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ENSURING THE SEISMIC RESISTANCE OF A BUILDING USING A GEOTECHNICAL SEISMIC INSULATING SCREEN

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This paper considers the issue related to the protection of buildings and structures against seismic influences and the prevention, exclusion, or reduction of seismic hazards. The catastrophic destruction of modern «earthquake-resistant» buildings in Turkey and Taiwan has shown that existing methods of strengthening and reinforcing structures are not perfect and require further study. Analysis of existing approaches to ensuring seismic resistance showed that seismic insulation and seismic suppression systems still do not have a scientific and technical justification for the effectiveness of their operation from the point of view of ensuring the stability of structures. The estimation-dynamic models of the «base-seismic insulation-structure» system developed to date do not always make it possible to simulate the joint work of their interaction during an earthquake and account for the transformation of the seismic impact on the structure. An alternative technique has been devised, a geotechnical seismic insulation screen, as a seismic insulation system that reduces the intensity of seismic loads on the structure and ensures its seismic resistance. In a specific example, the effectiveness of this seismic insulation system is confirmed. This seismic insulation technique in the form of damper screens is characterized by reliability and manufacturability in ensuring the seismic resistance of objects under construction.

The results of computational and experimental modeling of the interaction of an earthquake-insulated structure with a ground base found that the values of axial forces and bending moments in a building with a seismic insulating screen are less than in a building without seismic insulation by 30–40 %.

The geotechnical seismic insulation screen makes it possible to advance the development of new seismic insulation techniques and determine their effectiveness. This technique will also be effective when strengthening the base and seismic insulation systems of historical monuments, protecting them against seismic and dynamic influences

Keywords: seismic impacts, ground movement, seismic protection and seismic insulation, geotechnical damper of horizontal stresses, geotechnical seismic insulating screen

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1. Introduction

One of the main ways to ensure the seismic resistance of structures considered by design engineers is increasing the bearing capacity of the main structural elements of the building. According to scientists, an increase in cross-sections leads to an increase in the weight and stiffness of the load-bearing elements. This, in turn, increases the inertial load on the building. This technique of ensuring seismic resistance is dangerous in the construction of multi-story and high-rise buildings [1].

To solve this problem, alternative methods and means of seismic protection and seismic insulation of buildings and structures have been developed, reducing the intensity of seismic loads and improving their seismic resistance [2].

The results of numerous scientific studies are implemented in the practice of earthquake-resistant construction. According to scientists in the field of earthquake-resistant construction, active seismic insulation, as a new scientific direction, does not have a unified methodology and scientific-technical justification that would make it possible to draw objective conclusions about its effectiveness [3].

Due to the dynamism of the development of applied science, construction practice has received various devices for seismic protection and seismic insulation of buildings, which reduce the intensity of seismic loads on buildings and contribute to increasing their seismic resistance. Analyzing numerous studies of theoretical and experimental nature, many scientists evaluate their effectiveness according to two criteria: the degree of reduction of inertial seismic loads on the structure and the magnitude of the relative displacements of the protected object relative to the base or foundation [4].

Therefore, studies tackling the development of new techniques of seismic insulation, differing in new principles of action, better properties of damping oscillations, and characteristics of the effectiveness of their work to ensure the seismic resistance of the building, are very relevant.

2. Literature review and problem statement

The seismic resistance of buildings and structures is ensured by the choice of a structural system that takes into consideration the joint operation of the structure with a nonlinearly deformable ground base and the design scheme of buildings for seismic loads.

Works [5, 6] report the results of studies into modern theories of seismic resistance, as well as a procedure for calculating buildings for seismic impacts. It is shown that the theory of seismic resistance should take into consideration the wave nature of the seismic movement of the soil, namely:

– calculation of the lengths of the dominant seismic waves and coefficients of reducing the intensity of the seismic impact;

– modeling of rotational components of seismic motion based on a wave model and given three-component accelerograms of translational motion for calculation in the time domain;

– determining the dynamism coefficients from translational and rotational accelerograms for quasi-static calculation.

Taking into consideration the wave nature of the movement of the earth's surface, the authors propose a generalized wave model of seismic motion as a universal approach for assessing seismic rotations.

Existing theories of seismic resistance and calculation procedures do not give a definitive answer to the effectiveness of applying a particular theory. Searches are underway, more complex models are being developed, focused on new design principles.

Work [7] describes in detail the nature of the seismic movement of the earth's surface, and the quantitative and qualitative characteristics of the dynamic properties of soils. The results of the study show that the spatial variability of the site array and the characteristics of the ground motion depend on the input parameters of the shear wave velocity. Wave propagation is simulated using 2D-finite difference software FLAC2D. Based on the results of numerical modeling, intensity parameters in different ranges of speed, amplitude, and wavelength were obtained. The nonlinear effect of the intensity of soil movement was established. At the same time, many questions remain regarding the frequency, wavelength, and phase velocity of their propagation.

Therefore, the nature of the seismic movement of the soil remains multifaceted, as evidenced by the results of studying many destructive earthquakes. Assessing the nature and strength of the movement of the earth's surface requires numerous theoretical and experimental studies using modern digital technologies.

Despite the significant achievements of scientists and engineers in the field of design and construction in seismically hazardous areas, the problem of ensuring the seismic resistance of buildings and structures against seismic impacts remains a task of paramount importance.

Paper [8] reports the results of the practice of designing and building facilities on weak soils and shows the advantages of the seismic protection system in the form of a seismic insulating belt for buildings of a rigid structural scheme. The design of seismic insulation in the form of a sliding layer between the base and the spatial foundation platform made it possible to reduce the design seismic loads on the supporting structures by up to 30 %. Numerical experiments on seismic resistance of buildings of various structural schemes with an earthquake-insulating belt were also carried out and the dynamic characteristics of the building under various external influences were obtained. The developed models of seismic insulation on computer programs correlate well with the results of the numerical solution of the dynamic problem.

Despite these advantages, a seismic insulation structure in the form of a spatial foundation platform with a sliding layer is a complex and costly system.

There are alternative ways to solve important problems of modern construction, such as horizontal, and vertical seismic barriers in the form of a screen – a shell screen that protects the building from surface waves of an earthquake or underground explosions.

Paper [9] gives general approaches, prerequisites for the development and prospects for the use of building protection from all forms of seismic waves. The results of the study proved the prospects for seismic shielding of the soil of buildings and structures and the assessment of their effectiveness in earthquake protection. The earthquake protection screen is seen as a barrier to dampening the wave-type effect and can better respond to all random ground movement factors. However, the issues of screen designs, the size of the screen wall in height and thickness, and much more are not considered. Many researchers note the thickness, and location of the screen relative to the building, and the material of the screen as one of the decisive factors of their effectiveness.

Studies [10] on the design models of the «structure-base» system for seismic effects have shown the effectiveness of the damping layers as wave reflectors in the ground mass, at the boundary of materials with different properties. The proposed mathematical model is based on the theory of P. Chadwick where Rayleigh waves cannot propagate if the surface of the half-space is pinched. Accordingly, it is possible to modify the surface of the half-space on which Rayleigh waves propagate. In that work, the task of mathematical modeling of the propagation of surface Rayleigh waves and their interaction with seismic barriers was set. The authors considered a model of the environment in the form of a plate measuring 401×200×1 meters, on the surface of which a horizontal barrier of 25×1×1 meters was installed. The results of the numerical experiment found that the barrier reflects the bulk of the wave energy, reduces the energy of movement at the inner boundary of the barrier. The dependence of the displacement magnitude on the density of the barrier material was also established.

At the same time, in numerical experiments for determining the movement in the region before and after the barrier, the frequency and wavelength parameters are taken as a constant value. The work would be more important if the influence of these parameters on the efficiency of wave barriers were considered.

In [11], the authors present numerical simulations of the interaction of Rayleigh surface waves with piles and show the effect of the wave barrier in the form of rows of piles as a method of vibration protection of buildings and underground structures against surface waves. The effect of the number of rows, their diameter and length on the amplitude and acceleration of the wave beyond the barrier was established. Such a wave barrier reduces the amplitude of movements, speed, and acceleration of points in the protected zone.

There, the issue of the shape of the barrier, the types and properties of the damping barrier materials are also not considered. All these issues are the subject of further research.

Paper [12] considers options for seismic barriers used to protect buildings and structures against the effects of surface acoustic waves. It is shown that the choice of geometric and physical parameters of seismic barriers, in addition to the frequency of seismic waves, is affected by the speed of propagation of Rayleigh waves. The developed mathematical model of seismic barriers, based on the equation of the bimodular theory of elasticity during deformation in the elastic zone, made it possible to study the behavior of the soil massif under the influence of dynamic loads. Using numerical methods, the problems of interaction of the incident dynamic wave for elastic half-plane with a vertical seismic barrier and for semi-plane without a seismic barrier were solved. The effectiveness of seismic barriers was evaluated in comparison with the decrease in the amplitudes of displacement and acceleration at the points of the surface before and beyond the seismic barrier.

The effectiveness of seismic barriers was determined by comparing two types of barriers, different in density and Young modulus. It was possible to consider barriers in the spectrum of influence of their size, damping properties of materials and location conditions on reducing seismic impacts.

Paper [13] reports the results of a numerical experiment on the effectiveness of barriers in the form of open and filled trenches, sheet piles, etc. The results were evaluated by taking into consideration the reduction of displacements of soil particles on the earth's surface under pulsed loads. The properties of damping materials were assessed by the decay of the ground motion curve with the different modulus of elasticity. The effect of influence on the efficiency of the barrier of the parameters of the damping material was established. The influence of the location of barriers from the source of disturbance and the effectiveness of the insulation system were also studied. It is noted that the intensity of soil movement is suppressed both geometrically and materially. In that work, based on an extensive parametric study of the behavior of open and filled trench barriers, the effectiveness of the seismic insulation system in the form of trench fences was determined. It is possible to disagree with some conclusions regarding open trenches, which are inefficient in operating conditions, especially for the seismic insulation system of buildings and structures. When determining the effectiveness of any system, it is necessary to proceed from the organizational and technological reliability of their arrangement. Thus, it is necessary to take into consideration the manufacturability of their arrangement, as well as the life cycle of any system.

As an alternative technique, a seismic insulation system in the form of a screen was proposed to protect buildings and structures against seismic influences, which reduces seismic effects on the building [14].

The essence of technological advancement is to arrange a star-shaped screen located around the building to protect the building from seismic influences. The screen consists of reinforced concrete sections facing bulges toward surface waves. The inner part of the screen is filled with sandy soil with a mass equal to the mass of the building being erected. The disadvantage of this patent is the complexity in the arrangement technology, material intensity, respectively, the increase in the cost of the shell screen.

A screen was also invented to protect buildings and structures against seismic influences and vibration [15]. The screen is an internal and external row of wells filled with protective building material with damping properties. The screen, as a system that reflects horizontal surface impacts, does not protect the building from vertical wave shocks. Also, the disadvantage of the screen is the technical and technological problems of its arrangement under difficult ground conditions.

Active seismic insulation systems, which were used earlier and currently as seismic protection means, are compensators for irreversible deformation of the «backfill» of bulk material. However, this system also has advantages and disadvantages. In addition to the complexity in the arrangement of such a system, there is no sufficient assessment of its effectiveness.

Variants of vertical and horizontal barriers to protect the building from an earthquake were investigated. The best option for seismic insulation according to the structural scheme, shaping, and technology of the damping layer device is a geotechnical barrier (screen). A geotechnical barrier is a surface layer with modified properties. Modification of the properties of the damping screen can be achieved by various methods. The most effective method is to create a layer with specified properties using jet cementation.

Patent studies of seismic insulation systems in the form of absorbent screens have shown that the design solutions for their arrangement have a common scheme. Solid or intermittent rows of wells or trenches along the perimeter of a building, filled with porous or solid structures, located in the ground, are absorbent or vibration-reflecting screens.

The disadvantages include the complexity of the technology of their arrangement, great laboriousness, and material intensity. As well as the lack of a regulatory and technical base for calculation and design, and organizational and technological reliability of their arrangement.

The practical application of geotechnical barriers in the form of wave curtains requires the accumulation of experimental data and the development of a comprehensive theory of calculation. This would make it possible to calculate and construct the elements of the wave system (the structure and geometry of the base, the structure of the foundation, and the construction object itself) and determine the impact they have on the bearing properties of the building system.

Experimental and computational studies with different screen shapes, with different materials for their filling, have shown that the effectiveness of damper barrier screens depends on many factors. The parameters of each damper should be taken separately, with the justification of their effectiveness as a seismic insulation system, taking into consideration specific regional soil conditions [16, 17].

In this regard, it is necessary to conduct experimental and computational studies into the effectiveness of geotechnical damping barriers – screens. At the same time, the damper screen can be termed geotechnical for the following reasons:

– the seismic insulation system is arranged in a spatial geotechnical environment;

– as a damping screen material, a ground layer of the base of the building is used, which in Eurocode is considered as a geotechnical material;

– when installing seismic insulation systems in the form of a damping screen, geotechnical techniques and technologies for fixing and hardening soils are used.

The nature of the operation of seismic insulation screens depends on many factors: the type of soil of the base, its physical and mechanical characteristics, the seismic activity of the area, the level of groundwater, and others. These factors also greatly influence the choice of the type and material of the damper screen.

In the future, a seismic insulation system in the form of a geotechnical seismic insulation screen can be considered.

3. The aim and objectives of the study

The purpose of this study is to develop a seismic insulation system in the form of a geotechnical seismic insulating screen, which reduces seismic and man-made impacts on the building. Modeling a seismic insulating screen with certain damping properties will make it possible to ensure the seismic resistance of buildings under various geological conditions.

To accomplish the aim, the following tasks have been set:

– to investigate the dynamic properties of soils as an object of transformation of surface oscillations of seismic effects on the building; – to simulate shapes, structural schemes, and technical parameters of the seismic insulation screen;

– to conduct experimental and computational studies into the seismic insulation screen model on the example of one object and substantiate its organizational and technological reliability.

4. The study materials and methods

The research is aimed at solving a set of problems, including numerical methods for calculating the dynamic state of structures during an earthquake, and experimental and computational studies with reference to the location in specific engineering and geological conditions.

Emphasis is on modeling the joint operation of the «base-structure» system to determine their interaction during an earthquake and take into consideration the transformation of the seismic impact on the building. Modeling the interaction of surface seismic waves with the seismic insulation system makes it possible to determine the effect of reducing the energy of the earthquake on the building. To determine the technical parameters of the seismic insulation system, an experimental study into the nature of seismic waves in the ground environment was carried out.

It is established that the speed of the longitudinal wave, depending on the parameters of the elastic medium, depends on the density of the medium, the parameters of Lamé, the modulus of elasticity, the Poisson coefficient, and the modulus of ground shear.

Transverse *S*-waves, moving in both vertical and horizontal directions, cause shear deformations of the ground environment in solid rocks. In loose, soft soils, they lead to turns in soil volumes and are the cause of rotational movements of the medium. The speed of *S*-waves is always less than the speed of *P*-waves. The speed of the transverse wave also depends on the density of the medium, the Lame parameter equal to the shear modulus.

In the ground environment, from the action of seismic forces, surface *L*-waves (long waves) are manifested – Love and Rayleigh waves (*LQ* and *LR* waves, respectively). While Love waves cause only horizontal displacements of the ground, Rayleigh waves cause both horizontal and vertical displacements. According to available studies, Rayleigh waves carry most of the energy of the earthquake focus, cause surface shocks and are the main cause of the destruction of structures.

The amplitude of oscillations due to the resistance of the soil to the movement of its particles decreases and attenuates or the process of damping of oscillations occurs. A graphic representation of the attenuation of oscillations is shown in Fig. 1.

The attenuation of the amplitude of oscillations is estimated by the damping coefficient, which is defined as the ratio of two adjacent decreasing amplitudes on one side of the time axis (Fig. 3).

In Kazakhstan, seismic impact parameters are assessed by class, depending on the construction region and the type of soil conditions characterized by stratigraphic profiles and parameters [18].

The value of the average transverse wave velocity $\nu_{s,30}$, from the upper 30-meter ground thickness, is determined from [18].

$$v_{s,30} = \frac{30}{\sum\limits_{i=1,N} \frac{h_i}{v_i}}, \quad (1)$$

where h_i and ν_i are the values of the thickness (in meters) and the speed of propagation of the transverse wave (with a level of shear deformations of 10^{-5} or less) for each *i*-th layer with a total number of layers of *N*. The norms consider the parameters of the upper 30-meter soil stratum. For the layer of soil located below this stratum, additional surveys are carried out.

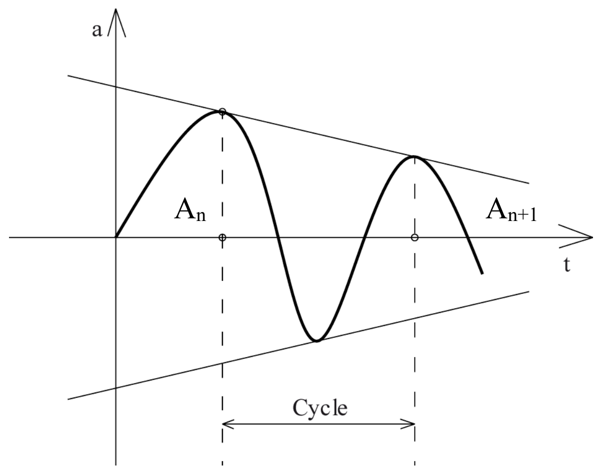

Fig. 1. Attenuation of oscillation amplitude

The dynamic properties of soils characterize the soil stratum as a medium for the propagation of oscillations (elastic, damping, and filtering properties). Therefore, their dynamic instability is determined, manifested as an increase in deformability and a decrease in soil strength during dynamic loading [19, 20].

The magnitude of the dynamic impact on the soil is significantly affected by the intensity of oscillations during seismic influences.

The intensity of the oscillations is characterized by the seismicity coefficient, defined as the ratio of the magnitude of the seismic acceleration to the magnitude of the acceleration of gravity. The seismicity coefficient, in turn, depends on the dynamism and shape of the structure's natural oscillations.

In order to study the dynamic properties of soils, a procedure for recording seismic waves when passing through the ground medium in the laboratory was developed. The experiment was conducted in the scientific laboratory at KazGASA. As an experimental installation, a tray with the following geometric dimensions was designed (Fig. 2): length, 178 mm; width, 19 cm; height, 70 cm. The front and sides of the tray are covered with plexiglass. The impulse of the force effect on the ground is transmitted through a rod with a metal disk at the end. The transfer of the dynamic effect to the ground medium through the impact pendulum made it possible to simulate and register the oscillatory process. The rod-emitter of the impact is immersed in the body of the soil at a distance of 40 cm from the left edge of the bench.

Equipment from ZETLAB was used to record the data. The spectrum analyzer ZET 017-U8 (Russia) is a device for measuring the characteristics of an electrical signal and is designed to analyze and record the spectral, as well as correlation composition of signals and their generation. Together with a Windows-based computer and ZETLAB software, the spectrum analyzer acts as measuring instruments.

Fig. 2. Geotechnical tray for recording seismic vibrations

Registration of signals in the body of the soil was carried out using six accelerometers BC 111 (Fig. 3, *a*), located in two rows at a distance of 75 and 150 cm from the pulse source (Fig. 3, *b*).

With a force effect on the ground, oscillations are excited, which are subsequently captured by accelerometers. The recorded vibration data are transmitted to the spectrum analyzer, with the help of which it is possible to study and analyze the information obtained (Fig. 4).

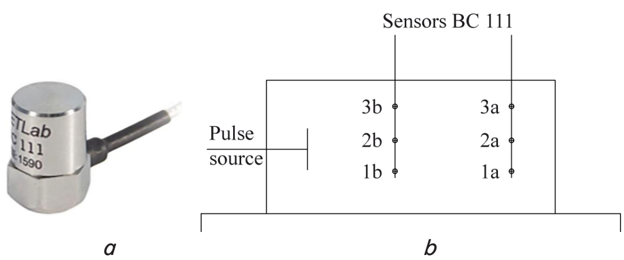

Fig. 3. Procedure for recording seismic vibrations: *a* — sensor view — accelerometer BC 111; *b* — schematic arrangement of sensors relative to the pulse source

In the experimental study, 3 types of soil models were used:

1. Model soil – a mixture of sandy soil with rubber chips and oil;
2. Model soil with the arrangement of a damping layer of soil bitumen with a thickness of 10 cm;
3. Model soil with the arrangement of a damping layer of soil-cement with a thickness of 10 cm.

Characteristics of sandy soil: fine sand, dusty; humidity – 25 %; density – 1,800 kg/m^3; porosity 0.7.

Characteristics of the second model of soil bitumen: a slurry-like mixture of sand and bitumen; humidity – 30 %; density – 2,000 kg/m^3.

Characteristics of the third model of soil-cement: cement-sand mortar of the brand M150; humidity – 30 %; density – 2,000 kg/m^3.

Dynamic tests on model soils were carried out at five values of the impact force, 5, 10, 15, 20, 25 N. To minimize errors under the same boundary conditions, 5 experiments were conducted at each loading stage. It is not rational to conduct more than 5 tests, due to the possibility of soil compaction in the area of the pulse source. The acceleration values were defined as the arithmetic mean, in order to avoid possible gross errors. The standard deviation of the sensors was also taken into consideration.

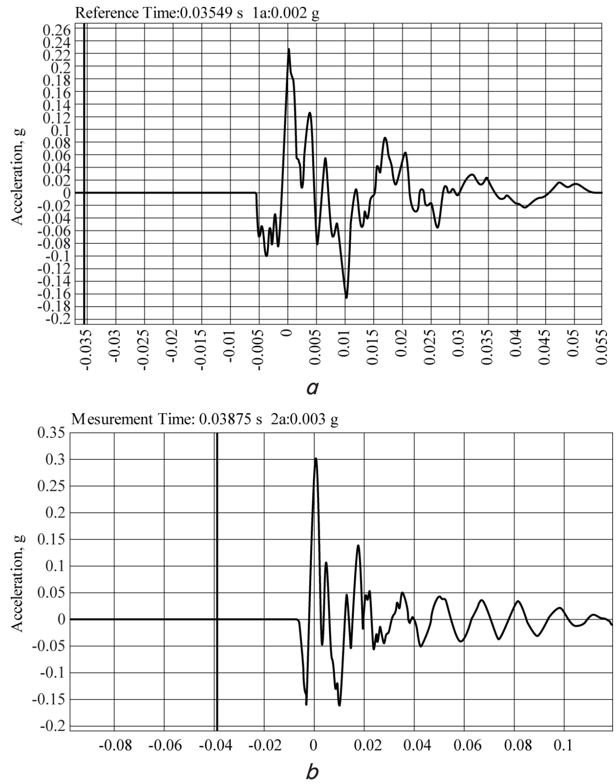

Fig. 4. Examples of recording accelerograms of ground vibration: *a* — recording accelerograms of the sensors of the first row; *b* — recording accelerograms of the sensors of the second row

Based on the results of our analytical and experimental studies, the structural form of the seismic insulating screen in the form of a cylinder-shell with certain technical parameters was chosen. The geometric dimensions of the seismic insulating screen are determined from the condition of equality of the mass of the soil enclosed in the shell with the mass of the building under construction. Hence, the radius of the cylinder is 21 m; height, 6 m. Cylinder-shell of a ground concrete column in two rows has a thickness of 1.2 m.

The geotechnical seismic insulating screen to protect buildings and structures against seismic influences is a geotechnical structure in the form of a cylindrical shell immersed in the ground. The space between the screen and the building is filled with damping backfill, which reduces the intensity of seismic vibrations (Fig. 9). As a damping backfill, sand with certain physical and mechanical characteristics is used, effective for damping soil vibrations.

To carry out comparative calculations and determine the effectiveness of the structural scheme of the seismic insulating screen, the project of a multi-story building under construction in the city of Almaty was chosen.

The comparative calculation was carried out to compare the model of the building with traditional seismic reinforcement and the model with a seismic insulating screen in the form of a cylinder, for seismic impact, using the PLAXIS software package.

The capabilities of the PLAXIS software package focused on determining the deformation and ensuring the stability of geotechnical structures under static and dynamic influences have made it possible to establish the stressed-strained state of the compared models.

5. Results of studying the dynamic parameters of soils, the design of the seismic insulating screen, and experimental calculation

5. 1. Results of studying the dynamic properties of model soils

As a result of our experimental studies on three soil models, the parameters of dynamic waves at different magnitudes of the force effect were recorded. Based on these results, a dependence plot of acceleration on the force of impact for three soil states is constructed (Fig. 5).

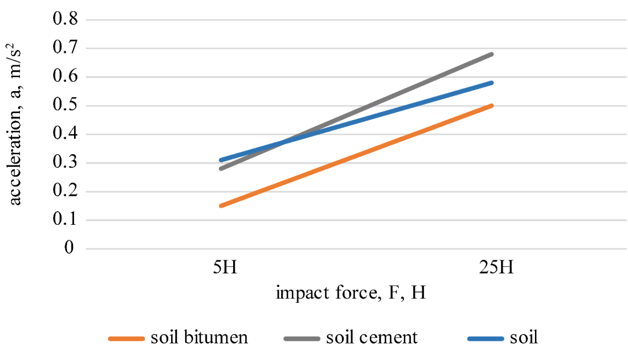

Fig. 5. Dependence plot of acceleration on the strength of the dynamic impact

The recordings of accelerograms of dynamic wave oscillations on the three types of model soils show a good correlation, with well-defined acceleration amplitudes and periods of oscillation.

Also, the established acceleration parameters at different values of the dynamic impact clearly show the damping of the material of the seismic insulating screen (Fig. 5).

5. 2. Results of modeling the shape and structural scheme of the seismic insulation screen

A structural scheme of a seismic insulating screen with certain damping properties has been designed, which makes it possible to isolate the building against intense seismic loads and increase its seismic resistance. The structure of the seismic insulating screen is arranged by drill-injection or jet technologies before the start of the development of the pit and the construction of the underground part of the building. In this case, the structure of the seismic insulating screen performs the function of a protective and anti-filtration wall (Fig. 6). The walls of the screen-shell are arranged from soil cement or soil-silicate injection piles in 2–3 rows. In this case, according to the technological parameters, the width of the wall is 2–3 m.

If seismic insulation of existing buildings is necessary, the horizontal part of the shell is arranged by horizontal drilling and injection of the mortar through the working chamber located next to the seismically isolated object.

The structural shape and parameters of the seismic insulating screen largely depend on the engineering and geological conditions of the construction site. At high values of hydrostatic pressure of groundwater, the shield-shell will provide an anti-filtration curtain. Accordingly, the thickness of the wall and the bottom of the shell screen is calculated on the combination of all influences.

Earlier, such a structural form of the shell screen was tested as an anti-filtration curtain at a real operating facility in the city of Almaty. As a result of designing a screen-shell from soil silicate, the underground part of the building was protected against aggressive groundwater.

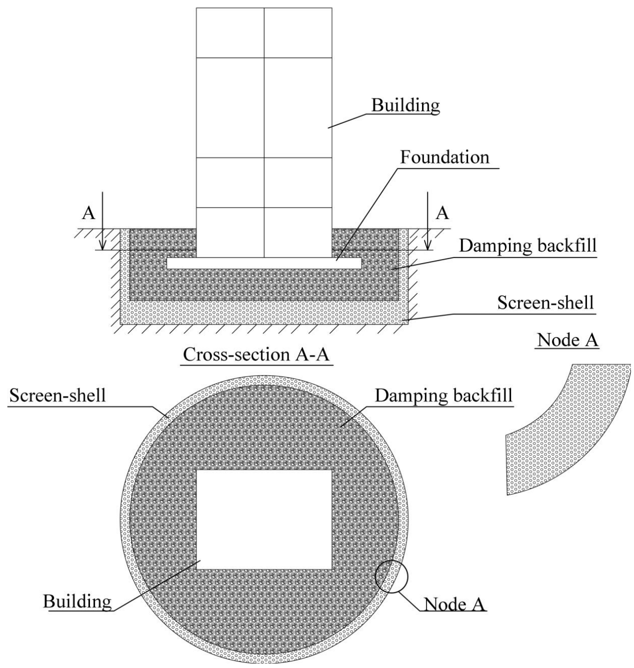

Fig. 6. Design diagram of the seismic insulation screen

5. 3. Results of the experimental-estimation studies into the interaction of the seismic insulation screen with the building

The results of our experimental-estimation studies of building models without seismic insulation and with seismic insulating screens on the example of one object are shown in the form of diagrams of axial forces and bending moments (Fig. 7, 8).

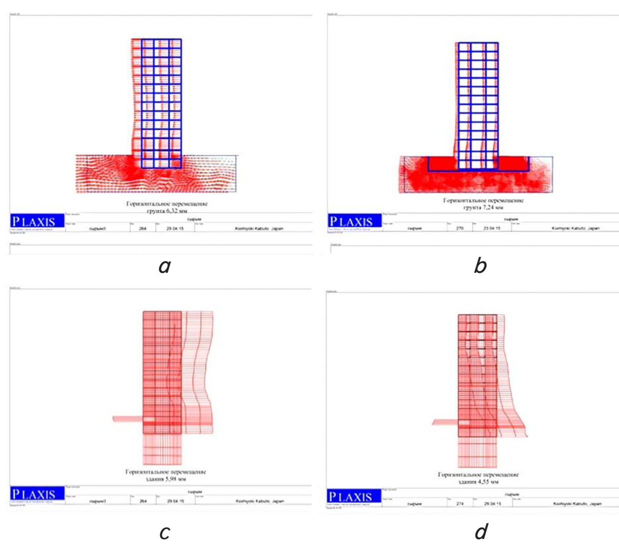

Fig. 7. The horizontal movement of soil and building: *a, c* – the diagram of soil and frame movement in non-insulated buildings; *b, d* – the diagram of soil and frame movement in buildings with seismic insulation

The PLAXIS software package made it possible to establish the stressed-strained state of the compared models and the condition of horizontal movements of the soil of the base and frame of the building. According to the results of our research (Fig. 7), it was established that the horizontal movement of the building is: for a building without seismic insulation – 5.98 mm, for a building with seismic insulation – 4.25 mm. Thus, it is shown that seismic insulation can reduce the displacement of the frame's masses and the magnitude of bending moments by 24 % and reduce the frequency of the frame's natural oscillations.

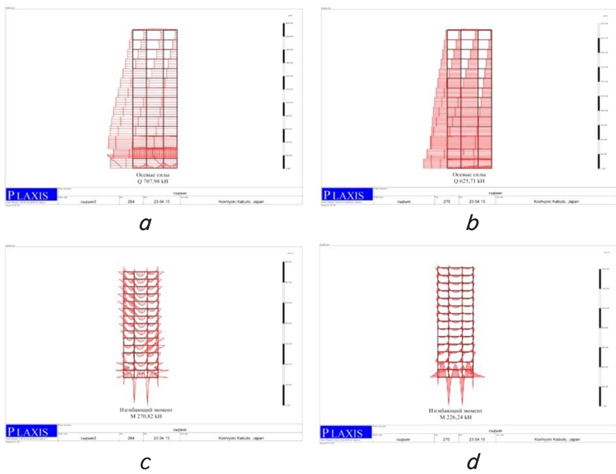

Fig. 8. Diagrams of axial forces and bending moments: *a, c* – the diagram of axial forces and bending moments in a building without seismic insulation; *b, d* – the diagram of axial forces and bending moments in a building with seismic insulation

The above diagrams of axial forces and bending moments (Fig. 8) demonstrate that the stressed-strained state in a building with a seismic insulating screen is 20–30 % less, compared to a building with a traditional seismic arrangement. While in a building with traditional seismic reinforcement the bending moment value is –270 kN, in a building with a seismic insulation screen – 226 kN. This fact shows the effectiveness of the seismic insulation screen.

6. Discussion of results of laboratory and estimation-experimental studies of the effectiveness of the seismic insulation screen

Our studies into the dynamic properties of soils were carried out according to the developed experimental procedure for recording the passage of elastic waves in the ground environment. The established values of the acceleration and amplitude of dynamic vibrations of the soil at different values of dynamic effects indicate the dependence of these parameters on the physical state of the soil environment.

The results of the registration of dynamic waves show a decrease in the parameters of dynamic waves when passing through a damping screen of soil bitumen and soil cement (Fig. 5). The close magnitudes of the acceleration and amplitude of oscillation for the model soil and the ground medium with the soil-cement screen can be explained by approximately the same properties in terms of density and humidity. The improved damping properties of the soil bitumen are uniquely related to the viscoelastic state of this medium.

As a result, the linear dependence of acceleration on the force of impact and the material of the seismic insulating screen was established (Fig. 5).

The seismic insulating screen, in the form of a cylinder-shell with the specified technical parameters, is a more efficient structural system providing the following advantages:

– an improved structural shape (shell) to reflect the vector of a seismic wave;

– the ability to control the technical parameters (dimensions), properties, and quality of the damper screen;

– the arrangement manufacturability of the damper screen using jet technology, etc.

The structure of the seismic insulation screen provides for its arrangement without preliminary development of the pit. Drilling wells in the underground part of the building, and injection with a binder/strengthening material to create a screen – a shell, makes it possible to reduce labor costs without placing any formwork and preserve the natural ground environment of the seismic insulating base.

At the same time, several issues remain regarding the evaluation of its effectiveness. The performance parameters of any system can be evaluated only after studying and comparing various systems that depend on many factors. Such factors include the shape and parametric data of damping screens-barriers, their structural schemes, the properties of screen materials used as a reflector or absorber of seismic waves, etc., which need to be studied in further research.

There are different approaches to determining the parametric characteristics of the shapes, dimensions, depth, and distance of damping barriers relative to the building. This task requires further theoretical and experimental research, including the construction of estimation models under different soil conditions. It is necessary to conduct experimental tests using a variety of shapes of shells and their interaction under seismic effects of different frequencies and amplitude.

Our analysis of the diagram of horizontal movements of the soil and the building with and without seismic insulation showed fairly good results. According to the results of our calculation, it was established that in a building with a seismically insulating screen, horizontal deformations (displacements) are greater than in a building without seismic insulation, which is explained by the structural movements of the loose damper backfill inside the screen. In addition, it was found that the values of axial forces and bending moments in a building with a seismic insulating screen are less than in a building without seismic insulation by 30–40 %. In this case, the seismic insulating screen, as a barrier that reflects surface waves, reduces the force of dynamic action, and the damping layer of bulk material absorbs the energy of oscillation. As a result, a building with a seismically insulating screen receives less impact on structural elements (for example, in columns) than a building without seismic protection. Similar results have been reported with the use of seismic insulation in the form of a sliding layer and in other studies. An example is the results of an assessment of the effectiveness of the integrated use of seismic isolating, damping and protective arrangements on the example of a 5-story frame building [8]. The effect of the joint use of a common foundation slab and the trench used to host the protective damping layer demonstrated a reduction in the displacement of masses and supports and the bending moment by 50 %, a decrease in the minimum frequency of natural oscillations by 12 %.

These results illustrate the effectiveness of the integrated use of a seismic insulating screen and a damping layer of sand, which improves the seismic protection of the structure and increases its seismic resistance with the correct choice of design characteristics.

As a result of the analysis of research, it was found that the effectiveness of the seismic insulation system depends on the choice of design models for the «structure-foundation» system. The calculation for seismic effects showed the effectiveness of the damping layers as a wave reflector in the ground mass [21–23].

The suggested procedure for arranging the seismic protection and seismic insulation system is technological enough and can be used in the renovation and strengthening of the foundations of architectural monuments, both existing and projected buildings and structures.

Our studies and calculations suggest the possibility of using different materials for the seismic insulating layer to increase the efficiency of seismic insulation. A damping screen or a barrier made of soil cement, soil silicate, or just a concrete fence will definitely show the different effects of absorption or reflection of seismic waves.

The proposed solutions for seismic insulation, with the arrangement of seismic insulating shells in the ground base of the building, require further study from a technological point of view, ensuring the practicality and manufacturability of construction production. The results of our estimation-experimental modeling of the interaction of a seismically insulated structure with a soil base make it possible to advance the development of new techniques of seismic insulation and determine their effectiveness.

7. Conclusions

1. A procedure for studying experimentally the dynamic properties of soils has been devised, which makes it possible to simulate the process of dynamic effects with the registration of the characteristics of elastic waves in the soil medium. After processing experimental data and approximating points with a polynomial of the fifth power, a linear dependence of the acceleration and amplitude of dynamic ground oscillations on the magnitude of dynamic effects was established. The amount of acceleration, with an impact force of 5 N for a model of soil bitumen is less than 10 % relative to the ground. With an impact force of 25 N, the difference in acceleration between the ground bitumen and the ground is 25 %. Thus, there was a decrease in the parameters of dynamic waves when passing through a seismic insulating screen from a soil bitumen. At the same time, the influence of parametric data of the seismically insulating damping screen on the acceleration and amplitude of dynamic ground vibrations requires further research.

2. The designed geotechnical seismic insulating screen, in the form of a cylinder-shell, according to technical parameters, is a more effective structural system of seismic insulation. Reducing the stressed-strained state of the model object by 30 % shows the effectiveness of the proposed seismic insulation system. Any type of foundation slab, vertical or horizontal barriers, are reflectors of seismic waves. In this respect, the cylindrical shape of the shell has a greater angle of reflection of wave effects, reducing the intensity of seismic effects by up to 25 %. The cylinder-shell is also distinguished by the manufacturability of its arrangement, using available construction technologies. Analysis of the studies and calculations carried out reveals the need to consider other forms and materials of the seismic insulating screen, which increase the effectiveness of seismic insulation to reduce the strength of dynamic effects on buildings and structures.

3. Our estimation-experimental studies have shown the effectiveness of the geotechnical seismic insulation shield-barrier as a reliable way to ensure the seismic resistance of buildings and structures. Comparing the results of our estimation-experimental studies has established that the values of horizontal movements, axial forces, and bending moments in a building with a seismic insulating screen are less than in a building without seismic insulation by 30–40 %. This shows the quality of the seismic insulating screen as a barrier that reduces the strength of the dynamic impact, reflects surface waves, or absorbs the energy of oscillation. As a result, a building with a seismically insulating screen receives less impact on structural elements by 30 %, and reduced natural oscillation frequencies by 12 % than buildings without seismic insulation.

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