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RESEARCH ARTICLE

EXPERIMENTAL STUDIES OF THE SEISMIC VULNERABILITY OF A BUILDING MODEL ON STRENGTHENED SOILS

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Abstract. *The article is devoted to the problems of assessing seismic vulnerability and ensuring the seismic resistance of buildings in earthquake-prone regions. The threat of destructive earthquakes necessitates comprehensive studies of building seismic performance and the development of methods to enhance it. One of the approaches to improving seismic resistance is the strengthening of foundation soils. The study examines a method for reinforcing soils with relatively weak seismic properties by means of geosynthetic materials. The paper presents the results of an experimental investigation of the seismic performance of a building model founded on soil reinforced with geogrid. The experiment was conducted using a shaking table that simulated dynamic loading in the form of seismic vibrations. A specially fabricated small-scale model of a single-storey masonry building was used as the test object. The foundation soil was prepared from local loam. Accelerograms along the X Y Z axes were recorded using sensors installed on the model and processed with ZET LAB software. To evaluate the effect of geosynthetic reinforcement on soil settlement under dynamic loading simulating earthquake action, measurements of foundation settlement were carried out at each stage of the experiment. The results of the study demonstrated the effectiveness of geogrid-reinforced soil in improving soil strength and reducing settlement. The analysis of the recorded accelerograms allowed conclusions to be drawn regarding the feasibility and efficiency of applying this soil reinforcement method to low-rise buildings in order to reduce seismic vulnerability in areas of elevated seismic risk.*

Keywords: *seismic vulnerability, seismic resistance, soil reinforcement, geosynthetics, foundation reinforcement.*

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ҒЫЛЫМИ МАҚАЛА

БЕКІМДЕЛГЕН ТҰРАҚТЫ ТОПЫРАҚТАРДАҒЫ ҚҰРЫЛЫС МОДЕЛІНІҢ СЕЙСМИКАЛЫҚ ОСАЛДЫЛЫҒЫН ЭКСПЕРИМЕНТ АРҚЫЛЫ ЗЕРТТЕУ

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Аңдатпа. *Бұл мақалада сейсмикалық осалдықты бағалау және сейсмикалық қауіпті аймақтардағы ғимараттардың сейсмикалық төзімділігін қамтамасыз ету мәселелері қарастырылған. Деструктивті жер сілкінісінің қаупі ғимараттардың сейсмикалық төзімділігін зерттеуді және оны жақсарту әдістерін әзірлеуді қажет етеді. Ғимараттардың сейсмикалық төзімділігін арттырудың бір әдісі ғимараттың іргетасындағы топырақты нығайту болып табылады. Бұл жұмыс салыстырмалы түрде әлсіз сейсмикалық топырақтарды. Бұл мақалада геогридпен күшейтілген топырақ іргетасындағы ғимарат моделінің сейсмикалық төзімділігін тәжірибелік зерттеу нәтижелері берілген. Эксперимент сейсмикалық тербелістерге ұқсас динамикалық әсерлерді имитациялайтын сейсмикалық платформада жүргізілді. Зерттеу нысаны ретінде тапсырыс бойынша бір қабатты блокты ғимараттың шағын көлемді макеті пайдаланылды. Топырақ іргетасы жергілікті саздан жасалған. Модельге орнатылған сенсорларды және арнайы ZET LAB бағдарламалық құралын пайдаланып, XYZ осьтері бойынша акселерограммалар жазылды. Жер сілкінісін имитациялайтын динамикалық әсерге байланысты геосинтетикалық арматураның топырақтың шөгуіне әсерін талдау үшін тәжірибенің әрбір кезеңінде жер асты қабатының шөгінділерінің өлшемдері жүргізілді. Зерттеу геогридпен күшейтілген топырақтың топырақты нығайтуда және шөгуді азайтудағы тиімділігін көрсетті. Акселерограммаларды талдау сейсмикалық қауіпті аймақтарда сейсмикалық осалдықты азайту үшін аз қабатты ғимараттардың топырақ іргетасын нығайтудың осы әдісін қолданудың мүмкіндігі мен тиімділігі туралы қорытынды жасауға мүмкіндік берді.*

Түйін сөздер: *сейсмикалық осалдық, сейсмикалық төзімділік, топырақты нығайту, геосинтетика, іргетастарды нығайту.*

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НАУЧНАЯ СТАТЬЯ

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ СЕЙСМИЧЕСКОЙ УЯЗВИМОСТИ МОДЕЛИ ЗДАНИЯ НА УПРОЧНЕННЫХ ГРУНТАХ

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Аннотация. *Статья посвящена проблемам оценки сейсмической уязвимости и обеспечения сейсмоустойчивости зданий в сейсмоопасных регионах. Угроза разрушительных землетрясений вызывает необходимость исследований сейсмоустойчивости зданий и разработки методов её повышения. Одним из способов повышения сейсмоустойчивости зданий является усиление грунтов в их основании. В работе рассмотрен метод усиления относительно слабых по сейсмическим свойствам грунтов армированием геосинтетическим материалом. В статье приведены результаты экспериментального исследования сейсмоустойчивости модели здания на усиленном геосеткой грунтовом основании. Эксперимент был проведен на сейсмоплатформе, имитирующей динамическое воздействие по типу сейсмических колебаний. В качестве объекта исследования была использована специально изготовленная мелкомасштабной модель одноэтажного блочного здания. Грунтовое основание было сформировано из суглинков. С помощью закрепленных на модели датчиков и программного обеспечения ZET LAB, были произведены записи акселерограмм по осям XYZ. Для анализа влияния геосинтетического армирования на осадку грунта в следствие динамического воздействия, имитирующего землетрясение, проводились замеры на каждом этапе эксперимента. Проведенное исследование продемонстрировало эффективность армирования геосеткой грунта для его усиления и снижения просадочности. Анализ акселерограмм позволил сделать выводы о целесообразности и эффективности применения данного метода усиления грунтовых оснований невысотных зданий для снижения сейсмической уязвимости в зоне повышенного сейсмического риска.*

Ключевые слова: *сейсмическая уязвимость, сейсмоустойчивость, усиление грунтов, геосинтетические материалы, армирование оснований.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountabilityfor the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

The main objective of earthquake-resistant construction is to minimize the risk of damage to buildings and structures and to ensure the seismic safety of the population. This goal is achieved through the use of seismic-resistant design solutions and the optimization of structural systems (**Abaev et al., 2020; Tuleyev et al., 2024**). As research in the field of seismic design shows, the use of multi-criteria approaches aimed at limiting damage and increasing the overall stability of buildings can significantly reduce potential seismic losses (**Harle et al., 2021**). With the steady growth of urban density and population concentration in earthquake-prone regions, the issue of protecting buildings from seismic impacts is becoming increasingly relevant and requires a comprehensive scientific and technical approach (**An & Zhang, 2022; Olivares et al., 2021**).

In areas with high seismic activity, special attention is given to minimizing potential damage to buildings during strong earthquakes. Effective design in such conditions requires not only compliance with standards, but also a comprehensive analysis of possible damage mechanisms, allowing vulnerable areas of structures to be identified in advance and appropriate protective measures to be developed (**Al-Ansari & Senouci, 2020**). Recent studies show that the use of comprehensive seismic protection, including seismic isolation, damping, and optimization of structural solutions, significantly increases building stability and reduces potential damage, thereby ensuring occupant safety (**Erdoğan et al., 2023**). The constant threat of destructive earthquakes necessitates systematic research into the seismic vulnerability of buildings, as well as the development and implementation of effective methods to reduce it at all stages of the life cycle of buildings and structures (**Aldakhov et al., 2025; Nigmetov et al., 2022**). Thus, seismic risk assessment and the implementation of innovative protection methods are becoming integral components of modern earthquake-resistant construction.

To better understand damage mechanisms, it is necessary to study not only seismic resistance, but also the behavior of buildings and structures under seismic loading (**Kirgizbayeva et al., 2025**). Seismic vulnerability assessment and the justification of seismic resistance of structures can be performed using both computational and experimental methods. Experimental studies represent an essential source of information for the theory of seismic resistance of structures and the assessment of their seismic vulnerability (**Zito et al., 2022; Mendes et al., 2010**). In some cases, they serve to verify the validity of theoretical hypotheses and calculation methods, while in others, they allow key dynamic characteristics of structures to be determined, such as acceleration, vibration frequency, and damping decrements. Research can be conducted both in the field and in the laboratory, including the use of seismic and vibration platforms, which enable detailed investigation of structural response to seismic impacts of a given intensity (**Xu et al., 2022**). The main limitation of field testing lies in the need to prepare a special test site capable of reproducing seismic loads close to real conditions on actual structures, which is often constrained by high labor intensity and cost (**Isaković et al., 2023**). It is therefore most convenient to test building models on seismic platforms, where various earthquake scenarios can be simulated. Such tests are carried out when it is necessary to conduct a comparative analysis of the behavior of different structural modifications and technical solutions under identical seismic loading conditions. These studies allow partial characterization of complex physical processes occurring in building structures under seismic loads, as well as consideration of their interaction with foundation soils.

Many researchers have conducted studies aimed at reducing the seismic vulnerability of buildings. Scientists in Kazakhstan have also made a significant contribution to this field of research. For example, in 2024, a group of Kazakhstani scientists (**Nietbay et al., 2024**) investigated the prospects of using geotechnical seismic isolation to reduce the vulnerability of buildings to seismic effects, particularly architectural monuments. In their work, the authors emphasize the importance of protecting cultural heritage and the potential of modern technologies under conditions of increased seismic activity. The results of the experimental study showed that the use of geotechnical seismic isolation is a promising approach in earthquake-resistant construction in Kazakhstan, as it significantly reduces soil seismicity at the building base, decreases the amplitude of seismic vibrations, and increases the seismic safety and durability of structures.

One of the reliable methods for reducing soil seismicity and increasing the seismic resistance of buildings and structures is the reinforcement of foundation soils. S.Zh. Jumadilova and co-authors (**Jumadilova et al., 2024**) examined issues related to construction in seismically active regions on weak, clayey, or subsiding soils. The authors studied the effectiveness of using the two-component polyurethane material GEOPUR to enhance soil bearing capacity under laboratory and field conditions.

Various reinforcement techniques are also applied to strengthen soil foundations in order to increase bearing capacity and reduce settlement. In recent years, geosynthetics have been increasingly adopted as reinforcing materials. This preference is explained by several advantages of geosynthetic materials over traditional solutions: high durability, effective soil particle interaction, and long service life. A review article (**Al-Salamy et al., 2022**) describes modern applications of geosynthetic reinforcement for increasing soil bearing capacity. The authors emphasize that the use of geosynthetics promotes more uniform stress distribution within the soil mass, improves particle interaction, and reduces settlement, making them an effective alternative to conventional soil reinforcement methods.

A group of researchers (**Cai et al., 2022**) conducted a series of laboratory experiments to evaluate the effect of geogrid reinforcement on soil strength characteristics, obtaining data on soil–reinforcement interaction for subsequent structural design. The study revealed that the mechanical behavior of reinforced soil is largely governed by lateral confinement conditions and geogrid design parameters. The results obtained clarify the mechanisms governing reinforced soil behavior and support more informed design of geogrid-reinforced structures.

The article (**Kleveko et al., 2021)** presents the results of a study examining the influence of geosynthetic reinforcement on the behavior of clay foundations. A series of laboratory and field tests were conducted, analyzing changes in the stress–strain state of the foundation following reinforcement. The results confirm the feasibility and effectiveness of using reinforcement in clay soils.

Recent studies demonstrate that reinforcing soil foundations with geosynthetic materials significantly enhances bearing capacity and structural stability under loading conditions. Scientists (**Zhao et al., 2024**) showed that horizontal–vertical geogrids improve stress distribution and reduce foundation deformation, resulting in a noticeable increase in bearing capacity.

Sanjay Kumar Shukla, in his book (**Shukla, 2016**), argues that, in addition to increasing bearing capacity and reducing soil deformation, geosynthetic reinforcement provides damping effects that mitigate dynamic loads. The author highlights the importance of this property when applying geosynthetics to protect structures from mechanical, dynamic, and seismic impacts.

In the context of construction in earthquake-prone regions, the question arises about the possibility and effectiveness of using this method in areas with increased seismic activity. For example, Chilean researchers (**González et al., 2018**) investigated a geogrid-reinforced soil wall supporting the Las Gaviotas bridge following the 2010 Mw 8.8 earthquake in Concepción, Chile. The study reported that the structure sustained no significant damage during the seismic event.

Kazakhstan is also actively exploring the application of geosynthetic materials under local soil conditions. For instance, Zh.K. Kanatova and co-authors (**Kanatova et al., 2024**) conducted a series of experiments analyzing the effect of geogrid installation on the strength of weak soils, with particular emphasis on changes in physical and mechanical soil properties. The results indicate that the use of geosynthetics represents a promising approach for reducing soil seismicity and improving strength, deformation, and settlement characteristics.

Recent research confirms that geosynthetic reinforcement of soil foundations effectively reduces settlement and deformation under seismic loading. Thus, the authors of the study (**Toksoy & Edinçliler, 2022)** demonstrated that reinforcing the sand cushion beneath a shallow foundation with geosynthetic material significantly reduces lateral displacements and vertical settlements under simulated earthquake loading. Hasen and Abbas (**Hasen & Abbas, 2024**) similarly reported that geogrid reinforcement effectively reduces foundation settlement during seismic events, particularly at lower acceleration levels.

The study (**Zhou et al., 2025**) examined the influence of geosynthetic reinforcement on the seismic stability of sandy soils under mainshock and aftershock loading. Shaking table experiments showed that geogrids reduce cumulative soil settlement by more than 50% compared to unreinforced conditions. Reinforcement also alters deformation patterns, promoting more uniform load distribution. These findings confirm the high effectiveness of geosynthetic reinforcement in enhancing the seismic stability of soil foundations and engineering structures in seismically active regions.

Despite the large number of studies on the use of geosynthetic reinforcement for soil improvement, its effectiveness in earthquake-prone regions has not yet been sufficiently investigated.

2 MATERIALS AND METHODS

As part of this study, an experimental investigation was conducted to assess the seismic stability of a model building founded on weak soil reinforced with geosynthetic material. The purpose of the experiment was to study the behavior of the building model (oscillations and the effects of dynamic loading simulating an earthquake) on a soil foundation made of local soils (loams), as well as the effectiveness and feasibility of using geosynthetic reinforcement in construction in earthquake-prone regions of Kazakhstan.

The experiment was conducted in two stages:

1. investigation of the seismic resistance of a building model on an unreinforced soil foundation;
2. investigation of the seismic resistance of a building model on a soil foundation reinforced with geosynthetic material (geogrid).

The tests were carried out on a seismic platform in the earthquake-resistant construction laboratory of the International Educational Corporation (IEC), which is designed to simulate dynamic effects such as seismic vibrations (**Figure 1**).

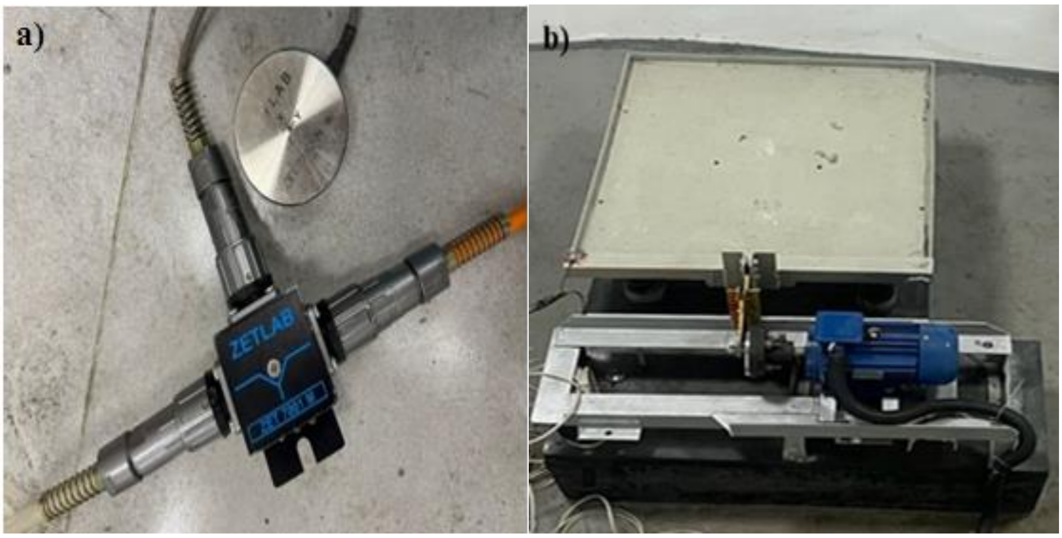

Figure 1 – General view of three-component sensors (a) and the seismic platform (b) (author's materials)

The seismic platform consists of a monolithic reinforced concrete foundation and a platform for placing the building or structural model, with the foundation and platform connected by springs. An electric motor mounted on the foundation is used to generate controlled dynamic loading. Experiments on this seismic platform are conducted as follows: compact three-component seismic sensors (accelerometers and seismometers) are installed and connected to the model in accordance with the experimental objectives. The interaction of all structural components of the seismic platform ensures three-dimensional controlled simulation of vibrations at the model placement site, closely approximating seismic loading conditions. A specific vibration level at the model placement site, as well as controlled stopping of vibrations, is achieved using a control panel. Seismic vibrations are recorded by seismic sensors connected to a computer, which processes the data using special ZET LAB software and displays the vibrations of the site for placing the model of a building or structure, as well as the vibrations of the models themselves in tabular or graphical form (**Tuleshov et al., 2023**).

Geogrid, one of the most commonly used types of geosynthetics, was selected as the reinforcing material for the experiment. It is widely applied in construction projects where reinforcing elements are subjected to significant tensile forces. Therefore, when designing structures reinforced with geosynthetics, particular attention must be given to tensile strength characteristics. For this purpose, prior to the seismic experiment, tensile strength tests of geogrid samples were performed using a tensile testing machine installed in the IEC geotechnical laboratory (**Figure 2**).

Figure 2 – Tensile testing machine of the geotechnical laboratory (a) and the process of conducting a tensile test of a geogrid sample (b) (author's materials)

As a result of tensile strength testing of the geosynthetic material samples, the following values were obtained:

1) the tensile strength of a single-layer geogrid sample with a width of 20 cm was 21.5 kg;
2) the tensile strength of a double-layer geogrid sample with a width of 20 cm was 48 kg.

It should be noted that the tensile strength of the double-layer geogrid exceeded the combined strength of two single layers, which can be explained by additional friction and adhesion effects between the layers.

The soil foundation composed of non-draining loam soil was formed in a transparent organic glass box with dimensions of 950 × 950 × 950 mm and installed on the seismic platform. During the first stage, the soil base was tested without reinforcement, while during the second stage, reinforcement using geogrid was applied. During the experiment, soil level changes in the box were recorded before and after seismic excitation at both stages in order to determine settlement induced by dynamic loading.

A small-scale building model with dimensions of 450 × 450 mm and a height of 450 mm was constructed for the experiment. The model was assembled from gypsum blocks measuring 80 × 55 × 25 mm, which were cast in advance using a gypsum–water mixture with a ratio of 1:2. A universal polymer adhesive was used as the bonding mortar between the blocks. To increase loading on the model, a rigidly fixed cover with an additional weight was installed to simulate permanent loads. The prepared one-story building model was placed in the soil box with a shallow embedment of 15 mm. The sensors were fixed in strict accordance with the XYZ coordinate axes.

For the experiment, the sensors were arranged as follows:

– sensors No. 1 and No. 2 — installed on the building model;

– sensors No. 3 and No. 4 — installed on the soil foundation;
– sensor No. 5 — installed on the seismic platform;
– sensor No. 6 — installed on neutral ground.

For the first stage of the experiment, the soil foundation was formed using local loam soil and compacted mechanically by manual tamping with a plastic hammer. The thickness of the soil layer for the first stage was set to 200 mm. **Figure 3** presents the prepared soil foundation and the small-scale building model with installed sensors.

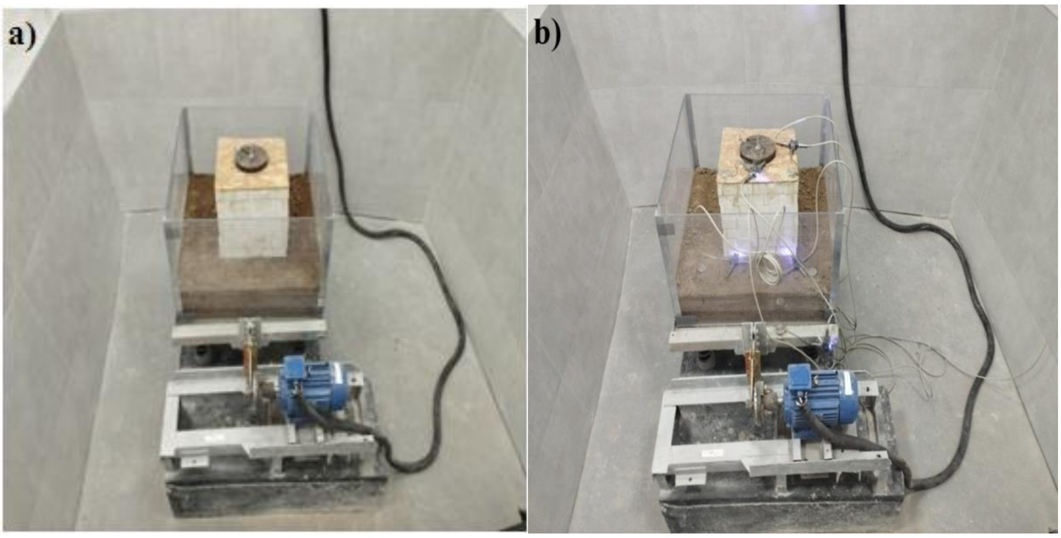

Figure 3 – First stage of the experiment: soil foundation and small-scale building model (a); model with attached sensors (b) (author’s materials)

For the second stage of the experiment, the soil foundation was constructed from the same loam soil and reinforced with two layers of geogrid. To achieve this, a 100 mm thick soil layer was excavated, the reinforcing material was placed, and the soil was compacted using partial wetting and manual tamping. The total soil thickness for the second stage was also set to 200 mm to ensure comparability of settlement results. **Figure 4** illustrates the geogrid installation process, the reinforced soil foundation, and the building model with installed sensors.

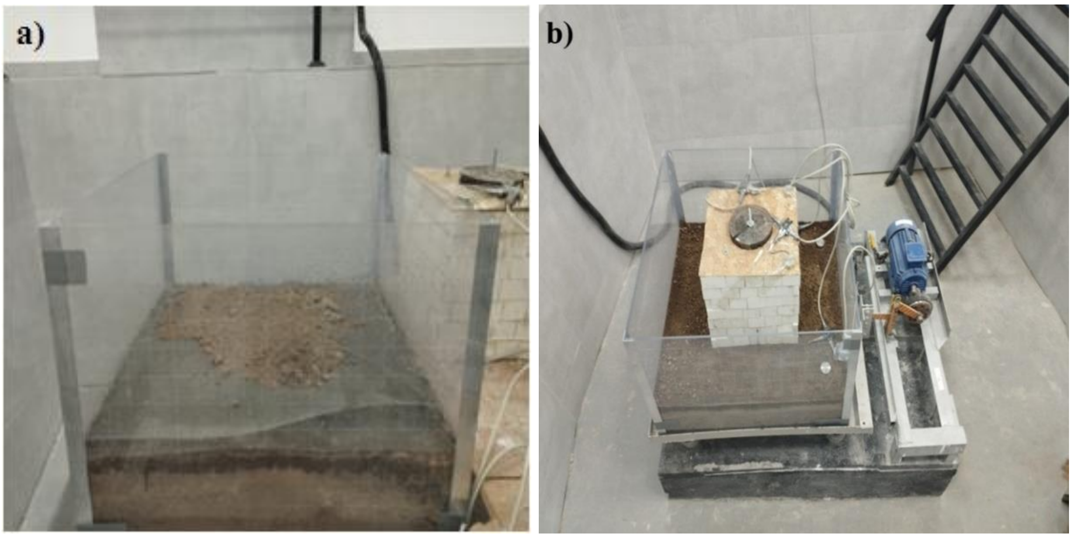

Figure 4 – Second stage of the experiment: soil reinforcement using geogrid (a); model installed on reinforced soil foundation with sensors (b) (author’s materials)

3 RESULTS AND DISCUSSION

During the experiment, comparative testing of reinforced and unreinforced soil foundations yielded the following results:

1) during the first stage of the experiment, measurements indicated that soil settlement after dynamic loading simulating seismic vibrations was 9 mm, based on the average of measurements taken from four sides of the model;

2) after soil reinforcement, settlement under a similar level of seismic excitation averaged 5 mm, also calculated as the mean value of measurements from four sides of the model.

The results of changes in settlement levels due to dynamic loading simulating seismic activity indicate an improvement in the deformation characteristics of weak soil resulting from the inclusion of geosynthetic material. The experimental data obtained showed that, as a result of soil reinforcement with geogrid, the settlement of the loam subgrade decreased by a factor of 1.8. Accordingly, reinforcement with geogrid enhanced the strength characteristics of the soil due to additional adhesion and an increase in bearing capacity. Thus, based on the experimental results, it can be concluded that soil deformation properties improve as a result of geosynthetic reinforcement, while strength properties are enhanced due to the contribution of the reinforcing material to load-bearing behavior.

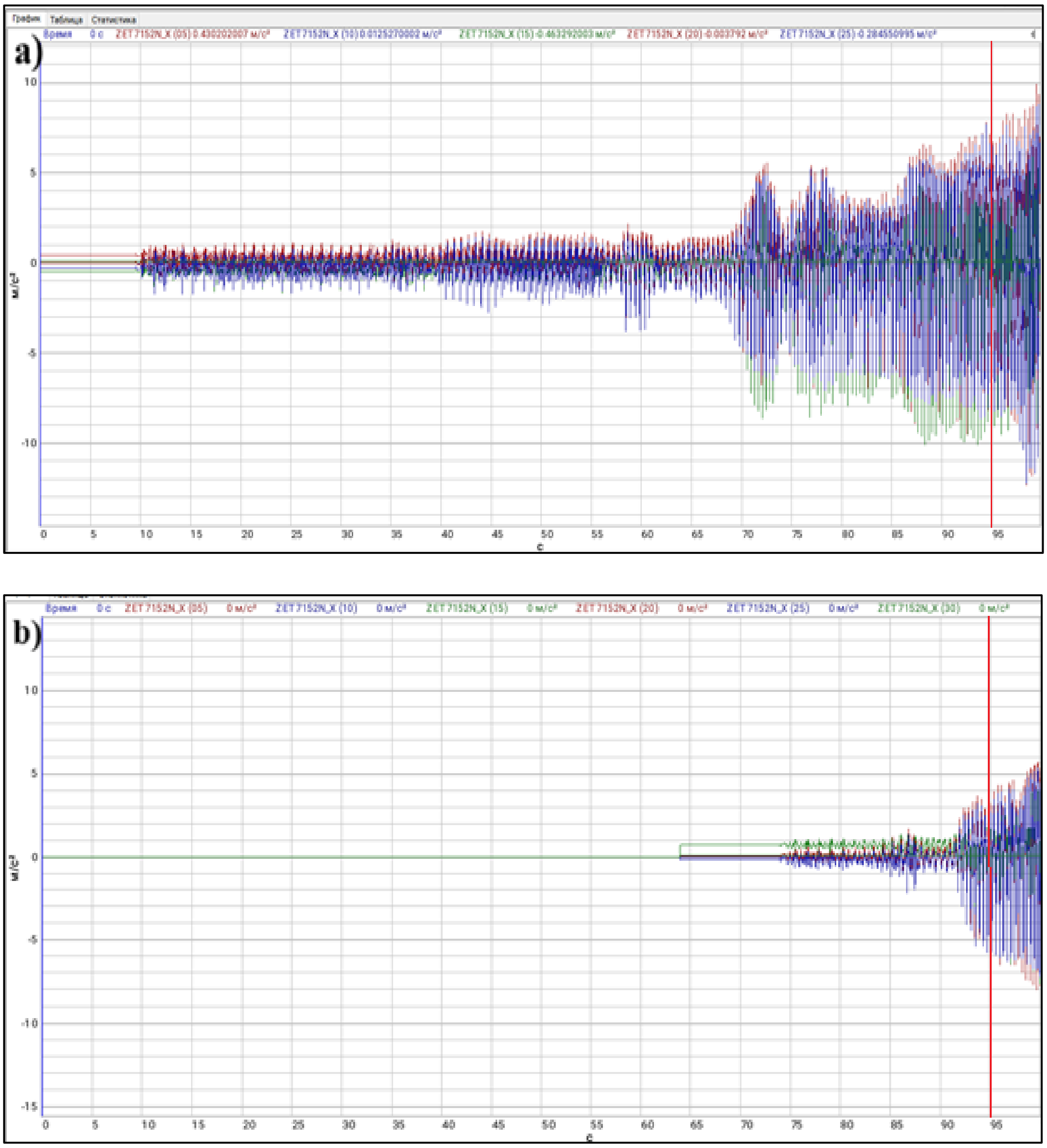

Figure 5 – Accelerogram recordings for the first (a) and second (b) stages of the experiment (author’s materials)

For further comparative analysis of the influence of soil reinforcement on changes in model behavior during simulated seismic loading, accelerograms were recorded from seismic sensors for both the first and second stages of the experiment. **Figure 5** presents the accelerogram records obtained during the experimental program.

Analysis of the accelerogram recordings clearly demonstrated differences in the model response to seismic loading between the first and second stages of the experiment (**Figure 5**). The graphs show that, during the first stage of the experiment, noticeable swaying of the model and soil foundation occurred approximately 10 seconds after activation of the electric motor. In contrast, during the second stage of the experiment, following soil reinforcement, the response of the model to seismic excitation changed significantly, with swaying initiating only after approximately 75 seconds. Thus, based on comparative analysis of the accelerogram records, it can be noted that the dynamic response of the small-scale model was substantially altered after reinforcement, allowing the model to remain stable for a considerably longer duration without loss of firm contact with the soil foundation.

For comparative analysis, a section of the graph was selected for the 95-second time interval of the first and second stages of the experiment, which is marked with a vertical line in Figure 5 for better perception. The dynamic loading applied to the model during this interval corresponded to seismic vibrations of 5–6 points. It should be noted that, since the seismic platform represents an artificial source of forced vibrations, certain limitations apply; specifically, the acceleration amplitude is inversely proportional to the mass of the tested model.

The results obtained were also presented in tabular form, including acceleration values recorded by each sensor, as well as a complete statistical analysis of the data, comprising minimum and maximum acceleration values, arithmetic mean, root mean square value, and standard deviation (**Tables 1 and 2**).

Table 1

Data obtained in the first stage of the experiment using the program ZET LAB

Experimental values	**Time, sec**	**Acceleration along the X-axis, m/s^2**	**Acceleration along the Y-axis, m/s^2**	**Acceleration along the Z-axis, m/s^2**
min value	0,000	- 3,287	- 0,500	- 9,268
max value	98,980	0,697	1,815	10,320
root mean square value	57,726	1,667	0,862	9,740
standard deviation	28,870	1,302	0,731	0,307
fundamental frequency	0,010	0,060	0,060	0,060

For further comparison of the model response under similar seismic excitation levels, accelerogram records from both experimental stages were analyzed for identical loading conditions. Specifically, a 95-second time interval corresponding to both stages of the experiment was selected for analysis. During this interval, the applied dynamic loading corresponded to seismic vibrations of 5–6 points. The results demonstrate an improvement in the seismic stability of the model founded on reinforced soil compared to the unreinforced condition. During the first stage of the experiment, the recorded acceleration reached an average value of 7.5 m/s^2, which initiated loss of firm contact between the model and the soil foundation. Thus, it was established that, during the first stage, simulation of seismic effects exceeding 5–6 points led to disruption of soil–structure interaction and subsequent loss of seismic stability of the model. During the second stage of the experiment, under a comparable seismic loading level, the average acceleration decreased by nearly 1.5 times, reaching approximately 3 m/s^2. These results confirm a reduction in soil seismicity at the model base and an increase in the seismic stability of the small-scale building model as a result of geosynthetic reinforcement.

To determine and record the moment of loss of strong soil-model contact and establish the corresponding level of dynamic impact, the duration of the second stage of the experiment was extended to 110 seconds (**Figure 6**).

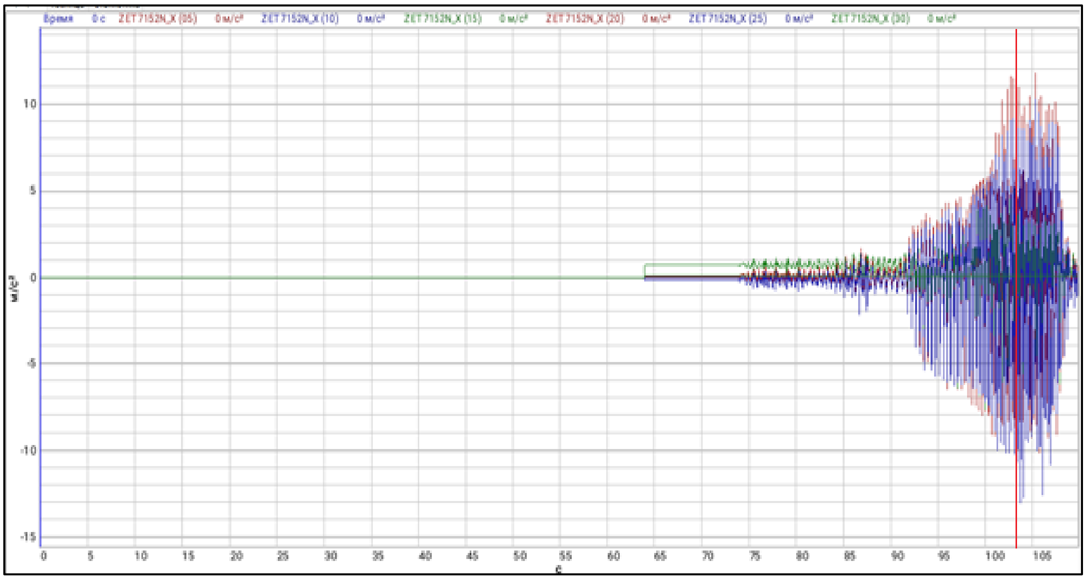

Figure 6 – Accelerogram recordings from the second stage of the experiment with a duration of 110 seconds

Further intensification of dynamic loading during the first stage of the experiment resulted in complete loss of model stability. The recorded acceleration reached an average value of 9.735 m/s², approaching the acceleration due to gravity, which caused excessive rocking of the model and eventual detachment from the soil foundation. Analysis of the accelerogram records showed that loss of stability, excessive rocking, and separation of the model from the soil occurred at approximately 103 seconds after the start of the experiment, when seismic excitation levels increased to 9–10 points (**Figure 6**). Thus, the experiment demonstrated that the technical solution of reinforcing the soil foundation with geogrid is most effective at seismic intensity levels of 7–8 points, while its effectiveness may decrease at higher seismic intensities.

Table 2

Data obtained in the first stage of the experiment using the program ZET LAB

Experimental values	Time, sec	Acceleration along the X-axis, m/s^2	Acceleration along the Y-axis, m/s^2	Acceleration along the Z-axis, m/s^2
min value	0,000	- 4,401	-7,655	-11,307
max value	109,980	2,893	5,211	11,869
root mean square value	63,499	0,633	1,038	1,790
standard deviation	31,757	0,633	0,989	1,789
fundamental frequency	0,010	0,020	0,013	0,022

5 CONCLUSIONS

The scientific novelty of the study is the experimental confirmation of the effectiveness of geosynthetic reinforcement for strengthening undrained soils (loams) under construction conditions in seismically hazardous regions. Experimental testing confirmed changes in the behavior of the soil–building model and an increase in its seismic resistance as a result of soil reinforcement. The seismic resistance of the small-scale model founded on loam reinforced with geogrid corresponds to seismic impacts with intensities of 7–8 points on the Richter scale. With further increases in seismic intensity, this technical solution for strengthening the soil foundation becomes less effective, as it leads to high-amplitude frequency dynamic loading and increased rocking of the model, which ultimately disrupts stable soil–structure interaction.

Based on previous research, it can be concluded that geosynthetic reinforcement is most effective in loose soils characterized by high deformability. The results of the experimental investigation presented in this study confirm that the examined technical solution for soil foundation strengthening can be effective for construction in regions with increased seismic hazard.

Analysis of the experimental results allows the following conclusions to be drawn:

1. Reinforcement of the soil foundations of buildings or structures with geosynthetic material increases the strength and deformation properties of the soil.
2. Geosynthetic reinforcement reduces the settlement of soil foundations due to seismic impact, compared to the settlement of unreinforced foundations under similar conditions.
3. Experimental data indicate the feasibility and effectiveness of this technical solution for improving the seismic resistance of low-rise buildings with rigid structural designs in earthquake-prone regions.

Thus, the use of geogrids for reinforcing foundation soils reduces settlement, increases stiffness, and enhances the bearing capacity of the soil mass. Geosynthetic reinforcement, through improved soil adhesion and interaction, ensures the stability of structures against overturning and sliding loads. Experimental data indicate that the incorporation of geosynthetic materials into soil foundations effectively reduces settlement under both static and dynamic loads, including seismic excitation. These findings provide a strong basis to conclude that geogrid-reinforced soils improve the operational performance of structures under various loading conditions, particularly given the durability of geosynthetic materials.

At present, the application of geosynthetic materials in the construction industry in Kazakhstan remains limited, primarily due to insufficient practical experience and a lack of comprehensive research. The potential use of geosynthetics as reinforcement for the foundations of buildings and structures to reduce seismic vulnerability has not yet been fully explored. Therefore, continued research into the effectiveness of geosynthetic reinforcement for construction in regions with increased seismic hazard is considered necessary to ensure enhanced seismic safety.

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