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COMPARATIVE ANALYSIS OF WEAK SOILS: EVALUATING GEOSYNTHETIC APPLICATIONS FOR ENHANCED STABILITY AND LOAD-BEARING CAPACITY

СРАВНИТЕЛЬНЫЙ АНАЛИЗ СЛАБЫХ ГРУНТОВ: ОЦЕНКА ПРИМЕНЕНИЯ ГЕОСИНТЕТИЧЕСКИХ МАТЕРИАЛОВ ДЛЯ ПОВЫШЕНИЯ УСТОЙЧИВОСТИ И НЕСУЩЕЙ СПОСОБНОСТИ

ӘЛСІЗ ТОПЫРАҚТАРДЫ САЛЫСТЫРМАЛЫ ТАЛДАУ: ТҰРАҚТЫЛЫҚ ПЕН КӨТЕРГІШТІК ҚАБІЛЕТТІ АРТТЫРУ ҮШІН ГЕОСИНТЕТИКАЛЫҚ МАТЕРИАЛДАРДЫ ҚОЛДАНУДЫ БАҒАЛАУ

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Keywords:
weak soils, geosynthetics, geotechnical properties, soil improvement, load-bearing capacity.

ABSTRACT
Weak soil conditions present significant challenges in various civil engineering projects, including construction, slope stability, and infrastructure development. Weak soils are found in several regions, many loess and silty soils are most widespread in the central and southern Kazakhstan regions. This study presents a comparative analysis of weak soils, focusing on solid loam and plastic sandy silt specimens collected from regions in central and southern Kazakhstan. The research evaluates the effectiveness of geosynthetic applications in enhancing the stability and load-bearing capacity of these soil types. Through comprehensive laboratory testing, including liquid and plastic limit tests, determination of swelling potential, the geotechnical properties of both soils are examined. Investigations are conducted to determine the impact of geosynthetics on soil reinforcement, deformation control, and load distribution. Through a detailed analysis of the literature and experimental studies of the geotechnical properties of weak soils, this research explores conventional and innovative techniques employed for soil improvement. This study offers practical guidelines for engineers and researchers to optimize soil strengthening strategies, ensuring durability and reliability in civil engineering applications.

Түйінді сөздер:
әлсіз топырақтар, геосинтетика, геотехникалық қасиеттер, топырақты жақсарту, көтергіштік қабілет.

ТҮЙІНДЕМЕ
Әлсіз топырақтар құрылыс, еңіс тұрақтылығы және инфра-құрылымды дамыту сияқты азаматтық инженерия жобаларында маңызды мәселелер тудырады. Әлсіз топырақтар Қазақстанның көптеген аймақтарында кездеседі, әсіресе орталық және оңтүстік өңірлерде лёсс және лайлы топырақтар кең таралған. Бұл зерттеуде орталық және оңтүстік Қазақстан өңірлерінен алынған тығыз саздақ пен пластикалық құмды лай үлгілеріне негізделген әлсіз топырақтардың салыстырмалы талдауы ұсынылады.

Зерттеу осы топырақ түрлерінің тұрақтылығы мен көтергіштік қабілетін арттырудағы геосинтетикалық материалдарды қолданудың тиімділігін бағалауға бағытталған. Сұйықтық және пластикалық шектерді анықтау, ісіну мүмкіндігін бағалау сияқты кешенді зертханалық сынақтар арқылы екі топырақтың геотехникалық қасиеттері зерттелді. Геосинтетикалардың топырақты арматуралау, деформацияны бақылау және жүктемені таратуға әсері қарастырылады. Әлсіз топырақтардың геотехникалық қасиеттеріне арналған әдебиеттер мен тәжірибелік зерттеулерді жан-жақты талдау арқылы топырақты жақсартудың дәстүрлі және инновациялық әдістері зерделенеді. Бұл зерттеу инженерлер мен зерттеушілерге топырақты нығайту стратегияларын оңтайландыру бойынша практикалық нұсқаулар ұсына отырып, азаматтық құрылыс саласында беріктік пен сенімділікті қамтамасыз етуге бағытталған.

Ключевые слова:
слабые грунты,
геосинтетика,
геотехнические свойства,
упрочнение грунтов,
несущая способность.

АННОТАЦИЯ

Слабые грунты представляют собой серьезную проблему для различных объектов гражданского строительства, включая возведение зданий, обеспечение устойчивости откосов и развитие инфраструктуры. Слабые грунты распространены в ряде регионов, особенно в центральных и южных областях Казахстана, где преобладают лёссовые и илистые почвы. В данной работе представлен сравнительный анализ слабых грунтов с акцентом на плотный суглинок и пластичный пылевато-песчаный ил, образцы которых были отобраны из различных регионов Центрального и Южного Казахстана. Исследование направлено на оценку эффективности применения геосинтетических материалов для повышения устойчивости и несущей способности этих типов грунтов. Посредством комплексных лабораторных испытаний, включая определение границ текучести и пластичности, а также потенциальной набухаемости, исследуются геотехнические свойства обоих типов грунтов. Анализируется влияние геосинтетических материалов на армирование грунта, контроль деформаций и распределение нагрузок. На основе подробного анализа научной литературы и экспериментальных исследований геотехнических характеристик слабых грунтов рассматриваются как традиционные, так и инновационные методы их упрочнения. Работа предлагает практические рекомендации для инженеров и исследователей по оптимизации методов укрепления грунтов с целью обеспечения долговечности и надежности строительных объектов.

INTRODUCTION

Weak soils, characterized by low shear strength, high compressibility, and limited load-bearing capacity, present significant challenges in civil engineering design and construction. These geotechnically unstable soils, including loess and silty deposits, are widely distributed across various regions, particularly in central and southern Kazakhstan. Their presence compromises the stability and long-term performance of foundations, infrastructure, and slopes, necessitating the development of effective soil stabilization measures. A thorough understanding of their geotechnical behavior under different loading conditions is essential for optimizing reinforcement strategies and ensuring structural safety and durability (Sánchez-Garrido et al., 2022).

Globally, weak soil conditions have posed substantial engineering challenges. In Mexico City, highly compressible lacustrine clays from its ancient lakebed have led to excessive settlement and structural tilting, while Shanghai faces similar geotechnical issues due to soft alluvial deposits. Rapid urbanization has exacerbated these problems, increasing the vulnerability of infrastructure to differential settlement and foundation failure (Utepov et al., 2021). In Kazakhstan, Astana is built on weak, clayey soils prone to settlement, further aggravated by high groundwater levels and severe frost conditions, necessitating pile foundations and advanced soil stabilization techniques. Conversely, Shymkent, located in southern Kazakhstan, is underlain by fine-grained, porous loess soils, which are highly collapsible upon saturation (Utepov et al., 2022).

Despite advancements in soil stabilization techniques, the lack of region-specific geotechnical data often results in the inefficient application of soil improvement methods that may not be fully optimized for local conditions (Baitova and Zhambakina, 2021). Furthermore, while many studies focus on the short-term effectiveness of soil treatment techniques, long-term performance assessments remain insufficient. Addressing these research gaps is essential for developing sustainable and resilient solutions to weak soil challenges in civil engineering projects.

A proven method for addressing weak soil challenges is the application of geosynthetics, synthetic materials engineered to enhance the mechanical behavior of soils. Geosynthetics, including geogrids, geotextiles, and geomembranes, are widely employed for their ability to improve shear strength, reduce settlement, and enhance load distribution. Their effectiveness in reinforcing weak soils, controlling deformation, and minimizing erosion makes them a cost-efficient and environmentally sustainable solution for soil stabilization (Shakhmov et al., 2018). However, despite their extensive application, further research is required to assess their long-term performance across different soil conditions, particularly in regions with complex geotechnical characteristics. Comprehensive studies are necessary to optimize geosynthetic applications for varying soil types, ensuring their efficiency and durability in diverse engineering projects (Rad et al., 2024).

This study focuses on two prevalent weak soil types—solid loam and plastic sandy silt, commonly found in Kazakhstan's central and southern regions. Both soil types are characterized by their susceptibility to deformation and low load-bearing capacity, making them suitable candidates for evaluating the impact of geosynthetics on soil stability and strength. By conducting a comparative analysis of these soil types, this research aims to provide valuable insights into the effectiveness of geosynthetics in enhancing the engineering properties of weak soils.

Through a series of laboratory tests, including the determination of liquid and plastic limits, swelling potential, and bearing capacity, the geotechnical properties of both solid loam and plastic sandy silt are thoroughly examined. Additionally, the study investigates the impact of geosynthetic materials on improving soil reinforcement, controlling deformation, and enhancing load-bearing capacity. The findings of this study contribute to the growing body of knowledge on soil improvement techniques, providing engineers and researchers with practical guidelines for optimizing geosynthetic applications in the stabilization of weak soils. The results offer critical insights into the sustainability and applicability of these techniques in civil engineering projects, ensuring more reliable and durable solutions for construction and infrastructure development in regions with weak soils.

MATERIALS AND METHODS

This study integrates a comprehensive review of existing literature with experimental research to evaluate the properties of two predominant weak soil types—solid loam and plastic sandy silt. A combination of laboratory investigations and advanced measurement techniques is employed to assess the effectiveness of geosynthetics in improving the engineering characteristics of these soils. The experimental framework is guided by a system-structural approach, which focuses on soil improvement techniques and property analysis. By utilizing modern research methodologies and state-of-the-art testing equipment, this study ensures high reliability and accuracy in its findings, contributing to a deeper understanding of geosynthetic applications in soil stabilization (GOST 12248-2010).

Soil samples were collected from designated sites in central and southern Kazakhstan, specifically from regions where solid loam and silty sandy loam are the predominant soil types. The samples were carefully prepared and preserved for laboratory testing. Prior to testing, the soil samples were air-dried to a consistent moisture content and then sieved to remove large particles, ensuring a uniform sample for analysis.

A series of standard geotechnical tests were conducted on the soil samples to determine their physical and engineering properties. The liquid and plastic limit tests were used to determine soil plasticity, with the liquid limit measured using a Casagrande apparatus for solid loam and a balance cone (Vasiliev cone) for silty sandy loam. The swelling potential was evaluated using an oedometer test, measuring volume changes upon water absorption. These tests provided insights into soil behavior and the effectiveness of geosynthetics for reinforcement (Das, 2010).

This study systematically reviews the selection and application of geosynthetic materials, focusing on the commonly used geogrids and geotextiles for reinforcing weak soils. The literature review examines existing research on the effectiveness of these materials in enhancing soil mechanical properties and load-bearing capacity. Additionally, various application methods, including different types and layering configurations of geosynthetics, are analyzed based on their reported influence on soil behavior under diverse conditions. The review provides insights into the interaction between geosynthetics and weak soils, assessing the potential benefits of these materials in soil stabilization and improvement.

Accurate laboratory characterization of soil properties is essential for foundation design, soil improvement strategies, and quality control in geotechnical engineering. Natural soil deposits often exhibit significant nonhomogeneity, requiring precise laboratory evaluations to ensure the applicability of theoretical soil mechanics equations in practical engineering contexts (Awwad et al., 2019).

Experimental investigations were conducted to analyze the influence of geosynthetic materials on the geotechnical properties of weak soils. A comparative analysis was performed to assess the geotechnical behavior of solid loam and silty sandy loam, focusing on their response to geosynthetic reinforcement. Furthermore, statistical methods were employed to quantify the significance of the observed improvements in soil properties, providing a robust assessment of the effectiveness of geosynthetics in enhancing soil performance (Yerzatova et al., 2025).

RESULTS AND DISCUSSION

Table 1. Liquid and plastic limit test results of the soil No.1

The cup №	The cup mass (g)	The moisture soil mass (g)	The dry soil mass (g)	Number of blows	Moisture content (%)
1	2	3	4	5	6
Liquid limit test					
17	7.6	18.9	16.2	33	31.4
47	7.7	27.2	22.5	16	31.8
2	7.5	26.1	21.6	28	31.9
324	7.9	19.3	16.6	34	31.0
8	12.4	29.0	25.0	14	31.7
			Liquid Limit:	25	31.56

End of table 1

Plastic limit test					
97	7.7	14.6	13.5	-	18.9
3	7.7	15.1	14	-	17.5
				Plastic Limit:	18.2
Note – compiled by the author based on data from Yerzatova et al. (2025)					

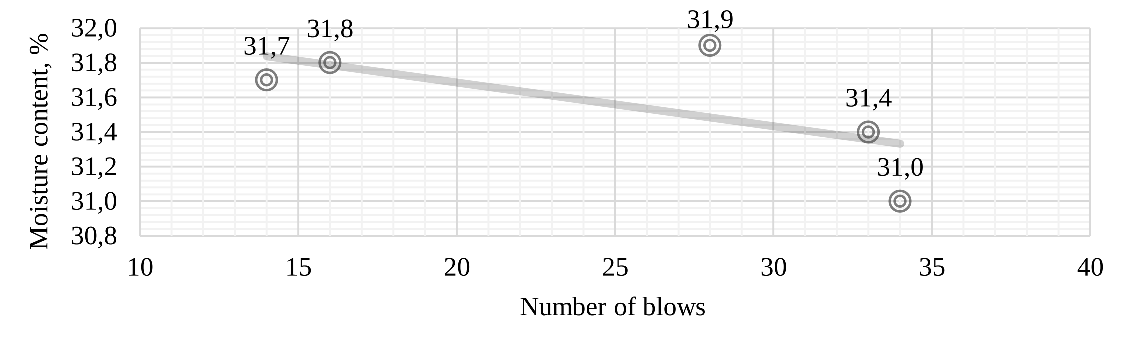

Figure 1. Liquid limit diagram of the soil 1

Note – compiled by the authors based on (Yerzatova et al., 2025)

The liquid and plastic limit test results for soil sample 1, presented in Table 1, indicate a liquid limit of 31.56% and a plastic limit of 18.2%, resulting in a plasticity index of 13.36%. The moisture content values recorded during the liquid limit test range from 31.0% to 31.9%, demonstrating slight variations and indicating consistent soil behavior under varying compaction energies. The trend observed in the liquid limit diagram in Fig. 1 confirms the soil's transition from a liquid to a plastic state as the number of blows increases, indicating its moderate plasticity. With a plasticity index above 10%, the soil can be classified as medium-plastic, which implies it may be prone to some degree of shrinkage and swelling. These characteristics make it more suitable for applications requiring stabilization techniques, such as geosynthetic reinforcement or chemical treatment, to enhance its load-bearing capacity and reduce deformation risks under load. Further investigation, including shear strength and permeability tests, is recommended to fully evaluate its engineering properties.

Table 2. Liquid and plastic limit test results of the soil No.1

The cup №	The cup mass (g)	The moisture soil mass (g)	The dry soil mass (g)	Number of blows	Moisture content (%)
Liquid limit test					
1	5.11	16.66	14.50	31	23
5	6.00	19.68	17.05	21	23.8
9	5.35	19.13	16.54	15	23.15
14	5.47	16.19	14.16	34	23.36
19	5.32	17.37	15.09	24	23.34
			Liquid Limit:	25	23.33
Plastic limit test					
0478	5.29	12.29	11.21	-	18.24
0488	5.36	12.31	11.26	-	17.80
				Plastic Limit:	18.02

Figure 2. Liquid limit diagram of the soil 2

Note – compiled by the authors

The liquid and plastic limit test results for soil sample 2, presented in Table 2, indicate a liquid limit of 23.33% and a plastic limit of 18.02%, resulting in a plasticity index of 5.31%. These values classify the soil as having low plasticity, suggesting it is likely composed of silty or sandy material. The moisture content variations observed in the liquid limit test show consistency, indicating a uniform composition and moderate sensitivity to moisture changes. The downward trend observed in the liquid limit diagram in Fig. 2 indicates the soil's transition from a liquid to a plastic state as compaction energy increases. The low plasticity index implies that the soil exhibits minimal shrinkage or swelling potential, making it suitable for applications requiring stable subgrades or reinforced foundations. However, further investigations, including shear strength and compaction studies, are recommended to confirm its performance under load-bearing conditions.

The determination of normative and calculated values of soil characteristics for IGE and CSE is conducted in accordance with normative document on statistical treatment of the test results (GOST 20522-96).

The analysis reveals that the normative values of liquid limits are 31.56% for soil No. 1 and 23.33% for Soil No. 2, with calculated values slightly lower at 31.25% and 23.1%, respectively. Statistical checks confirm that deviations between the measured and normative values fall within acceptable confidence intervals, as demonstrated by the inequalities satisfying the statistical check. The mean square deviations are 0.36 for soil No. 1 and 0.3 for soil No. 2, indicating low dispersion and consistent measurements.

Given in Table 3, the coefficients of variation are 0.0114 and 0.0129, reflecting minimal variability, while the accuracy indices of 0.011 and 0.012 affirm high precision. Reliability coefficients of 1.01 for both soils indicate strong statistical reliability and confidence in the calculated values. These findings suggest that the soils exhibit stable properties suitable for engineering applications, though soil 1 demonstrates slightly higher variability and liquid limit values, implying potentially greater plasticity and moisture retention capacity compared to soil No. 2. The results underscore the necessity of tailored stabilization techniques to ensure structural integrity under varying conditions.

Table 3. Comparative statistical analysis

Denomination of a value	Formula	Soil No. 1	Soil No. 2
1	2	3	4
The normative value of soil, X_n (%)	$X_n = \bar{X} = \frac{1}{n}\Sigma X_i$, (1)	31.56%	23.33%

End of table 1

1	2	3	4
Statistical check	$\lvert X_n - X_i \rvert > \nu \cdot S$, (2)	$\lvert 31.56 - 31.4 \rvert < 1.92 \cdot 0.36$, $0.16 < 0.69$ $\lvert 31.56 - 31.8 \rvert < 1.92 \cdot 0.36$, $0.24 < 0.69$ $\lvert 31.56 - 31.9 \rvert < 1.92 \cdot 0.36$, $0.34 < 0.69$ $\lvert 31.56 - 31.0 \rvert < 1.92 \cdot 0.36$, $0.56 < 0.69$ $\lvert 31.56 - 31.7 \rvert < 1.92 \cdot 0.36$, $0.14 < 0.69$	$\lvert 23.33 - 23 \rvert < 1.92 \cdot 0.3$, $0.33 < 0.576$ $\lvert 23.33 - 23.8 \rvert < 1.92 \cdot 0.3$, $0.47 < 0.576$ $\lvert 23.33 - 23.15 \rvert < 1.92 \cdot 0.3$, $0.18 < 0.576$ $\lvert 23.33 - 23.36 \rvert < 1.92 \cdot 0.3$, $0.03 < 0.576$ $\lvert 23.33 - 23.34 \rvert < 1.92 \cdot 0.3$, $0.01 < 0.576$
The mean square deviation, S	$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_n - X_i)^2}$, (3)	0.36	0.3
The coefficient of variation, V	$V = S / X_n$, (4)	0.0114	0.0129
The accuracy index, ρ_α	$\rho_\alpha = \frac{t_\alpha V}{\sqrt{n}}$, (5)	0.011	0.012
The reliability coefficient, γ_g	$\gamma_g = 1 / (1 \pm \rho_\alpha)$, (6)	1.01	1.01
The calculated value of soil, X (%)	$X = X_n / \gamma_g$, (7)	31.25%	23.1%
Note – compiled by the authors			

Based on the results in Table 3, the calculated liquid limit values for the two soil samples were determined to be 31.25% for soil No. 1 and 23.1% for soil No. 2. These values are slightly lower than the normative liquid limits, suggesting minimal variability and consistent measurement reliability.

The liquid limit of soil No. 1 indicates its medium plasticity, which reflects higher moisture retention and deformation potential compared to soil No. 2, which exhibits low plasticity and limited moisture sensitivity. The statistical reliability coefficients of 1.01 for both samples confirm the accuracy of these findings, emphasizing the suitability of the soils for engineering applications when paired with stabilization techniques like geosynthetics.

To identify the type of soils, it was necessary to determine the characteristics of the soil, such as plasticity (I_P) and liquidity index (I_L), by results taken from limit tests (Gunaratne, 2006).

For the soil No. 1:

$$I_{P1} = (\omega_L - \omega_p)100\% = (0.316 - 0.189)100\% = 12.7\%, \tag{8}$$

$$I_{L1} = (\omega - \omega_p)/(\omega_L - \omega_p) = (0.1789 - 0.189)/(0.316 - 0.189) = -0.08, \tag{9}$$

Where ω is natural soil moisture, ω_L is at the yield point, and ω_P is at the rolling edge. Since $7 < I_P \leq 17$ and $I_L < 0$, the denomination of soil No. 1 according to GOST 25100-2020 is «Solid Loam» (GOST 25100-2020). The denomination according to ASTM D 2487 is lean clay with an index CL (ASTM D2487-17). Based on the ISO 14688-2:2017 system, this soil falls under the category of a very stiff loam, which corresponds to a lean clay.

For the soil No. 2:

$$I_{P2} = (\omega_L - \omega_p)100\% = (0.233 - 0.180)100\% = 5.3\%, \quad (8)$$

$$I_{L2} = (\omega - \omega_p)/(\omega_L - \omega_p) = (0.1968 - 0.180)/(0.233 - 0.180) = 0.317, \quad (9)$$

As $1 \le I_P \le 7$ and $0 \le I_L \le 1$, the denomination of soil No. 2 according to GOST 25100-2020 is «Plastic Sandy Silt» (GOST 25100-2020). The denomination according to ASTM D 2487 is Silty clay with an index CL-ML (ASTM D2487-17). According to the ISO 14688-2:2017 system, this would be categorized as a very soft–stiff soil with silty characteristics.

To determine the swelling potential of the soil, the process begins with measuring the natural moisture content. The soil sample is subsequently dried in a controlled laboratory oven to remove any residual moisture. Once dried, it is finely ground using a porcelain dish and passed through a No. 1 mesh sieve to ensure particle size uniformity. This sieving process guarantees consistent soil texture for accurate testing. After measuring the natural moisture content, water equivalent to the recorded value is added to the dried soil sample (Teltayev et al., 2020).

The moist soil is then carefully weighed and placed into a cylindrical mold with a diameter of 100 mm and a height of 150 mm. The interior surface of the mold is coated with technical petroleum jelly or grease to minimize friction and ensure smooth compaction. The soil is compacted in layers, with each layer compressed after every 50 mm to achieve uniform density and structural consistency. This compaction method prevents voids and enhances reliability in the evaluation (Shakhmov et al., 2016).

Once compacted, the mold is wrapped with thermal insulation, such as cotton, to maintain stable temperature conditions throughout the testing period. The insulated mold is then transferred to a laboratory freezing chamber, where the swelling potential of the soil is assessed under controlled environmental conditions.

Measurements were conducted at 12-hour intervals on a soil sample subjected to controlled freezing conditions within a laboratory freezing chamber. After each removal, the mass and height of the sample were recorded to monitor volumetric and weight changes. Following the measurements, the sample was immersed in water to assess its saturation and subsequent behavior under soaking conditions. This procedure ensured systematic data collection for evaluating the sample's swelling potential and structural stability, facilitating detailed analysis of soil performance under freeze-thaw cycles (GOST 12248.6-2020). This experimental approach provides a systematic evaluation of soil behavior under freezing conditions, simulating field scenarios for enhanced accuracy.

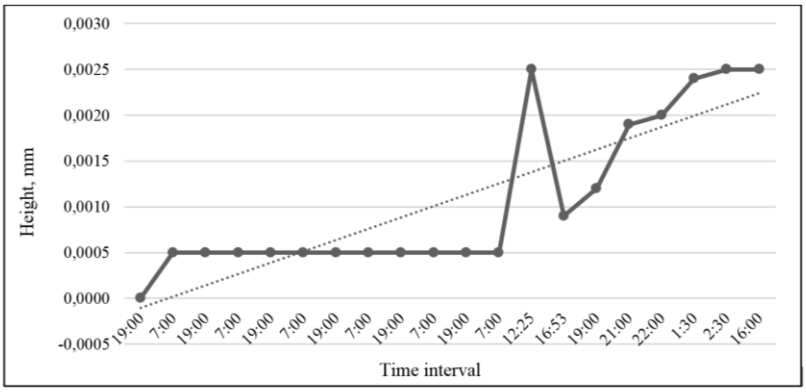

Figure 3. The graph of the measurement of the degree of swelling potential of the soil
Note – compiled by the authors

The graph illustrates the variation in the height of a soil sample over time under controlled freezing and soaking conditions.

During the initial phase (0–84 hours), the sample exhibits minimal expansion, maintaining a stable height with slight fluctuations (~0.0005 mm). This stability indicates low initial swelling potential, likely due to insufficient moisture absorption or freezing-induced compaction. A sharp increase in height (to ~0.0025 mm) occurs during the critical transition (96–108 hours), reflecting a sudden phase change or ice lens formation, characteristic of freezing-induced volumetric expansion. This behavior highlights the soil's vulnerability to frost heave when exposed to freezing temperatures. After the peak (108–132 hours), the height decreases briefly before stabilizing at ~0.002 mm. This reduction suggests partial structural collapse due to thawing and water drainage, which is followed by gradual re-expansion. The sample stabilizes, showing reduced fluctuations, which may indicate saturation equilibrium (132–144 hours). The overall upward trend (dashed line) underscores cumulative swelling effects influenced by freeze-thaw cycles. The observed swelling trends highlight the soil's susceptibility to frost-induced deformations. This analysis emphasizes the need for reinforcement strategies, such as geosynthetics, to mitigate swelling and enhance structural stability under cyclic freeze-thaw conditions.

Geosynthetics, which include materials such as geotextiles, geomembranes, geogrids, and geocells, are widely utilized in geotechnical engineering to perform functions such as reinforcement, separation, filtration, protection, and drainage. These materials have proven effective in improving the mechanical characteristics of weak soils, enhancing their load-bearing capacity, and ensuring structural stability. Their integration into civil engineering practices has gained substantial attention due to their efficiency in addressing soil performance challenges and facilitating sustainable construction solutions (Al-Subari et al., 2020).

Numerous studies have examined the behavior of geosynthetics using triaxial tests, emphasizing the influence of factors such as specimen size, confining pressure, reinforcement configuration, layer spacing, and mechanical properties like stiffness, friction, and tensile strength. These investigations consistently show that reinforced specimens demonstrate higher peak strength, reduced residual strength loss, decreased dilation, and improved cohesion (Utepov et al., 2023). Benessalah et al. (2016) observed that incorporating geosynthetics in soils enhances shear strength and minimizes lateral deformation, with the degree of improvement depending on the number of reinforcement layers and confining pressure.

Abdelkader et al. (2016) highlighted the importance of sample preparation methods, as they substantially affect the compressive strength of specimens. Researchers have assessed the effects of reinforcement orientation and footing geometry on bearing capacity and settlement behavior. Lavasan and Ghazaviet (2012) noted that mobilized tensile forces within geosynthetics contribute to increased bearing capacity and reduced settlement, reinforcing their effectiveness as soil stabilizers.

The presented numerical simulation results depict the deformation patterns of weak soil under applied loading conditions, focusing on the zones with maximum settlement. The analysis compares two scenarios: without geogrid reinforcement and with geogrid reinforcement. The evaluation of the critical red zone, representing the area with the most significant settlement, provides a detailed understanding of the effectiveness of geosynthetic materials in reducing soil deformation.

In the initial scenario given in Fig. 4 without geogrid reinforcement, the maximum settlement reaches 0.05392 m, localized in the red zone directly beneath the applied load. The deformation pattern exhibits high concentration, with settlement intensity diminishing outward from the load application area. This concentrated settlement indicates inadequate load distribution, emphasizing the limited load-bearing capacity of the unreinforced soil. Such deformation could lead to structural instability, particularly in weak soils prone to excessive settlement under heavy loads.

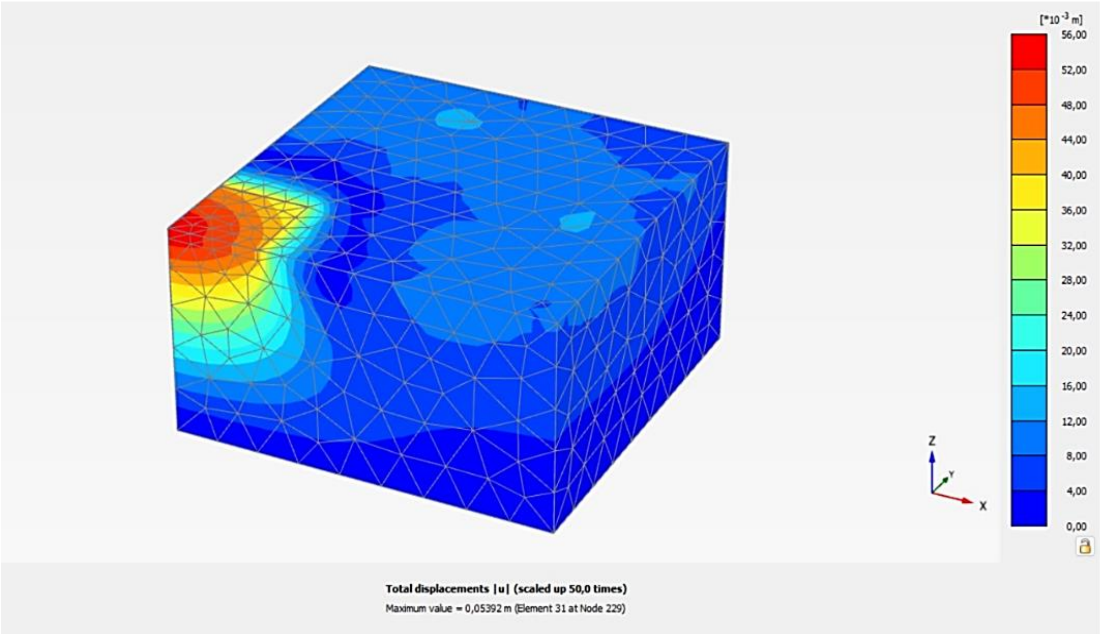

Figure 4. Total displacement analysis of the soil sample under applied loading conditions
Note – compiled by the authors

Conversely, in the second scenario given in Fig. 5, where geogrid reinforcement is applied, a significant reduction in settlement is observed. The maximum displacement in the critical red zone decreases to 0.01614 m, representing an approximate 70% reduction compared to the unreinforced condition. Additionally, the deformation pattern becomes more uniform, with the red zone significantly reduced in size and intensity. This improvement highlights the geogrid's ability to redistribute loads effectively across a broader area, mitigating localized stress concentrations and enhancing the soil's overall load-bearing capacity.

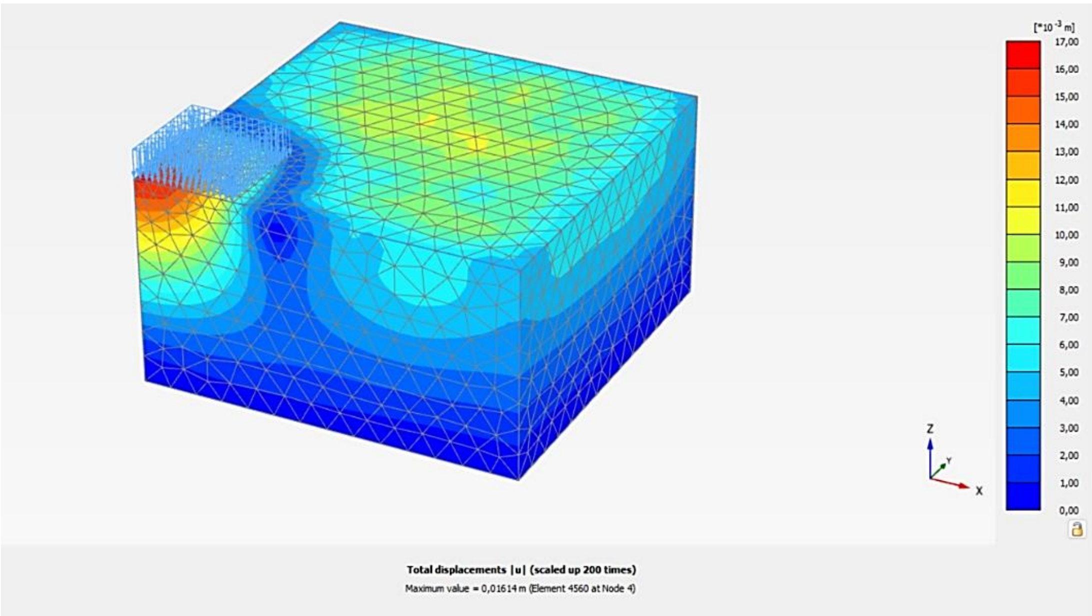

Figure 5. Total displacement analysis of the soil sample with geogrid reinforcement under applied loading conditions
Note – compiled by the authors

The comparative analysis underscores the substantial influence of geogrid reinforcement in mitigating excessive settlement in weak soils. The geogrid's inclusion improves load transfer mechanisms within the soil, resulting in a more stable deformation profile and reducing the risks of structural failures associated with excessive settlements. The findings align with existing research emphasizing the role of geosynthetic materials in soil stabilization and bearing capacity enhancement.

These results demonstrate that geogrid reinforcement effectively addresses settlement issues in weak soils, particularly in critical zones under high loading. The reduction in maximum settlement and the redistribution of deformation provides strong evidence for incorporating geosynthetics in foundation design to improve the performance and stability of soil-structure systems.

CONCLUSION

This study has provided a comprehensive investigation into the characteristics and behavior of weak soils, focusing on their mechanical performance and swelling potential under controlled laboratory conditions. Systematic analysis of soil samples revealed key factors influencing soil stability, including moisture content, compaction, and temperature variations, which are critical for understanding their engineering properties.

The integration of experimental data with numerical modeling and prior studies demonstrated that geosynthetics, particularly geogrids and geotextiles, significantly improve soil performance by enhancing cohesion, reducing settlement, and increasing load-bearing capacity. Numerical simulations confirmed that geogrid reinforcement can reduce settlement in critical zones by approximately 70%, ensuring more uniform load distribution. These results have clear practical significance for foundation engineering, road construction, slope stabilization, and infrastructure projects in regions where weak soils are prevalent, such as central and southern Kazakhstan. In particular, the findings are valuable for designing stable subgrades, mitigating frost-induced deformations in cold climates, and improving the reliability of structures built on collapsible loess and silty deposits.

At the same time, the research acknowledges certain limitations. The tests were conducted under controlled laboratory conditions, which may not fully replicate long-term field performance. Factors such as durability of geosynthetics under varying climatic conditions, chemical interactions with soil, and large-scale construction practices were beyond the scope of this study. Therefore, while the results provide strong evidence of the effectiveness of geosynthetics, their practical implementation should be adapted to site-specific conditions.

Future research should extend this framework by conducting field-scale experiments, evaluating additional geosynthetic types, and considering long-term environmental impacts. Such efforts will refine design guidelines and broaden the applicability of geosynthetics in geotechnical engineering.

In conclusion, this research underscores the critical role of geosynthetics in improving the mechanical characteristics of weak soils and offers practical recommendations for civil engineering projects. By highlighting both the benefits and limitations, the study contributes to the development of more resilient, sustainable, and cost-effective soil stabilization strategies for real-world applications.

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