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RESEARCH ARTICLE

EFFICIENCY OF CLAY SOILS REINFORCEMENT IN CONSTRUCTION

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Abstract. *This article analyses methods for reinforcing clay soils during the construction of foundations. Clay soils possess specific physical and mechanical properties that present challenges in construction. The article examines these properties to understand the causes of problems encountered when erecting structures on such soils. Particular attention is paid to modern reinforcement technologies – the use of geosynthetic materials. Their types, characteristics and methods of application are described. The mechanisms of interaction between geosynthetics and clayey soil and their influence on the stability and deformation characteristics of the foundation are examined. The results of laboratory and field tests assessing changes in the strength and deformation characteristics of the soil following reinforcement are presented. The methodologies, equipment and data processing methods are described. Graphs and tables are provided, illustrating changes in soil characteristics depending on the type and quantity of reinforcing material. A comparative analysis of reinforcement methods has been carried out based on criteria of technical effectiveness and economic viability. The costs of materials, labour intensity, duration of works and the resulting effect (increased load-bearing capacity, reduced deformations) have been assessed. Based on the analysis, recommendations are proposed for selecting the optimal reinforcement method depending on construction conditions, the type of structure and the required characteristics of the foundation. In conclusion, promising areas for further research are discussed: the application of new materials and technologies, and the improvement of methods for calculating and designing reinforced foundations. The need for further research to expand the scope of application of reinforced soils and to improve their reliability and durability is emphasised.*

Keywords: *soil reinforcement, clay soils, foundation construction, geosynthetics, soil strength properties, soil deformability, reinforcement efficiency, economic feasibility*

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ҒЫЛЫМИ МАҚАЛА

ҚҰРЫЛЫСТАҒЫ САЗДЫ ТОПЫРАҚТЫ НЫҒАЙТУДЫҢ ТИІМДІЛІГІ

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Аңдатпа. *Мақала іргетас құрылысында қолданылатын сазды топырақтарды нығайту әдістерін зерттеуге арналған. Сазды топырақтардың физикалық және механикалық қасиеттерінің ерекше ерекше жиынтығы құрылыста белгілі бір қиындықтар тудырады. Мақалада осы қасиеттер егжей – тегжейлі қарастырылып, мұндай топырақтарда құрылыс жүргізу кезінде туындайтын мәселелердің себептерін түсінуге бағытталған. Қазіргі заманғы арматуралау технологияларын, атап айтқанда геосинтетикалық материалдарды қолдануға ерекше назар аударылады. Геосинтетикалық материалдардың түрлері, олардың сипаттамалары және топырақ құрылысында қолдану әдістері терең зерттелген. Геосинтетикалық материалдар мен сазды топырақ арасындағы өзара әрекеттесу механизмдері және бұл өзара әрекеттесудің негіздің жалпы тұрақтылығы мен деформациялық сипаттамаларына әсері қарастырылған. Мақалада топырақты нығайтқаннан кейін оның беріктік және деформациялық сипаттамаларындағы өзгерістерді бағалауға бағытталған зертханалық және далалық сынақтардың нәтижелері ұсынылған. Сынақ рәсімдері, қолданылған жабдықтар және алынған деректерді өңдеу әдістері сипатталған. Нығайтқыш материалдың түрі мен мөлшеріне байланысты топырақ сипаттамаларындағы өзгерістерді көрсететін графиктер мен кестелер берілген. Техникалық тиімділік пен экономикалық негізділік критерийлеріне сүйене отырып, топырақты нығайтудың әртүрлі әдістерінің салыстырмалы талдауы жүргізілді. Материалдардың құны, еңбек сыйымдылығы, жұмысты аяқтау мерзімі және негіздің көтергіш қабілетін арттыру мен деформацияны азайту тұрғысындағы нәтижесі бағаланды. Талдау негізінде құрылыс алаңының нақты жағдайларына, құрылым түріне және негіздің талап етілетін сипаттамаларына байланысты оңтайлы нығайту әдісін таңдау бойынша ұсыныстар жасалды. Мақала сазды топырақты нығайту саласындағы әрі қарай зерттеуге перспективалы бағыттарды талқылаумен аяқталады. Онда жаңа материалдар мен технологияларды қолдану мүмкіндіктері, сондай – ақ нығайтылған негіздерді есептеу және жобалау әдістерін жетілдіру мәселелері қарастырылды. Нығайтылған топырақтардың қолдану аясын кеңейту және олардың сенімділігі мен беріктігін арттыру үшін қосымша зерттеулер жүргізу қажеттігі ерекше атап көрсетілген.*

Түйінді сөздер: *топырақты нығайту, сазды топырақтар, іргетас құрылысы, геосинтетикалық материалдар, топырақтың беріктік қасиеттері, топырақтың деформациялану қабілеті, нығайту тиімділігі, экономикалық тиімділік*

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НАУЧНАЯ СТАТЬЯ

ЭФФЕКТИВНОСТЬ АРМИРОВАНИЯ ГЛИНИСТЫХ ГРУНТОВ В СТРОИТЕЛЬСТВЕ

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Аннотация. *Статья посвящена исследованию анализа методов усиления глинистых грунтов, применяемых при возведении фундаментов. Глинистые грунты обладают специфическим набором физико-механических свойств, представляющих определённые трудности при строительстве. В статье детально изучаются эти свойства, чтобы понять причины возникновения проблем, связанных с возведением сооружений на таких почвах. Особое внимание уделено современным технологиям усиления, в частности, применению геосинтетических материалов. Подробно описаны типы геосинтетиков, их характеристики и способы применения в грунтовом строительстве. Рассмотрены механизмы взаимодействия геосинтетических материалов с глинистым грунтом и влияние этого взаимодействия на общую устойчивость и деформационные характеристики основания. В работе представлены результаты лабораторных и полевых испытаний, направленных на оценку изменений в прочностных и деформационных характеристиках грунта после его усиления. Описаны методики проведения испытаний, используемое оборудование и методы обработки полученных данных. Приведены графики и таблицы, иллюстрирующие изменение характеристик грунта в зависимости от типа и количества армирующего материала. Проведён сравнительный анализ различных методов усиления грунтов по критериям технической эффективности и экономической оправданности. Оцениваются затраты на материалы, трудоёмкость работ, сроки выполнения и полученный эффект в виде повышения несущей способности основания и снижения деформаций. На основании анализа предложены рекомендации по выбору оптимального способа усиления в зависимости от конкретных условий площадки строительства, типа сооружения и требуемых характеристик основания. В заключение статьи обсуждаются перспективные направления дальнейших исследований в области усиления глинистых грунтов. Рассматриваются возможности применения новых материалов и технологий, а также вопросы совершенствования методов расчёта и проектирования усиленных оснований. Подчёркивается необходимость проведения дополнительных исследований для расширения области применения усиленных грунтов и повышения их надёжности и долговечности.*

Ключевые слова: *армирование грунтов, глинистые грунты, строительство оснований фундаментов, геосинтетика, прочностные свойства грунта, деформируемость грунта, эффективность армирования, экономическая целесообразность*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

One of the most difficult and critical aspects of the construction process for buildings and structures is working with clay soils, which are characterized by low bearing capacity, high plasticity, and susceptibility to deformation. These properties can lead to significant problems, such as settlement of building foundations and structures. Construction on clay soils is a complex engineering task due to the specific properties of these soils, such as high compressibility, tendency to swell and shrink, and low bearing capacity. These characteristics make it necessary to take special measures to reinforce the foundations in order to ensure the stability and durability of the structures being erected.

Clay soils are one of the most common types of soil found in nature. They are characterized by a high clay content, which makes them particularly susceptible to deformation and various types of damage. Clay is a mineral substance with high plasticity, low permeability, and compressibility, which makes it difficult to work with in engineering. It is formed as a result of the destruction of minerals under the influence of water and other physical and chemical processes. Clay soils have special physical and mechanical properties that must be taken into account when designing and constructing various structures.

Clay soils are classified based on their physical and mechanical properties and composition, according to various characteristics such as particle size distribution, clay particle content, plasticity, moisture content, and other parameters. Depending on these characteristics, clay soils are divided into several main types:
- loam - clayey soils of medium plasticity, containing 20% to 40% clay. They have good load-bearing capacity and can be used for building foundations and road surfaces;
- clays - highly plastic clay soils containing more than 40% clay. They have high compressibility and require special measures for reinforcement during construction;
- Sandy-clay soils are soils containing both clay and sand. They have medium plasticity and can be used for the construction of various structures.

Professor V.V. Okhotin **(Okhotin, 2012)** developed a classification of clay soils according to their physical and mechanical properties **(Table 1)**.

Table 1
Classification of clay soils (author's materials)

<table>
<tr><th rowspan="2">Soil name</th><th colspan="3">Particle content, % by weight</th></tr>
<tr><th>clayey</th><th>dusty</th><th>sandy</th></tr>
<tr><td>Heavy clay</td><td>>60</td><td>-</td><td>< 3</td></tr>
<tr><td>Clay</td><td>60-30</td><td>-</td><td rowspan="8">More than dusty</td></tr>
<tr><td>Heavy loam</td><td>30-20</td><td>-</td></tr>
<tr><td>Medium loam</td><td>20-15</td><td>-</td></tr>
<tr><td>Light loam</td><td>15-10</td><td>-</td></tr>
<tr><td>Loam</td><td>10-3</td><td>< 20</td></tr>
<tr><td>Sand</td><td>< 3</td><td>20-50</td></tr>
<tr><td>Dusty sand</td><td>< 3</td><td>> 50</td></tr>
<tr><td>Dusty soil</td><td>< 3</td><td></td></tr>
</table>

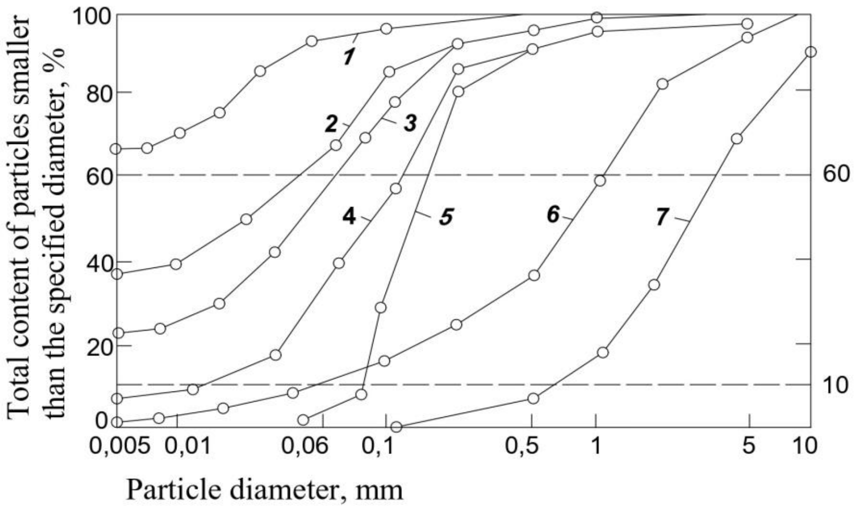

Figure 1 - Curves of the granulometric composition of sandy-silty-clay soils:
1 - heavy clay; 2 - light clay; 3 - loam; 4 -sandy loam; 5 - heterogeneous sand; 6 - homogeneous sand; 7 - gravelly sand.
(author's materials)

According to the curves **(Fig. 1)**, it is possible to determine the soil heterogeneity coefficient, where d60 and d10 are the diameters of particles smaller than which are contained in the soil by mass, i.e., 60 and 10 percent:

$$C_u = d_{60}/d_{10} \quad (1)$$

Clay soils can be either natural or artificially created. Natural clay soils are formed as a result of a long process of geological formation, while artificial clay soils can arise as a result of human activity, for example, when production waste solidifies.

Problems associated with the use of clay soils in construction may include clay soil shrinkage. Clay soils have a tendency to settle and shrink over time, which can lead to deformation and damage to structures. This phenomenon is particularly pronounced in conditions of changing humidity, when clay absorbs water and expands, and then shrinks as it dries. Such humidity cycles can cause cracks, which in turn can lead to serious structural problems. In addition to shrinkage, clay soils are also prone to swelling in winter. As the moisture content in the soil increases, clay can expand significantly in volume, placing additional stress on structures. This phenomenon can be particularly dangerous for buildings located in areas with high groundwater levels.

Another problem is the low permeability of clay soils, which hinders drainage and can lead to water accumulation in underground layers. Clay soils are highly dense, which can complicate the construction process and require additional effort. This can cause problems not only with building foundations and road surfaces, but also lead to drainage issues and increase the likelihood of flooding.

Due to their characteristics, clay soils require a special approach during construction work. Reinforcement of clay soils is necessary to increase their bearing capacity and reduce deformation during construction, improve their mechanical properties, and increase their resistance to various types of loads. Various methods are used for this purpose, such as soil reinforcement with reinforcement, injection works, and the installation of geogrids.

Let's consider several methods used in preparing foundations for building construction.

One of the main methods of strengthening foundations on clay soils is the use of pile foundations **(Garcia & De Albuquerque, 2019)**. Piles driven into more stable soil layers allow loads to be transferred to stable horizons, minimizing the impact of deformations in the upper layers. In addition, the use of bored piles and screw piles can significantly improve the characteristics of the foundation.

Study **(Kanatova et al., 2024)** presents a comprehensive analysis of the influence of geosynthetic materials on the strength characteristics of soils under triaxial compression and single-plane shear conditions. Particular attention is paid to evaluating the effectiveness of geogrids as a means of strengthening weak soils and identifying optimal options for their application. The results of the study provide important data for specialists in the field of geotechnical design and contribute to increasing the durability of engineering structures.

Another approach is to use drainage systems, which help lower the groundwater level and reduce the water saturation of clay layers **(Kumar et al., 2019)**. This, in turn, reduces the risk of soil swelling and shrinkage, which is especially important in conditions of seasonal temperature and humidity fluctuations.

The study in **(Dzhumadilova et al., 2024)** presents methods and a sequence of works using GEOPUR two-component polyurethane material to increase the bearing capacity of soils. The application of this technology has a triple effect: increased moisture resistance and sealing; stopping or reducing water inflow into underground structures; stabilizing soil cementation with increased stability of building foundations and underground structures. The process involves structuring and strengthening the soil, rock, and structures.

Methods of artificial soil stabilization involve the use of ready-made reinforcing elements made of various materials with high mechanical characteristics. In his work **(Dzhumadilova, 2025)**, the author notes that, unlike other groups of methods that change the properties of the soil and are more difficult to control, structural methods such as reinforcement are more popular. This group includes technologies such as the creation of soil cushions and soil reinforcement.

The article discusses the use of GEOPUR two-component polyurethane resin for strengthening sandy soils. Particular attention is paid to the process of soil stabilization by means of high-pressure cement injection, which improves water resistance, stabilizes the soil structure, and increases the strength of the anchorage. The study analyzes the effect of this resin on the physical and mechanical properties of weak and loose soils, confirming its effectiveness for consolidating such soil types.

It is also worth noting the methods of mechanical and chemical soil reinforcement **(Dzhumadilova, 2024)**. Mechanical compaction can be achieved using vibratory equipment or static pressure, which increases the density and bearing capacity of clay layers. Chemical reinforcement involves the use of special additives, such as cement or polymer solutions, which change the structure of the soil and increase its strength characteristics.

In their study **(Anagnostopoulos, 2007)**, the authors conducted experimental tests of the physical and mechanical properties of loam using the triaxial compression method under conditions of spatial stress simulated by a special device, thereby confirming the advantages of triaxial compression for accurate simulation of real loads.

2 MATERIALS AND METHODS

Let us take a closer look at the main methods of reinforcing clay soils, analyze their effectiveness and impact on foundation characteristics, and evaluate the advantages and disadvantages of various approaches. Reinforcement can significantly improve the mechanical characteristics of soil, increase its resistance to external loads, and minimize the risk of deformation of buildings and structures.

Soil reinforcement can be performed in various ways, depending on the conditions and requirements of the project:

The use of geogrids improves load distribution and increases soil strength. Geogrids **(Fig. 2)** can be made of polymer materials and laid in layers of soil.

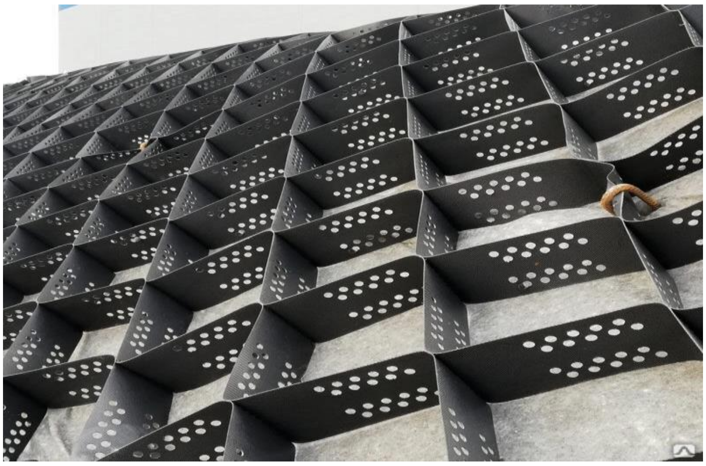

Figure 2 - Standard grid without perforation **(catalogue XY Geosynthetics, 2024)**

The advantages of using geogrids for foundations include increased load-bearing capacity, creation of a durable excess water filtration system, reinforcement of the building's soil base, reducing the risk of foundation damage due to external factors such as groundwater and soil deformation, and reducing the amount of building materials required to form the foundation cushion by 25-45% **(Fig. 3)**.

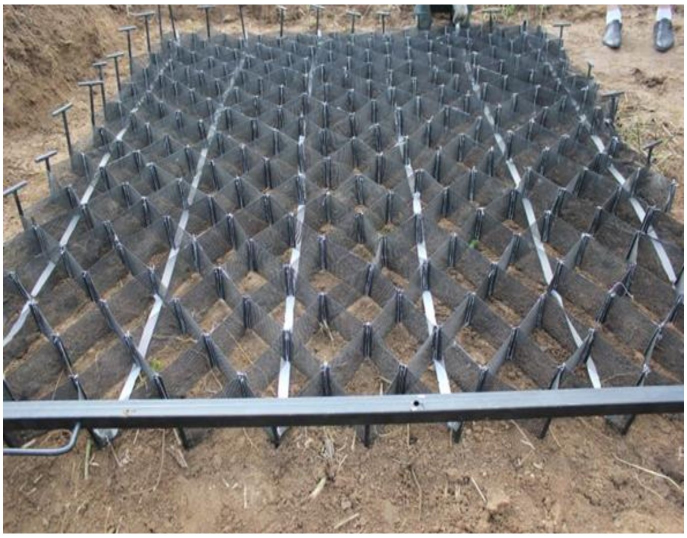

Figure 3 - Geosynthetic structure **(catalogue SW-Servis, 2024)**

In recent years, methods of reinforcing clay soils have been increasingly used in construction practice, which significantly improve their strength characteristics and resistance to deformation **(Kanatova & Dzhumadilova, 2024; Palmeira, 2009)** Reinforcement can be carried out in various ways, including the use of geosynthetic materials, metal elements, and other technologies **(Indraratna et al., 2011)**. The effectiveness of these methods is becoming particularly relevant in modern construction, where the requirements for the quality and reliability of structures are constantly growing.

The authors **(Ezzein & Bathurst, 2014)** conducted research based on measurements obtained from the interaction between soil and reinforcement using a device developed to evaluate the behavior of geosynthetically reinforced soil, taking into account the changing vertical distances between the reinforcement. The experiments included tests of geosynthetically reinforced soil with three layers of reinforcement: an actively tensioned layer and two passively tensioned adjacent layers. Shear stresses from the actively tensioned reinforcement were transferred to the passively tensioned reinforcement layers through the intermediate soil medium. It was concluded that the change in lateral soil pressure increases with increasing tensile deformation of the reinforcement and vertical distance between reinforcements, and decreases with increasing vertical stress.

Studies **(Wang et al., 2016)** have shown the tensile characteristics of geosynthetic reinforcements under static and constant loads. Tests were conducted to study the cumulative effect of load on the tensile capacity and behavior of geogrid reinforcements. Issues related to the mechanics of load transfer and reinforcement displacement were considered. According to the results obtained, under static load, the geogrid underwent gradual deformation with increasing load. No peak load was observed with the loading system used, and the deformation of the geogrid mainly occurred near the point of load application.

Scientists **(Morsy & Zornberg, 2021; Touahmia, 2014)** conducted mathematical modeling using the finite element method. The volume V of reinforced soil, when its bearing capacity is equivalent to that of the reinforced soil foundation, will be expressed as:

$$(V - nV_f)k_s E_l + nV_f E_f = E_{g.b} V \quad (2)$$

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It follows from (2) that:

$$k_s = \frac{\mathrm{E}_{g.b} V - \mathrm{n} E_f E_f}{(V - nV_f) E_f} \text{ and } V_f = \frac{V(\mathrm{E}_{g.b} - k_s E_l)}{\mathrm{n}(E_f - k_s \mathrm{E}_l)} \quad (3)$$

A mathematical model of a horizontally reinforced foundation showed that the bearing capacity of reinforced soil foundations, with compaction inside the soil of certain sizes, becomes an order of magnitude higher than that of non-reinforced foundations. At the same time, it has a high economic effect and reduces the cost of constructing buildings and structures.

The next method involves the use of geotextile materials to separate soil layers, prevent mixing of different soil types, and improve drainage **(Fig. 4)**. This can help reduce deformation and increase foundation stability.

Figure 4 - Geotextile under the foundation **(catalogue Baurex, 2024)**

The introduction of special solutions–injection reinforcement (e.g., cement or polymer) into the soil using injections–improves its strength characteristics and reduces settlement **(Fig. 5)**.

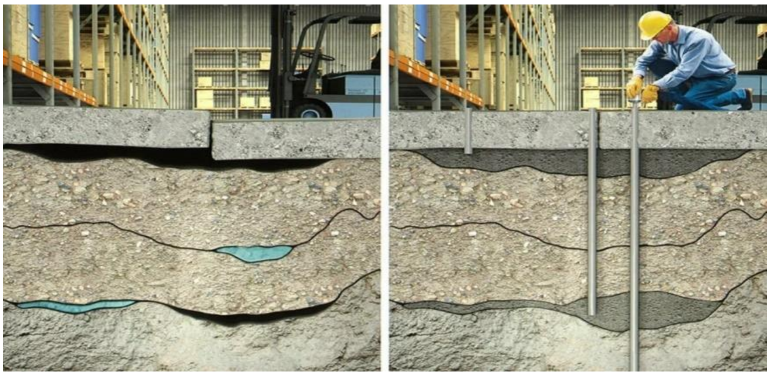

Figure 5 - Soil reinforcement by injection method **(catalogue SK Stroiz, 2024)**

3 RESULTS AND DISCUSSION

The use of various methods to reinforce the base under foundations improves the reliability and stability of structures. Injection reinforcement improves soil properties and increases its bearing capacity. Injection reinforcement has demonstrated a significant increase in the strength of the base. The method has made it possible to significantly increase the bearing capacity of the soil by filling its voids and creating additional bonds between particles.

The use of geotextile materials helps to separate soil layers and prevent them from mixing, which contributes to even load distribution. It has proven effective in preventing the migration of fine particles and improving drainage properties. Geosynthetically reinforced soil, geogrids, and geonets improve soil stability and ensure even load distribution. The models implemented have demonstrated that geotextiles reduce horizontal displacement and prevent the separation of shifting layers under vertical loads.

The geosynthetically reinforced soil method improved the stability of the structure. Experimental observations confirmed that the use of geosynthetics significantly increases the angle of internal friction and allows for a reduction in the size of the foundation, which leads to material savings and lower costs.

Mathematical modeling of the application of a horizontal reinforcement package showed that this method of foundation reinforcement can significantly improve the bearing capacity of the soil and reduce the likelihood of deformations and deformation processes. The modeling showed a significant increase in the shear strength limit, which leads to an increase in the stability of the foundation. Calculations demonstrated that horizontal reinforcement elements significantly reduce deformation and prevent potential structural integrity failures.

The use of various methods to reinforce the base for foundations in clay soils is a necessary and effective way to increase the reliability and stability of structures, which allows to extend their service life and ensure safe operation **(Grushin, 2019)**. The use of various reinforcement methods, such as injection reinforcement, geotextile materials, geosynthetic elements, geogrids, and horizontal reinforcement packages, significantly increases the strength and stability of foundations. The methods described not only increase the load-bearing capacity, but also optimize the cost processes in construction. The integration of models and practical applications of these methods makes it possible to study and predict the behavior of foundations in various operating conditions in more detail, which is an important aspect for increasing the reliability and durability of structures.

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4 CONCLUSIONS

To introduce and optimise methods for reinforcing clay soils into design and construction practice, it is recommended that the following measures be implemented at key stages. Systematic implementation of these recommendations will ensure a transition to the widespread, technically and economically sound application of reinforcement as a reliable foundation for construction on weak clay soils.

Stages of implementing measures in design and construction practice:

1. At the engineering survey stage.

Supplement standard physical and mechanical soil tests with specialised tests to assess 'soil–reinforcement' interaction parameters (direct shear, pull-out).

2. At the design stage:

– apply numerical modelling (FEM) using software packages (PLAXIS, GeoStudio) to account for soil non-linearity, phased construction and settlement prediction;

– for standard solutions, develop reference manuals with optimised reinforcement parameters (embedment depth, spacing, material type), based on proven methodologies;

– provide for a monitoring system (geodetic surveys, strain gauging) to verify the calculation models.

3. During the construction phase:

– ensure incoming quality control of geosynthetic materials;

– strictly adhere to technical specifications (level subgrade, tension, overlap of geosynthetic sheets, gentle compaction);

– provide training and professional development for staff working with geosynthetics.

4. In the area of regulatory support:

– update regulatory documents to include modern calculation methods (composite mechanics, FEM) and new types of geosynthetic materials;

– develop industry standards for testing methods for 'soil–reinforcement' contact.

5. In the area of scientific research, promising areas include:

– studying the long-term creep behaviour of geocomposites in aggressive environments;

– developing combined technologies (reinforcement with soil-cement elements, bored-injected piles with geosynthetic casings);

– developing methods for non-destructive testing of reinforcement condition in completed structures.

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