Engineering protection of the subgrade from sand drifts using geomaterials, as exemplified by the Bukhara-Miskin railway line

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Abstract. In arid regions of southwestern Uzbekistan, protecting the railway subgrade from wind-blown sand is a priority engineering task. This paper presents a systems approach to selecting and applying geomaterials for the Bukhara–Misken railway: climatic-geotechnical zoning, assessment of sand-drift intensity, a decision matrix based on wind loading, and a techno-economic evaluation. The proposed measures (geogrids, geotextiles, geomats, aerodynamic barriers, and biopolymer stabilizers) enhance subgrade stability, reduce maintenance costs, and extend maintenance intervals. The approach is transferable to transport infrastructure in desert zones of Central Asia.

Keywords: railway, subgrade, arid zone, aeolian processes, sand drift, geomaterials, geogrids, geotextiles, Bukhara-Misken, climatic zoning, erosion control.

1. Introduction

Railway construction and operation in arid regions are strongly influenced by aeolian processes such as deflation, wind erosion, and sand accumulation [1-3]. In areas with loose sand and sparse vegetation – such as Iran, China, and Central Asia – sand drifts cause slope instability and higher maintenance costs [2, 4, 5].

In southwestern Uzbekistan, particularly along the Bukhara-Misken line, sand encroachment up to 1 m in height occurs frequently. This requires durable engineering and technological solutions. Geosynthetics can redistribute stresses, limit deformations, and reduce sand transport [5-8].

International practice (China, Saudi Arabia) shows that the most effective protection combines base reinforcement, aerodynamic barriers, and biopolymer surface stabilization [4, 9, 10]. The choice of geomaterial type must consider local geotechnical and climatic conditions [7, 11-13].

The aim of this study is to develop an adaptive engineering protection system for the railway subgrade using geomaterials, tailored to wind load and sand-drift intensity on the Bukhara-Misken railway.

The main objectives are:

1) To perform climatic-geotechnical zoning of the railway section.

2) To determine sand-drift intensity [4, 5, 12].

3) To develop a decision matrix linking wind speed and sand-drift volume.

4) To evaluate the technical and economic effectiveness of geomaterials and aerodynamic barriers [11, 14, 15].

The scientific novelty lies in integrating climatic zoning, a cubic sand-drift model, and a matrix-based algorithm for selecting protective measures, which increases subgrade stability and reduces maintenance costs [7, 8, 10].

2. Materials and methods

2.1. Climate and geotechnical zoning

For the Bukhara–Miskin railway line (≈ 356 km), zoning was carried out according to the degree of aridity based on data from Uzgidromet (1990-2020) [16, 17]. As a result, the following climatic zones were identified:

– Slightly arid zone (0-39 km) – characterised by relatively moderate climatic conditions: average annual precipitation is 120-150 mm, and average wind speed is 2-3 m/s. Sand drifts are less pronounced here, but are possible in conditions of local soil blowing.

– The mid-arid zone (40-166 km) has a drier climate, with precipitation ranging from 80 to 100 mm/year. The main feature is a steady wind regime with an average speed of 4-6 m/s, which contributes to the movement of sand masses, especially near areas with disturbed vegetation cover.

– The highly arid zone (167-356 km) has the most extreme climatic conditions. Precipitation does not exceed 70 mm/year, and wind activity increases significantly: the average wind speed exceeds 7 m/s, with gusts of up to 12-15 m/s regularly recorded. This zone experiences the greatest manifestations of aeolian activity, including the formation of dunes and massive sand drifts, especially near areas with low anthropogenic protection.

An engineering-geological characterisation (granulometry, filtration, vegetation cover, deflation) has been carried out for each zone [5, 12, 13].

2.2. Sand transport model and parameter sensitivity

The intensity of sand transport was determined using the formula [4, 5, 12]:

$$Q = C * \frac{\rho * u^3}{g}, \quad (1)$$

where Q – sand transport volume, m^3/m/year; C – empirical coefficient (accepted within the range of 0.1–0.25 depending on the type of sand); ρ – sand density (1600 kg/m^3); u – average annual wind speed, m/s; g – acceleration due to gravity (9.81 m/s^2).

Table 1. Matrix for selecting optimal design and technological solutions depending on wind speed and sand transport volume

Average annual wind speed u, m/s	Sand transport volume Q, m^3/m/year	Recommended solution	Type of material used
Up to 8	< 5	Biological stabilisation of slopes, minimal reinforcement	Geomats, biomaterials, mulching covers
8-10	5-10	Light reinforcement; local wind protection nets	Non-woven geotextiles, mesh barriers
10-12	10-15	Reinforcement of the embankment base with geogrids, partial aerodynamic barriers	Biaxial geogrids, aerodynamic screens
12-14	15-20	Comprehensive reinforcement of the base and slopes, installation of barriers along the contour of the embankment	High-strength geogrids, dense geotextiles, barrier structures
14-16	20-25	Multi-level protection: reinforcement, two rows of aerodynamic barriers, surface stabilisation	Reinforcing geocomposites, geomaterials, shielding barriers
More than 16	> 25	Comprehensive system: base reinforcement, anti-erosion slope systems, chemical soil stabilisation	Reinforced geogrids, geomembranes, biopolymer stabilisers

Since $Q \propto u^3$, the intensity of sand transport Q is proportional to the cube of wind speed u. In engineering calculations, discretisation was used for wind speed intervals and corresponding ranges of sand transport volume, as shown in Table 1 [8, 10].

Parameter (C) has a scaling effect: when it increases from 0.10 to 0.25, the value (Q) increases approximately 2.5 times, which was taken into account when validating the calculated data based on field observations [15, 18, 19].

2.3. Decision matrix

The matrix $\{u; Q\}$ defines the transition from biostabilisation (low u, low Q) to multi-level systems with reinforcement and aerodynamic barriers [1, 6, 8, 10].

It is used to design local risk segments [15, 19, 20].

2.4. Performance criteria

The effectiveness assessment included: (i) reduction in sand transport volume (ΔQ, %); (ii) increase in slope stability coefficient K; (iii) increase in inter-repair period ΔT (years); (iv) reduction in annual operating costs ($\Delta OPEX$, %).

3. Results and discussion

Zoning revealed heterogeneous conditions: 0-39 km – low impact ($Q \approx$ 2.5-4.0), 40-166 km – moderate ($Q \approx$ 10-15), 167-356 km – high ($Q \approx$ 25-30) [12, 13, 16].

The application of the matrix reduced Q by 60-80 %, increased K to ≥ 1.5, increased ΔT by 3-5 years, and reduced OPEX by 15-18 % [15, 18, 21].

For clarity, a 'step-by-step' schedule of correspondence between u ranges and measures has been developed (Fig. 1) [8, 10, 18, 22].

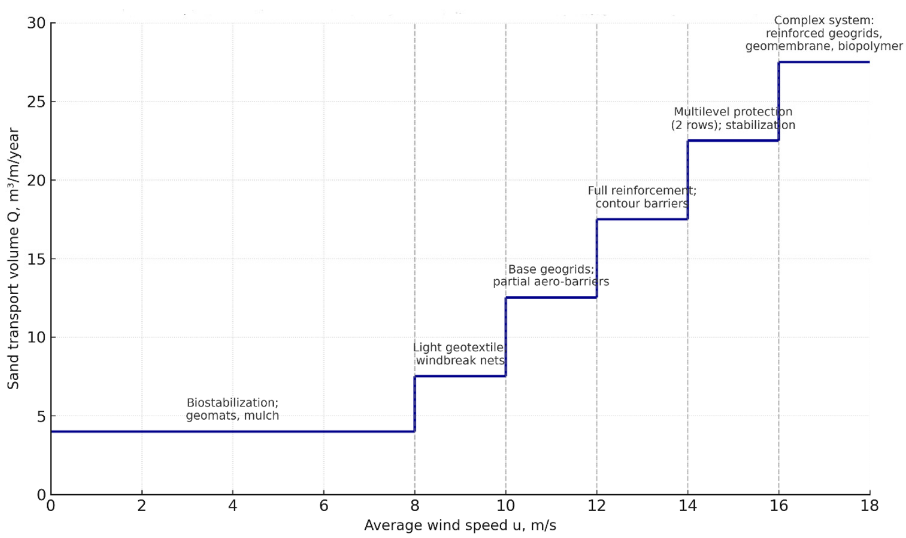

Fig. 1. Stepwise diagram of wind speed vs protection levels

The diagram (Fig. 2) illustrates the distribution of types of measures along the route: in the slightly arid zone – biological methods; in the moderately arid zone – reinforcement and barriers; in highly arid zones – integrated systems with biopolymers [22, 23].

This cascading approach ensures a balance between technical and economic efficiency and confirms the versatility of the method for the desert regions of Central Asia [5, 7, 8, 15, 24].

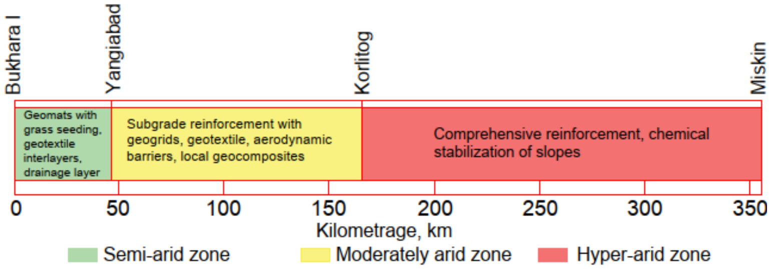

Fig. 2. Scheme of protection types along Bukhara-Misken line

4. Conclusions

An adaptive algorithm for the engineering protection of railway subgrades in arid regions has been developed, based on climatic zoning and a cubic model of sand transport.

The matrix of design and technological solutions provides a differentiated selection of protective measures: from biostabilisation of slopes to multi-level reinforcement systems and aerodynamic barriers. The use of geogrids, geotextiles, geomats and biopolymer stabilisers reduces sand transport by 60-80 %, increases the slope stability coefficient to $K \geq 1.5$ and reduces operating costs by 15-20 %.

The proposed methodology can be used in the design, modernisation and operation of railways in desert areas of Central Asia and similar climatic conditions. Further research is aimed at assessing the durability of geomaterials and refining the empirical parameters of the sand transport model.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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