ABSTRACT

of the dissertation by Saule Zhakimbekovna Jumadilova titled:
"Modern effective methods of soil reinforcement for creating reliable foundations for buildings and structures" submitted for the degree of Doctor of Philosophy (PhD) in the educational program 8D07321 – «Construction»

Relevance of the Research.

With the expansion of the city of Almaty and the shortage of areas formed by strong coarse-grained soils, increasingly unfavorable areas, both from a construction and seismic standpoint, are being utilized for development. These areas include regions composed of macroporous, loess deposits, water-saturated and saturated soils, which form mountainous and foothill regions, as well as underdeveloped adjacent territories. These areas are often located on hillsides and slopes with inclinations greater than 15 degrees to the horizontal, as well as on plateaus. It is precisely these areas that are designated for the construction of transport infrastructure, industrial and commercial facilities. Additionally, lands in peripheral urban zones, predominantly filled with artificial deposits, weak clay soils, or collapsible soils, are allocated for civil construction projects, including social infrastructure and affordable housing.

One of the key challenges is construction in seismically active areas, which poses certain difficulties in foundation design and structure erection. Under such conditions, specialized engineering measures are required to improve the reliability of foundations. Global practice has shown that improving the construction properties of soils is not only an effective method for enhancing the safety of structures but also an economically beneficial solution for the early stages of construction. In this context, soil reinforcement and stabilization technologies continue to evolve actively.

The dissertation examines modern effective methods of soil reinforcement for creating reliable foundations for buildings and structures under complex geological conditions. Currently, many technologies have been developed and successfully applied for the strengthening and stabilization of weak soils, which are used in various construction projects. This is particularly important in seismically active zones, where foundation reliability is a key safety factor.

Modern methods such as injection technologies, the use of geosynthetic materials, and deep soil mixing (DSM) technologies significantly improve the physical and mechanical properties of weak soils. These methods reduce the likelihood of deformations and increase the load-bearing capacity of foundations even in complex engineering-geological conditions. It is important to note that the advancement of these methods occurs not only through the introduction of new materials but also through the development of engineering solutions, such as the use of composite materials and innovative technologies for real-time monitoring of soil foundation conditions.

The aim of the dissertation is to conduct theoretical and experimental research to substantiate the most effective methods for reinforcing weak clay, water-saturated, and fill soils.

The object of the research consists of weak clay, sandy, loess and other soils with low bearing capacity, high compressibility, and susceptibility to deformations under load, which are used as foundations.

The subject of the research includes methods and technologies for reinforcing weak soils, aimed at increasing their load-bearing capacity and reducing deformation properties during the construction of buildings and structures.

Research objectives:

– identify the most effective methods for reinforcing weak soils, considering the specific characteristics of regional soil conditions;

– investigate the mechanical properties and application of geosynthetic materials to increase the load-bearing capacity of fill and weak soils;

– evaluate the effectiveness of injection compounds (resins) and other additives for improving the properties of loose sands, clayey, and gravel soils;

– study the application of the wet deep mixing method for strengthening loess and water-saturated soils, as well as the effectiveness of reinforcing soil-cement columns;

– justify the effectiveness of weak soil reinforcement methods on specific projects using modern geotechnical software and finite element methods.

Scientific novelty of the dissertation consists of the following:

– test setups were developed for assessing the tensile strength of geosynthetic materials to obtain short-term and long-term strength parameters under different loading conditions;

– a methodology for testing geosynthetic materials, reflecting their performance in soil foundations was developed;

– data on the short-term and long-term strength of geosynthetic materials used for reinforcing fill soils were obtained;

– parameters of reinforced soils with various compositions and properties were obtained when reinforced with polyurethane resins and other additives;

– key physical and mechanical parameters of soil-cement columns constructed in the soils of Southern Kazakhstan were obtained;

– a relationship between soil properties and their petrographic and physical composition, as well as their initial state, was established;

– the need for similar studies to control the quality of reinforcement in all areas where the deep mixing technology is recommended was identified;

– a test rig for model testing of reinforced soil-cement columns under compression was developed and manufactured;

– patterns of increasing load-bearing capacity using various reinforcing materials were identified, and the conditions for their practical application were determined.

Practical significance of the dissertation:

– practical recommendations have been developed for the use of polyurethane foams to reinforce loams, sands, and coarse-fragment soils, improving their stability during construction;

– data on the long-term strength of geosynthetic materials have been obtained, and their behavior under stepped and prolonged loading has been studied;

– it has been established that DSM soil-cement columns exhibit anisotropic properties in the vertical and horizontal directions, with their mechanical parameters depending on moisture content;
– it has been determined that additional reinforcement of soil-cement columns increases their uniaxial compressive strength and, accordingly, the load-bearing capacity of the reinforced soil mass

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– it has been established that DSM soil-cement columns exhibit anisotropic properties in both vertical and horizontal directions, with their mechanical parameters depending on moisture content;
– it has been determined that additional reinforcement of soil-cement columns increases their uniaxial compressive strength and, consequently, the load-bearing capacity of the reinforced soil mass.

The following methods were used in the dissertation: laboratory studies, which involved the creation of test setups for geosynthetic materials and soil-cement columns, as well as strength and tensile testing of various samples, such as injection compounds and reinforced elements; theoretical research, aimed at analyzing existing soil reinforcement methods based on scientific literature and standards, developing testing methodologies to assess the impact of reinforcement on the strength of soil-cement columns, and substantiating the role of soil-geosynthetic interaction in increasing load-bearing capacity; field tests, to evaluate the effectiveness of injection and mechanical reinforcement methods at construction sites and to monitor the durability of reinforced soils; economic analysis, which involved calculating the feasibility of various reinforcement methods, considering costs, project timelines, and their operational efficiency; computer modeling, using PLAXIS 3D and MIDAS 3D software, to optimize the selection of soil reinforcement methods under different loads based on construction conditions.

Key points to be defended:
– results of laboratory and field studies on selecting the optimal amount of polyurethane foam in soil masses composed of loams, sands, and coarse-fragment soils to enhance their strength and stability;
– results of laboratory studies on the long-term strength characteristics of geosynthetic materials, including hexagonal geogrid TX-170, polypropylene geogrid SD-40, uniaxial geogrid SO-90, and nonwoven geotextile;
– methodology for testing geosynthetic materials, reflecting their performance in soil foundations;
– research results on the conditions necessary to achieve the required strength of soil-cement columns under various engineering and geological conditions;

– research results on the potential to increase the strength of soil-cement columns through additional reinforcement using I-beam or pipe profiles, as well as spatial frameworks made of reinforcing bars.

The reliability of the dissertation results is confirmed by the use of certified equipment for conducting field and laboratory tests, comparison of the obtained results with those of other researchers, sufficient replication of tests and studies, and the comparison of test results with analytical calculations in PLAXIS 3D.

The author's personal contribution to science lies in setting the research objectives, conducting field and laboratory tests, determining the optimal consumption of polyurethane foam for reinforcing weak soils, developing a methodology for reinforcing DSM columns, and obtaining new data on the strength and effectiveness of geosynthetics within the reinforced soil mass.

The testing and implementation of the dissertation's scientific results confirmed the practical value of the developed methods and their successful application in real-world conditions. The following confirmations of implementation were obtained for the dissertation topic: Act of practical implementation of the dissertation research results at "AsadService" LLP dated April 10, 2024; Act of practical implementation at "Geofocus" LLP dated May 15, 2024; Act of implementation of the research results into the educational process at TOO International Educational Corporation Ltd. dated June 24, 2024. The main provisions of the work were presented and discussed at international seminars:

- interuniversity scientific seminar "Digital Engineering in Civil Construction" at StPPU (2024);

-international seminar "Engineering Surveys, Design, and Construction of Earthquake-Resistant Buildings and Structures" (2024).

The results of the dissertation research have been published in the following scientific journals:

1. The use of geosynthetic materials to increase the bearing capacity of soil cushions // A Scientific Internet-Journal «Nanotechnologies in construction». 2024, 16 (4), 342-355.
2. Sposoby zashchity fundamentov ot korrozii ikh preimushchestva i nedostatki // Vestnik Kazakhskoy golovnoy arkhitekturno-stroitel'noy akademii. 2017, 3(65), 209-213.
3. Technology for strengthening soil materials using two-component polyurethane material GEOPUR // QazBSQA Khabarshysy. 2024, 1(91), 65-77.
4. Issledovaniya vliyaniya armirovaniya geosinteticheskimi materialami na prochnost' gruntov v usloviyakh trekhosnogo szhatiya i odnoplostnostnogo sreza // QazBSQA Khabarshysy. 2024, 3(93), 121-139.
5. Injection of two-component Geopur resin for strengthening sandy soils // QazBSQA Khabarshysy. 2024, 3(93), 95-107.
6. Issledovanie fiziko-mekhanicheskikh svoystv geosinteticheskikh materialov primenitel'no dlya raboty v gruntovykh osnovaniyakh // Vestnik AO «KazNIISA». 2023, 4(10,11,12), 78-94.

On the dissertation topic, six scientific papers have been published including: 1 article in journals indexed by Scopus and Web of Science databases;

4 articles in journals from the list of the Committee for Quality Assurance in the Sphere of Science and Higher Education of Ministry of Science and High education of the Republic of Kazakhstan; 1 article in other publications of the Republic of Kazakhstan.

Structure and volume of the dissertation work The dissertation is presented on 169 pages of typed text and consists of an introduction, 5 sections, and main conclusions. The main body of the text contains 133 pages, with 36 pages of appendices 23 tables, 80 figures and the list of references includes 100 sources.

Main content of the work. The introduction of the dissertation substantiates the relevance of the research, which is related to the need to improve the load-bearing capacity of weak soils under complex geological conditions during construction. The aims and objectives of the research are formulated, focusing on the development and optimization of soil reinforcement methods to enhance their stability and durability. The scientific novelty is justified by proposing new approaches to soil reinforcement and evaluating their effectiveness.

In the first chapter, "Review of modern methods for strengthening weak soils," a comprehensive review of literature sources is provided, examining the existing methods for reinforcing weak soils. Special attention is given to techniques such as injection of strengthening compounds, Jet Grouting, Deep Soil Mixing, and the use of geosynthetic materials. The main technologies for implementing these methods are described, and their advantages, disadvantages, and areas of application are identified. Theoretical approaches to evaluating the effectiveness of these methods are analyzed, along with their practical application in construction. Based on the analysis, key research gaps are identified, justifying the need for further study and optimization of reinforcement technologies to improve the load-bearing capacity of soils in the southern regions of Kazakhstan.

Conclusions for Chapter One:

1. An analysis of soil reinforcement methods was conducted, highlighting the most advanced and effective techniques for strengthening weak macroporous, water-saturated clayey, sandy, and fill soils, as well as other structurally unstable soils.
2. The application of new injection materials, such as polyurethane foams, was studied. Their advantages and disadvantages were identified, and research directions for their potential use in reinforcing weak macroporous, water-saturated, and fill soils in confined urban construction conditions were outlined.
3. Modern foundation reinforcement technologies that do not require soil removal were explored. The use of rolled elements and the wet deep mixing method allows for deep reinforcement by increasing initial soil density and enhancing load-bearing capacity with the addition of reinforcing elements.
4. Various types of geosynthetic materials were identified, whose application can increase load-bearing capacity and reduce deformations in embankments and soil cushions made of fill soils.
5. The geological diversity of the regions, using the examples of Almaty and Shymkent deposits, was demonstrated. Key types of soils were identified that cannot be used as foundations for buildings and structures without replacement or reinforcement. Basic structural schemes for reinforcing weak foundations using modern methods and technologies were proposed.

In the second chapter, “Injection Method for Foundation Reinforcement with Strengthening Compounds,” the injection method for reinforcing foundations using the two-component resin Geopur is discussed. The conditions and programs for conducting experiments are described, including the parameters of sandy, cohesive, and gravel soils, as well as the selected reinforcement methods, such as injection technologies. The results of the tests, including changes in the physical and mechanical properties of the soils, such as density, compressive strength, and deformation characteristics are presented. Based on the data obtained, an analysis of the method’s impact on improving the load-bearing capacity of the soils was conducted, along with an evaluation of its effectiveness for foundation reinforcement.

Conclusions for Chapter Two:

1. The natural properties of the soils subject to reinforcement using injection of strengthening compounds were selected and studied, and a research program was developed.
2. Reinforcement of sandy soils with varying initial densities, loam in natural and water-saturated states, and gravel soils with different initial densities was carried out. Data on the physical and mechanical properties before and after reinforcement were obtained.
3. Data on the consumption of Geopur polyurethane resin required to achieve the necessary strength for each type of tested soil were collected.
4. Based on the injection method studies, the following resin compositions are recommended depending on soil type: for firm and semi-firm clay soils—Geopur 082/180; for plastic and flowing clay soils—no less than Geopur 082/290; for sands—Geopur 230; for gravel soils—Geopur 082/90.
5. For injection operations, it is recommended to use IBO anchor rods of types R32S and R32N, depending on the soil characteristics. The consumption of materials for reinforcing loams and other soil types ranges from 100 to 600 kg/m^3, depending on their condition and type.
6. Field tests were conducted at a site to reinforce loams and coarse-fragment soils to a depth of 3 meters from the surface. Control samples were taken along the length of the injection anchors to assess the quality of the reinforcement process. Monolithic masses were sampled to study the injection process during the reinforcement of coarse-fragment soils with different initial densities.

In the third chapter, “Justification for Soil Reinforcement Using the Deep Soil Mixing (DSM) Method,” the Deep Soil Mixing (DSM) method for soil reinforcement is examined. The properties of soils when applying this method are described, and the physical and mechanical characteristics of soil-cement columns are determined. A laboratory research program is presented, detailing the methodologies and equipment parameters used, followed by an analysis of the results. The chapter also focuses on the strength of composite columns. As part of the research, composite columns were reinforced using steel I-beams, pipes, and rebar in the form of a spatial framework. Four models were created for testing. The results of DSM reinforcement are presented, and an analytical calculation of the DSM models was conducted for comparison. The chapter also provides a justification for the effectiveness of using the Deep Soil Mixing method for soil reinforcement.

Conclusions for Chapter Three:

1. Experimental DSM columns were prepared to control the quality of mixing and homogeneity of uniaxial compressive strength of soil-cement reinforcement elements. Control samples were taken 28 days after the expected strength gain in both horizontal and vertical directions. Tests were conducted in natural and water-saturated conditions. Data on the physical and mechanical properties of the soil before and after reinforcement were obtained.
2. A testing program for DSM column models at a 1:10 scale was prepared, with various options for reinforcing the column shafts. Metal profiles in the form of I-beams, pipes, and spatial frameworks made of rebar were used for reinforcement.
3. A special setup for testing the DSM models under compression was developed. The tests were carried out with a stepwise increasing load until failure. Graphical dependencies were obtained showing the change in deformation of the model with increasing vertical force.
4. Control samples were tested in a triaxial compression apparatus. Samples with a diameter of 50 mm were tested, with compressive strength and deformation modulus being the controlled parameters.
5. The test results of trial piles showed variations in compressive strength depending on moisture content. An issue with the mixing of coarse sand and local loam in the upper part of the test piles was observed, leading to a heterogeneous composition and inconsistent strength along the height of the DSM shaft. The tests revealed actual compressive strength values and anisotropy between vertical and horizontal strength values, with a difference of about 20-28%, and a reduction in strength under water saturation reaching up to 10%.
6. The compression test results of the DSM model samples demonstrated a significant increase in load-bearing capacity due to reinforcement. The increase amounted to 100-150% compared to the unreinforced columns. A limitation of the physical modeling was the absence of lateral confinement, which is typical for DSM behavior in soils.

In the fourth chapter, “Surface Reinforcement of a Soil Cushion Reinforced with Geosynthetic Materials,” the research methodology and equipment parameters used to study soil reinforcement with geosynthetic materials are described. Laboratory studies were conducted to determine the mechanical properties that characterize the long-term tensile strength of geosynthetics, aimed at increasing load-bearing capacity. Special attention is given to tests on the interaction at the soil-geosynthetic interface, including an analysis of the interaction between geosynthetics and gravelly soils. The chapter concludes with the presentation of test results and an assessment of the effectiveness of using geosynthetic materials for reinforcing soil cushions.

Conclusions for Chapter Four:

1. Test setups were developed and prepared for testing geosynthetic materials, including geogrids, geotextiles, and geomembranes, under tension to determine long-term strength parameters. These setups allow for testing with stepwise increasing loads until failure, as well as constant loads over extended periods.
2. A testing program was developed to determine the mechanical parameters of the main geosynthetic materials in use.

3. The shear apparatus was upgraded to study the properties at the soil-geosynthetic interface. Results were obtained for tests with gravelly soil and hexagonal geogrid at the shear plane contact.
4. Tensile strength testing of geosynthetic materials under kinematic conditions showed a reduction in strength at break for all materials. The reduction ranged from 28% to 42% for various types of geogrids. The relative elongation at break decreased by 8.6% for hexagonal geogrid and by 30% for biaxial geogrid, while uniaxial geogrid showed an increase in relative elongation. For geotextiles, tensile strength decreased by 15.7%, while relative elongation increased by 26.5%. These results likely reflect the long-term strength of the materials.
5. Tests using the modified shear apparatus with gravelly soil showed that the effectiveness of enhancing the mechanical properties of soil cushions reinforced with geosynthetic materials depends on accurately determining the properties at the geosynthetic-soil interface.

In the fifth chapter, "Recommendations for the Calculation and Design of Reinforced Foundations," finite element calculations were presented using the MIDAS GTS NX software, with examples from construction sites in Almaty and Shymkent. The chapter also includes the results of the software-based analysis of the stress-strain state of the foundation before and after reinforcement. These results include the evaluation of stresses along the foundation base and an analysis of the deformations in the building's foundation. The calculations confirmed a reduction in deformations and an increase in load-bearing capacity when reinforcing the soil foundation, which positively impacts the stability and durability of the structure.

Conclusions for chapter five:

1. The example of foundation reinforcement calculations in Almaty showed that without reinforcement, the maximum foundation settlements exceeded the allowable limits (settlements for Blocks 1-10 ranged from 17.04 to 20.22 cm, and the parking structure deformed by 18.5 cm), and the soil’s load-bearing capacity was unsatisfactory.
2. The utilization factor of the soil's load-bearing capacity under the foundation base was 132.9%, exceeding the standard. A combined reinforcement method was proposed, including a gravel cushion (0.6-1.2 m thick) and deep soil mixing (DSM) columns with diameters of 1000-1200 mm and lengths of 4-9.5 m.
3. After reinforcement, the settlement was reduced to 3.4-4.56 cm, which meets the regulatory standards.
4. In Shymkent, the foundation reinforcement calculation example showed that without reinforcement, the maximum settlement of the foundation slab for Block A was 43.06 cm, and the differential settlement was 0.0032, exceeding the limits set by SP RK 5.01-102-2013 (22.5 cm and 0.0030, respectively).
5. After reinforcing the foundation with DSM soil-cement piles (Ø1000 mm, 14 m long, 820 units), the maximum settlement was reduced to 17.76 cm, and the differential settlement to 0.0021, which complies with the standards. The forces in the piles did not exceed the allowable load (1384.2 kN < 1396.8 kN).

CONCLUSION

1. A significant portion of the intensively developed territory in southern Kazakhstan is located on soils with specific properties. These include subsiding, loess, swelling, and overly saturated weak soils. Construction practice shows that building on such soils requires measures for reinforcing soil foundations.
2. Injection technology is recommended for reinforcing soils in constrained urban development conditions. This recommendation is based on the compact nature of the equipment used and the sufficient effectiveness of the reinforcement process. The following two-component polyurethane compositions are recommended for use: for firm and semi-firm clays—Geopur 082/180; for plastic and flowing clays—Geopur 082/290; for sands—Geopur 230; for gravel soils—Geopur 082/90. IBO anchor rods are used for injection: type R32S for gravel soils and type R32N for clay and sandy soils. Geopur consumption rates are: for firm loams—100 kg/m³, for stiff plastic loams—300 kg/m³, for soft plastic loams—600 kg/m³; for sands—100 kg/m³, for gravel soils—150-200 kg/m³, and for firm clay soils—180-200 kg/m³.
3. It was found that the average density of the reinforced soil generally decreases. This is due to the expansion and volume increase of the Geopur resin after its introduction. The initial density decreases, ranging from 1.28 t/m³ at a depth of 0.9 m to 1.48 t/m³ at a depth of 4.2 m. It is believed that the closer to the surface, the lower the natural pressure, and the greater the likelihood of soil loosening during the foaming process of the Geopur material. It was established that upon the introduction of Geopur, the texture of the soil becomes structured, transitioning from the class of dispersed soils to the class of semi-rocky soils. The strength of the structured soil increases and is characterized by the uniaxial compressive strength, R. The studies showed that the value of R varies with depth, ranging from 1.94 MPa at a depth of 0.9 m to 4.57 MPa at a depth of 4.2 m. These data indicate a sufficient strength gain as a result of the injection process.
4. The use of the wet deep mixing (DSM) technology for soil reinforcement in the regions of Kazakhstan is a pioneering process, making the determination of the physical and mechanical parameters of the reinforcing elements essential for accurately assessing the actual load-bearing capacity of the reinforced masses. For testing purposes, experimental soil-cement columns were prepared, and samples were taken along the height of the columns up to 2 meters from the column head in both horizontal and vertical directions. Since the groundwater level at the site is near the base of the piles, the sampling area was limited to the beginning of this level. Uniaxial compression tests were conducted on the samples in both natural and water-saturated conditions.
5. The test analysis showed that in pile No. 1, compressive strength depends on moisture content, highlighting the need to account for it when evaluating mechanical characteristics. In the upper part of pile No. 2, the mixing of coarse sand was observed, which explains the absence of significant changes in compressive strength under varying moisture conditions. The increase in sand content does not affect strength properties when saturated. For pile No. 3, it was observed that the natural groundwater level influences the strength of the soil-cement.

6. IEC (International educational corporation) and JCS «KazRICA»conducted studies on soil-cement columns at experimental construction sites, sampling from depths of 2-3 meters for testing in uniaxial and triaxial compression devices. The results revealed a strength anisotropy of 20-28% and a reduction in strength under water saturation conditions by up to 10%.
7. Laboratory studies on 1:10 scale column models with different types of reinforcement demonstrated a significant increase in material load-bearing capacity. The increase amounted to 100-150% compared to unreinforced columns. A limitation of the physical modeling was the absence of lateral confinement, which is characteristic of DSM performance in soils. Further studies on column models, considering lateral confinement, are ongoing.
8. The reliability of the laboratory test results was confirmed by analytical calculations using PLAXIS 3D software. The calculations used parameters comparable to the ones in the physical models. The results confirmed the effectiveness of reinforcing soil-cement columns with stiffer materials, showing a reduction in deformations and an increase in the load-bearing capacity of DSM columns.
9. Based on the results of the conducted tests, it is difficult to draw definitive conclusions due to the limited number of samples available for analysis. To fully understand the behavior of soil-cement in such engineering and geological conditions, additional tests are required. This will provide more extensive data and allow for a more accurate assessment of the material's characteristics, which, in turn, will contribute to the development of more effective solutions and ensure the foundation's reinforcement.
10. Tensile tests on geosynthetic materials under kinematic loading conditions showed a reduction in tensile strength for all materials. The reduction ranged from 28% to 42% for various types of geogrids and geonets. Relative elongation at break decreased by 8.6% for hexagonal geogrid and by 30% for biaxial geogrid. However, for uniaxial geogrid, an increase in relative elongation was observed. For geotextiles, tensile strength decreased by 15.7%, while relative elongation increased by 26.5%. These results reflect the materials' strength under prolonged tensile loads.
11. Tests using the modified shear apparatus, with gravelly soil as an example, demonstrated that the effectiveness of improving the mechanical properties of soil cushions reinforced with geosynthetic materials depends on accurately determining the properties at the geosynthetic-soil interface. Such studies should be continued with other types of soils.
12. The data presented in the dissertation reflect the results of the soil reinforcement methods under static conditions only. The impact of seismic activity on reinforced foundations may reveal factors that could affect the overall performance of reinforced soil masses. These factors should be studied in future research and incorporated into recommendations for real projects.
13. The data presented in the dissertation reflect the results of the application of the considered soil reinforcement methods under static conditions only. The impact of seismic activity on reinforced foundations may reveal factors that could affect the overall performance of reinforced soil masses. These factors need to be studied in our future research and will be incorporated into recommendations for real-world projects.