International Journal of GEOMATE
(Geotechnique, Construction Materials and Environment)
ISSN: 2186-2982 (P), 2186-2990 (O), Japan

Vol. 31, Issue 144, August, 2026, PP.1-8; DOI: 10.21660/2026.144.5488

ANALYSIS OF THE INTERACTION BETWEEN GEOGRID-REINFORCED SOIL AND SUBSIDING SOILS

*Tymarkul Muzdybayeva[1], Beibit Akhmetov[2], Bakhytnur Nukhayeva[3], Dilnaz Aldisheva[4]

[1,3,4] Faculty of Architecture and Civil Engineering, L.N. Gumilev Eurasian National University, Astana, Kazakhstan,
[2]Architecture and Construction Faculty, Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan.

*Corresponding Author, Received: 18 Feb. 2026, Revised: 18 April 2026, Accepted: 07 May 2026

ABSTRACT: Over two-thirds of Kazakhstan's territory consists of subsiding soils, posing a significant risk of structural failure for new construction. This article aims to address the challenge of construction on subsiding soils by evaluating the effectiveness of geosynthetic reinforcement in a real-life example: a footbridge on the Kaskelen-Uzynagash road. The construction site involved problematic light brown loams with a low deformation modulus (E_{def} = 2.9 MPa). In order to reinforce the ground, a crushed stone cushion (fraction 20-40 mm) reinforced with Tensar TriAx TX170 geogrids (aperture size 40 mm) was used, and the obtained data show that the geogrid locks with the crushed stone to form a stiff composite platform. This method effectively doubled the bearing capacity (by 2.0–2.5 times) and raised the equivalent elastic modulus by 6–15%. We recorded a 50% drop in substrate deformation and found that residual deformation accumulated 1.3–1.4 times more slowly. Additionally, shear stresses decreased by 25-80%, leading to much more uniform load distribution. These results prove that geogrid reinforcement is a practical and highly efficient way to control the stress-strain state in collapsible soil environments.

Keywords: Subsiding soil, Geosynthetic materials, Geogrid

1. INTRODUCTION

Vast territories of the Republic of Kazakhstan include completely different soil types and construction conditions, with subsiding soils – mainly loess-like loams – covering nearly two-thirds of its territory, particularly in the Almaty, Kyzylorda, and South Kazakhstan regions [1]. To ensure long-term structural integrity, advanced soil stabilisation methods and techniques are employed, as the construction and maintenance of any infrastructure on this type of soil is quite challenging.

According to national building codes and regulations, ensuring the durability and stability of structures on such terrains follows three fundamental strategic principles [2]:

1. Removing subsidence properties of soil by compaction or fixation;
2. Penetration of subsiding layers of soil with piles or soil replacement techniques
3. Implementation of integrated protective measures against the harmful effects of subsiding compression: preparation of the basis; solutions for water safety and construction.

The first two strategies focus on preventing soil deformation entirely. However, traditional methods such as deep pile driving or massive soil excavation can be prohibitively costly, time-consuming, and labour-intensive, particularly for extensive linear structures like highways, railways, and footbridges. Furthermore, chemical stabilization methods can have adverse environmental impacts. The third strategy must be meticulously planned during the design stage to successfully manage and mitigate the future consequences of soil failure.

In this context, a highly promising and sustainable alternative for managing subsiding soils involves the application of geosynthetic materials. Integrating geosynthetics-specifically geogrids-into the foundation design offers a modern, cost-effective way to enhance the strength, stability, and service life of structures built on problematic soils [3-4]. The fundamental reinforcement mechanism of a geogrid relies on the mechanical interlocking between the rigid geogrid apertures and the coarse granular aggregate (such as crushed stone). This interaction creates a stiff, mechanically stabilized composite layer. The lateral confinement provided by the geogrid restricts the horizontal displacement of aggregate particles under load, thereby widening the vertical stress distribution angle and significantly reducing the concentrated pressures acting on the underlying weak subgrade.

In recent years, the international scientific community has paid significant attention to the interaction between soils and geosynthetic reinforcement. Recent studies confirm the high efficiency of geogrids in various geotechnical applications. For instance, previous studies [5] investigated the geosynthetic-soil interface shear characteristics, demonstrating that geocomposites significantly improve the performance of weak subgrades by providing effective tensile reinforcement and separation. Similarly, Pham and Hoang [6] conducted comprehensive 2D stability analyses of mechanically stabilized earth walls, emphasizing the critical role of geosynthetics in preventing global structural failure under different soil conditions. Furthermore, the investigation [1] evaluated the effects of geogrids on the shear behavior of soils, proving through direct shear tests that the inclusion of geosynthetics substantially increases the soil friction angle and overall shear strength. While these recent studies thoroughly explore the mechanical properties of reinforced sands and retaining structures [1-5], there remains a limited amount of field-based research specifically addressing the stress-strain behavior of highly subsiding (collapsible) loams under direct foundation loads in sharp continental climates.

To address these requirements, the rest of the paper is organized as follows: Section 2 presents the research significance, highlighting the novelty of the study. Section 3 details the materials and methodology, including the engineering-geological conditions of the Kaskelen-Uzynagash site and the characteristics of the TriAx geogrid. Section 4 discusses the results of the field experiments, focusing on the comparative analysis of the stress-strain state and bearing capacity of reinforced versus unreinforced foundations. Finally, Section 5 provides the main conclusions drawn from this research.

2. RESEARCH SIGNIFICANCE

The significance of this study lies in addressing the instability of subsiding soils, which cover over 60% of Kazakhstan's territory [7]. While geosynthetics are widely used, the novel contribution of this work lies in analytically identifying a critical hidden risk: applied foundation pressures can exceed the initial subsidence pressure ($\boldsymbol{P_{sl}}$) upon wetting, despite sufficient ultimate bearing capacity. Furthermore, the novelty is highlighted by quantitatively demonstrating an 80% reduction in shear stresses and a two-fold increase in the equivalent deformation modulus by using Tensar TriAx geogrids. These findings provide critical data for preventing structural failures and updating national building codes.

3. MATERIALS AND METHODS

3.1 Geotechnical Conditions of the Region

Subsidence is a rapidly occurring phenomenon characterized by the sudden destruction of the soil structure under its own weight or external loads upon saturation [1]. The mechanism of this collapse is explained by the immediate softening and partial dissolution of solid crystalline internal bonds (cementation) within the soil. When collapsible soil becomes saturated, its strength decreases sharply, while compressibility increases significantly, as confirmed by numerous experimental studies. For example, the angle of friction (ϕ) can decrease by 1.5 to 2 times, and cohesion can drop by up to 10 times.

This unstable soil structure is a particularly complex geotechnical category, which creates complex problems for construction.

Features of the structural properties of the soil are as follows:

For the natural subsiding soil (loam):

- porosity is very high n = 45…50%;

- low degree of saturation S_r < 0,5; low moisture content W = 8-16%;

- grain size distribution is characterized by a high content of silt particles (0.05-0.005 mm), ranging from 60 to 75%;

- high strength in a dry state.

The main characteristics of collapsible (subsiding) soils, determined during engineering and geological surveys, include:

- relative subsidence ε_{sl} ;

- initial subsidence pressure p_{sl};

- initial subsidence moisture content W_{sl}.

Relative subsidence ε_{sl} is the relative vertical deformation obtained under pressure after full saturation. This specification is used as a classification index: if $\varepsilon_{sl} \geq 0.01$, the soil is considered collapsible.

The relative subsidence of the soil is determined based on oedometer compression tests using Eq. (1):

$$e_{sl} = (h_{n,p} - h_{sat,\,p}) / h_{n,\,g}\,, \qquad (1)$$

where,

$h_{n,p}$ – height of the soil sample at natural moisture content under the applied pressure P;

$h_{sat,\,p}$ – height of the soil sample after full saturation under the same pressure P;

$h_{n,\,g}$ – height of the sample under a load equal to the natural overburden stress.

Initial subsidence moisture content W_{sl} is the minimum moisture content at which subsidence properties begin to manifest. Initial subsidence pressure P_{sl} is the minimum pressure at which soil subsidence occurs upon saturation. This value is determined in the laboratory from the compression curve where ε_{sl} = 0.01 (Fig. 1b). If the applied pressure is less than the subsidence pressure, or if the condition ε_{sl} < 0.01 is met, the soil is considered non-collapsible.

The initial subsidence pressure is determined using the in-situ test pit wetting method. The planar dimensions (width and length) of the excavation must not be less than the thickness of the subsiding soil layer. The bottom of the excavation is lined with a drainage layer (crushed stone). To measure vertical deformation at various depths, deep bench marks (telltales) are installed in drilled boreholes throughout the entire subsiding soil. Subsequently, water is poured into the pit until the entire soil mass is fully saturated.

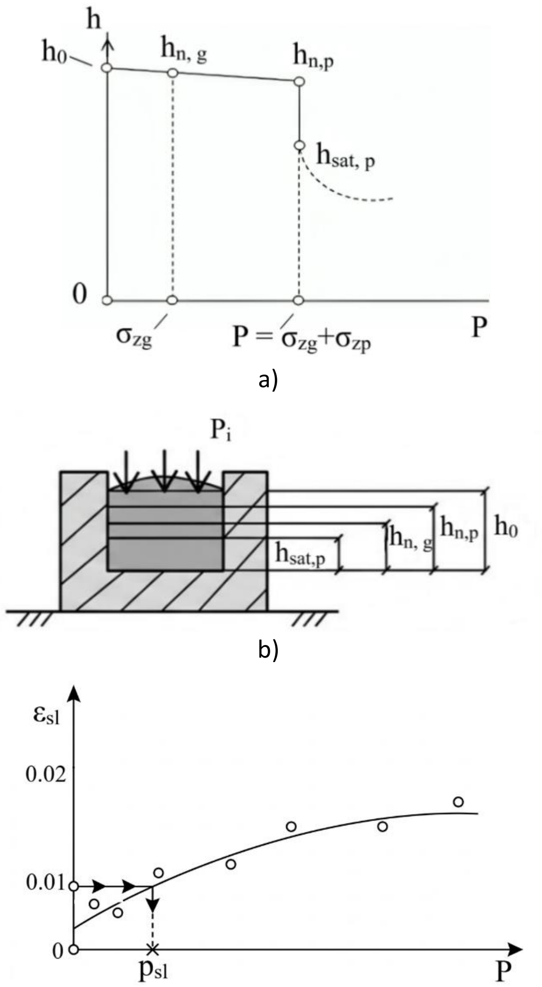


Fig. 1 Oedometer test results for determining the characteristics of subsiding soils. a – plot for determining relative subsidence; b – plot for determining initial subsidence pressure

As the soil becomes saturated, it settles significantly under its own weight. As shown in Fig. 2, the bottom of the pit settles considerably, and the surrounding surface may exhibit tension cracks and deformations. This process poses a potential risk to existing buildings and underground utility networks located near the construction site [8].

Through geodetic monitoring of the deep bench marks, the deformation of each soil layer is measured. The stress level at the depth where subsidence begins under the soil's self-weight is identified as the initial subsidence pressure P_{sl}. The higher the initial subsidence pressure, the more resistant the soil is to moisture-induced collapse.

This experiment allows to classify subsiding soil types based on their behavior under self-weight:

- Type I Subsiding Soils: Soils where the settlement due to self-weight after full saturation does not exceed 5 cm.

- Type II Subsiding Soils: Soils where the settlement due to self-weight after full saturation exceeds 5 cm.

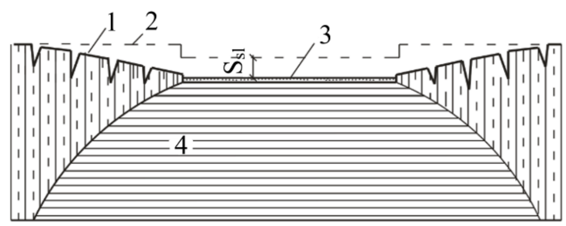


Fig. 2 Deformation of the soil layer due to wetting: 1 – soil surface level after wetting; 2 – soil surface level before wetting; 3 – sand drainage layer; 4 – water-saturated soil

To mitigate the subsidence risk of this water-saturated loam, a reinforced foundation base was designed. The schematic cross-section of this reinforced base, detailing the crushed stone layers and geogrid placement, is illustrated in Fig. 3

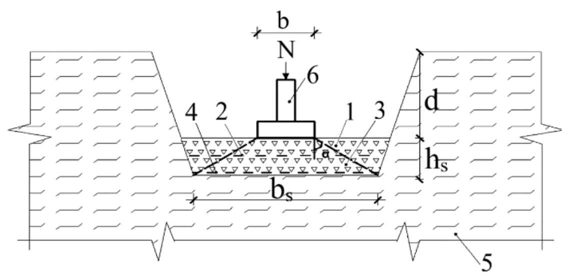


Fig. 3 Cross-sectional scheme of the reinforced foundation base: 1 – top crushed stone cushion; 2 – upper geogrid reinforcement; 3 – bottom crushed stone cushion; 4 – lower geogrid reinforcement; 5 – natural foundation soil (loam); 6 – column foundation

The complete stratigraphic profile, layer thicknesses, and detailed physico-mechanical specifications of all foundation materials (including the geogrid and crushed stone) are summarized in Table 1, arranged in sequential order from top to bottom. The geotechnical properties of the soil were obtained directly from the official engineering-geological site investigation report conducted for the construction of the pedestrian crossing on the Kaskelen-Uzynagash highway. The parameters were determined through standard geotechnical laboratory testing (such as triaxial compression and direct shear tests) in accordance with national building codes. According to these survey data, the natural subgrade is characterized as water-saturated loam. Consequently, this fully saturated state was specifically adopted in the analysis to simulate the most critical operating conditions, effectively addressing the severe loss of bearing capacity typical for such subsiding soils upon wetting.

Table 1 Physico-mechanical properties of the foundation soil (top-to-bottom sequence)

Type of soil	Layer thickness, m	Physico-mechanical properties
1.Top Cushion Layer (Crushed igneous rock)	0.2	Fraction: 20–40 mm; Crushability grade: M > 800
2.Upper Reinforcement (Tensar TriAx TX170)	Interface	PP; Aperture: 40x40x40 mm; Tensile strength: 20-22 kN/m; Radial Stiffness: 390 kN/m
3. Bottom Cushion Layer (Crushed igneous rock)	0,3	Fraction: 20–40 mm; Crushability grade: M > 800
4.Lower Reinforcement (Tensar Triax TX170).	Interface	Placed directly on natural soil
5.Light brown loam, porous, hard consistency, layered structure, dense.	> 15.0 m	Unit weight: 0.0143 MN/m^3 Cohesion (C): 0.054 MPa Internal friction angle (ϕ): 20 Deformation modulus, (E_{def},): 2.9 MPa

3.2 Geogrid Selection and Reinforcement Methodology

Authors consider the column foundation (Type F-2) with base dimensions of 2.7x2.7 m (7.29 m^2).

The average pressure at the foundation base is R= 0.05 MPa.

The main task is to strengthen the subgrade to reduce the stress-strain state. The pressure exerted on the natural base should not exceed its maximum permissible value. According to engineering-geological surveys, the initial subsidence pressure is P_{sl} = 0.025 MPa.

At the same time, the settlement (total deformation) of the base must not exceed the maximum permissible limits specified in SP 5.01.102-2021* (5.1).

According to SN RK 5.01-02-2021, section 5.3.1, "Depending on the soil type, degree of peat content, layer thickness, and thickness of organic soil, it is recommended to use sand, crushed stone, or gravel cushions under the foundations (column, strip)". According to Section 6.6.17 of SP 50-101-2004, "In accordance with the requirements of section 5.8 (p.5.8.3, e), constructive measures should be provided, including soil reinforcement with special geogrids". Furthermore, the application of geogrids to reinforce the foundation adheres to the requirements of SN RK 5.01-02-2021, clause 2.69.

Additionally, the use of geogrids to reinforce the artificial base is supported by the requirements of ST RK 2792-2015*, clause 5.

The selection of the Tensar TriAx geogrid is justified by its near-isotropic stiffness properties. Unlike traditional biaxial geogrids, which have tensile strength primarily in two orthogonal directions, the triangular geometry of TriAx provides multi-directional load distribution. This is particularly important for the complex stress states found in subsiding soils under traffic loads. The interaction between the aggregate and the geogrid creates a mechanically stabilized layer (MSL). The main function in this case is reinforcement through lateral restraint and confinement of the aggregate. The aperture size of the geogrid was selected to match the particle size distribution of the crushed stone to ensure maximum interlocking.

Consequently, the interaction between the Tensar TriAx geogrid and coarse granular material (crushed stone) provides a rigid composite layer formation and uniform distribution of load on weak subgrade, which consequently prevents the spread of non-uniform deformation in the construction [9].

Advantages of applying geogrid include:

- the uniformity of the base (homogeneous), which is essential for the support of the foundation (pavement), as a result increasing the reliability of its operation throughout the region;
- the penetration of coarse granular materials into the underlying weak soil is virtually eliminated (preserving the design thickness of the drainage layer by eliminating the penetration of crushed stone into the bottom layer) (Fig. 4);
- provides optimal conditions for compaction to the required crushed stone layer thickness, and thus

achieves the design value of its elastic modulus and deformation modulus;

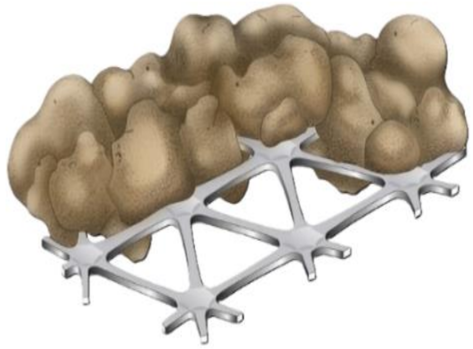


Fig. 4 Interlocking of crushed stone within geogrid cells (formation of the mechanically stabilized layer)

The installation process assumed in the design includes:

1) Preparation of the subgrade and removal of the vegetative layer;

2) Laying the geogrid directly on the leveled surface without wrinkles;

3) Backfilling with crushed stone (fraction 20-40 mm) "from oneself" to avoid the movement of construction equipment on the unprotected geogrid;

4) Layer-by-layer compaction to achieve the required density coefficient.

3.3 Analytical Calculation of bearing capacity

The bearing capacity of the natural soil base and its deformations under saturated conditions were evaluated using an analytical approach based on the limit state design method. The ultimate bearing capacity (R) was determined according to the following constitutive Eq. (2) specified in the national building codes [2]:

$$R = \frac{\gamma_{c1}\gamma_{c2}}{k}\left[M_{\gamma}k_z b\gamma_{II} + M_q d_1\gamma'_{II} + \left(M_q - 1\right)d_b\gamma'_{II} + M_c c_{II}\right] \quad (2)$$

The complete list of input parameters and empirical coefficients used in the analytical model is summarized in Table 2. The calculation results showed that while the ultimate bearing capacity of the soil (R = 0.296 MPa) safely exceeds the applied foundation pressure (P = 0.05 MPa), a critical issue arises regarding subsidence. The current foundation pressure is twice as high as the initial subsidence pressure (P_{sl} = 0.025 MPa). This significant discrepancy confirms the severe risk of soil collapse upon wetting and strongly justifies the necessity of implementing geogrid reinforcement to distribute the stresses more effectively.

Table 2. Input parameters and coefficients for bearing capacity calculation

Parameter	Symbol	Value	Unit
Serviceability coefficients	$\gamma_{c1}\gamma_{c2}$	1.0	-
Reliability coefficient	k	1.1	-
Dimensionless factor (width)	M_{γ}	0.51	-
Dimensionless factor (depth)	M_q	3.06	-
Dimensionless factor (cohesion)	M_c	5.66	-
Foundation width	b	2.7	m
Soil unit weight (below/above base)	$\gamma_{II}, \gamma'_{II}$	0.0143	MN/m^3
Specific cohesion	c_{II}	0.054	MPa

4. RESULTS AND DISCUSSION

To reduce the vertical deformation of the base, the artificial reinforcement construction is designed to use the Tensar TriAx geogrid in one of the most effective and appropriate ways to increase operational stability and durability. The accumulation dynamics of residual deformation considerably decrease (Fig. 5 and 6).

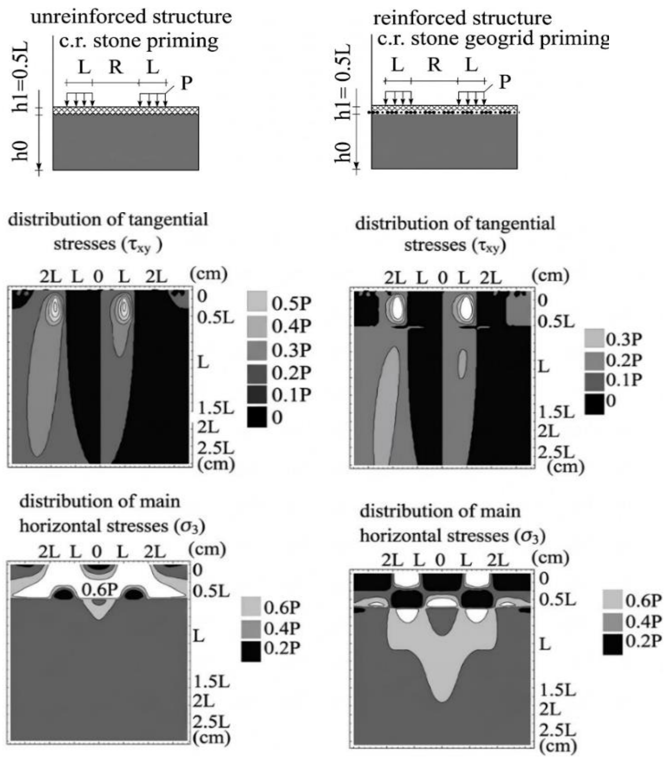


Fig. 5 Stress distribution characteristics under a single load cycle in unreinforced and Tensar TriAx geogrid reinforced structures

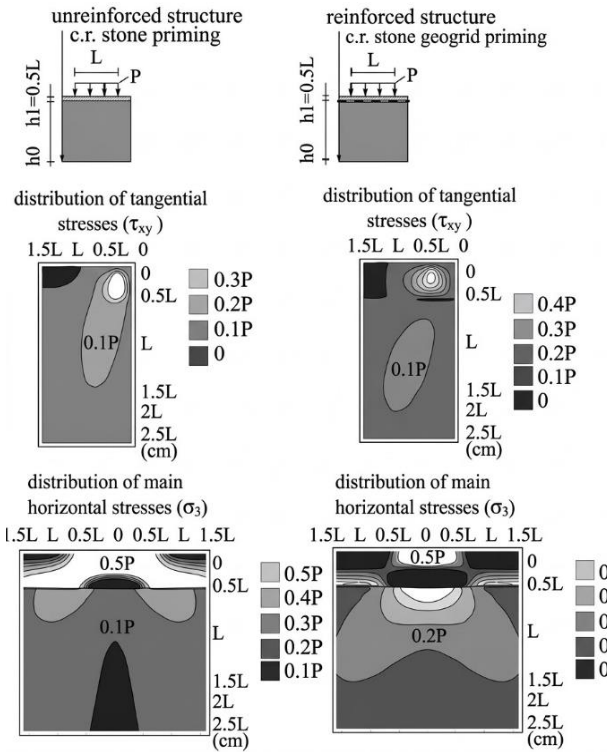


Fig. 6 Stress distribution characteristics under repeated loading in unreinforced and Tensar TriAx geogrid reinforced structures

This is due to the concentration in the "crushed stone-geogrid" layer that is resistant to shear, preventing the development of significant shear stress (τ_{xy}) even in the weak underlying layer. In addition, there is a tendency for growth and concentration under confining σ3 stresses, which leads to a decrease in the coefficient K in Eq. (3). Here, the value of the stress-strain state of the structure, where the magnitude is often determined by the load combination, is controlled by the deformation of the medium (Fig. 5, Fig. 6).

This is reflected in the results of experimental research as well as their application in road construction [10];

$$K = \frac{(\sigma_1 - \sigma_3)(1 - \sin\varphi)}{2(\sigma_3 \sin\varphi + C\cos\varphi)} \quad (3)$$

where σ_1, σ_3 - principal stresses; ϕ - internal friction angle; C - specific cohesion.

- if the linear dependence of stress and deformation is maintained, the ultimate load-bearing capacity increases (Fig. 7);

The mechanism of improvement observed in the results can be theoretically explained by the confinement effect. When the vertical load is applied to the road surface, the aggregate particles attempt to spread laterally. The geogrid resists this lateral movement through friction and interlocking, thereby creating a lateral confinement pressure. This additional confining stress significantly increases the modulus of the aggregate layer. The reduction in vertical deformation (Fig. 10) indicates that the reinforced composite acts as a stiff slab, bridging over the weak localized zones of the subsiding soil.

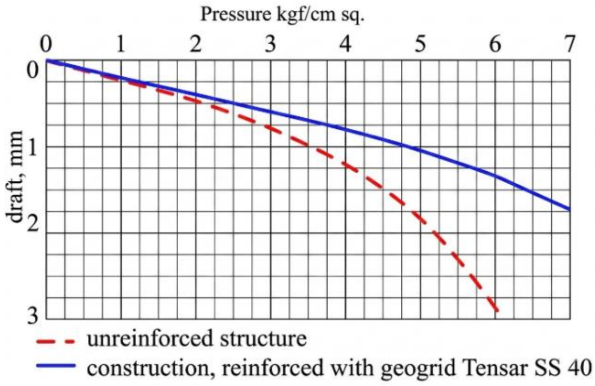


Fig. 7 Comparative graph of the bearing capacity of the structure

The deformation characteristics of the structure containing the geogrid reinforcement are improved (Fig. 8, 9).

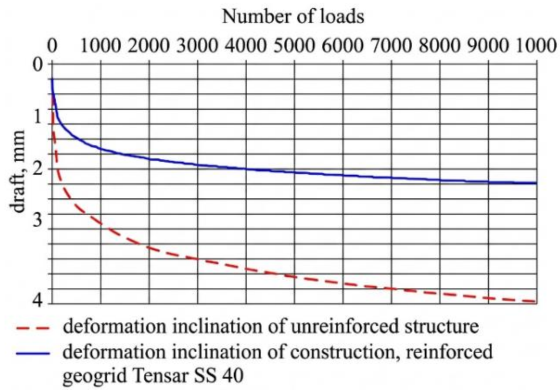


Fig. 8 Comparative graph of accumulation of residual deformation of the structure under repeated short-term loading

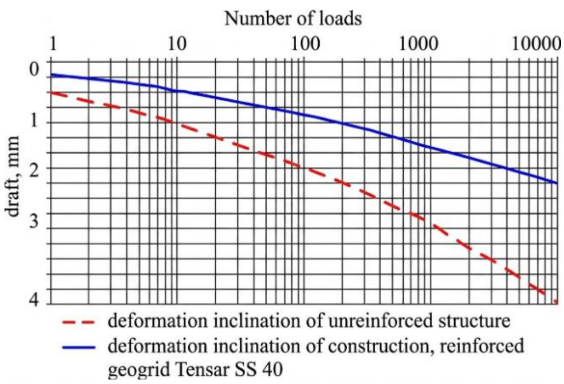
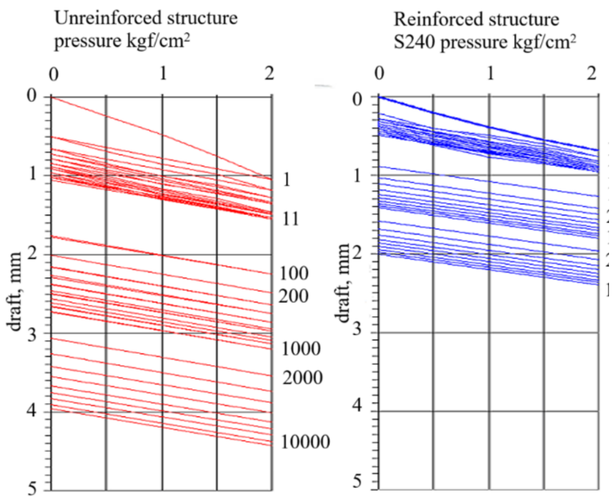


Fig. 9 Comparative graph of accumulation of residual deformation of the structure under the influence of multiple short-term loads (detail view)

This effect effectively reduces the stress concentration on the subgrade, preventing the activation of subsidence properties mentioned in Section 3.1. The analysis confirms that the triangular aperture structure offers superior radial stiffness, which is critical for minimising differential settlement in the heterogeneous soil conditions.



$$\frac{S_y}{S_o} = \frac{0.389}{2.003} = 0.194 \qquad \frac{S_y}{S_o} = \frac{0.5}{3.965} = 0.126$$

Fig. 10 Comparative graph of structural deformation

According to the results of the research, the reinforcement with crushed stone allows the equivalent elastic modulus of the construction to increase by 6- 15%, decreases the value of shear stress in the layer by 25-80%, and in the case of significant settlement, increases the deformation modulus more than twice [11-13].

In addition to the advantages of using the above-mentioned geogrid, it extends the service life of the structure to overhaul, with the additional advantage of increasing the bearing capacity of the geogrid-reinforced base by 2 to 2.5 times.

Comparisons with other reinforcement methods, such as finite element analysis of geogrids [14] and geocomposites [15], confirm these findings. Studies using the Mohr-Coulomb criterion also support the strength increase [16]. Similar improvements in ultimate bearing capacity, lateral displacement control, and load-settlement responses were recently observed in geogrid-encased stone columns and reinforced foundations [17]. Even other alternative and environmentally friendly soil stabilisation techniques, such as novel chemical or biological improvement methods [18], tyre aggregates [19], show the general trend of increasing bearing capacity, but TriAx geogrids offer specific structural advantages for this type of subsiding soil.

In addition to mechanical strength, it is also important to consider the climatic factors of Kazakhstan, characterised by a sharp continental climate with significant seasonal temperature fluctuations. Although this study focused on mechanical loading, the use of geosynthetics provides additional benefits regarding durability. The reinforced layer prevents the intermixing of the expensive base material (crushed stone) with the wet, fine-grained subgrade during the spring thaw period. This separation function maintains the structural integrity of the road pavement and drainage capacity over time, directly addressing the issues of durability raised in the Introduction. Comparison with similar studies on rural road pavements [19-20] confirms that the introduction of a reinforcing layer increases the inter-repair period by 1.5-2 times, which is economically efficient for the region.

5. CONCLUSIONS

This article evaluated the interaction between geosynthetic reinforcement and subsiding soil layers to increase the durability and service life of engineering structures. Based on the analytical assessment and the specific conditions of the "Kaskelen-Uzynagash" project presented in this paper, the following conclusions can be drawn:

1. The use of the Tensar TriAx geogrid is extremely effective and rational in order to reduce the high level of foundation deformation. With the help of the geogrid, it is possible to achieve an even distribution of deformation and reduce the deformation of the subgrade by 50%.

Due to the triangular geometry and diagonal connections of the TriAx system, the stress can be distributed in all directions over a larger area. As a key indicator of this effectiveness, the bearing capacity of the foundation increases by 2.0-2.5 times compared to unreinforced bases.

2. The accumulation of residual deformation under cyclic loads decreases by 1.3-1.4 times.
3. According to the results of the research, crushed stone reinforced with geogrids increases the overall (equivalent) modulus of elasticity of the structure by 6 ÷ 15%, reduces the value of shear stress in the layer by 25 ÷ 80%, and increases the deformation modulus by more than two times.
4. In addition to these mechanical indicators, the research verifies the solution's durability under harsh climatic conditions. The geogrid effectively prevents layer intermixing during seasonal freezing and thawing cycles, which is critical for the region. Ultimately, this strategy extends the inter-repair period of the facility by 1.5-2 times,

proving its economic viability in comparison to traditional soil replacement techniques.

6. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Prof. E.C. Shin (Incheon National University), Baimukhanbmedova A (L.N. Gumilev Eurasian National University).

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