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Energy-Based Evaluation of Dynamic Soil-Structure Interaction Process Under Seismic Impact from Explosion

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Abstract. This study presents the results of instrumental observations of the interaction process of an underground structure with the soil environment under explosion-induced seismic impact. During seismic impact, the soil imparts kinetic energy to underground structures, the value of which depends on the contact area of the structure and the soil and the conditions of interaction. In this regard, the energy-based evaluation of the process of joint vibration of the underground structure and the environment under explosive seismic waves is of great significance. The analysis of energy release in terms of frequencies shows that the energy of seismic radiation at different frequencies of the spectrum is not the same, and there is a well-defined maximum in the energy spectrum at small equivalent distances, i.e. at a certain frequency value much more energy is released than at other frequencies. Mathematical expressions are provided for calculating the total energy of ground vibrations, estimated proportion of energy propagating in the soil, and the energy received by the underground structure during their

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interaction. A formula is proposed for calculating a dimensionless coefficient of the vibration process, indicating the share of energy transmitted through the soil to the underground structures. Three zones are identified that characterize the relationships of the forces of interaction in the contact area. The first is the zone with a linear relationship between the force and the deflection of the structure. Then, in the next zone, the proportionality between the values is violated with the loss of the elastic nature of the interaction. In the third zone, the underground structure slides relative to the ground. Aspects of the interaction of a thin-walled structure with the soil are considered. Calculations show that the obtained relationships can be used with sufficient accuracy to evaluate the seismic intensity of explosive seismic waves.

Keywords: calculation of vibration energy, underground explosions, seismic waves, vibrations of the structure of the structure, kinetic energy, discrete spectra, seismic and explosive vibrations, stress modeling, deformation diagram

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Энергетическая оценка процесса взаимодействия в динамической системе «грунт — сооружение» при сейсмовзрывных воздействиях

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Аннотация. Приведены результаты инструментальных наблюдений по исследованию процесса взаимодействия подземного сооружения с грунтовой средой, при сейсмовзрывных воздействиях. При сейсмических воздействиях грунт сообщает подземным сооружениям кинетическую энергию, величина которой зависит от площади контакта сооружения и грунта, условий взаимодействия. В этой связи большое значение имеет энергетическая оценка процесса совместного колебания подземного сооружения и среды при действии сейсмовзрывных волн. Приведены дискретные спектры энерговыделений на разных частотах, построенные на основе экспериментально полученных результатов. Анализ энерговыделения по частотам показывает, что энергия сейсмического излучения на различных частотах спектра не одинакова, а в энергетическом спектре при малых приведенных расстояниях имеется четко выраженный максимум, т.е. на определенной величине частот выделяется значительно больше энергии, чем в других частотах. Приведены математические выражения для расчета общей энергии колебаний грунтовой среды, оценки соотношения энергии, протекающей в грунте, и энергии, получаемой подземным сооружением при их взаимодействии. Предложена формула для расчета безразмерного коэффициента колебательного процесса, показывающего долю энергии,

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передаваемой через грунт на подземные сооружения. Выделены три зоны, характеризующие зависимости сил взаимодействия в контактной области. Первая зона характеризуется линейной зависимостью между силой и относительным перемещением сооружения. Затем в следующей зоне пропорциональность между значениями нарушается с потерей упругого характера взаимодействия. В третьей же зоне происходит скольжение подземного сооружения относительно грунта. Рассмотрены особенности взаимодействия тонкостенного сооружения с грунтовой средой. Расчеты показывают, что полученные зависимости с достаточной точностью могут быть использованы при оценке сейсмической интенсивности сейсмовзрывных волн.

Ключевые слова: расчет энергии колебаний, подземные взрывы, сейсмические волны, колебания конструкции сооружения, кинетическая энергия, дискретные спектры, сейсмовзрывные колебания, моделирование напряжений, диаграмма деформирования

Заявление о конфликте интересов. Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов. Все авторы внесли равноценный вклад в разработку концепции и проведение исследования, рецензирование, редактирование и написание текста.

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1. Introduction

Safe operation of buildings and structures is ensured by designing the foundation and underground parts of buildings taking into account various negative factors [1; 2; 3]. In seismically active territories, earthquakes not only cause damage to structures due to vibration, but, in some cases, there is also dynamic liquefaction of soils accompanied by a complete or partial loss of stability of the soil base [1].

The main regulatory document in the field of design and construction of foundations of buildings and structures in Russia, the main regulatory document SP 22.13330.2016[1] recommends to design considering the dynamic effects from equipment installed in buildings, surface and underground transportation, construction works and other sources (clause 5.8.11). To take into account additional strain of soil due to cyclic and vibration loads, a reduction factor is used, the use of which is associated with the correction of the deformation modulus obtained from the results of static tests [4]. This approach to the quantitative evaluation of additional strain is called quasi-static, since it can be used within the framework of conventional static methods of calculating settlement of structure foundation [3].

Design of foundations for safe operation can be performed by analytical methods regulated by both Russian and international standards [5]. At the same time, there is a possibility of calculations by numerical methods, using specialized geotechnical software systems that implement the finite element method (FEM) and the finite difference method (FDM) [6]. The main analytical method for calculations of foundations of buildings and structures with respect to the serviceability limit states under dynamic impact is the method of layer-by-layer elementary summation with the use of a reduction factor of the deformation modulus.

Russian building code SP 23.13330.2011[2] states that the basis for computational and experimental evaluation of dynamic properties of soils are the results of field and laboratory tests of soils. Experimental studies are effectively performed by observing the behavior of the structural model or the structure itself in situ. Extensive measurements of vibration parameters of structures during seismic impact from underground explosions, which most fully reflect natural tectonic earthquakes, can be considered the most perfect experimental method of studying the behavior of structures. Energy-based evaluation of the process of joint vibration of the underground structure and the environment under explosive seismic waves is of great significance.

The problem of energy-based evaluation of soil behavior during the propagation of seismic and explosive seismic waves was studied in [7–11].

[1] SP 22.13330.2016. Foundations of buildings and structures. JSC “SIC “Construction”, 2016.

[2] SP 23.13330.2011. Foundation of hydraulic structures. Moscow: Minregion of Russia, 2011.

The deformation characteristics of soils under cyclic loading depend significantly on the level of average stress, porosity and strain amplitude. Dynamic effects of this nature occur during earthquakes. At present, the main parameters used in engineering dynamic analysis of stability of soil bases are dynamic shear modulus *G* and damping ratio *D*.

Damping ratio (or subsidence, decay ratio) *D* characterizes the property of materials to absorb dynamic impact.

Russian [12–15] and international scientific literature [16–20] present systematized test results of measuring shear modulus and damping ratios of cohesive and non-cohesive soils under cyclic (low- and high-frequency) loading.

The values of dynamic shear modulus of soils are determined in accordance with the international regulation "Standard test methods for the determination of the modulus and damping properties of soils using the cyclic triaxial apparatus" using the diagrams of deformation loops plotted in τ–γ coordinates (Figure 1).

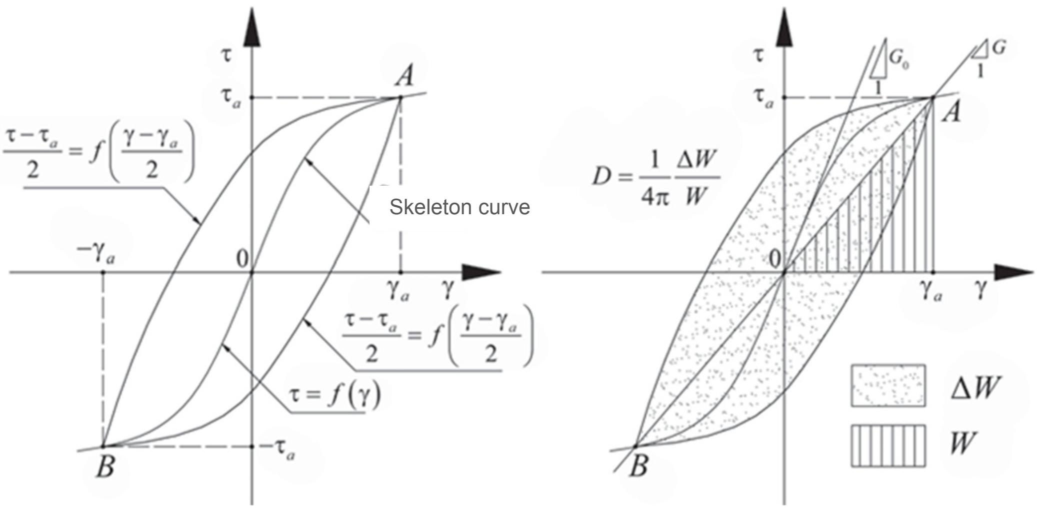


Figure 1. Determination of the dynamic shear modulus and damping ratio by the hysteresis loop:
W is the stored energy after one cycle; Δ*W* is the energy loss after one cycle [1]
S o u r c e: made by A.Z. Ter-Martirosyan and E.S. Sobolev [1]

Dynamic shear modulus *G* and damping ratio *D* are calculated according to the formulas

$$G = \frac{\tau_a}{\gamma_a}, \tag{1}$$

where *G* is the shear modulus, kPa; τ_a is the amplitude of shear stress τ, kPa; γ_a is the amplitude of shear strain γ, unit fraction,

$$D = \frac{1}{4\pi}\frac{\Delta W}{W}, \tag{2}$$

where *D* is the damping ratio, unit fraction; Δ*W* is the energy loss after one "loading-unloading" cycle, quantitatively equal to the area of the hysteresis loop; *W* is the maximum stored energy after one cycle, quantitatively equal to the area of triangle $0\tau_a\gamma_a$.

Based on the results of dynamic triaxial compression tests of soil, it is possible to perform ultimate limit state calculations — dynamic stability of the soil base using the liquefaction potential. Liquefaction potential is a characteristic of the soil base as a whole or individual geotechnical elements of the base, showing the safety factor of the soil body under dynamic loading of specific intensity. Commonly, such calculations are performed in conditions of seismically active territories and allow to ensure safe operation of buildings and structures.

In addition to the presented analytical methods of calculation of foundations taking into account dynamic properties, nowadays, numerical methods of modeling soil-structure interaction are widely used [1]. Numerical methods allow to model the soil-structure interaction more accurately, apply any types of natural and anthropogenic dynamic impacts, and take into account physical and mechanical properties of soil base [21–23]. Implementation of the analysis in specialized geotechnical software systems allows to design foundations taking into account dynamic effects with a high degree of accuracy and to ensure safe operation on the basis of reliable prediction.

In [1; 24], a finite element model of a heterogeneous soil body interacting with a structure of finite stiffness was considered (results of numerical modeling in PLAXIS 2B v.8). In the same works, isofields and the soil bearing ratio of a heterogeneous base were obtained.

At the same time, it should be noted that the number of works that consider the behavior of an underground structure in terms of the energies of the structure and the soil environment is very small.

2. Purpose

The main purpose of this study was to investigate the behavior of the underground structure in terms of the energies of the structure and the soil environment in full-scale conditions. The methodology of experiments, information about soil conditions and other data are given in [12; 24].

3. Results of Experimental and Theoretical Studies

In the seismic impact process, the soil imparts kinetic energy to an underground cylindrical thin-walled structure, the magnitude of which depends on the area of contact between the structure and the soil, interaction conditions, etc. In this regard, in order to objectively estimate the energy characteristics of an underground structure, it is necessary to address the seismic energy density, i.e. the amount of energy received through a unit area of contact to the structure.

In [11], the ground vibration energy density was calculated using the following formula by S.V. Medvedev:

$$E_r = \frac{1}{2}\gamma c \sum v_i^2 T_i n_i \ , \tag{3}$$

where γ is the soil density in g/cm^3; c is the wave propagation velocity in the soil, cm/sec; v_i is the velocity amplitude in cm/sec, which is defined as one half of the measured individual amplitude due to the wave reflection effect; T_i is the period of vibration in sec.

Figure 2 shows discrete energy release spectra plots at different frequencies based on experimentally obtained results. Here, attention should be paid to the spectrum of a well-defined maximum, i.e., at a particular frequency much more energy is released than at other frequencies.

Figure 2 shows that the energy of explosive seismic waves at different frequencies of the spectrum is not the same, and there is a well-defined maximum in the energy spectrum of vibration. The peak where the maximum is pronounced is always observed not at the beginning of the frequency range. Frequency $f_{\max}$, which carries most energy, changes with distance.

At small equivalent distances, a pronounced maximum is observed in the high-frequency region of the vibration spectrum; at equivalent distances of 7.4 and 0.8, respectively, the frequencies correspond to 20 and 12.5 Hz, and with increasing equivalent distance, the peak is observed already in the low-frequency zone of the spectrum. At the equivalent distance values of 14.7; 16.0; and 24.5, the frequency values are 10 Hz; 9.1 Hz; and 7.1 Hz, respectively.

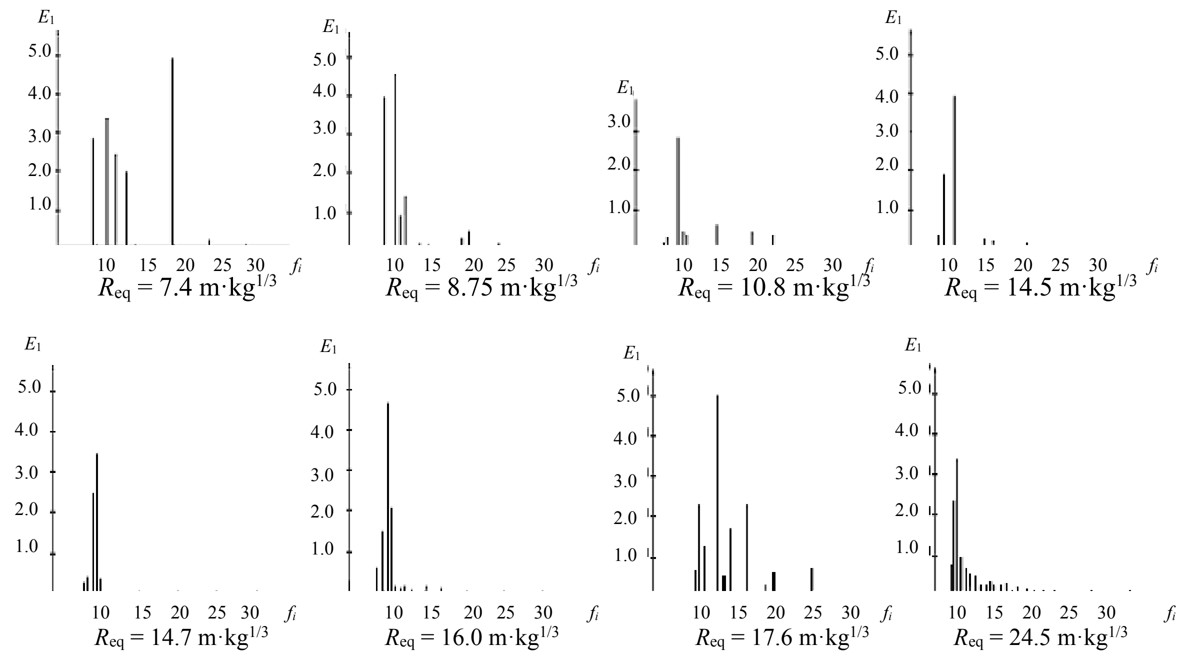


Figure 2. Discrete energy release spectra at different frequencies for different equivalent distances
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

Figure 3 presents a graph based on the experimentally obtained results, which shows the changes in the magnitude of the carrier frequencies as a function of the equivalent distance. The graph shown in the figure demonstrates that the frequency corresponding to the maximum energy value changes with the increase in the equivalent distance. Here, starting from some value of the equivalent distance, a decrease in frequency is observed. As the equivalent distance increases, the number of peaks increases, i.e., in these cases the spectra are enriched with low-frequency components of the peaks, and their magnitude decreases.

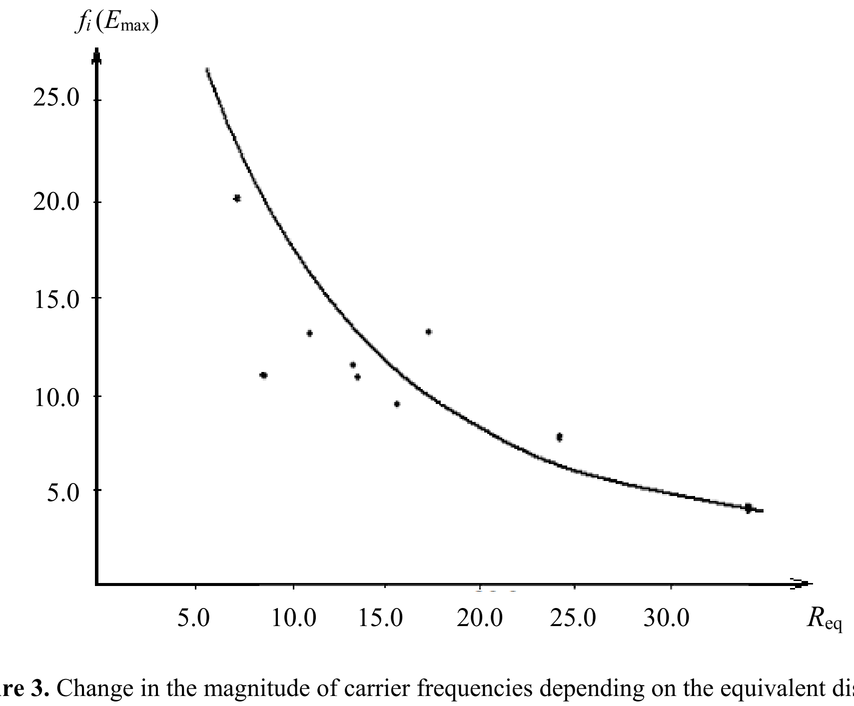


Figure 3. Change in the magnitude of carrier frequencies depending on the equivalent distance
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

The total vibration energy of the soil environment is calculated based on records for each of the three components: two horizontal and one vertical:

$$E_r = E_{h1} + E_{h2} + E_{vert}\,. \tag{4}$$

Since each component is commensurable with each other, based on [9], the following expression can be written for the considered case:

$$E_{gr} = E_{h1} = 0.35E_r \tag{5}$$

and taking (3) into account, the following can be written:

$$E_{gr} = 0.35 \cdot \frac{1}{2}\gamma c_p \sum v_i^2 T_i\,. \tag{6}$$

To estimate the ratio between the energy propagating in the ground and the energy received by the underground structure during their interaction, the following expression is used:

$$\eta = E_k \big/ E_{0.gr}\,, \tag{7}$$

where E_k is the kinetic energy received by the structure as a result of the interaction with the ground; $E_{0.gr}$ is the energy propagating over an area equal to the cross-section of the underground structure, defined by the following formula:

$$E_{0.gr} = E_{gr} S\,. \tag{8}$$

Kinetic energy E_k is defined by the following formula:

$$E_k = \frac{1}{2} M\,\dot{u}^2\,, \tag{9}$$

where M is the mass of the underground structure defined by the following formula:

$$M = \pi\rho^2\left(R^2 - r^2\right)L\,, \tag{10}$$

where ρ is the density of the structure; R and r are the external and internal radii of the structure, respectively; L is the length of the structure; $\dot{u}$ is the amplitude of displacement velocity of the structure under explosive seismic waves (recorded using seismometric channel).

Substituting (10) into (9) results in the following:

$$E_k = \frac{1}{2}\pi\rho^2\left(R^2 - r^2\right)L\dot{u}^2\,. \tag{11}$$

The following expression can be composed from (7), (9) and (11):

$$\eta = \frac{\pi\rho(R^2 - r^2)\dot{u}^2 L}{(0.35\gamma c_p \sum v_i^2 T_i)S}\,. \tag{12}$$

This dimensionless value can be called the “reduction” ratio of vibrational energy in the dynamic soil-structure system or the “transfer” ratio. The above coefficient, by meaning, shows the share of energy transferred through the ground to the underground structure, as a result of their interaction under explosive seismic waves.

The curve of η as a function of the intensity of seismic vibration, obtained on the basis of formula (12), is shown in Figure 4.

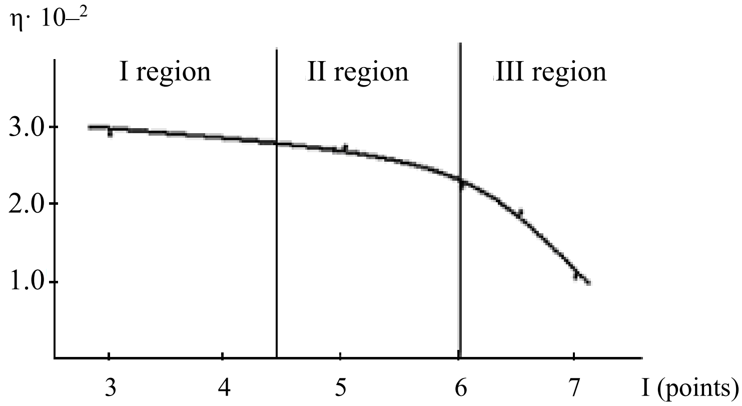


Figure 4. Relationship between ratio η and the intensity of explosive seismic vibration of the soil

S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

Figure 4 shows that with increasing intensity of the explosive seismic vibration of the soil, ratio η slightly decreases. With increasing intensity of vibration due to underground explosions, the total amount of kinetic energy received by the underground structure increases, but the ratio η decreases.

Three regions can be distinguished in the general qualitative characteristic of the relationship between contact forces of the structure with the soil and their relative displacement, according to the experimental diagrams of the test results. The first one corresponds to the stage of loading the structure, when the relationship between the forces and relative displacement of the structure is linear. In this case, the soil is being compacted, and elastic and viscous properties of the body, but not plastic ones, are revealed.

At the second stage, the proportionality between the interaction forces and the displacement of the structure is violated and the elastic character of the interaction is lost. With the increase of the external load, it is possible to observe sliding of the underground structure relative to the ground in the third region (Figure 4). This implies that with increasing intensity, the share of energy transferred from the ground to the structure decreases.

In the interaction process, when the strength properties of the structure and the surrounding soil are markedly different and physically complex, the displacement of the structure relative to the ground during seismic impact is observed. The interaction results in the reduction of vibrational energy in the dynamic soil-structure system, and therefore this parameter is increasingly attracting the attention of experimental researchers. In addition to the above, when the structure is thin-walled, the complexity of the interaction process between the structure and the environment is aggravated. Following this tradition during the experiments, attention was also paid to studying this parameter. Figure 5 shows the relationship between the values of displacements $(\tilde{U}, \tilde{V}, \tilde{W})$ of the structure relative to the ground and ratio η.

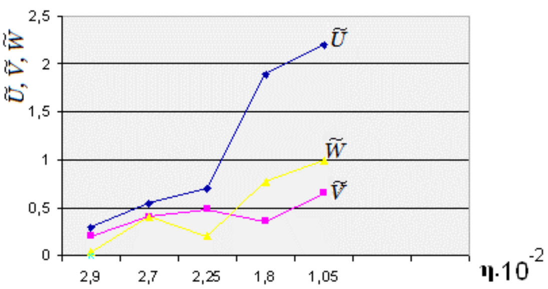


Figure 5. Relationship between the soil-structure relative displacement and the energy “reduction” ratio η $\left(\eta = E_{struct}/E_{gr}\right)$

S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

The above results can be used to predict the behavior of underground thin-walled structures subjected to explosive seismic waves. The calculations show that the relationships established in this paper can be effectively used in estimating the intensity of explosive seismic waves.

Cyclic liquefaction of soils must be considered along with vibration issues in case of explosive seismic impact.

Design of hazardous industrial facilities requires safe earthquake-proof design solutions. As a result of the construction of the Nizhnekamsk Reservoir in the Republic of Tatarstan, the groundwater level rose and a number of areas were flooded along the Kama River. This rise in groundwater level and the presence of tectonic faults in the area of Kamskiye Polyany provoked an increase in the level of seismic activity of the considered territories of the Kama River coast. According to the OSR-97 seismic zoning map, earthquakes with intensity of 7.0 points are forecasted on medium soils in the territory of the Republic of Tatarstan. As a result, dynamic properties of soil bases need to be evaluated during surveys and seismic-resistant reinforcement needs to be used in the design and construction of structures.

Considering the above, the effect of seismic load from a possible earthquake on the change of physical and mechanical properties of soils needs to be taken into account when designing foundations of critical structures [1–3; 5–8].

The site under study is located in the water area of the Kama River, north-east of the Republic of Tatarstan. The results of seismic microzoning of the construction site show that the seismic activity of the site with the given soil base is estimated at 7.0 points on the MSK-64 scale with an acceleration of 143 cm^2/sec at short and medium vibration periods. The accelerograms of the scenario earthquakes and their corresponding response spectra are presented in Figure 6.

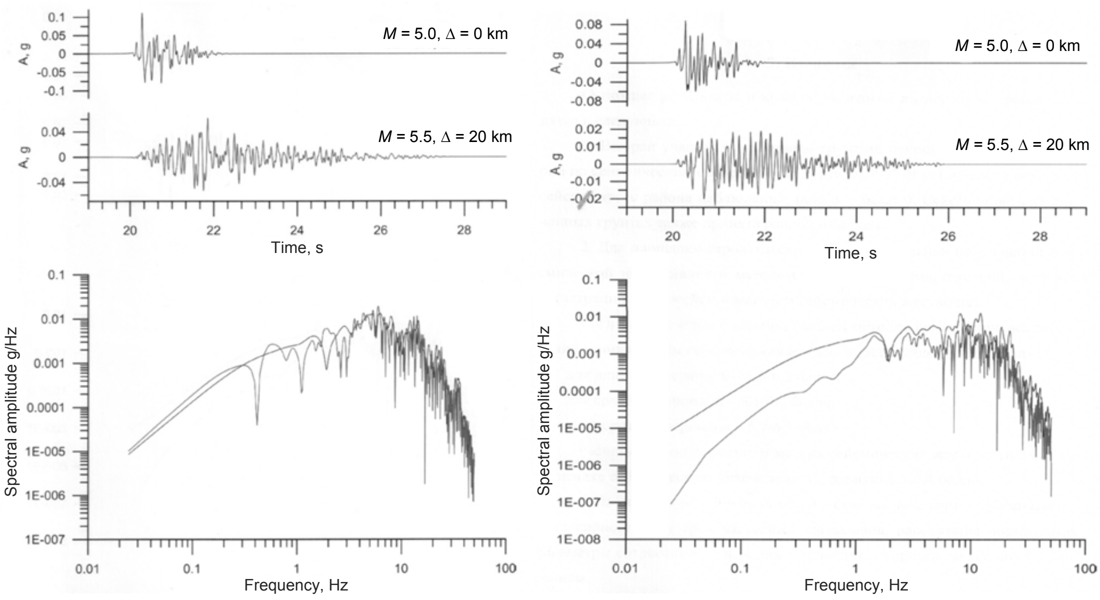


Figure 6. Scenario earthquake accelerograms of and their corresponding reaction spectra
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan,I.T. Mirsayapov, V.T. Erofeev

To investigate the dynamic stability of clay and water-saturated sandstone layers from the position of assessing the possibility of their liquefaction under seismic effects corresponding to the design (predicted) seismic activity of the site, laboratory triaxial cyclic loading tests equivalent to the seismic impact in terms of force were carried out.

When modeling the deformation conditions in which the soil is subjected to seismic impact in real field conditions, the predicted seismic load is modeled before cyclic loading based on the methodology proposed by H.B. Seed and I. Idriss [16].

According to this methodology, seismic loading can be characterized by the magnitude of the equivalent cyclic shear stresses (CSR) for an earthquake of a given recurrence and intensity:

$$CSR = \frac{\tau_{av}}{\sigma_v^{'}}, \tag{13}$$

where τ_{av} is the average expected cyclic shear stress at the specified magnitude; $\sigma_v^{'}$ is the vertical overburden stress.

It is assumed that before the earthquake, the soil element located under the horizontal surface is subjected to consolidation for a long time in state K_0 (K_0 is the ratio of horizontal and vertical stresses during consolidation in natural conditions). During an earthquake, a series of successive cyclic shear stresses act on this soil element under undrained conditions. These stresses are applied in the absence of lateral deformation, because the flat earth surface is assumed to extend infinitely in the horizontal direction.

In practical calculations, in order to assess the liquefaction potential of clayey and sandy soils with different degrees of water saturation, the average values of shear stresses caused by an earthquake at depth h are determined from the expression

$$\tau_{av} = \left(0.65 \cdot \frac{\gamma \cdot h}{g}\right) \cdot a_{\max} \cdot r_d . \tag{14}$$

The value of $a_{\max}$ is taken from the accelerogram of the earthquake with respect to peak horizontal accelerations for horizontal components of vibration.

The number of loading cycles (N) in the laboratory experiment simulating seismic impact depends on the duration of the earthquake, and therefore on the magnitude of the earthquake.

The analysis (approach) described above gives the maximum value of the expected cyclic shear stress due to earthquake (τ_{av}), which corresponds to one half of the axial dynamic load in triaxial dynamic tests (Figures 7 and 8).

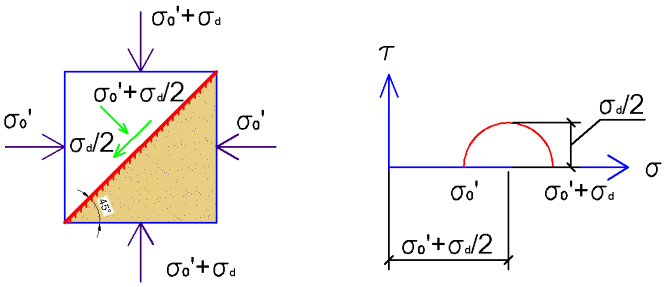


Figure 7. Modeling of stresses in a soil sample under triaxial compression during cyclic loading
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

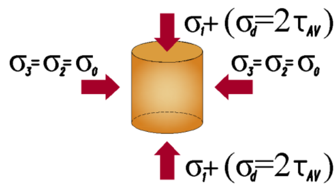


Figure 8. Stress state of the soil during laboratory simulation of equivalent triaxial cyclic loading
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

Based on the methodology mentioned above, a strength model of layered soil base composed of sandy and clayey soil with different degrees of water saturation during scenario earthquakes has been developed. The model takes into account the possibility of acceleration of the soil body in three directions, as well as the mutual interference of layers of different stiffness.

To quantify the liquefaction capacity of water-saturated sand and clay layers under random irregular multidirectional seismic impact, correction functions are introduced for cyclic strength obtained under steady-state cyclic loading in order to take into account the discussed features of real seismic loading C_2 and C_5 [12].

Based on the developed model, the equivalent parameters of regular cyclic loading were determined for laboratory studies of liquefaction resistance of sandy and clayey soils of the construction site under the following design characteristics of the scenario earthquake: magnitude 7.0, acceleration A = 143 cm^2/s, fundamental frequency ≈2 Hz, fundamental period of vibration 0.56 sec.

The following strength criteria are adopted to evaluate the resistance to liquefaction:

1. Emergence of axial deformation under triaxial cyclic loading less than 5 %;
2. Pore pressure coefficient $\beta = p_w / \sigma_{cp}$ must be ≤ 0.6;
3. The width of the hysteresis loop at the 30th loading cycle must be less than the width of the loop at the 29th cycle of loading, i.e. $\Delta\varepsilon_{30} \leq \Delta\varepsilon_{29}$.

Experimental studies of liquefaction resistance were performed on 143 series of undisturbed (134 series) and disturbed (9 series) soil samples (three twin samples in each series) in a triaxial compression device (stabilometer) under cyclic loading conditions with parameters equivalent to those of a scenario earthquake with an intensity of 7.0 points installed for the construction site. In the process of experimental studies, the main parameters characterizing the state of sandy and clayey soils under cyclic loading were established: axial and radial strains, pore pressure, effective and average stresses.

The conducted experimental studies allowed to establish patterns of strain growth under equivalent cyclic loading.

By analyzing the obtained results, it can be concluded that in soil samples of different degree of water saturation, which are subjected to cyclic triaxial compression equivalent to seismic loading with intensity of 7.0 points, strains develop with different intensity (Figure 9). At the initial stage, the development of strains is more intense due to post-compaction of the specimen, afterwards the strains stabilize. In all specimens tested under the cyclic loading equivalent to the design scenario earthquake with intensity of 7.0 points, the magnitude of axial strain does not exceed 3.0%, the pore pressure coefficient is less than 0.6, the ratio $\Delta\varepsilon_{30} / \Delta\varepsilon_{29}$ is less than 1. In the process of testing, there were no external signs of reaching the ultimate resistance (formation of barrel and inclined shear plane).

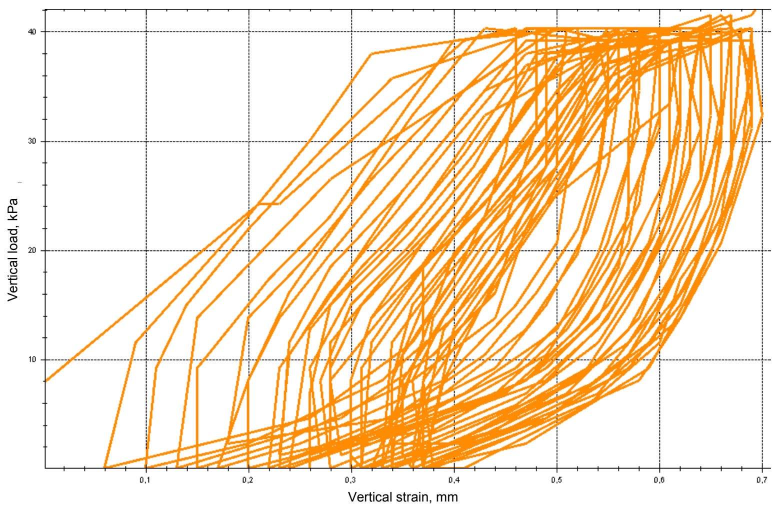


Figure 9. Sample deformation diagram during cyclic loading
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

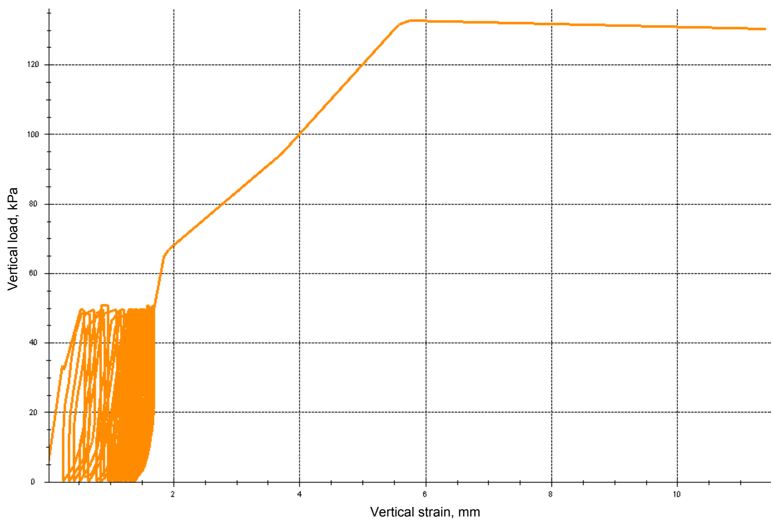
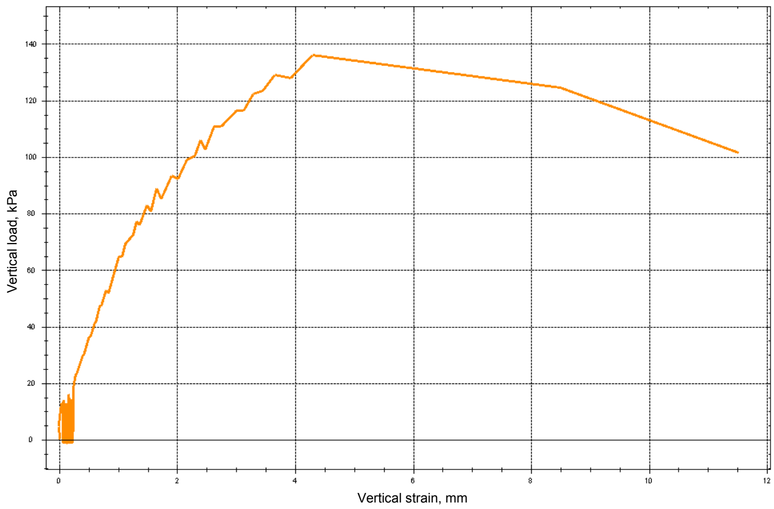


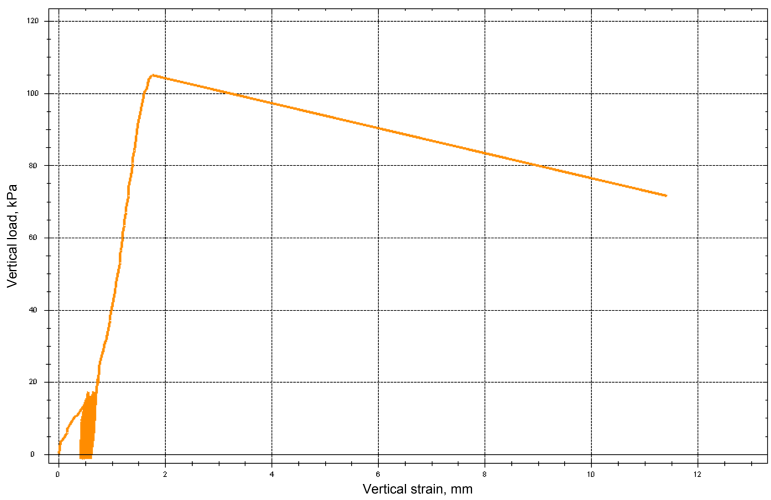
Figure 10. Sample deformation diagram according to the “crushing” pattern
S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

After cyclic loading test with parameters equivalent to the design scenario seismic impact, the soil samples were brought to failure by deviatoric static loading according to the “crushing” pattern (Figure 10). It was found that, in general, seismic impact on soils did not lead to a decrease in the ultimate deviatoric load compared to the results of static loading.

There was a difference in the character of static fracture along the “crushing” trajectory of sandy and clayey soils. The clayey soil samples fractured on the descending branch of the $(\sigma_1–\sigma_3)$ — ε_1 diagram (Figure 11, *a*), while the sandy soil samples fractured on the ascending branch of the stress-strain diagram (Figure 11, *b*). This fact is explained by different initial density of the soils.



a



b

Figure 11. Sample deformation diagram according to the “crushing” pattern:
a — clay; *b* — sandstone

S o u r c e: made by B.S. Rakhmonov, Kh.S. Sagdiev, A.Z. Ter-Martirosyan, I.T. Mirsayapov, V.T. Erofeev

4. Conclusion

1. The process of dynamic soil-structure interaction under explosion-induced seismic impact has been evaluated.

2. It is shown that the most comprehensive study method is exploring the behavior of the structure in full-scale conditions with energy-based evaluation of the process of joint vibration of the underground structure and the ground environment under explosive seismic waves.

3. During seismic action, the soil imparts kinetic energy to the underground structure, the magnitude of which depends on the area of contact between the structure and the soil and the conditions of their interaction.

4. Discrete energy release spectra at different frequencies were obtained and plotted on the basis of experimentally obtained results.

5. It was found that the energy of explosive seismic waves at different frequencies of the spectrum is not equal, and there is a well-defined maximum in the energy spectrum of vibration. That is, more energy is released at a certain frequency than at other frequencies. At the same time, the frequency, which has more energy, changes with distance.

6. Mathematical expressions for calculating the total energy of soil vibration and the energy received by the underground structure during interaction with the soil are given.

7. The ratio of the vibrational process, which shows the share of energy transferred through the soil to the underground structure, is introduced. Relationships between the ratio and the intensity explosive seismic vibration of the soil are shown.

8. Three regions are defined on the experimentally obtained force-displacement diagram. The first one corresponds to the stage when the relationship between the forces and relative displacement of the structure is linear. At the second stage, the elastic character of the interaction is lost. At the third one, sliding of the underground structure relative to the ground is observed.

9. It is shown that the above results can be used to predict the behavior of underground thin-walled structures under the influence of explosive seismic waves.

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