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PROTECTION OF OBJECTS FROM THE INFLUENCE OF LONG-TERM DYNAMIC LOADS

Purpose. The paper is devoted to justification of rational parameters of the protective structure for the existing buildings located on the loess soils and subjected to the influence of vibrodynamic loads from the surface source, which allows reducing the tilt of the structure and the settlement of the foundation.

Methodology. The methods of numerical modelling of geotechnical processes for estimating the parameters of the stress-strain state of the “soil-structure” system are applied.

Findings. It is established that the protection of the building foundation located on the loess soil from the surface dynamic load is provided by an anti-vibration barrier (protective shield) made of a material with the deformation modulus $E \geq 15\,000$ MPa. It is proved that the foundation deformations decrease nonlinearly with an increase in the barrier depth from 15 to 25 m, and at a barrier depth of $H = 20$ m there is a maximum reduction of the foundation settlement and tilt of the building. It is shown that from the viewpoint of manufacturability and cost efficiency, the most rational is a protective barrier made of soil-cement piles created by the jet-grouting technology.

Originality. A new numerical model of the “soil-structure” geotechnical system was developed to evaluate the parameters of the stress-strain state of the loess soil, underlying the buildings and structures. A distinctive feature of the model is the use of values of the strength parameters of loess soils obtained during long-term dynamic tests under laboratory conditions. The regularities of the change in the stress-strain state of the “soil-structure” geotechnical system under the influence of long dynamic loads from the surface source for various parameters of the vibration shield are investigated.

Practical value. The developed numerical model makes it possible to evaluate the impact of dynamic loads from surface sources on objects located on loess soils. The obtained parameters of protective screens can be used for protection of objects located on loess soils in the area of dynamic loads from technological equipment and transport.

Keywords: *loess soil, dynamic loads, vibration, acceleration, shear resistance, protective shield*

Introduction. Ensuring the reliable and safe operation of various buildings and structures has always been of primary importance. Recently, in the design, construction and operation of facilities, more and more attention has been paid to the issues of their technical protection against dynamic impacts.

Almost all elastic bodies – buildings and structures, bridges, foundations, ground massifs, which transmit mechanical waves over considerable distances – are subjected to dynamic (in particular, vibrational) loads. Dynamic impacts arise because of work of technological or construction equipment, railway transport, public transport, blasting operations, construction and operation of underground transport facilities, and others.

Mechanical oscillation (vibration) reduces the strength, stability and durability of objects and structures, worsens the sanitary and hygienic conditions of people staying inside buildings, and disrupts the operation of devices and automatic systems.

Vibration can cause compaction and disturbance of the soil structure, which in turn leads to a change in the water conductivity and moisture content of the rocks. As a result, the resistance of the entire massif to external influences is reduced, deformation (landslide) processes are activated, and the bearing capacity of the foundation soil within the zone of dynamic influence decreases.

Statement of the problem. To improve human life safety and protect objects from the impact of dynamic loads, a number of methods and technologies are used that can be divided into the following groups:

- structural protection of foundations and object elements from the dynamic influences;
- location of objects outside the dynamic impact zone;
- application of protective barriers (screens) between the source of dynamic loads and the protected object.

Constructive protection of objects is reasonable if the dynamic load from equipment (pump, compressor, and others) or from a moving vehicle is directly transferred to the bearing elements, leading to their rapid deterioration and provoking the destruction of the entire building or structure. The traditional way to prevent the negative impact of vibration is to increase the rigidity of the structure due to increase in the size of the foundation, cross-section of columns, beams and other elements. This allows increasing the structure load, but, as a result, the cost of the structure is significantly increased.

The second way to protect objects – their location behind the zone of dynamic influences – can be applied if there are free territories around the objects that do not

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involve subsequent development. However, for the already built-up and limited area, this method is not acceptable. In addition, the magnitude of dynamic loads from various sources (road and rail transport, blasting, technological and construction equipment) tends to increase. The degree of influence of technogenic factors on the geological environment over the last 30 years has increased by almost an order of magnitude.

Thus, a more relevant direction at present is the development of engineering methods for protecting various objects from dynamic loads (the third group).

Analysis of the recent research and publications. The most common and effective methods used to protect objects from various dynamic (vibration, shock) loads are wave barriers (screens). They can be non-filled or filled with low-modulus materials (rubber, clay, slag) trenches, as well as a number of solid piles, metal piles, or monolithic concrete walls, and others. At the same time, trenches with low-modulus materials are considered more effective.

As for the effective depth of wave barriers (protective trenches), the authors of the known papers have disagreements. For example, in [1] barriers of insignificant depth are offered in the form of a trench with a width of 0.5...1.0 m and a depth of 3...5 m filled with granular material (crushed stone, gravel) or material with a substantially different density (slag, agloporite). Similar parameters of protective trenches are given in [2]. To protect buildings from tram vibration, the author [3] offers a vibration barrier with a depth equal to the depth of freezing of the ground and a width of 0.25...0.3 m.

The experience of applying vibration protection from nearby metro lines is given in [4]. Regarding the parameters of protective trench, it is indicated that to reduce the oscillations effectively, its depth should be approximately equal to the length of the Rayleigh wave (8... 20 m), and the internal filling of the trench should have a significant heterogeneity. To do this, the trench must be empty or filled with low-modulus material.

The authors of [5] explain the reason for the low efficiency of wave barriers by the large wavelength from the source of oscillations with insufficient dimensions of the barriers. Therefore, the wave diffracts at the bottom and walls of the trench without significant loss of the energy. In order to weak the transmitted vibration, the barrier must be sufficiently deep, correspond to the dimensions along the perimeter and block the direct visibility of the object from the source.

In addition to the data of practical experience and recommendations, there are also results of studies of engineering parameters of wave barriers obtained with using effective methods.

It should be noted, that the solution of various engineering problems taking into account a large number of influencing factors by analytical methods is very difficult, and sometimes impossible. At the present stage, the justification of the parameters of engineering structures in complex geological conditions, taking into account several influencing factors, is the most effective with the use of modern software based on various numerical methods.

It is efficient to use the finite element method (FEM) to find the solution of the interaction of the “soil-structure” geotechnical system under dynamic loads. A number of studies performed show that the results obtained using the FEM have a good representation and sufficient accuracy for engineering tasks.

Thus, in [6], the slope stability estimation by the finite element method was performed, taking into account a number of influencing factors for the inhomogeneous soil massif. This made it possible to choose the engineering parameters for the protection of the investigated site. A similar approach was adopted by the authors [7] in modelling the stability of a rock slope under controlled failure.

In [8], the investigation results of the earth surface settlement caused by the construction of a transport tunnel in the urban area are presented. To protect the Sagrada Familia cathedral, located in the zone of tunnel influence, it was planned to construct a wall of bored piles. On the basis of the three-dimensional model, the influence of the protective wall located between the tunnel and the cathedral on the nature and magnitude of the earth’s surface settlement was studied. However, this work does not take into account the dynamic component of a nearby transport tunnel.

In [9], the protection of the foundation against dynamic effects with the use of trench barriers is considered. The research was carried out using the FLAC software. The source of the dynamic impact was the vertical shock load $P = 1.0$ MN. As a barrier, two options are considered – a concrete wall and an unfilled trench. A homogeneous soil mass was simulated. However, the authors did not consider the influence of the material properties of the barrier on its efficiency as a protective structure.

It should also be noted, that a more important parameter in assessing the building setting is its tilt, i.e. the difference in the settlement of the foundation external points, which is not taken into account in the above studies.

Objective of the article. The purpose of the study is to justify the rational parameters of the protective structure for the existing building located on the loess soil and subjected to the influence of dynamic loads from the surface source, which allows reducing the tilt and settlement of the structure.

Presentation of the main research and explanation of scientific results. The choice of rational parameters of protective structures should be geomechanically justified and take into account the material of structures, their dimensions, and also the properties of the rock on which the protected object is located. For the study, it is advisable to use modern software that allow taking into account geometric and geotechnical parameters with the engineering accuracy of the results.

For carrying out numerical studies, the software FLAC 2D was used. This software uses the finite difference method in calculations.

Dynamic analysis is based on the example of a building constructed on the subsiding ground exposed to dynamic loads from moving vehicles or process equipment (Fig. 1).

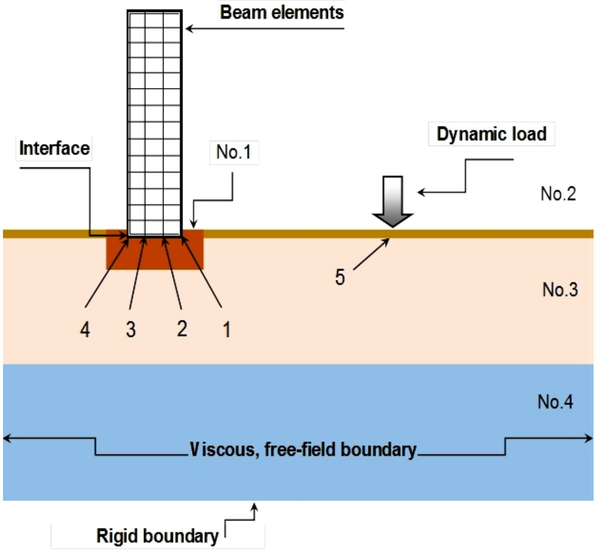


Fig. 1. The calculation scheme for solving the problem of the influence of dynamic loads on a building

The "loess soil – structure" system on several horizontal layers of subsidence ground in the zone of a dynamic load was simulated. The physical and mechanical properties of soils were assumed to be typical for the conditions of Dnipro city, according to the data of soil investigation (Table 1). A compacted soil layer was introduced under the foundation of the structure.

The most important elements, which are included in the calculation scheme (Fig. 1) are as follows:

1. The source of the dynamic load is the railroad. According to [10], the greatest impact on the level of vibration from moving vehicles will occur for the axis load of the train and the speed of its movement. Harmonic oscillation from the axis is transferred to the rail, sleepers and then into the ground.

For rail transport, the axial load can vary significantly from a few tons and several tens of tons for a freight train. In the present studies, the axial load is 240 kN, which is uniformly distributed over the sleeper width of 3 m. In this case, the load is applied to grid points (0.5 × 0.5 m) and the load will be 34 kN per point, respectively.

The dynamic coefficient will depend on the speed of the train, and according to [11], it will be 1.0 for the movement of the railway transport within the industrial site.

Table 1

Physical and mechanical properties of the soil layers

Soil layers	Density, ρ kg/m^3	Deformation modulus, E, Pa	Poison's ratio, ν	Cohesion, c, Pa	Angle of internal friction φ, grad	Thickness, m
No. 1	2000	$35 \cdot 10^6$	0.3	$18 \cdot 10^4$	35	10
No. 2	1800	$20 \cdot 10^6$	0.3	$5 \cdot 10^3$	16	2
No. 3	1770.0	$20 \cdot 10^6$	0.3	$5 \cdot 10^3$	26	28
No. 4	3100.0	$42 \cdot 10^9$	0.1	–	–	35

2. The object of dynamic effects is a high building (tower-type headgear) on a slab foundation. The calculation for dynamic effects was performed taking into account the inertia forces.

3. The base of the building foundation. Taking into account the soil compaction, the design scheme includes the layer of compacted soil (soil layer No.1, Fig. 1), the thickness of which is assumed to be equal to the depth of the highly compressible soil. The interaction of the soil and the structure was realized with the help of an interface element available in the FLAC 2D, which allows introducing additional parameters – the stiffness of soil and the Mohr-Coulomb failure criterion to prevent a slip along the base of the foundation.

4. A soil medium of the dynamic load propagation is represented by loess loam (layers No. 2 and 3) and bed rock (layer No. 4).

Strength characteristics of loess soils were taken according to the results of previous studies for static [12] and dynamic [13] tests within the given values of the accelerations a = 0...4.3g m/s^2 and humidity ω = 11...22 % and correspond to:

- cohesion at long-term shear test

$$c_\infty = e^{-1.59 - 0.012 \cdot a - 9.05 \cdot \omega};$$

- angle of internal friction during short-term dynamic shear test

$$\varphi_{0din} = e^{0.1 - 0.009 \cdot a - 7.735 \cdot \omega};$$

- angle of internal friction during long-term dynamic shear test

$$\varphi_{\infty din} = e^{-1.28 - 0.017 \cdot a - 3.762 \cdot \omega}.$$

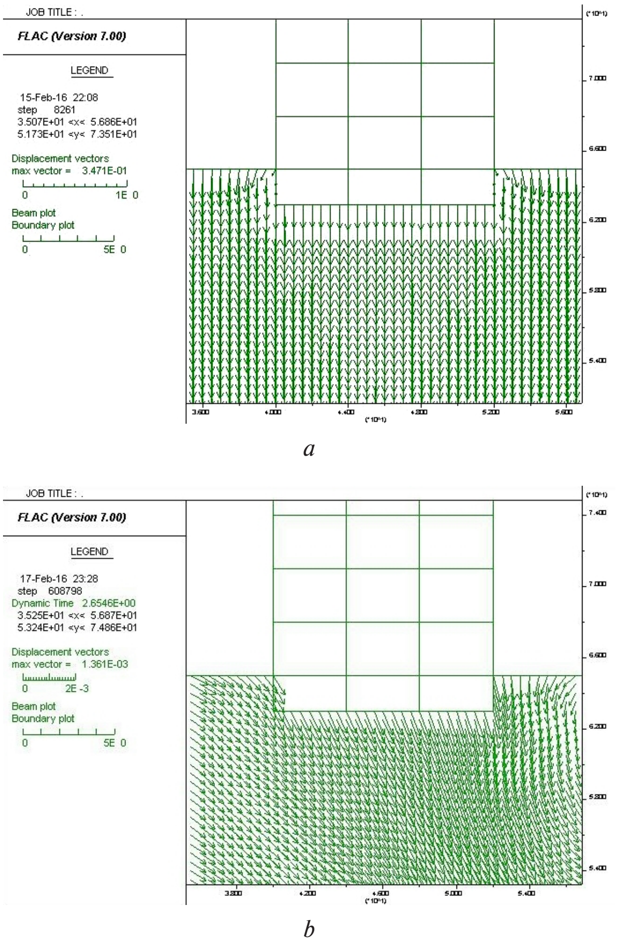
The results of numerical calculation show that the behaviour of the "soil-structure" system varies depending on the static and dynamic conditions. Uneven deformations, horizontal displacements and tilt of structure can occur after application of dynamic loads (Fig. 2).

To protect the object from deformations, a protective barrier is provided on the way of propagation of vibrations from the dynamic load.

In order to exclude the deformation of the structure during the construction work of the protective barrier, it is placed at the distance of $L = 10$ m to the protected object. This distance is outside the deformation zone due to the weight of the structure and also allows the necessary technological equipment to be placed for the construction. The width of the barrier is taken $b = 0.5$ m.

The effective deformation modulus E and the depth H of the barrier (Fig. 3) were studied. As fillers for a trench, materials with a deformation modulus from 5 to 50 000 MPa were considered (Table 2).

The protective barrier, depending on the material used, can absorb the energy of seismic waves in the ground or reflect it, changing their direction, creating a safe zone for the protected structure. Using the numerical simulation, the behaviour of the barrier can be checked with the velocity or displacement vectors after application of the dynamic load (Fig. 4).



a

b

Fig. 2. The displacement vectors from the building's own weight (a) and under dynamic load (b)

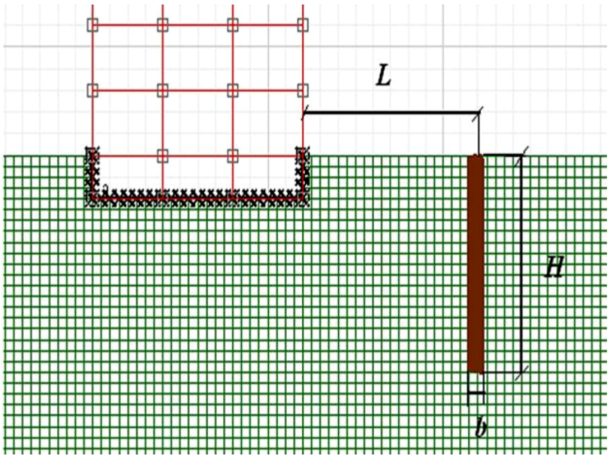


Fig. 3. Calculation scheme to justify the parameters of the protective barrier

Table 2

Physical and mechanical characteristics of the protective screen

№	Material	Deformation modulus E, MPa	Poison's ratio, ν	Density, ρ, kg/m³
1	Rubber crumb	5	0.49	460
2	Keramzit	7000	0.40	350
3	Soil-cement mixture 1	15000	0.35	1800
4	Soil-cement mixture 2	25000	0.30	2000
5	Concrete	50000	0.20	2400

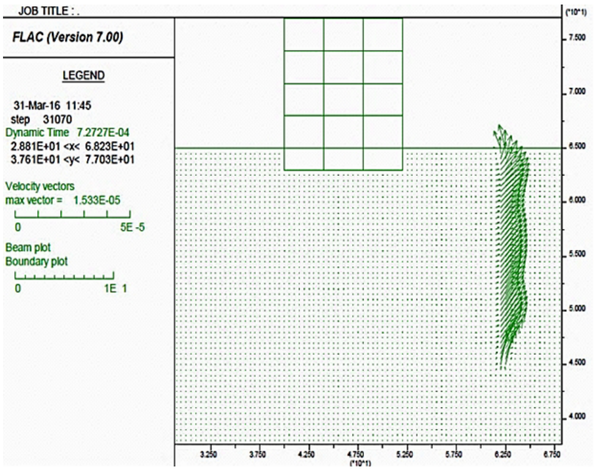


Fig. 4. The direction of the velocity vector of the soil particles at interacting with the protective barrier

The results of the investigations for various parameters of the protective screen are shown in Fig. 5. The efficiency was assessed by the magnitude of the maximum deformation, tilt and the values of acceleration at the foundation of the structure.

Due to the analysis of the results, the most effective material for protecting a building from dynamic impacts is a soil-cement mixture with the deformation modulus $E \geq 15\ 000$ MPa. The optimal depth of the protective barrier is equal to 20 m.

The results of the studies to determine the most effective depth of the barrier are shown in Fig. 6.

According to the results of numerical studies, the use of low-modulus materials such as rubber or expanded clay as protective barrier leads to an increase in deformation of the soil at the base of the structure. Therefore, their use to protect objects from dynamic effects in subsidence loess soils is not recommended. The final choice of the protective barrier requires an analysis of their technological and economic indicators.

To create a protective screen with the required deformation characteristics, the technology "slurry wall" or jet grouting technology can be used.

The use of high-modulus materials (monolithic concrete, reinforced concrete with a deformation modulus $E \geqslant 30\ 000$ MPa) implies the use of the "slurry wall" technology.

"Slurry wall" is one of the most progressive and universal technologies to build the enclosing and supporting structures, anti-filtration or vibration-proof screens in the soil.

The "slurry wall" method can be used close to existing facilities, the volume of excavation is very small, and there is no need for pumping water and backfilling. After trench-

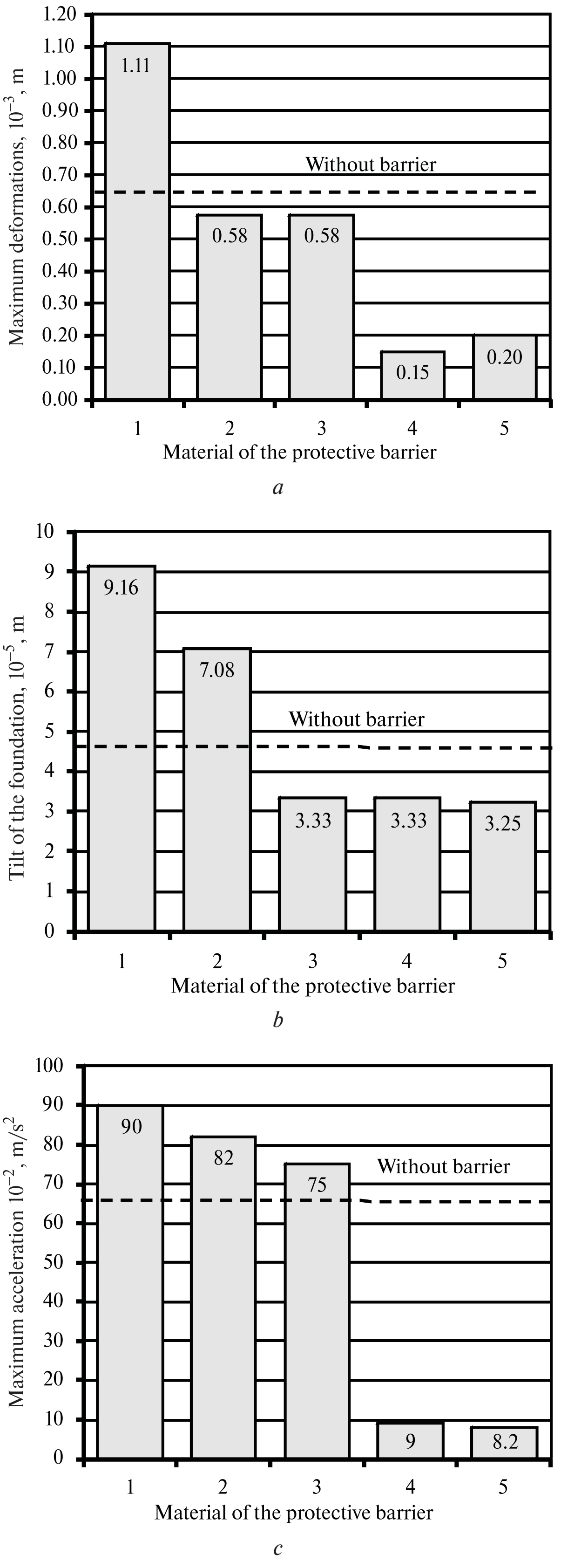


Fig. 5. The values of the maximum deformations (a), the foundation tilt (b) and the maximum acceleration at the base of the structure (c) for various materials of the protective barrier:

1 – rubber crumb; 2 – keramzit, 3 – soil-cement mixture 1; 4 – soil-cement mixture 2; 5 – concrete

ing, they can be filled with monolithic concrete, reinforced concrete, prefabricated reinforced concrete elements.

The development of trenches with a width of 0.4... 1.1 m is performed by drilling units, drilling milling machines, bucket machines or excavators to a depth of 50 m or more.

The main disadvantage of the "slurry wall" is a complex technology, which requires the use of expensive machines and mechanisms. When creating a trench, the surface is exposed by the entire length and depth of the protective screen. In urban areas with a branched utility system, this is very difficult. The re-laying of the utilities considerably complicates the work, increases the duration and cost of construction. High work labour input and technological complexity determine the high cost of construction of the "slurry wall".

Creation of a screen with a deformation module $E = 15\ 000...25\ 000$ MPa is possible with the use of a jet-grouting technology.

The jet-grouting technology consists in using the energy of a high-pressure jet of cement mortar for destruction and one-time mixing of soil with cement mortar in the "mix-in-place" mode. After the solidification of the solution around the well, soil-concrete structures are formed in the form of a cylinder with high strength, deformation and anti-filtration characteristics with a diameter of 600 to 2000 mm. The depth of soil-cement piles is determined by the capabilities of the drilling equipment and can be 50 m or more.

The shape of the piles can also vary, depending on the design of the monitor, through which the solution is

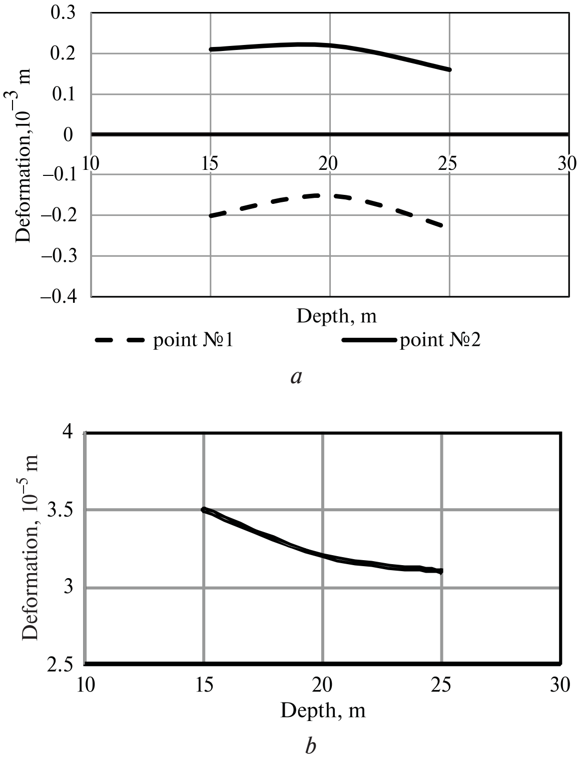


Fig. 6. The efficiency of the protective barrier with depth:

a – deformation of the extreme points of the building; b – foundation tilt supplied, and the appropriate manipulation with it. For example, when rotating and slowly lifting the monitor, a pile of cylindrical cross-section is formed. When lifting without turning, the piles are blade-like. The main advantages of the technology include high performance, simplicity, economy and ability to work in urban conditions. The strength of the soil-cement material is easily regulated by the quantity and grade of cement supplied to the soil mass. At the same time, this technology makes it possible to obtain a low-modulus ground-cement mixture. For this purpose, additives which reduce the density and deformation properties of the mixture – surface-active or foaming reagents, gas-forming agents and polystyrene pellets – can be added to the composition.

Another advantage of jet-grouting technology, in comparison with the “slurry wall” is that soil-cement piles can be constructed without opening the surface. In some parts, the barrier does not have to be brought to the surface level without disturbing the upper layer of soil. For example, where power cables, pipelines, and others are laid. Thus, the problem of existence of an underground network of utility system when creating protective barriers can be resolved.

The cost of creating barriers with jet-grouting technology, according to a number of manufacturers in terms of the volume of the finished soil-cement construction of the protective screen is 5...6 times cheaper than the cost of “slurry wall”.

Thus, from the viewpoint of manufacturability and the cost of work, a protective barrier made of soil-cement piles, created by the jet-grouting technology without rotating the monitor is the most effective.

Conclusions and recommendations for further research. The developed numerical model makes it possible to evaluate the effect of dynamic loads from surface sources on objects located on loess soils. Numerical studies have shown that the use of low-modulus materials such as rubber or expanded clay as the protective barrier does not reduce deformations. Therefore, their use to protect objects located on subsidence loess soils from dynamic influences is not recommended.

The most effective for this purpose is a protective screen with a depth of at least 15 m with a deformation modulus of at least 15 000 MPa, and soil-cement piles constructed using jet-grouting technology may have the necessary engineering properties.

The obtained parameters of the protective barrier can be used for saving the objects located on loess soils in the area of dynamic loads from technological equipment and transport in the dense urban and industrial areas.

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Охорона об’єктів від дії тривалих динамічних навантажень

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Мета. Обґрунтування раціональних параметрів охоронної конструкції існуючої будівлі, розташованої на лесовому ґрунті, від поверхневого джерела вібродинамічних навантажень, що дозволяє знизити крен споруди та осадки фундаменту.

Методика. Застосовані методи чисельного моделювання геомеханічних процесів для оцінки параметрів напружено-деформованого стану системи „споруда – ґрунтовий масив“.

Результати. Встановлено, що захист фундаменту будівлі, розташованої на лесовому ґрунті, від впливу поверхневого джерела динамічного навантаження забезпечується використанням віброзахисного екрану з матеріалу з модулем деформації $E \geq 15\,000$ МПа. Доведено, що деформації фундаменту знижуються нелінійно при збільшенні глибини екрану від 15 до 25 м, а при глибині екрану $H = 20$ м відбувається максимальне зниження осадки фундаменту й крену споруди. Показано, що, з позицій технологічності та вартості виконання робіт, найбільш раціональним і економічно ефективним є захисний екран із ґрунтоцементних паль, що створюються за струменевою технологією закріплення ґрунтів.

Наукова новизна. Розроблена нова чисельна модель геотехнічної системи „споруда – неоднорідний ґрунтовий масив“ для оцінки параметрів напружено-деформованого стану масиву лесового ґрунту, що є основою споруди. Відмінною особливістю моделі є використання значень параметрів міцності лесових ґрунтів, отриманих при тривалих динамічних випробуваннях у лабораторних умовах. Встановлені закономірності зміни напружено-деформованого стану геотехнічної системи „споруда – неоднорідний ґрунтовий масив“ при впливі поверхневого джерела тривалих динамічних навантажень для різних параметрів віброзахисного екрану.

Практична значимість. Розроблена чисельна модель дозволяє проводити оцінку впливу динамічних навантажень від поверхневих джерел на об’єкти, розташовані на лесових ґрунтах. Отримані параметри захисних екранів можуть бути використані при охороні об’єктів, розташованих на лесових ґрунтах, у зоні дії динамічних навантажень від технологічного обладнання й транспорту.

Ключові слова: *лесовий ґрунт, динамічні навантаження, вібрація, віброприскорення, опір на зсув, характеристики міцності, захисний екран*

Охрана объектов от воздействия длительных динамических нагрузок

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Цель. Обоснование рациональных параметров охранной конструкции существующего сооружения, расположенного на лессовом основании и подверженного воздействию вибродинамических нагрузок от поверхностного источника, позволяющей снизить крен сооружения и осадки фундамента.

Методика. Применены методы численного моделирования геомеханических процессов для оценки параметров напряженно-деформированного состояния системы „сооружение – грунтовый массив“.

Результаты. Установлено, что защита фундамента здания, расположенного на лессовом основании, от воздействия поверхностного источника динамической нагрузки обеспечивается устройством вибрjudзащитного экрана из материала с модулем деформации $E \geq 15\,000$ МПа. Доказано, что деформации фундамента нелинейно снижаются при увеличении глубины экрана от 15 до 25 м, а при глубине экрана $H = 20$ м происходит максимальное снижение осадок фундамента и крена здания. Показано, что, с позиций технологичности и стоимости выполнения работ, наиболее рациональным и экономически эффективным является защитный экран из грунтоцементных свай, создаваемых по струйной технологии закрепления грунтов.

Научная новизна. Разработана новая численная модель геотехнической системы „сооружение – неоднородный грунтовый массив“ для оценки параметров напряженно-деформированного состояния массива лессового грунта, являющегося основанием сооружения. Отличительной особенностью модели является использование значений прочностных параметров лессовых грунтов, полученных при длительных динамических испытаниях в лабораторных условиях. Установлены закономерности изменения напряженно-деформированного состояния геотехнической системы „сооружение – неоднородный грунтовый массив“ при воздействии длительных динамических нагрузок от поверхностного источника для различных параметров виброзащитного экрана.

Практическая значимость. Разработанная численная модель позволяет проводить оценку воздействия динамических нагрузок от поверхностных источников на объекты, расположенные на лессовом основании. Полученные параметры защитных экранов могут быть использованы при охране объектов, расположенных на обводненном лессовом основании, в зоне действия динамических нагрузок от технологического оборудования и транспорта.

Ключевые слова: *лессовый грунт, динамические нагрузки, вибрация, виброускорение, сопротивление сдвигу, защитный экран*

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