Seismic vibrations of complex relief of the surface of the Naryn canyon (on the Norin river in Kyrgyzstan) during large-scale underground explosions

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Abstract. In this paper the problem of the propagation of seismic blast waves in a deformable half-space with complex free surfaces of the Noryn Canyon (on the Noryn River in Kyrgyzstan) during large-scale underground explosions is discussed. In the explosion, according to a specially developed technique camouflage action charges were used. It was found that, granites in the fault zone are intensely fragmented and fractured. On the plane of the cracks, traces of sliding and friction clay are noticeable. The lowest values of elastic wave velocities are observed in the zones of tectonic cracks and in the surface of the massif. With depth, the velocity increases similarly to the change in fracturing. A theoretical formulation, solution methods and algorithm for the problem of propagation of seismic blast waves in a viscoelastic half-space (with a complex relief of the free surface) are proposed. The aim of the work is to study their dynamic behavior, create a methodology, develop and implement ideas when conducting full-scale experiments and measuring parameters that determine the dynamic behavior of half-space with complex surface and ground rails under seismic and explosive effects. Field experiments and corresponding theoretical studies in this formulation were carried out for the first time.

1. Introduction

The study of seismic blast waves excited by point explosions has been the subject of a number of works of both theoretical and experimental nature \cite{1-4}. The aim of these works is to study the problems of the physics of seismic wave propagation both in real media and in laboratory conditions. Studies of changes in the amplitudes of seismic-explosive vibrations depending on the epicentral distance are the subject of \cite{5,6}, which states that these amplitudes decrease with increasing distance \( r \), inversely proportional to \( r^{-1.5} \). However, measurements in some experiments \cite{7, 8} were not confirmed by this dependence, but indicate a more complex dependence. M.A. Sadovsky proposed an empirical formula expressing the relationship between the amplitude (\( k \)), the weight of the explosive charge (\( q \)) and the distance (\( r \))

\[ A = k(q^{1/3} r^{-1})^{0.5}. \]  

(1)

In the process of experimental work, it was found that the speed \( V \) of seismic vibrations for many types of soils, except for water-saturated soils, depends little on the geological conditions of the blasting area. In this regard, to determine the speed of soil vibrations during explosions, the following calculation formula was adopted:

\[ V = 200(q^{1/3} r^{-1})^{1.5}. \]  

(2)
It is known that when waves propagate in an elastic homogeneous medium, soil displacements caused by body waves change inversely with the first and second degrees of distance. Surface waves, however, decrease with a distance much slower, inversely proportional to the square root of the distance; therefore, the approximation for the ground velocity [9] is given by the following expression

\[ v = a\rho^{1/2} + b\rho + c\rho^2, \]  
(3)

where, \( p = q/r; a, b, c \)-constant coefficients determined from experimental data using the least squares method. Barkan D.D. [10] proposed a slightly more general formula for the amplitudes of soil displacement, which takes into account the absorption of energy of surface waves by the soil:

\[ a = k\sqrt{q \left[ \frac{1}{r^2} + \frac{c_1}{r} + \frac{c_2}{\sqrt{r}} e^{-ar} \right]}, \]  
(4)

Here is the multiplier \( e^{-ar} \) takes into account the absorption of energy of surface waves by the soil, and\( c_1, c_2 \)-some empirical constants, little dependent on the properties of the soil, which are taken into account by the coefficient \( k \). S.V. Medvedev and G.A. Lyamzina made an attempt to derive a formula for determining the speed of soil oscillation from the energy of elastic body waves, that passed through a unit surface of a hemisphere of radius \( r \). In [11], the relationship between the maximum value of the ground vibration velocity, explosive charge weight, and distance was derived from a direct relationship between the energy of seismic waves during an explosion and the vibration velocity.

\[ V_{\text{max}} = \kappa \sqrt{\frac{g}{\gamma T}} \cdot \sqrt{\frac{q}{r^3}}, \]  
(5)

Where \( V_{\text{max}} \)-the highest speed of soil vibrations in the radial component in cm / sec; \( k \)-coefficient taking into account the seismic action of the explosive charge and equal to \( 7.5 \times 10^4 \text{cm}^3/\text{sec} \); \( g \)-gravity acceleration in \( \text{m}^2/\text{sec}^2 \); \( c \)-seismic wave propagation velocity in \( \text{m} / \text{sec} \); \( \gamma \)-period of oscillation in sec; \( q \)-weight of explosive charge in kg.

The U.S. Mining Bureau (USBM - US Bureau of Mines) for the speed criterion accepts "pseudo-speed", which is guided by almost all foreign researchers [12], and equal

\[ ppv = k(d/W^{0.5})^{-\beta}. \]  
(6)

which, in essence, this approach is a tacit modification of the formula of M.A. Sadovsky. Here \( k \) and // are empirical coefficients; \( d \)-distance between the center of the explosion and the registration point; \( W \)-mass of explosives.

In numerous studies, an attempt is made at various levels of complexity to take into account those factors affecting the speed of the soil environment during explosive actions. In [13], regression formulas were obtained which, for the propagation velocities of seismic blast waves in the soil of 1200-1400 m / s (glacial deposits, basalts), predict the magnitude of the main parameters of explosive pulses quite well. In [14, 15], it is believed that the main determinants of the intensity of soil motion are the conducted energy and the duration of the explosive pulse, which is confirmed by the results of experimental measurements in explosions of a wide energy range, close in power to nuclear. In [16, 17], an attempt is made to explain the physical picture of what is happening at short-circuit phenomena by applying the principle of superposition, taking into account the spread of time, triggering moderators, obeying the normal distribution. However, the authors themselves acknowledge that the degree of reliability of the recommendations can be considered acceptable only with the number of explosive steps approaching infinite. Many researchers note that the empirical formulas for predicting the speed of seismic-explosive vibrations of the soil environment are not universal.

American researchers L.D.Lith, E.G. Rockwell, F.I. Crandell [18] consider the energy of seismic blast waves to be the best criterion for their destructive ability. They proposed for practical use an explosion energy coefficient proportional to \( \gamma^2 \).
where \( ER \) is the explosion energy coefficient; \( A \) – displacement amplitude, cm; \( f \) – frequency of oscillations, Hz. The authors found that for a variety of surface buildings and structures, the energy coefficient is critical, and it depends only on the amplitude and frequency of vibrations, for comparison we can make mutual recalculations of these quantities:

\[
ER = 10.8 A^2 f^2, \quad (7)
\]

The critical values and 2-3 cm / sec correspond to energy coefficients \( ER = 39-54 \) and \( ER = 1.1-2.5 \). To the critical energy coefficient \( ER = 20-40 \) corresponds the speeds \( \vartheta = 8.5-12.1 \text{sm/sek} \). The fluctuation limits, established by foreign researchers, are close to the limits, recommended by M.A. Sadovsky. M.A. Sadovsky proved that, in underground explosions and natural earthquakes, the density of seismic energy and the volume of sources of elastic waves are close and are described almost identically. Based on a comparison of natural and explosive earthquakes, on the basis of similarity considerations, he introduced the concept of a source: the spherical source of an earthquake.

Literature data on the relationship between the source energy and the predominant period of seismic vibrations are just as contradictory, as numerous. In the press, one can read the denial of the existence of such a dependence, and another – most of them, suggest a very strong connection between the periods and the energy of the explosion, in the form \( \tau \sim E^n \), where \( n = 1/3 \), as follows from the generally accepted theory of the similarity of explosions. However, as a rule, experimental data correspond to significantly less values of this coefficient. The state of our knowledge about the true state of things in this case indicates, firstly, that the magnitude of the periods depends on many factors, which are rather difficult to take into account, and secondly, that the formal application of the theory, when the similarity conditions are not met may cause significant errors.

Thus, as the main parameters for assessing the seismic effect of an explosion in soils, one should take the displacement velocity and the oscillation period at the wave front as a function of the reduced charge mass or reduced distance.

2. Methods

2.1 Statement of the problem and methodology of the experiment

For a theoretical study of the dynamic behavior of a deformable half-space with complex free surfaces of the Noryn Canyon (on the Noryn River in Kyrgyzstan), the elasticity theory equation is used for large-scale underground explosions. The relationship between stress and strain is as follows[19-21]:

\[
\sigma_{ik} = \bar{\lambda} \theta \delta_{ik} + 2 \bar{\mu} \varepsilon_{ik}. \]

Here \( \sigma_{ik} \) - stress tensor, \( \varepsilon_{ik} \) - strain tensor, \( \theta \) - volumetric deformation, \( \bar{\lambda} \) and \( \bar{\mu} \) - operator modulus of elasticity[22-24]:

\[
\bar{\lambda} \phi(t) = \lambda_{01} \left[ \phi(t) - \int_0^t R_{\bar{\lambda}}(t - \tau) \phi(t)d\tau \right];
\]

\[
\bar{\mu} \phi(t) = \mu_{01} \left[ \phi(t) - \int_0^t R_{\bar{\mu}}(t - \tau) \phi(t)d\tau \right], \quad (8)
\]

\( \phi(t) \) – arbitrary time function; \( R_{\bar{\lambda}}(t - \tau) \) and \( R_{\bar{\mu}}(t - \tau) \) – relaxation nuclei and \( \lambda_{01}, \mu_{01} \) – instant moduli of elasticity. The equations of motion of half-space when exposed to seismic blast waves has the following form[25-28]:

\[
\bar{\mu} \nabla^2 \ddot{u} + (\bar{\lambda} + \bar{\mu}) \text{grad} \text{div} \ddot{u} = \rho \frac{\partial^2 \ddot{u}}{\partial t^2}, \quad (9)
\]
where \( \vec{u}(u_x, u_y, u_z) \) - medium point mixing vector, \( \rho \) - material density. The solution to equation (2) is in the form [29,30]

\[
\vec{u} = \text{grad } \varphi + \text{rot } \vec{\psi}.
\]

(10)

If the displacement vector is depicted in the form of a potential and solenoid form, then the displacement of the medium satisfies the wave equation:

\[
c_p^2 \Gamma_{kp} \nabla^2 \varphi - \frac{\partial^2 \varphi}{\partial t^2} = 0; \quad c_s^2 \Gamma_{ks} \nabla^2 \psi_y - \frac{\partial^2 \psi_y}{\partial t^2} = 0;
\]

\[
c_s^2 \Gamma_{ks} \nabla^2 \psi_z - \frac{\partial^2 \psi_z}{\partial t^2} = 0, \quad c_s^2 \Gamma_{ks} \nabla^2 \psi_x - \frac{\partial^2 \psi_x}{\partial t^2} = 0,
\]

(11)

where

\[
\Gamma_{kp} = 1 - \Gamma^C_R(\omega_R) - \Pi^S_R(\omega); \quad \Gamma_{ks} = 1 - \Gamma^C_S(\omega_R) - \Pi^S_S(\omega),
\]

longitudinal wave propagation speed, \( c_s^2 = \mu/\rho \) - shear wave velocity. If the potentials of longitudinal and transverse waves are known, then one can determine the displacement of each point of the medium[31-35]:

\[
u_x = \frac{\partial \varphi}{\partial x} + \frac{\partial \psi_z}{\partial y} - \frac{\partial \psi_y}{\partial z}; \quad \nu_y = \frac{\partial \varphi}{\partial y} + \frac{\partial \psi_x}{\partial z} - \frac{\partial \psi_z}{\partial x};
\]

\[
u_z = \frac{\partial \varphi}{\partial z} + \frac{\partial \psi_x}{\partial x} - \frac{\partial \psi_y}{\partial y}; \quad \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}.
\]

(12)

Solutions of wave equations (11) are sought by the method of separation of variables. The solution of the wave equation (11) is expressed in terms of exponential functions.

Figure 1 shows the distribution curves of the time-average energy density in the Rayleigh wave in depth for media with a Poisson's ratio in the range 0-0.5 (all real media). Average energy densities are related to average surface energy densities (\( z = 0 \)). As can be seen from the graph, for all solid media, the energy density first decreases rapidly with distance from the free surface, then this decrease slows down (at \( \nu < 0,1 \)) or is replaced by a maximum (at \( \nu > 0,1 \)), after which there comes a smooth exponential decline in the energy density with depth.

If we consider the records of the speed of soil vibration, we note that, the initial, relatively simple in shape signal, is observed at small reduced distances. Points that are foundations of structures always have a more or less clearly defined layered structure. As a result of this, in addition to the direct waves reaching the observation point, along the shortest distance, waves reflected by different layers propagate in the soil, which have time to interact with the layers and interfering with direct waves, significantly complicate the general nature of the movement of the soil.

In the practice of hydraulic engineering and mining construction, there is a tendency to consolidate the parameters of waterworks and mining enterprises, and consequently increase the height and volume of dams being built, the depth and volume of overburden operations. With the increase in the scale of structures, the requirements for their reliability and accuracy of ensuring their design parameters and characteristics increase. The concept of a large-scale explosion means an explosion of such a scale, the parameters of which are commensurate with the corresponding parameters of the structures being built with its help, and its volume exceeds the volume of the latter. In particular, such explosions can be cited as an example of explosions that allow using directed rock explosions to build the largest dam of the Kambarata hydroelectric complex on the Noryn River in Kyrgyzstan.
Figure 1. Average dependencies in time $t_1$ energy density in the Rayleigh wave from relative depth $1 - \nu = 0; 2-0.1; 3-0.2; 4-0.3; 5-0.4; 6-0.5$

The Naryn Canyon section, selected for the location of the hydroelectric complex, with a complex relief with high (400-700m.) sides of medium steepness (Figure 2) is composed of brittle, small-block, easily fragmented silicified granites, weathered to a considerable depth. The construction of the dam was envisaged by a series of directed explosions with millisecond slowdowns from both sides of the canyon, with a total charge weight of about 270,000 T. This circumstance required a more thorough, accurate forecast of the seismic effect of the upcoming explosions on the environment, including the above critical structures.

Figure 2. Canyon section under the dam for Kambarata Hydroelectric Power Station

For this purpose, it was planned to conduct experimental explosions in the gorges of the Burlykiya region, and the Uch-Terek region. The main task of the experimental explosions, in addition to the above, was the experimental verification and refinement based on the results of observations of the estimated mass of the explosive charge, the shape and volume of the explosion funnel, the forecast for the outline of the bulk of the collapsed rock for the conditions of the main explosion, and the study of the action of the linear deep loosening charge on the slope of the mountain range in the narrow U-shaped part of the river canyon. The sites of the experimental explosions in the gorges, in terms of the nature of the relief of the free surface, fully corresponded, on a reduced scale, to the conditions of the explosion for the construction of the dam of the Kambarata hydroelectric station in the Naryn region (Figure 2). The experimental explosion site is composed of intrusive rocks, which include granites, porphyry granite and diabases. Slopes with gentle slopes are covered with deluvial deposits up to 10 m thick, which are a mixture of fragments of granite measuring 10 ÷ 100 cm (50%) and sandstone 2 ÷ 10 mm (up to 20%)
with sandy loamy loam aggregate (up to 30%). The deposits are loose and loosely bound, covered with shrubs and grass (Figure 3). The area of the experimental explosion is crossed by two tectonic faults having an angle of incidence 60-70°. The width of the zone of one fault varies within 25–75 m, of the other about 3.5 m. The granites in the fault zone are intensely fragmented and fractured. On the plane of the cracks, traces of sliding and friction clay are noticeable. The displacement amplitude of the rocks along the first fault is about 10 m, and along the second, about 1 m. In addition to faults, the massif at the explosion site is broken by several systems of large and small tectonic cracks. The width of the opening of large cracks varies from 5 ÷ 20 mm to 200 ÷ 250 mm, the length of the cracks from 5 ÷ 10 m to 150 ÷ 300 m. The width of the opening of small cracks varies from 0.5 mm to 10-20 mm, the length from 1 cm to 1-10 m. A study of the fracturing of the rock mass on the surface and in underground mine workings revealed zones of intensive weathering with a thickness of 15 m. and weak weathering with a thickness of more than 65 m. The zone of non-weathered rocks has not been opened by drilled mines. As a result, the average volumetric weight of granites was established, longitudinal velocity $C_p$ and transverse $C_s$ waves, compressive strengths $\sigma_{c}$, and stretching $\sigma_{r}$, the distance between the cracks, and the width of the opening of the cracks, the value of blocking rocks and the coefficient of fracture voids ($K_T$). The lowest values of elastic wave velocities are noted in the zones of tectonic cracks and in the surface of the massif. With depth, the velocity increases similarly to the change in fracturing. In the area of the geological adit, at a depth of 25 m to 60 m, the velocity of longitudinal waves $C_p$ varies in the range of 1.8-3.7 km / s, the average value $C_p = 2.5$ km / sec.

Figure 3. Sectional view of the gorge (Section BB).

The parameters of seismic blast waves on the free surface of the earth were recorded using the S-5-C and OSP-2M geophones. The signals from the sensors were recorded using loop oscilloscopes of the N-044.3 type. Copies of the waveforms obtained in measuring points 1, 2 and 3 are shown in Figure 3. On the oscillograms, several main groups of waves can be traced. These groups are especially clearly visible on the recording of the component of the motion of the soil surface in the farthest point № 3. Based on instrumental data, the values of the horizontal velocity of soil displacement on a seismic wave are determined depending on the magnitude of the charge and distance in the form:

$$V = 73.2 \left( \frac{V}{R} \right)^{1.32} \text{ cm/sec}.$$ (13)

From the geological description it follows that the mountain massif in the explosion site is broken by numerous cracks and therefore, as a whole, appears to be fragile. This is also evidenced by the low values of the elastic wave propagation velocities measured at the observation points. Relatively large values $\sigma_{c}$ and $\sigma_{r}$ rather characterize the strength of granite in individual pieces of a small size, rather than an explosive mass as a whole. An experimental explosion was planned to be carried out in a
narrow U-shaped part of the canyon of the Uch-Terek river on the slope of the mountain massif (the slopes of the canyon are steep 35-45° up to 200m high. The lower charge 48 m long is designed to discharge mountain mass, and the upper charge 94 m long is loosening. The total mass of charges \( Q = 2060t \), including 1391t is laid in the lower, and 649t in the upper mine adits. The composition of the explosive charge of igdanite: 50t ammonite, 200t diesel fuel, the rest ammonium nitrate. The lower charge, which has a significantly smaller line of least resistance, forms a zone comprising approximately 25\% of the collapse prism volume. With this arrangement of charges, it is possible to ensure the formation of a higher dam, to improve the conditions for the outflow of the bulk of the soil collapsed by the upper charge (75\%), since as a result of the discharge free space will be formed for its acceleration. The fault existing on the explosion site and 6 fracture systems developing from it is accompanied by a crushing and alteration zone of rocks with a thickness of about 20 m and a zone of increased fracturing with a thickness of up to 100 and more meters.

3. Results and Discussions

In Figures 4–7 shown the total displacement (A) versus time for different reduced distances.

![Figure 4. The dependence of the total displacement (A) on time for \( R_{pr} = 14.5 \) reduced distances](image-url)
Figure 5. The dependence of the total displacement (A) on time for $R_{pr} = 14.7$ reduced distances

Figure 6. The dependence of the total displacement (A) on time for $R_{pr} = 16$ reduced distances
The graphs show that at various reduced distances the energy level of seismic blast waves is not the same, it is difficult to distinguish a clearly defined maximum corresponding to the largest amount of energy throughout the oscillation process. Regardless of what numerical values the acceleration of the vibrational motion of soil particles takes, the negative effect of seismic blast waves in the form of energy throughout the oscillatory process remains at a high level. This circumstance can lead to intensive accumulation of potential energy in the body of the structure and an increase in this characteristic to the limit value can lead to negative (phenomena) consequences. Volumetric weight of bedrock is on average $\gamma = 2.69 \text{t/m}^3$, dry compressive strength of the rock $\sigma_{\text{c}} = 1000 - 1250 \text{kg/cm}^2$, slightly loses strength at full water saturation.

Copies of the waveforms obtained in measuring points 1, 2 and 3 are shown in Figure 8 (R (km), J (ball)). On the oscillograms, several main groups of waves can be traced. These groups are especially clearly visible on the recording of the component of the movement of the soil surface in the farthest point No. 3. To assess the nature of damage in the danger zone and the intensity of the impact, the maximum speeds were calculated depending on the distance. The significant difference in the values of the velocity of horizontal oscillations in the epicenter of the explosion according to formula (8) compared with others is explained by the fact that the massif in the explosion site is broken by faults and numerous cracks, i.e. the stronger its attenuation in the central zone of the explosion, the lower the output of the explosion energy into the seismic wave. On the whole, the mountain range is fragile, which is confirmed by the low value of the velocity of propagation of elastic waves measured in the area of the explosion. With epicentral distances of more than 500 m, the results of the calculation formula (8) are in good agreement with the data obtained by the formula (9).
Figure 8. The dependence of the size of the zones of concussion on the intensity of ground vibrations: * correspond to formulas (8) and (13).

Therefore, formulas (8) and (9) are recommended for use in large-scale explosions in areas with rocks with strong fracturing and strong rocks, respectively. Substituting in (9) the dependences of the horizontal oscillation velocity on the explosion energy and the distance (8) and (9), we obtain the ratio between the size of the zone of a particular intensity of destruction on a given point and explosion power:

\[
R = 7.0 \cdot 10^3 \cdot Q^{0.33} \cdot J^{-3.7}, \text{м} \quad (14)
\]

\[
R = 2.0 \cdot 10^3 \cdot Q^{0.34} \cdot J^{-3.7}, \text{м} \quad (15)
\]

The sizes of zones with different intensities of seismic impact of the Uch-Terek experimental explosion, depending on the distance of the location of the structures, are shown in Fig. 3. Prior to the explosion, the technical conditions of buildings and structures located in the area of seismic blast waves were evaluated. Safe distances are determined depending on the nature of the building, the presence of damage in buildings, cracks in the walls [19,20]. A survey of structures in five commercial sheep and one dairy farms, which consist of adobe bricks (adobe adobe), brick residential buildings and a nightmare, was carried out. According to the results of the survey, it is possible to note the low quality of construction works performed with deviations from the current norms and rules at all considered structures in the radius of seismic hazardous areas.

Surveyed and registered 22 buildings for various purposes, mainly located in the zone of 5-7.5 point intensity of the seismic impact of the experimental explosion. Based on the analysis of the consequences of the explosion, it was found that in 25% of buildings significant damage was found,
in some cases - collapses or partial collapse of the walls. In the remaining structures, moderate (30%) or light (45%) damage was found, depending on their condition before the explosion and location. Studying the nature of the behavior of the soil environment under the seismic effects of underground explosions is of great practical interest. Of particular interest is the study of periods of forced vibrations of the soil, which, in turn, determines the stress-strain state of buildings and structures. As a result of processing the experimental results, empirical relationships are obtained for this type of soil, making it possible to predict the visible periods of soil oscillations in the following form:

\[ T = 0,031 \frac{\rho R}{g} T = C^{0.3} \]

Numerous instrumental observations of the effects of strong earthquakes on the earth's surface show that the intensity of seismic vibrations depends on many factors, including the ground conditions, the level of groundwater, the resonance properties of soils, but also on the terrain. To study the seismic effect of industrial explosions, as well as to evaluate the hilly terrain, during the passage of seismic blast waves and their effect on structures for various purposes in mountainous regions, we organized instrumental observations of the dynamic behavior of soils and buildings during industrial explosions near the Noryn River. When conducting instrumental measurements, registration of seismic vibrations of the soil was carried out near with a total charge mass of 16112 kg. The distance from the place of the explosion to the registration point was 460 m. The explosion was short-delayed with 5 slowdown groups. Slow interval between groups 25 ms. The recorded maximum velocity of soil vibrations was 0.91 cm / s, the displacement amplitude was 0.24 mm, and the seismicity coefficient turned out to be 220. As mentioned above, the velocity of soil particles at the base of the structure is taken as a criterion for the seismic hazard of explosions \( V_{\text{max}} \).

For serviceable industrial buildings, a definitely allowable rate of ground vibration is usually accepted. \( V_{\text{max}} = 5 \text{ cm/s} \), and for residential buildings - 3 cm / s. In our case, restrictions will be imposed by industrial buildings career management. The building is two-story, brick. They have damage in the form of cracks in the plaster. Given the actual condition of these buildings, it is possible to take as the maximum permissible vibration velocity \( V_{\text{max}} = 2 \text{ cm/s} \).

Knowing the limiting speed of soil vibrations and the value of the seismicity coefficient \( k \), determined experimentally, it is possible to determine the maximum explosive charge mass according to the formula (5) depending on the distance between the place of the explosion and the protected object.

4. Conclusions

1. Based on the experimentally obtained results, empirical dependencies are obtained for calculating the maximum values of the displacements of the structure.

2. Analysis of the waveforms in three mutually perpendicular directions showed that each component reaches its maximum at different times of the oscillation process.

3. It has been established that the rise time of the maximum displacement of the underground structure in the waveform does not correspond in value with the rise time of the maximum of the soil environment surrounding the underground structure.

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