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Economic efficiency of innovative subgrade reinforcement technologies for railway trackbed

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Abstract: This article presents a systematic analysis of the effectiveness of standard design solutions for railway subgrade reinforcement under the specific conditions of Uzbekistan, based on long-term monitoring data. In the context of high-speed train operations (160–200 km/h), the stability, deformation resistance, and operational reliability of the subgrade are considered key factors for ensuring safety. Observations conducted on experimental sections confirm the positive outcomes of using geosynthetic materials (geotextiles and planar geogrids), including reduced settlement, decreased ballast contamination by soil particles, extended service life, and lower routine maintenance costs. The study develops structural and technological recommendations adapted to the complex climatic and geological conditions of Uzbekistan. Based on monitoring results, the economic efficiency of subgrade reinforcement technologies is evaluated. The advantages of an integrated engineering approach are substantiated, including uniform load distribution, improved drainage conditions, and extended intervals between repairs. A comparative analysis with international experience is also provided.

Keywords: rail joint zone, vertical dynamic stresses, geosynthetic materials, geotextile, planar geogrids, local reinforcement, impulse attenuation, efficiency coefficient, subgrade stability

1. Introduction

Modern maintenance and repair of railway infrastructure requires, first of all, a set of technical measures aimed at restoring the strength and stability of the earthwork, which is the main load-bearing element of the track structure. In recent years, in domestic and foreign practice, large-scale design solutions have been developed aimed at strengthening the main area of the earthwork in order to carry out major repairs of the railway network, as well as their adaptation for high-speed train traffic.[1-4] Such solutions are regulated on the basis of current building codes and regulations (Urban planning standard construction, building codes, industry road methodological documen) and departmental instructions of railway administrations.[8-13]

In the context of modernization of railway lines and their preparation for high-speed passenger traffic (up to 200 km/h), strengthening the main area of the earthwork and reconstruction of the ballast prism are of particular importance. Practical experience shows that when the loads from rolling stock increase, as well as when the requirements for road smoothness and stability increase, it is the condition of the earthwork that becomes a decisive factor for the duration of operation and safety.[1,2]

2. Research methodology

The main task of standard design solutions is to restore the required load-bearing capacity of the earthwork soils, reduce deformations, and increase the durability of the road surface. In this case, the following important engineering principles are implemented:

increasing the strength of the soil base by compaction, replacement, or stabilization;

ensuring a drainage system and reducing the moisture content of the base, since excessive moisture is one of the main causes of deformations;

reduction of contact stresses by distributing loads from rolling stock over a wider area;

creation of conditions that serve to increase the interval between repairs for extending the service life of the road.

Soil replacement and reinforcement

The most traditional method of reinforcing the earthwork is its renewal with durable and stable materials by partial or complete replacement of the soils of the main area. During major repairs, weak soils are excavated to a depth of 0.5-1.0 m and replaced with sand-gravel mixture or gravel. In cases of localized deformations, gravel cushion layers with a thickness of 0.3-0.5 m are used, which allows for rapid restoration of the section's load-bearing capacity.

In some cases, soil stabilization with binding materials (cement, lime, fly ash) is used. This approach allows increasing the modulus of deformation and reducing the degree of water saturation. Such solutions are especially relevant for areas with the prevalence of swelling and weak soils.

Application of reinforcing layers and ballast pads

When reinforcing the earthwork, additional reinforcing layers are traditionally constructed, consisting of gravel, a sand-gravel mixture, and asphalt concrete. They perform two main functions:

- redistribution of loads passing from the sleepers to the soil base;
- reduction of dynamic impacts from rolling stock.
- The thickness of the reinforcing layer varies from 0.2 to 0.6 m depending on engineering and geological conditions and road category. On high-speed railways, according to design standards, the minimum thickness of the

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gravel or sand-gravel mixture layer should be at least 0.4 m. [9-12]

Compaction and stabilization technologies

Among standard solutions, the most common is the compaction of the soil base using mechanical means. Vibration boards, road compactors, and impact compactors are used in this process. As a result of compaction, the modulus of elasticity of the soil is brought to normal values (20-30 MPa for sandy soils, 12-20 MPa for clay soils).

In some cases, there is a practice of soil stabilization by thermal or chemical methods. The thermal method is rarely used mainly in glacial zones, while chemical methods (cementation, silicatization, liming) are widely used in areas where settling and swelling soils are widespread.

Traditional reinforcement methods

Before the introduction of geosynthetic materials, the following standard methods were used as reinforcing intermediate layers:

- Laying of masonry layers;
- construction of wooden or concrete pavements;
- use of rigid plates or large prefabricated elements in zones of increased load (for example, in rail joints).

These solutions served to increase the local stiffness of the structure, but they required large material costs and did not provide long-term efficiency under conditions of high traffic intensity.

3. Results and Discussion

The *Standard solution schemes*

During the design work and pilot tests, the following standard schemes were identified:

- Cleaning of gravel to a depth of ≥40 cm, laying of geotextile and flat geogrids;
- work is performed manually without removing the rail and sleeper railing;
- high technological convenience and efficiency are ensured;
- significantly reduces stresses in the lower layers, performs waterproofing and isolating functions;
- is an economically viable option for favorable geological conditions.
- Practice shows that these standard solutions remain relevant in major repairs, especially in cases where high-speed road conversion is not required.
- *Limitations of standard technologies*
- Despite their widespread use, traditional methods have a number of serious drawbacks:
- high labor intensity and duration of repair work;
- high material costs when replacing soils at great depths;
- limited efficiency under conditions of high-speed movement (dynamic influences lead to rapid accumulation of deformations);
- the need for frequent repeated interventions and short maintenance periods.

These factors necessitated the development of improved technologies based on geosynthetic materials and modern organizational and technological solutions.

The effectiveness of the application of standard design solutions and technologies for strengthening the earthwork can be reliably confirmed only through systematic monitoring of their condition. The dynamic impact of rolling stock on high-speed railways is significantly higher than on regular high-speed lines, which makes the issues of stability and durability of the earthwork more relevant.

By observing the condition of the road on experimental and operational sections, it is possible to objectively assess the effectiveness of standard solutions used in strengthening the main area. Long-term monitoring of high-traffic railway lines has shown that the quality of design and technological measures directly affects the long-term stability of the track and the need for current repairs.

According to the analysis of the track measuring car data:

The root mean square deviations of road subsidence decreased by 1.5 times and remained at the level of ≈1 mm after repair;

the need for straightening work has decreased (except for final straightening after stabilizing settlement).

Organization of the monitoring system

- The observations are aimed at determining the influence of the implemented constructive solutions on the following aspects:
- maintaining the priority and design status of the main site;
- uniform distribution of loads on the soil base;
- durability of geosynthetic materials and polymer additives under operating conditions;
- Determination of the need and frequency of planned preventive work (pressing, straightening, ballast filling).

The monitoring system consists of the following components:

Geodetic measurements: regular surveying of the profile and longitudinal surface of the earthwork, monitoring of settlement and angle of inclination.

Instrumental methods: the use of track gauge cars and laser control systems to determine the level and level of the road; dynamic testing of rolling stock at speeds of 60-160 km/h.

Engineering and geological studies: determination of the moisture state of the soils of the main area; laboratory analysis of samples taken from geotextile horizons.

Operational observations: recording the volume and frequency of lifting and driving operations; assessment of the condition of the ballast and separating layers during opening.

Key observation results

Application of reinforcement with geotextile:

reduced the intensity of contamination of the ballast prism with soil particles by 2-3 times;

even under unfavorable conditions of moisture, the stability coefficient of the earthwork was maintained at the level of 1.25-1.35.

Application of reinforcement with complex solutions (geotextile + flat geogrids):

synergistic effect: uniform load distribution, stabilization of the moisture regime, and improvement of drainage conditions were observed.

Observations conducted on high-speed lines in Germany, France, and China show that the introduction of standard solutions based on polymer materials increases the service life of the earthwork by an average of 15-20%. However, in foreign practice, automated monitoring systems (geometers, vibration sensors, moisture sensors) are used as mandatory elements.

In the conditions of Uzbekistan, especially on the lines of the JSC "Uzbekistan Railways" system, monitoring-based approaches and adapted design solutions are of particular importance due to sharp temperature fluctuations, arid climate, wind erosion, sand movement, and the presence of saline soils.[16]

The results of observations on the effectiveness of standard solutions for strengthening the main area of the earthwork are presented in Table 1 and Figure 1.

Table 1

Conclusion of observations on the effectiveness of standard solutions for strengthening the main area of the earthwork

Strengthening technology	Main effect	Service life (increase)	Economic effect
Geotextile (separating and filtering layer)	Reduction of ballast contamination by 2-3 times; stabilization of the stability coefficient (1.25-1.35)	+3-4 years (interim repair period from 6-8 to 9-12 years)	Reduction of lifting and driving costs by 20-25%
Flat geogrids (in the zone of rail joints)	increasing stability in high-dynamic zones; reduction of driving operations by 1.5-2 times	+4-5 years	Reduction of current maintenance costs in the arrow and joint zones by 25-30%
Complex application (geotextile + flat grid)	Synergistic effect: humidity regulation, even load distribution, improvement of drainage	+5-6 years (for standard service life)	Reduction of operating costs by 20-25%, extension of the repair interval up to 12 years

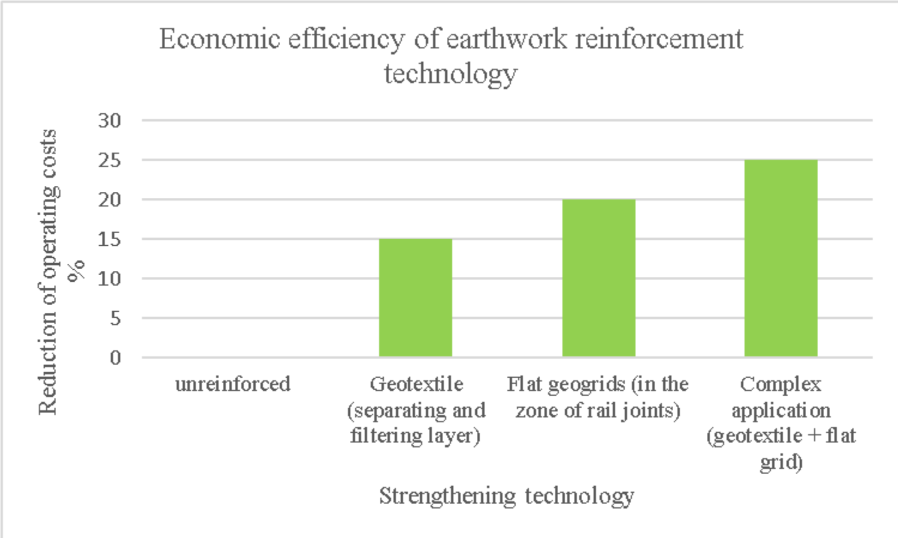

Fig. 1. Effectiveness of standard solutions for strengthening the earthwork

The conducted observations have proven the high effectiveness of applying standard design solutions using geosynthetic materials. These technologies provided the following results:

increasing the stability of the earthwork and reducing the risk of deformation;

extension of the road's inter-repair service life by an average of 15-20%;

reduction of operating costs by reducing the volume of repair work.

The introduction of standard solutions consisting of geotextiles and flat geogrids is considered a justified and expedient direction in the practice of strengthening the main area of the earthwork, especially in the preparation of main lines for high-speed train traffic.

Proper use of reinforcing materials makes it possible to significantly increase the stability of the earthwork and extend the intervals between repairs. However, design flaws or violations of technological discipline lead to the opposite effect: the operational quality of the road decreases, and there is a need to limit the speed of movement.

4. Conclusion

The use of complex solutions with geosynthetic materials increases the inter-repair period by 15-25% and reduces operating costs by 20-30%.

The use of geotextile and a flat geogrid increases the stability coefficient of the earthwork to 1.25-1.35 and reduces ballast contamination by 2-3 times.

reduces operating costs by reducing the volume of repair work. uniform load distribution, stabilization of the moisture regime, and improvement of drainage conditions.

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