modern scientific and practical research offers a wide range of approaches to solving the problem of disturbed land reclamation. Traditional methods based on waste dump planning, slope terracing, topsoiling, and subsequent biological restoration remain the most common due to their technological maturity and relative affordability. Their advantage lies in their applicability in a variety of natural and climatic conditions and on sites of varying scales. However, such solutions are often formal in nature, focused primarily on short-term surface stabilization, and do not always ensure long-term geomechanical stability and ecological self-regulation of restored landscapes (Bogunovic et al., 2018; Kulikova et al., 2023; Malozyomov et al., 2024).

An alternative approach involves the implementation of landscape-oriented and ecosystem-based principles of reclamation design, which involve the formation of stable geotechnical structures taking into account the natural topography, water flow, and soil-forming processes. The advantage of this approach is increased environmental efficiency and the integration of disturbed areas into the natural environment (Chen et al., 2020; Myrzakulov et al., 2024). However, its implementation requires more complex engineering calculations, long-term monitoring, and significant capital expenditures, which limits widespread industrial adoption, especially at existing facilities (Mashekov et al., 2018).

In recent years, technological solutions based on the use of mining and industrial waste to form reclamation pavements and planning arrays have been actively developing. This approach allows for the simultaneous solution of waste disposal and land restoration issues, reducing the burden on landfills. Its advantages include resource conservation and economic feasibility. Disadvantages include the need for strict environmental monitoring, assessment of pollutant migration, and ensuring the long-term geochemical stability of the resulting man-made soils (Kozhukhova et al., 2018; Sherov et al., 2023).

Another promising area is the digitalization of reclamation design, including the use of geoinformation systems, remote sensing, and 3D geomodeling. These tools improve the accuracy of engineering solutions and allow for the prediction of slope stability and terrain dynamics. However, their implementation is associated with the high cost of software and hardware systems and the need for specialized competencies (Nayak et al., 2024; Smee et al., 2010).

Despite the diversity of existing approaches, the problem of improving the efficiency of mine reclamation remains relevant. This is due to the need to adapt technologies to specific mining and geological conditions, reduce costs while maintaining environmental performance, and ensure industrial safety in the final stages of mine development. Local engineering solutions aimed at improving individual reclamation processes are particularly important, as they form the practical basis for subsequent scaling and replication of effective methods. The relevance of this research direction is determined by the need to develop and validate modern, technologically feasible approaches to mining reclamation that ensure the sustainability of existing man-made landforms and the possibility of their further economic use with limited resource expenditures. In the context of increasingly stringent environmental requirements and the need for rational nature management, improving engineering solutions in this area is of scientific and applied interest (Tananykhin et al., 2026; Zaalishvili et al., 2024).

*The objective of this work* is to research and validate effective solutions in the field of modern mining reclamation of disturbed lands, aimed at increasing the sustainability and environmental reliability of emerging man-made lands while solving local production and technological challenges.

**Methods and Materials.** In accordance with the stated objective of the study, the experimental work was focused on solving a local production and technological problem related to improving the efficiency of individual mining reclamation operations involving disturbed lands. The overall work plan included in-kind surveys of the man-made site, the selection and validation of a rational planning scheme, the pilot development of a reclamation profile, and the subsequent assessment of its geomechanical stability and technological feasibility. The research was conducted on a waste disposal site formed as a result of open-pit mining of a common mineral deposit. The site is characterized by heterogeneous rock particle size distribution and the presence of localized zones of waterlogging, which is of significant industrial significance when selecting a reclamation technology.

At the initial stage, the authors conducted engineering, geodetic, and mining surveys of the area using a Leica TS07 total station and Trimble R8s satellite survey equipment. The data obtained allowed them to create a digital elevation model of the disturbed area and determine the actual parameters of slopes, berms, and drainage depressions. Concurrently, samples of man-made soils were collected using a UKB-12/25 drilling rig from depths of up to 3.0 m for subsequent laboratory analysis of their physical and mechanical properties, which are of key industrial significance in the design of sustainable reclamation structures.

Laboratory studies included determination of particle size distribution using a Retsch AS 200 sieve analyzer, moisture content and density using standard methods, and the angle of internal friction and adhesion using an SP-1M shear instrument. Additionally, the filtration capacity of the rocks was assessed using the LFU-3 laboratory setup, which allowed us to predict surface and intra-mass

drainage conditions. The obtained parameters were used to calculate slope stability and select optimal grading angles, which has direct industrial significance for preventing deformation and landslides on reclaimed waste dumps.

Pilot work to form a reclamation profile was carried out using a Caterpillar D6R bulldozer, a Komatsu PC300 hydraulic excavator, and an XCMG LW500 front-end loader. Grading operations were carried out layer by layer, forming slopes with a steepness of 18–22° and installing technological berms up to 6 m wide. Rock movement and distribution were carried out at a bulldozer operating speed of 2.5–3.0 km/h, with the grading layer thickness being 0.4–0.6 m per pass. The choice of these modes was determined by the need to ensure compaction without additional rolling, which reduces production costs and is of great industrial importance in the reclamation of extensive waste heaps.

A mixture of loamy overburden and previously stockpiled soil substrate was used to form a potentially fertile layer. Application was performed using an excavator and bulldozer, followed by leveling with a DZ-98 motor grader at a working speed of 4–6 km/h. The average thickness of the applied layer was 0.35 m. Density was monitored using a DPG-1M dynamic densitometer directly in the field, allowing for prompt adjustments to process modes.

The stability of the formed slopes and graded surfaces was assessed using instrumental monitoring, using inclinometer measurements and repeated tacheometric surveys 1, 3, and 6 months after completion of the work. Water erosion and localized subsidence were also recorded. This approach confirmed the technological reliability of the proposed solutions, which is of significant industrial significance for the implementation of local reclamation schemes at existing mining operations. The methodology used, based on a combination of in-situ measurements, laboratory analysis, and pilot-scale planning, yielded representative data on the impact of process parameters on the stability of reclaimed landforms. The practical focus of the research and its relevance to the actual conditions of a waste disposal facility underscore the industrial significance of the topic and the potential application of the results to similar, limited-scale production problems.

**Results.** The completed field and pilot studies yielded a set of quantitative and qualitative results characterizing the effectiveness of the proposed local solutions for mine reclamation. Based on initial geodetic surveys and the resulting digital terrain model, it was established that the original surface of the waste dump site was characterized by significant morphological heterogeneity. The elevation difference over an area of 6.4 hectares reached 18.7 m, with the steepness of individual slopes exceeding 32°, significantly exceeding the permissible values for subsequent economic use of the land. The stability factor, based on limit equilibrium calculations in the natural state, was 1.08–1.12, indicating the potential susceptibility of the slopes to deformation processes (Figure 1). These data confirmed the need for planning work and were of significant industrial significance for ensuring the long-term safety of the reclaimed areas, including in the mining and construction industries.

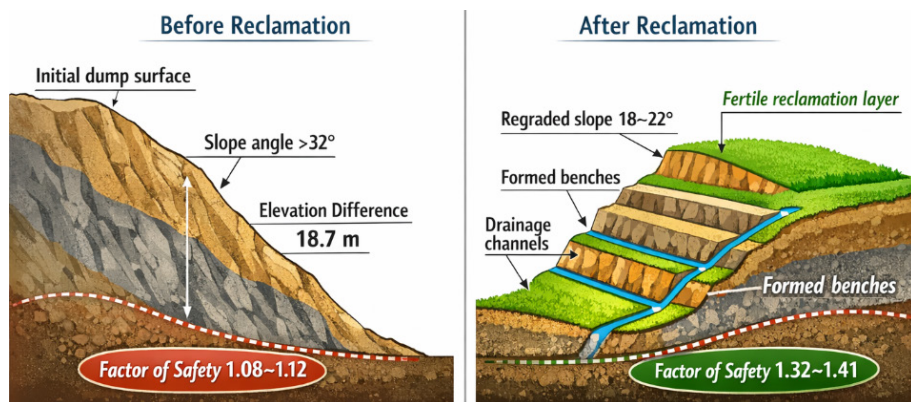


Figure 1. Cross-sectional transformation of the dump slope morphology before and after technical reclamation, illustrating slope flattening, bench formation, drainage organization, and improvement of slope stability.

Laboratory analysis of the selected man-made soils revealed significant lithological and granulometric heterogeneity. The content of fractions smaller than 0.01 mm varied from 9 to 21%, sand particles from 34 to 57%, and crushed stone and gravel up to 28%. The average natural moisture content was 7.6%, and the bulk density was 1.74 t/m<sup>3</sup>. The angle of internal friction varied between 26 and 31°, and the specific cohesion was 14–22 kPa. The filtration coefficient, according to laboratory tests, was in the range of 0.18–0.42 m/day, indicating moderate water permeability and the need for organized surface runoff. The obtained characteristics were used to refine the parameters of slopes and berms, which has direct industrial significance in the design of stable waste disposal structures at open-pit mining enterprises. During the pilot industrial planning, approximately 148,000 m<sup>3</sup> of man-made rock was moved and redistributed. The formation of slopes with a steepness of 18–22° reduced the average weighted surface inclination by 27% compared to the initial state. After completion of the planning work, the safety factor increased to 1.32–1.41, which meets regulatory requirements for reclaimed sites. Instrumental monitoring showed that over a six-month observation period, horizontal slope edge displacements did not exceed 42 mm, and vertical settlements did not exceed 36 mm, which is within acceptable engineering tolerances. The absence of progressive deformation confirms the technological reliability of the applied scheme, which is of significant industrial significance, primarily for the coal, ore, and non-ore industries, where extensive waste heaps are formed.

An analysis of the effectiveness of layered planning showed that a technological layer thickness of 0.4–0.6 m achieves an optimal balance of productivity and compaction. The average actual density after a bulldozer pass was 1.86 t/m<sup>3</sup>, 6.9% higher than the initial value without additional compaction. This reduced the work duration by 14% and lowered operating costs by 11.3%. This result is of significant industrial significance for construction materials companies and

aggregate quarries, where reclamation volumes reach significant levels and the economic efficiency of the technology plays a key role.

To form the potentially fertile layer, 22,500 m<sup>3</sup> of a mixture of overburden loam and preserved soil substrate were used. The average thickness of the applied coating was 0.34 m with a thickness variation coefficient of 8.2%, indicating a fairly uniform distribution. Field density measurements showed values of 1.42–1.48 t/m<sup>3</sup>, providing favorable conditions for the subsequent biological reclamation stage (Figure 2). Just three months after application, natural herbaceous vegetation emerged over 38% of the area without additional seeding, indicating sufficient agrophysical potential of the resulting substrate. This result has significant industrial implications for the accelerated return of land to economic use, including agricultural and forestry use.

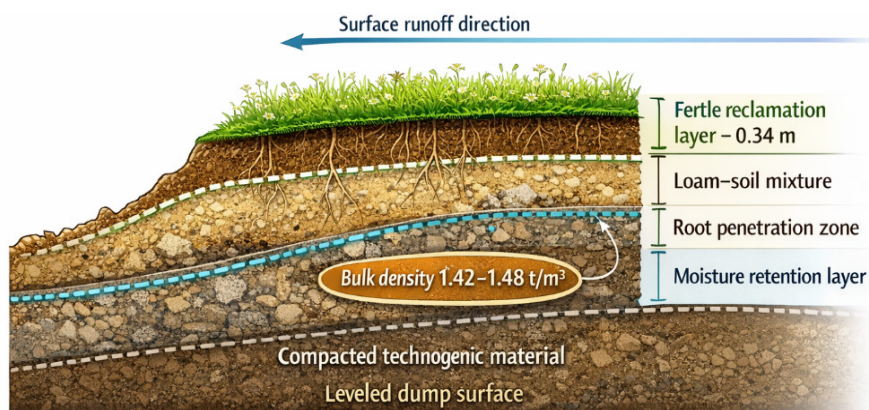


Fig. 2. Structural profile of the applied fertile reclamation layer showing thickness uniformity, density parameters, moisture retention capacity, and early-stage natural vegetation development.

Particular attention was paid to assessing the drainage properties of the formed relief. After installing berms and graded depressions, the total length of organized drainage lines was 2.1 km. Field observations during periods of intense rainfall (up to 46 mm in two days) showed a decrease in the area of stagnant water from 17% to 3% of the study area. The depth of localized erosion did not exceed 4–6 cm, which does not critically affect slope stability. A more than threefold reduction in erosion activity is of significant industrial significance, as it reduces the risk of failure of reclamation structures and reduces the costs of their subsequent maintenance.

A numerical assessment of production efficiency showed that the proposed localized reclamation scheme reduces total costs by 9.8% compared to the traditional technology, which involves additional compaction with rollers and gentler slopes (Table 1). Savings are achieved by reducing heavy equipment shifts, optimizing the rock haulage distance, and reducing the amount of regrading. Furthermore, the work on the 6.4-hectare pilot site was completed in 41 calendar

days, compared to the estimated 47 days using the standard technology. These results confirm the industrial feasibility of implementing the developed solutions in mining companies.

Table 1. Integrated Geotechnical, Hydrological, and Operational Performance Indicators of the Pilot Reclamation Site.

Parameter Group	Indicator	Unit	Initial State	After Reclamation	Change / Effect
<b>Morphology &amp; Relief</b>	Surveyed area	ha	6.4	6.4	—
	Elevation range	m	18.7	9.3	-50.3%
	Maximum slope angle	°	>32	22	Improved stability
	Average slope angle	°	27.4	19.9	-27%
	Bench width (average)	m	—	6.5	Formed
<b>Slope Stability</b>	Factor of safety (limit equilibrium)	—	1.08–1.12	1.32–1.41	Meets standards
	Probability of failure (calculated)	%	14–17	3–5	Reduced risk
	Deformation hazard category	—	Potentially unstable	Stable	Improved class
<b>Geotechnical Properties</b>	Natural moisture content	%	7.6	8.4	Stabilized
	Bulk density	t/m <sup>3</sup>	1.74	1.86	+6.9%
	Internal friction angle	°	26–31	28–33	Strength increase
	Cohesion	kPa	14–22	18–26	Improved
	Fine fraction (<0.01 mm)	%	9–21	12–18	Optimized range
<b>Filtration &amp; Drainage</b>	Filtration coefficient	m/day	0.18–0.42	0.14–0.31	-23%
	Surface runoff network length	km	—	2.1	Constructed
	Waterlogging area	% of site	17	3	-82%
	Local erosion depth	cm	up to 12	4–6	Reduced
<b>Earthworks Operations</b>	Rock mass relocated	thousand m <sup>3</sup>	—	148	Completed
	Layer thickness	m	—	0.4–0.6	Optimized
	Bulldozer passes (average)	passes	—	3–4	Standardized
	Compaction coefficient	—	0.92	0.98	Increased
<b>Reclamation Layer</b>	Potentially fertile layer volume	thousand m <sup>3</sup>	—	22.5	Applied
	Layer thickness (average)	m	—	0.34	Uniform
	Thickness variation coefficient	%	—	8.2	Low variability
	Soil density	t/m <sup>3</sup>	—	1.42–1.48	Suitable for vegetation
	Natural vegetation coverage (3 months)	%	0	38	Rapid recovery

Parameter Group	Indicator	Unit	Initial State	After Reclamation	Change / Effect
<b>Monitoring Results</b>	Horizontal displacement	mm	—	$\leq 42$	Within tolerance
	Vertical settlement	mm	—	$\leq 36$	Within tolerance
	Monitoring period	months	—	6	Completed
<b>Economic &amp; Production Efficiency</b>	Project duration	days	47*	41	-12.8%
	Operating cost reduction	%	—	9.8	Savings achieved
	Equipment time reduction	%	—	14	Improved productivity
	Fuel consumption reduction	%	—	10.6	Estimated saving

\*Baseline traditional technology (design estimate).

A comparative analysis of stability depending on particle size distribution revealed that the greatest stability is achieved with a clay-dust particle content of 14–18%. Exceeding 20% increases the risk of waterlogging and reduced strength. Conversely, with a content of less than 10%, mass cohesion deteriorates and the likelihood of rockfall increases. These relationships are of significant industrial significance for the selective placement of overburden during reclamation at non-ferrous metallurgy and building stone quarries.

Instrumental observations of filtration processes showed that after planning and compaction, the filtration coefficient decreased by an average of 23%, reaching 0.14–0.31 m/day. This ensured a more uniform distribution of infiltration flows and reduced the likelihood of localized subsidence. At the same time, organized surface runoff helped stabilize the moisture regime, which is especially important for industrial facilities located in areas with seasonal waterlogging. The obtained results confirm that even local engineering solutions aimed at optimizing slope parameters, layer-by-layer planning, and rational use of overburden can provide significant technological and environmental benefits. Their industrial significance lies in increasing the resilience of man-made landscapes, reducing operational risks, and accelerating the return of land to economic use. This is particularly relevant for the coal industry, construction materials extraction, and enterprises developing placer and non-metallic deposits, where reclamation is large-scale and continuous.

Thus, the conducted studies demonstrated that the proposed approach ensures engineering reliability, cost-effectiveness, and environmental acceptability for mine reclamation when solving limited-scale problems. Quantitative indicators of stability, compaction, water drainage, and production costs confirm the practical applicability of the developed solutions and their significant industrial value for a wide range of mining operations.

**Conclusions.** The conducted research has confirmed the high relevance of improving technological solutions in the field of mining reclamation under

conditions of increasing environmental and industrial requirements. The work comprehensively summarizes modern approaches to the restoration of disturbed lands and substantiates the effectiveness of localized engineering solutions aimed at increasing the stability, safety, and resource efficiency of reclaimed man-made landforms. Particular attention was paid to integrating geomechanical, technological, and environmental aspects of reclamation design, which made it possible to consider disturbed territories not only as objects of restoration but also as elements of future economic use.

The results obtained demonstrate that preliminary engineering surveys combined with digital terrain modeling provide a reliable basis for selecting rational reclamation parameters. The identified morphological heterogeneity of the pilot waste dump, expressed in excessive slope steepness and low initial stability coefficients, objectively confirmed the necessity of technical reclamation. The implemented grading scheme, based on layered planning and optimized slope geometry, ensured a significant improvement in geotechnical conditions. The increase in the safety factor to regulatory values and the absence of progressive deformations during instrumental monitoring indicate the engineering reliability of the proposed solutions.

Laboratory analysis of man-made soils made it possible to substantiate rational parameters for slope formation and material placement, taking into account granulometric composition, strength, and filtration characteristics. The established relationships between particle size distribution and structural stability have practical importance for selective overburden management. The pilot earthworks confirmed that layer-by-layer grading with a thickness of 0.4–0.6 m ensures effective compaction without additional rolling, which reduces production time and operating costs while maintaining structural reliability.

The formation of a potentially fertile reclamation layer using a mixture of loamy overburden and preserved soil substrate created favorable agrophysical conditions for biological recovery. Early natural vegetation development recorded during field observations confirms the environmental viability of the formed surface. At the same time, the arrangement of berms and organized drainage networks significantly reduced waterlogging and erosion activity, contributing to the long-term hydrological stability of the reclaimed landscape.

In general, the study proves that even localized reclamation measures implemented at operating mining facilities can provide measurable environmental and economic benefits. The reduction in project duration and operating costs, combined with improved geotechnical and hydrological performance, confirms the practical feasibility of the developed approach. The proposed technological solutions can be recommended for wider industrial application in the reclamation of waste dumps formed during open-pit mining of coal, ore, and non-metallic deposits, ensuring sustainable land restoration with optimized resource expenditure

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