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Ensuring Stability of the Earthbed in Conditions of Over-Watering on Weak Soils in the Karaganda Region

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***Abstract.** The issues of ensuring the stability of the roadbed of railway transport tracks in conditions of waterlogging and weak soils are considered using the example of the Karaganda region. Given the peculiarities of the geological and climatic conditions of the region, high humidity significantly reduces the strength characteristics of the foundation, which leads to deformations and disruption of the geometry of the railway track. An analysis of the types of soils typical for the region, as well as their granulometric and physical-mechanical properties, is carried out. Particular attention is paid to the use of bitumen-containing materials and other modern strengthening technologies that ensure an increase in the bearing capacity and water resistance of the foundations. The paper presents the results of numerical modeling of the stress-strain state of the structure, allowing to assess the performance of the roadbed under vibration loads arising from the movement of rail transport. The proposed engineering solutions are aimed at increasing the reliability and durability of railway transport infrastructure facilities in complex hydrogeological conditions.*

***Keywords:** roadbed, weak soils, waterlogging, stability, Karaganda region, bitumen-containing materials, railway, railway transport.*

Introduction. Railway transport plays a key role in the socio-economic development of Kazakhstan, providing stable communication between regions, transportation of raw materials, products and passengers. This is especially relevant for the Karaganda region – one of the industrial centers of the country, where railways ensure the functioning of the metallurgical, coal and other industries.

The foundation of any railway line is the roadbed, the stability and reliability of which directly affects the safety and efficiency of transportation. However, in conditions of over-wetting and weak soils, typical for a number of areas of the Karaganda region, serious engineering problems arise. Excessive soil moisture leads to a decrease in their bearing capacity, deformations, subsidence, which entails damage to the track superstructure, increased repair costs and a threat to the safe operation of the railway infrastructure.

Modern climate change, accompanied by an increase in precipitation and floods, further exacerbates the problem of over-wetting of the roadbed. The stability of the roadbed of transport routes in the Karaganda region remains one of the most important tasks in the field of engineering geology and transport construction. The region is characterized by complex geomorphological conditions and the presence of areas with high humidity and weak soils, especially during periods of floods and intense precipitation.

Over-watering has a negative impact on the bearing capacity of the soil base, causing subsidence, deformation and destruction of the road surface, which significantly reduces the level of safety and reliability of the transport infrastructure. The increasing incidence of extreme weather conditions in recent years only exacerbates this problem.

Given the active development of the transport network in the region, the introduction of modern methods of soil strengthening and effective drainage systems is of particular importance. Among the most promising areas is the use of bitumen-containing materials that increase the water resistance and strength characteristics of weak foundations. An integrated approach to ensuring the stability of the roadbed can increase the reliability and durability of transport facilities, as well as reduce the costs of their maintenance and restoration.

Therefore, the development and implementation of effective technical solutions aimed at ensuring the stability of railway embankments in weak and waterlogged areas is becoming especially relevant.

Purpose of the study:

Increasing the stability of the railway track bed in conditions of waterlogging and weak soils using the example of the Karaganda region by analyzing geological features and using modern strengthening technologies.

Research objectives:

To study the geological and hydrological features of railway sections in the Karaganda region.

To analyze the physical and mechanical characteristics of local soils and determine their impact on the stability of the roadbed.

To examine and justify the effectiveness of using bitumen-containing and other modern materials to strengthen the foundation.

Perform numerical modeling of the stress-strain state of a structure under the influence of loads from railway transport.

Develop engineering recommendations to improve the reliability of the roadbed in difficult conditions.

Scientific novelty:

A comprehensive approach to ensuring the stability of the railway track bed has been developed, taking into account the specific climatic and geological conditions of the Karaganda region and based on the use of modern materials and numerical modeling. For the first time, the results of modeling the vibration impact of rolling stock on waterlogged foundations of the region are presented.

Practical significance:

The results of the study can be used in the design, construction and reconstruction of railway infrastructure in conditions of weak and waterlogged soils. The proposed technologies and engineering solutions allow increasing the durability of the roadbed, reducing operating costs and improving the safety of railway transport.

Materials and methods

The performance of the roadbed and its foundation is determined mainly by three groups of interrelated factors:

- the composition, condition and properties of the soils that make up the roadbed and its base (type of soil, its density, humidity, granulometric and mineralogical composition, reaction to alternating freezing and thawing, wetting – drying, dissipative and absorption capacities, etc.);

- the nature, magnitude of the acting forces and operating conditions (static, vibration and dynamic effects, intensity and frequency of movement, axle loads of rolling stock, train speed, their mass, etc.);

- design indicators of the track superstructure and its condition (type of rails, type of ballast, thickness of its layer, type of sleepers and their loading diagram, type of fastenings, presence of irregularities on the rails, etc.).

The interdependent influence of the above factors determines the performance of the roadbed and its foundation.

To study the prevalence of soils in the roadbed and its foundation, the railways of the Republic of Kazakhstan were divided into six conditional zones (Figure 1).

I – territory with a depth of soil freezing up to 1 m,

II – territory with a depth of soil freezing from 1 to 2 m;

III – territory with a depth of soil freezing over 2 m;

1, 2, 3, 4, 5 – conditional zones of railways on the territory of Kazakhstan.

- South, N 1 (sections of railways: Satimsak – Chengeldy, Shu -

Tyulkubas, Tyulkubas-Chengeldy);

- South-Eastern, N 2 (sections of the railways: Mointy – Sary-Shagan, Sary-Shagan – Shu, Shu – Otar – Almaty, Almaty – Sary-Ozek, Sary-Ozek – Aktogay, Aktogay – Druzhba);

- Vostochnaya, N 3 (sections of railways: Aktogay – Semipalatinsk, Semipalatinsk – Be-

Figure 1 – Conditional zones of railways of Kazakhstan

lagash, Shemonaikha – Zyryanovsk);

- Central, N 4 (sections of railways: Astana – Osakarovka, Osakarovka – Yuzhny, Yuzhny – Mointy, Zharyk – Zhezkazgan, Mointy-Sayak, Sayak -Aktogay);

- Western, N 5 (sections of railways: Kandagach – Saksaulskaya, Saksaulskaya – Satimsak, Uralsk – Chingirlau, Yaisan – Kandagach, Kandagach – Aty-rau, Kandagach – Sagiz, Sagiz – Atyrau, Makat – Oporny, Oporny – Uzen);

- Severnaya (sections of railways: Zhelezorudnaya – Koybagar, Koybagar – Sergeevka, Sergeevka – Astana, Astana – Makinsk, Makinsk -

Novoishimskaya, Novoishimskaya-Kostanay, Astana – Ermentau, Ermentau

- Pavlodar, Yesil – Arkalyk).

When studying soils by type, the following were considered:

- rocky and semi-rocky;

- coarse-grained, which were divided into boulder, pebble, and gravel;

- sandy, which are divided into: gravelly sand, coarse and medium-sized sand, fine and dusty sand; clayey – into sandy loam, loam and clay.

When examining clay soils, sandy and clayey soils with rocky inclusions of up to 25% were distinguished separately.

Using the data from the passports, the probability of the occurrence of various types of soils at the base of the roadbed is determined, and the most common types of soils at various depths are established.

When a rolling stock moves, the soil of the roadbed experiences pulsating loads. This type of soil operation affects the strength and, consequently, the bearing capacity of the main platform of the roadbed. Therefore, it is necessary to know the limits of change in the physical and mechanical characteristics of the soil.

The performance of the roadbed is significantly affected by the granulometric composition of the soil. N.A. Tsytovich noted in his work: "The properties of the soils are determined by the properties of the components, as well as their quantitative ratio, electromolecular, physicochemical, mechanical and other interactions between the components of the soils." Therefore, the granulometric composition of the soils of the foundation of the roadbed of the railways of the Karaganda region was studied, which is given in Table 1.

The study of soils showed that at the base of the railways of Kazakhstan they are very heterogeneous in granulometric composition: in most cases, particles of 0.05 – 0.005 mm in size predominate (up to 88%). The data in Table 1.2 show that according to granulometric composition, soils are distributed in the following way: larger particles are located on the surface of the earth, and with increasing depth, the soil particles become small. For example, if 56% of soils with sizes of 2 – 0.05 mm are located on the surface of the earth, then at a depth of 5 meters, soils with the above particles are distributedonly 20.7%. At the same time, the percentage of soils with particles less than 0.005 mm, with increasing depth, increases from 12% to 42.5%.

Figure 2 shows granulometric curves for typical soil types in the Karaganda region:

- Sand – predominance of large particles (fast passage through sieves);
- Sandy loam is an intermediate type with uniform distribution;
- Loam – increase in fine fractions, decrease in permeability;
- Clay – dominance of particles less than 0.005 mm, sharp rise in the curve in the fine-grained region.

The conducted analysis showed that the soils underlying the railway roadbed of the Karaganda region are significantly heterogeneous and dominated by fine fractions, especially at depths of over 2–3 meters. Such distribution has a negative impact on the filtration properties and bearing capacity of the foundation when exposed to dynamic loads from rail transport. The data obtained confirm the need

Table 1 – Summary statement of the granulometric composition of the soils of the foundations of the roadbed of the railways of the Karaganda region

No.	Soil type based on data from Karaganda region	Fraction	Diameter, mm	Content, %
1	Coarse-medium sand	> 2 mm	> 2	5-10%
	Sand	Coarse sand	2-0.5	25-35%
	Sand	Fine sand	0.5-0.1	30-40%
2	Sandy loam (sandy-clayey mixture)	Dust	0.1-0.05	10-20%
		Loam	0.05-0.002	5-15%
3	Clay (stone-clay base)	Clay	< 0.002	5-15%
4	Silt-clayey weak foundations (embankment base)	Silt/loam	< 0.002	15-30%

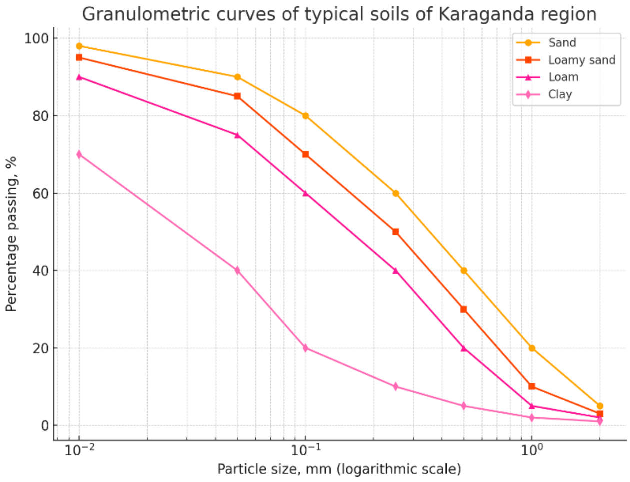

Figure 2 – Granulometric curves for typical soil types of the Karaganda region

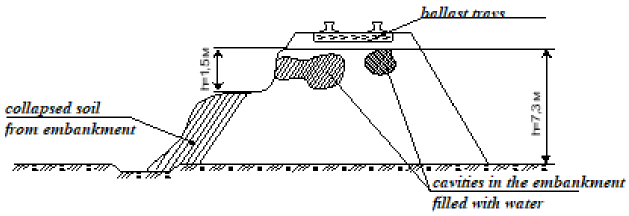

Figure 3 – Types of road pavement deformations characteristic of the conditions in the Karaganda region

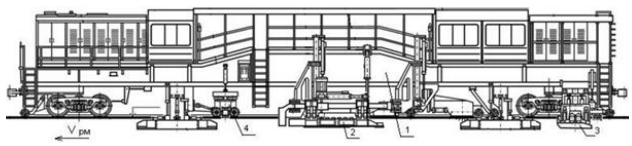

Figure 4 – The track renewal machine VPO-3-3000C

for specialized measures to strengthen the foundation and improve drainage to increase the stability of the roadbed in the complex engineering and geological conditions of the region.

Soil overmoistening leads to the deterioration of the earthwork structure by reducing its strength characteristics and stability. As a result, subsidence, deformations, and washouts may occur, posing a serious threat to transport infrastructure. In the Karaganda region, there are many areas with overmoistened soil, which require timely inspection and the implementation of engineering measures to stabilize the condition of the earthwork (Figure 3).

A wide range of track machines is involved in defect elimination. Figure 4 shows a machine designed for the leveling and compaction of the railway track.

The volume of transportation directly depends on the quality of railway roadbed compaction, as resulting defects can significantly reduce it and negatively affect the capacity of the railway infrastructure.

Statement of the problem and assignment of boundary conditions

In addition to the use of bitumen-containing materials, other effective technologies aimed at increasing the stability of the railway track bed, especially in areas with weak and waterlogged soils, are used in modern conditions. These solutions include the following:

1. Geosynthetic materials

Geotextiles, geogrids, geomembranes and other geosynthetics are widely used. They perform the functions of reinforcement, layer separation, filtration and drainage. Geotextiles prevent mixing of soil layers, improve load distribution and prevent subsidence. Geogrids allow for uniform distribution of vertical and horizontal loads, reducing deformation of the roadbed.

2. Chemical stabilization of soils

The use of cement, lime, ash, liquid glass and polymer additives allows to increase the strength characteristics of weak soils. Chemical stabilization is effective both as an independent solution and in combination with other methods. It increases the resistance of soils to moisture, frost and loads from rolling stock.

3. Deep compaction and reinforcement

To strengthen weak foundations, technologies of bored piles, sand-cement pillars, and vibration compaction are used. These methods allow the load to be transferred to stronger layers, reducing subsidence and increasing the bearing capacity of the roadbed.

4. Use of lightweight filling materials

To reduce pressure on a weak foundation, low-density materials such as expanded clay, foam glass, and expanded polystyrene (EPS) are used. They reduce the load on the soil, increase the stability of the embankment, and have good thermal insulation properties.

5. Installation of drainage systems

One of the most important conditions for ensuring the stability of the roadbed is effective drainage. Longitudinal, transverse and layer drainages prevent the accumulation of water in the embankment body and in the base, which is especially important during floods and heavy rainfall. The use of drainage layers helps reduce waterlogging and increase the strength of the base.

6. Mechanical replacement of weak soils

In areas with critically weak foundations, full or partial replacement of soil is practiced.

Weak soils are extracted and replaced with sand, crushed stone, slag or artificial foundations. In this case, cushions with drainage properties are installed and layer-by-layer compaction is carried out.

7. Thermal and electrical drying methods

In particularly difficult engineering conditions, electroosmosis and temporary freezing methods are used. Electroosmosis allows moisture to be removed from clay and dusty soils using an electric field, and freezing is used for temporary stabilization of the foundation, for example, during the construction of tunnels and complex crossings.

8. Strengthening structures and reinforced soil systems

To increase slope stability and prevent landslides, gabions, terramesh systems and reinforced soil retaining walls are used. They are especially effective on slopes, in conditions of unstable soils and high groundwater levels.

Thus, the modern approach to increasing the stability of the roadbed involves the use of a set of engineering solutions adapted to specific hydrogeological and climatic conditions. The most effective are combined technologies that combine strengthening, drainage and reinforcement of the foundation, which ensures reliable and safe operation of rail transport.

One of the effective ways to increase the stability of the railway roadbed on weak and waterlogged soils is the use of bitumen-containing materials. These materials can significantly improve the physical and mechanical characteristics of the base, increase its water and frost resistance, and reduce deformation processes that occur during operation.

Bituminous rocks, such as sand-bitumen mixtures, bitumen-mineral compositions and natural bituminous soils, have high adhesive capacity and are water-resistant. When introduced into the base of the roadbed, they simultaneously perform reinforcing, waterproofing and stabilizing functions. In particular, when mixed with local sands, clays or loams, the soil structure is modified, which increases its density and shear resistance.

In areas with waterlogged, weak-bearing soils in the Karaganda region, the use of such technologies is especially appropriate. The use of bitumen-containing rocks allows:

- reduce the water permeability of the base to a minimum level;
- prevent capillary rise of moisture;
- increase resistance to seasonal temperature changes;
- increase the service life of the roadbed without the need for frequent repairs.

The reinforcement technology may include preliminary excavation of weak soil, installation of a sand cushion, mixing with bitumen binders on site, compaction in layers with rollers. It is also possible to deliver ready-made bitumen-mineral mixtures to the site with subsequent laying and ramming.

Field and laboratory studies show that already with the introduction of 4-6% bitumen into the mineral base, a significant improvement in the bearing capacity is achieved. It is important to take into account the type of binder, temperature conditions of laying, uniformity of bitumen distribution and the method of compaction.

Thus, the use of bitumen-containing rocks is one of the promising solutions for strengthening the main platform of the railway track, especially in the complex hydrogeological conditions of the Karaganda region.

The technologies of compaction of ballast prism using machines provide for local impact through the compaction surface of the working element on a certain zone of the prism. As a result, the ballast material in this zone is compacted with the formation of the so-called compaction core. Segregation of zones of ballast material with different degrees of compaction is observed. After repeated force impact by the working element of the machine or operational load from trains, the distribution pattern of the said zones changes.

The vibrating working element excites oscillatory processes in the layer volume. In the zone of direct impact, there is an intensive restructuring of the crushed stone texture, and in remote zones, elastic and inelastic movements with attenuation are observed. The boundaries between the zones are blurred. Therefore, we can talk about two interrelated processes: on the one hand, segregation of zones of the compacted state of the ballast occurs, and on the other hand, diffusion of compaction throughout the volume of the prism. Let us consider these two interrelated processes on a mathematical model.

When using a model with full diffusion as a result of the effect of force P on the ballast volume V_H of size S_H along the direction of force action P, the achieved relative compaction settlement (Fig. 5, a):

$$E_y = 1 - \frac{V_y}{V_H}(1 - E_H), \quad (1)$$

where $V_H = V_y + V$ and V_y is the volume of ballast before and after the force action under consideration, m^3; V is the decrease in ballast volume during compaction, m^3.

As a result, a volume with a uniform distribution of the degree of compaction is formed (homogeneous volume).

Provided that there is a complete absence of diffusion of the degree of ballast compaction, as the compacting surface advances, a

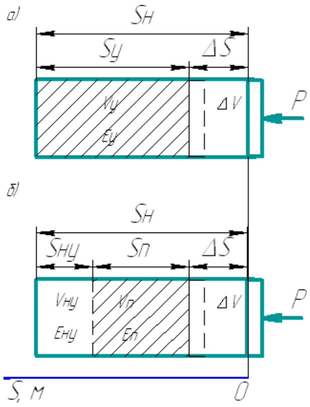

Figure 5 – Alternative models of formation of compaction zones of ballast material: a – with complete diffusion of the degree of compaction; b – with complete segregation of the extremely compacted zone

gradual increase in the zone of ultimate compaction $V_п$ occurs (Fig. 5, b).

$$V_п = \frac{V_1 + (1 - E_п)}{1 - E_п}. \qquad (2)$$

In this process, it can be considered that the change in shape occurs in the initial volume equal to $V_Н = V_п + V$, characterized by the initial value of the relative compaction settlement $E_Н$. Then formula (1) can be written as Δ:

$$E_п = 1 - \frac{V_п}{V_п + \Delta V}(1 - E_H). \qquad (3)$$

After transformations, we obtain an expression for determining the core of the extremely compacted ballast:

$$V_п = \frac{\Delta V(1 - E_п)}{E_п - E_H}. \qquad (4)$$

If we take the area of the vibrating surface and the area of the ballast as unitary, then we obtain formulas that connect its movement and the movement of the conditional boundary of the core into the ballast layer:

$$S_H = S_п + \Delta S,$$

$$S_п = \frac{\Delta S(1 - E_п)}{E_п - E_H}, \qquad (5)$$

where $S_Н$ and $S_п$ are the displacement of the ballast before and after the force impact under consideration, m; S is the displacement of the vibrating surface, m, Δ.

It should be noted that the largest displacements occur on the two edges of the sleeper base.

The integrated use of technologies for stabilizing weak foundations, including bitumen-containing materials, geosynthetics and

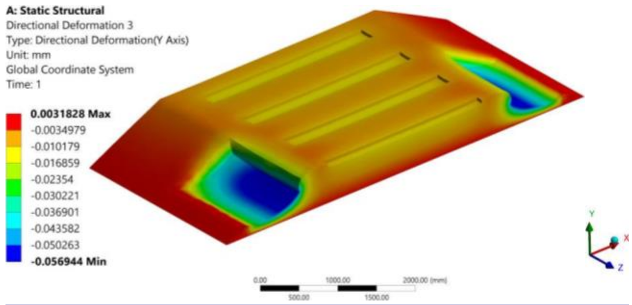

Figure 6 – The picture of strains in the vertical direction

vibration compaction of the ballast prism, allows to significantly increase the bearing capacity of the roadbed and reduce the risks of its deformation. Mathematical modeling of compaction processes confirms the effectiveness of the approach based on managing the segregation and diffusion of the compacted zone. This is especially relevant for the railway infrastructure of the Karaganda region, where waterlogging and weak soils require reliable and economically viable engineering solutions.

Conclusions

The conducted comprehensive analysis showed that ensuring the stability of the roadbed on waterlogged areas of weak-bearing soils in the Karaganda region requires a systematic approach combining engineering and geological studies, the use of modern building materials and modeling the stress-strain state of the structure. It was established that the main factors of loss of stability are excessive moisture, low filtration capacity and weak soil adhesion.

The use of bitumen-containing materials to stabilize the main platform of the roadbed has proven its effectiveness, providing a decrease in water permeability, an increase in shear strength and resistance to deformation. In addition, the results of numerical modeling in the Ansys WB environment confirmed that the implementation of these technologies contributes to the redistribution of stresses and a decrease in plastic deformations in the under-sleeper zone under the influence of dynamic loads, such as vibrations from rolling stock.

The proposed engineering solutions, adapted to the conditions of the Karaganda region, ensure increased reliability, durability and safety of the railway infrastructure. Their use is especially relevant in the context of climate change and more frequent extreme weather events, which increase the risk of loss of roadbed stability. The introduction of such technologies also allows for a reduction in maintenance costs and an extension of the inter-repair cycle of railway tracks.

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Қарағанды облысындағы әлсіз және шамадан тыс ылғалданған топырақтар жағдайында жер төсемесінің тұрақтылығын қамтамасыз ету

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Аңдатпа. *Қарағанды облысы мысалында суға қаныққан және әлсіз топырақтар жағдайында теміржол көлігі жолдарының жер төсемесінің тұрақтылығын қамтамасыз ету мәселелері қарастырылады. Өңірдің геологиялық және климаттық жағдайларының ерекшеліктерін ескере отырып, топырақтың ылғалдылығының жоғары болуы іргетастың беріктік сипаттамаларының айтарлықтай төмендеуіне әкеліп, жолдың геометриясының бұзылуына және деформацияларға себеп болады. Өңірге тән топырақ түрлерінің, сондай-ақ олардың гранулометриялық және физика-механикалық қасиеттерінің талдауы жүргізілді. Негіздердің көтергіш қабілетін және суға төзімділігін арттыруға мүмкіндік беретін битумқұрамды материалдарды және басқа да заманауи нығайту технологияларын қолдануға ерекше көңіл бөлінді. Жұмыста теміржол көлігі қозғалысынан туындайтын дірілдік жүктемелер әсерінен жер төсемесінің жұмыс істеу қабілетін бағалауға мүмкіндік беретін құрылымның кернеулі-деформациялық күйінің сандық модельдеу нәтижелері ұсынылған. Ұсынылған инженерлік шешімдер күрделі гидрогеологиялық жағдайларда теміржол көлік инфрақұрылымы объектілерінің сенімділігі мен ұзақ мерзімділігін арттыруға бағытталған.*

Кілт сөздер: *жер төсемесі, әлсіз топырақтар, шамадан тыс ылғалдану, тұрақтылық, Қарағанды облысы, битумқұрамды материалдар, теміржол, теміржол көлігі.*

Обеспечение устойчивости земляного полотна в условиях переувлажнения на слабых грунтах по Карагандинской области

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***Аннотация.** Рассматриваются вопросы обеспечения устойчивости земляного полотна железнодорожных транспортных путей в условиях переувлажнения и слабонесущих грунтов на примере Карагандинской области. Учитывая особенности геологических и климатических условий региона, повышенная влажность существенно снижает прочностные характеристики основания, что приводит к деформациям и нарушению геометрии железнодорожного пути. Проведён анализ типов грунтов, характерных для региона, а также их гранулометрических и физико-механических свойств. Особое внимание уделено применению битумосодержащих материалов и других современных технологий укрепления, обеспечивающих повышение несущей способности и водостойкости оснований. В работе представлены результаты численного моделирования напряжённо-деформированного состояния конструкции, позволяющие оценить работоспособность земляного полотна при вибрационных нагрузках, возникающих от движения железнодорожного транспорта. Предложенные инженерные решения направлены на повышение надёжности и долговечности объектов железнодорожной транспортной инфраструктуры в сложных гидрогеологических условиях.*

***Ключевые слова:** земляное полотно, слабые грунты, переувлажнение, устойчивость, Карагандинская область, битумосодержащие материалы, железная дорога, железнодорожный транспорт.*

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