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Research on dynamic impacts on geological environment, soil foundations, and structures

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Abstract. The article analyses the primary methods for determining dynamic characteristics. It has been established that the real environment in which the dynamic processes of seismic-explosive wave propagation occur is not described by an ideal model and is very difficult to describe with equations. The vibration acceleration resulting from the seismic action of explosions in quarry mining and processing plants has been calculated. It has been determined that the calculation can be performed using analytical methods and the finite element method (error of about 4%). It has been established that the application of the finite element method to calculate vibration acceleration during blasting operations in quarries enables the desired value to be calculated at any point of the object under study with reduced working time.

1. Introduction

The development of mineral resources in Ukraine is significant, as it ensures economic stability, energy security, technological independence and positions the country as a key global supplier of raw materials for high-tech industries. Ukraine has significant reserves of various mineral resources used in energy, metallurgy, construction, and other sectors, which increases its strategic value in the global market. Particular attention is paid to the development of ore minerals used in the production of steel, cast iron and other metals.

Often, such deposits are developed using open-pit mining methods, with explosives used to break up hard ore deposits.

Pigulevsky P.G. determined that according to the results of the analysis of registered data for the period 2011-2020 that the bulk of local seismic events are represented by powerful industrial explosions in quarries and mines. Over ten years, seismic stations have recorded more than a thousand industrial explosions with magnitude value greater than 2 [1].

Hundreds of tonnes of explosives can be detonated at the same time, creating a significant seismic impact on the environment. Seismic vibrations spread over considerable distances from the sites of blasting operations. The turning point for drilling and blasting operations in quarries and mines began in 2018, when their number and capacity increased several times [2]. Buildings and structures located in the zone of seismic vibrations will be subjected to regular dynamic loads, which can lead to undesirable consequences. The degree of seismic impact on buildings (structures) largely depends on soil conditions. The issue of seismic safety is particularly relevant in long-established mining enterprises, where, due to the expansion of the initial quarry contours, mining operations are coming into proximity to industrial and residential buildings and structures. When assessing the mechanical impact of seismic waves excited by explosions, attention should be paid to the nature of the movement of building elements (foundation and roof) at different time intervals. A comparison of the changes in the trajectory of the foundation and roof of the building reveals that the maximum displacement will occur in the roof. Horizontal displacements dominate over vertical ones. Despite the different trajectories of the building elements, the inelastic nature of the vibrations is clearly evident: the magnitude of the displacements in the direction of the explosion exceeds that in the opposite direction. Another common feature is the alternating loads that arise in the foundation and roof of the building under the mechanical action of seismic waves. This determines the strict requirements for conducting mass explosions – the permissible weight of the charge for carrying out explosive works in different deposits must not exceed the values determined by the allowable speed.

Seismic phenomena arising from explosions are a small-scale model of natural earthquakes. The source of seismic energy during an explosion is the explosive charge. The first attempts to schematically calculate the impact of a blast on soil (rock) were considered from the perspective of soil as an ideal, isotropic, elastic medium. This scheme was further improved by introducing tangential stresses associated with everyday stresses under boundary conditions of the Coulomb type.

It has been proposed to consider such soils as ideal compressible fluids based on experimental data on the propagation of blast waves in water-saturated sands. Such soils have a special equation of state, which takes into account the significant effect of gas trapped in the pore water.

When calculating the depth of charge placement in quarries, it can be disregarded, as it is significantly smaller than horizontal distances. To describe seismic processes using formulas, the explosive load can be represented as a concentrated impact on an elastic half-space.

However, with such approaches to solving the simplest one-dimensional problems, the question of constructing a general mathematical model of the soil environment was not raised. Such a model is known, taking into account all the basic mechanical properties of soils that are essential for dynamic processes (non-linear and irreversible volumetric deformability, elastic-plastic shear, dependence of the elastic limit during shear on pressure) [4].

Volumetric deformation is assumed to depend only on the average pressure (irreversibly), thereby ignoring the effects of dilatance. Shear deformability in the subcritical state is described by a linear-elastic model, and in the critical state by the Prandtl-Reiss model with the Mises-Schleicher-Botkin plasticity condition. The author proposes using this model for fast, dynamic processes. This model has a complex mathematical apparatus and is used in mathematical modelling.

It is important that all oscillation measurements obtained during industrial explosions should be filtered at a frequency of 20–50 Hz. And only after filtering the obtained seismograms can an assessment of the seismic safety of explosion data be carried out. Also, during seismic measurement work, software complexes (MiniMate Plus) should be used to record and compare seismic measurement protocols [4].

The purpose of the work is to determine the accuracy of calculations of dynamic characteristics using the existing mathematical apparatus and to determine the model for calculating the dynamic characteristics of soil foundations.

2. Methods

2.1. Overview of the primary methods for determining dynamic characteristics

To compare the intensity of vibrations from explosions of different scales, using absolute values of charge weight and distance from the centre of the blast does not provide a practical assessment of the process; therefore, the reduced distance ρ_1 (m/kg$^{1/3}$) is used:

$$\rho_1 = \frac{r}{\sqrt[3]{Q}} \tag{1}$$

where r is the distance from the explosion site, m; Q – total weight of charges, kg.

According to repeated observations, the dependence of the seismic wave velocity V (cm/s) on the reduced distance can be expressed as follows (M.A. Sadovsky's formula):

$$V = K \cdot \rho_1^{-1.5}, \quad (2)$$

where *K* is the seismicity coefficient for rock and semi-rock formations, 200-300, for sandy-clay soils with average water saturation and a thickness of more than 15 m, 300-450, for loose and water-saturated soils, 450-600 (in A.A. Vovk [6] up to 750), when observing seismic vibrations due to the influence of many unaccounted factors, there is a significant difference in parameters; therefore, two values are indicated for each soil condition – the average and the maximum. The maximum values of *K* are selected so that in 95% of cases the observed fluctuations did not exceed the level determined by formula (2) at the maximum value of *K*. This formula is recommended for use by several authors, including V.G. Afonin, A.A. Vovk, G.A. Vorotelak, V.A. Gavryk [6], Vyzhva S.A. [7], I.A. Yermakova [8], S.V. Medvedev, Yu.Ya. Savelyev, A.Kh. Dudchenko [9], Lyashenko V.I. [10]

The coefficients in the formula are specified experimentally by the authors, depending on the specific conditions of blasting operations, geological conditions of the site, charge shape, and other relevant factors.

Based on experimental research, V.I. Chepurnoi [11] proposes the following relationship between the oscillation velocity *V* and the charge mass *G*:

$$V = K_{\text{c}} \sqrt{G^3} \quad (3)$$

K_{c} – coefficient depending on the conditions of the explosion.

However, F.F. Aptikaev and A.I. Sapozhnikov argue that in M.A. Sadovsky's formula, only the coefficient K is determined experimentally. In contrast, the correctness of the scale coefficients for distances is not verified. Consequently, they believe that the results obtained using this method contain errors. Therefore, they propose that the best indicator for analysing potential damage caused by oscillations is the amount of energy absorbed by the structure during the vibration process [8].

G.O. Geniev determines horizontal displacements of the Earth's surface caused by concentrated shear seismic action using a complex of dimensionless similarity criteria. In his calculations, he modelled the soil as an elasto-viscous medium. However, under complex conditions, particularly when explosions are in proximity to the objects under investigation, the unchanged use of such models does not ensure the necessary reliability of calculations due to significant variations in oscillation intensity [8].

It is well-known that, under real-world conditions, the process of seismic-explosive wave generation and propagation acquires a random character, with the dynamic characteristics of the waves being random functions of time and distance. Seismic oscillations are represented as a stationary process, for which description is limited to a finite-dimensional distribution of ordinates, which are random variables. A statistical distribution function describes the process. However, a drawback of this approach is the absence of distribution laws for a broader range of mining and technical conditions. The presence of errors in calculations using the previously proposed formulas is associated with the fact that explosions are performed not in an infinite homogeneous space, but in a space with specific, often complex boundaries (explosions with one, two, or multiple free surfaces). As a result, velocity becomes dependent on the degree of the charge's remoteness from the boundary surface (depth of embedment), which should be reflected in the increased complexity of the equation. Furthermore, rock typically possesses a layered structure, with properties that vary by depth, which violates the principle of similarity. Even in the case of a homogeneous half-space, with significant charge depths, a violation of simpler similarity, such as M.A. Sadovsky's formula, is observed. This is because at considerable charge depths, the influence of gravity begins to manifest, which is not considered at shallower depths. In such cases, at least an approximate estimation of the probable ground velocities in the vicinity of the investigated objects is necessary. S.G. Onika [12] was a proponent of the probabilistic analysis of ground oscillations.

In work [12], S.G. Onika examined the prediction of seismic blast effects from the perspective of two research directions. The first direction is based on determining oscillation intensity by the nature of responses from mass-produced buildings. The maximum ground displacement velocity, caused by low-frequency components of the oscillation spectrum in the foundations of objects, is used as the seismic hazard criterion, and statistical estimates characterise its oscillations. The second research direction involves the application of the dynamic characteristics of displacement velocity oscillations, including correlation functions and spectral velocities. Methods from this direction expand the possibilities of predicting object reactions, taking into account the spectral composition of seismic oscillations. Based on graphical and statistical analysis, it has been demonstrated that the experimental data align best with Johnson's SL-distribution.

Based on the established law of seismic wave intensity distribution, a methodology is proposed for predicting oscillation intensity with a given probability of no damage, without conducting preliminary seismometric measurements. In developing the general concept of the interrelationship between the studied parameters, the idea of replacing prior oscillation measurements from experimental blasts with a computational experiment was realised. This computational experiment is designed to create a data sample with identical parameters from an information database, while also investigating the influence of blast parameters and soil properties on the estimation of the distribution's shape.

Equations have been derived for oscillation velocity, which determine its values with a given probability and the most probable values, respectively:

$$V = \frac{\exp(-y/u)}{\exp(u^{-2})} \frac{\sqrt{Q}}{R^n} \tag{4}$$

where Q is the mass of the explosive charge, kg; R – distance, m; n – seismic wave attenuation index, y – displacement, m; u – vibration acceleration, m/s^2.

According to one of the proposed methods, the parameters of the intensity coefficient's distribution shape are determined based on the identification of the projected blast parameters and information from a database regarding blast parameters and registered oscillations, followed by a calculation derived from the series' mean values and standard deviation.

The proposed methods provide a prediction of oscillation intensity based on the probable values of maximum displacement velocity in the frequency range most dangerous for commonly encountered objects. Such a determination of oscillation intensity stems from the generally accepted concept of seismic hazard for earthquakes, according to which the intensity (strength) of tremors is determined by the degree of damage they inflict upon the most widespread objects.

V.G. Chernyi [13] proposes applying a heuristic approach based on determining the probability of damage to buildings and structures under dynamic impact. The use of such an approach enables a clearer understanding of potential damage mechanisms to the object's foundation, and with sufficient statistics, can more explicitly define the degrees of reliability. However, it requires a substantial and representative set of damage and accident statistics.

Under these conditions, a need arises to develop new methods for conducting blasting operations, the evolution of which is based on modern understandings of explosive action.

Also well-known is the concept of seismic process mechanics, which is consistent with classical Newtonian mechanics. It substantiates the idea that the law of momentum conservation underpins the mechanics of seismic processes. Movements and destruction of material systems during tremors occur under the action of Newtonian forces – time derivatives of momentum. A model of the earthquake process is considered, viewing it as an impact resulting from the breaking of a rock block. Seismic radiation is represented as the propagation of momentum in a continuous medium. S.V. Tishchenko's research [14] is also based on the theory of mechanics. He applied the following assumptions: the constant medium is considered absolutely incompressible, neglecting changes in its volume; the effect of the explosion occurs instantaneously. He noted that the numerical value of the specific impulse of a blast is determined by the energy balance transferred to the medium during the explosion.

However, any theoretical data are surpassed in accuracy by measured data, due to the impossibility of accounting for all factors influencing the oscillatory process. For instance, E.O., Nesmashnyy, V.D. Sydorenko [15] proposed a method for measuring multi-channel oscillations to determine the level of seismic ground oscillations at the base of a building. In this method, the modulus of the maximum ground oscillation velocity vector Vmax was chosen based on its three projections onto the coordinate axes (two horizontal V_x and V_y and one vertical V_z) as follows: $V_{\max} = (V_x^2 + V_y^2 + V_z^2)^{1/2}$. Based on the maximum velocity value, the level of seismic vibrations was determined in points according to the scale.

Based on calculations and experimental data, for square or rectangular objects in plan, the maximum stress values are typically located near the corner points. This means that ground oscillation assessment should be conducted near the building's corners. However, a drawback of this method is the requirement for complex measuring equipment.

It is known that vibration causes changes in the deformation and strength characteristics of soil (compressibility significantly increases, and shear resistance sharply decreases). Therefore, a special dynamic model of the soil medium must be used to calculate the impulsive effects of dynamic loads. An ideal model does not describe the tangible medium in which dynamic processes of seismic-explosive wave propagation occur, and it is challenging to explain it with an equation. The model does not adequately account for general and local changes in tectonic, soil, and hydrogeological conditions at the source of the explosion, along the wave propagation path, and at observation points. By applying statistical theory, we can derive formulas tailored to specific blasting conditions. Therefore, for an accurate assessment of the impact of blasting operations on building and structure designs, it is necessary to apply a combination of computational methods with methods based on measurements of ground oscillation characteristics.

2.2. Research on the impact of blasting during rock excavation in open-pit mines of mining and processing plants on buildings and structures

This research aims to analyse the applicability of the finite element method for calculating the dynamic characteristics of building and structural foundations by comparing it with existing calculation methods [16]. A study was conducted on techniques for estimating the dynamic characteristics of building and structure foundations, using the example of the impact of blasting during rock excavation at JSC "Poltava Mining and Processing Plant," specifically on the tailing dam located approximately 1,000 m from the Dniprovske ore management quarry. The Dniprovske ore management operates the Horishni Plavni and Lavrykivske deposits (figure 1). Extraction work is carried out by blasting in accordance with the "Standard Project for Drilling and Blasting Operations in the Dniprovske Ore Management Haleshynske".

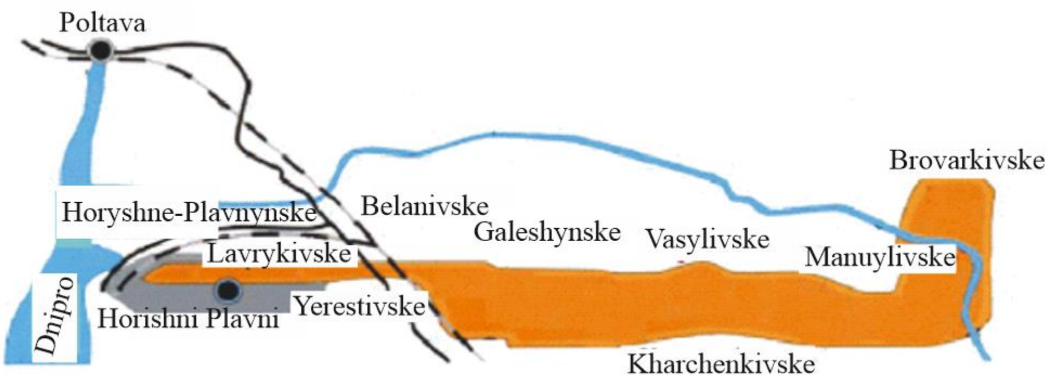

Figure 1. Location map of the Dnipro Ore Management deposits.

The achieved depth of the Dniprovske ore management quarry in its southern part is 308 m, and in the northern part, it is 150 m. The quarry's length is 5800 m, and its width is 1500 m. The Horishni Plavni and Lavrykivske deposits, which serve as the raw material base for the Poltava Mining and Processing Plant, are located in the Kremenchuk district of the Poltava region. The length of the deposit at Horishni Plavni is approximately 3 km, while at Lavrykivske, it exceeds 4.5 km. The thickness of the deposit within the commercial contour at Horishni Plavni varies from 50 to 60 m in its northern part to 270 m in the southern part, averaging 115 m. At Lavrykivske deposit, it varies from 23 to 71 m, with an average of 43 m. The bedrock is overlaid by loose deposits, represented by loams, sands, clays, silts, and sandstones with fragments of crystalline rocks. Beneath the loose deposits, the crystalline rocks are weathered.

The Poltava Mining and Processing Plant's tailings dam (a complex of hydraulic structures for receiving and storing waste tailings) is located southeast of the quarry. Processing Plant's tailings dam occupies an area of approximately 1400 hectares. The tailings dam is a system of dams that are periodically raised in height. The physical and geographical conditions of the site are characterised by the area belonging to the Dnipro Lowland on the left bank of the Dnipro River. The tailings dam is situated in the flat part of the Dnipro River floodplain, 40 km from the city of Kremenchuk.

The hydraulic gradient and groundwater movement are directed towards the Dnipro River and Sukhyi Kobeliachok, as well as towards the Poltava Mining and Processing Plant quarry, around which a depression cone has formed. To intercept the filtration waters of the tailings dam, lower the groundwater level, and divert drainage waters, a drainage canal, built around the tailings dam, is in operation. This canal is imperfect in terms of the degree of aquifer exposure.

The Poltava Mining and Processing Plant's tailings dam has been in operation since 1970. Initially, it consisted of 3 compartments. Currently, I and II are combined into a single system. The primary dams of all three compartments, up to a height of 10.0 m (to absolute elevations of 75.0 m for compartments I and II, and 76.0 m for compartment III), were constructed by hydraulic filling using alluvial sands from the tailings dam basin. The lengths of the enclosing dams for compartments I-II and III are 10.4 km and 11.7 km, respectively.

Since 1984, compartments I-II and III have been raised in height by 3–14 m to the design elevation of 89.0 m, with simultaneous filling of the tailings dam's functional capacity (figure 2).

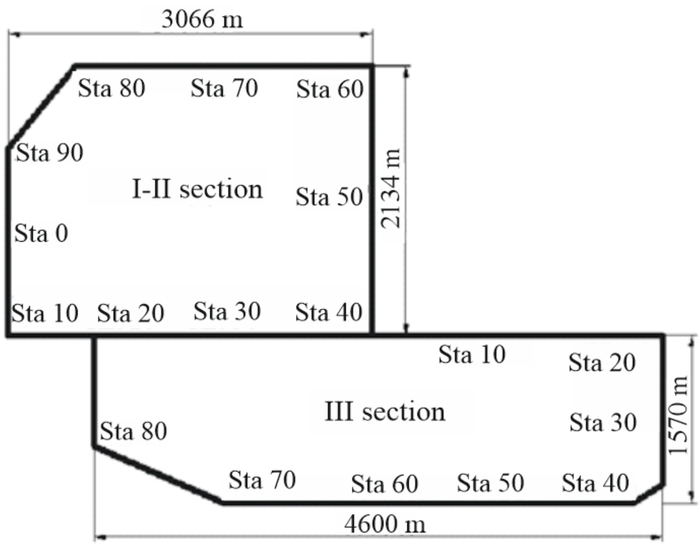

Figure 2. Diagram of the tailings storage facility plan of JSC "Poltava Mining and Processing Plant".

Currently, compartment I-II with an absolute crest elevation of 89.0 m is filled with sludge, and compartment III is being built up by filling with separate cards to an elevation of 87.2 m.

At the start of the tests, compartment I-II was filled with 144.82 million m^3 of tailings, and compartment III with 104.0 million m^3. The free capacity for receiving tailings in compartment III was 12.4 million m^3. After raising the dam of compartment III to the design elevation of 89.0 m, the free capacity of the tailings dam will increase to 22.6 million cubic meters, providing storage for tailings for a period of 5-7 years, depending on the volumes of raw material processing.

"Tailings" are a product obtained during the enrichment process, in which the content of the valuable component is lower than in the initial material and other products of the same processing operations. The composition of "tailings" includes fractions with a diameter of 0.1-0.001 mm. Silty particles prevail at 81.5%, sand particles account for 17.1%, and clay particles for 1.4% (table 1). The plasticity index of the "tailings", determined by a standard methodology, was I_p=1.2%. Samples were collected directly from the surface of the tailings dam area, which, at the time of sampling, was approximately 26.0 m above the Earth's surface.

Table 1. Granulometric composition of tailings.

Fraction diameter					Limits and degree of plasticity		
> 0.1	0.1-0.05	0.05-0.01	0.01-0.002	< 0.002	Plastic limit, W_L, %	Liquid limit, L_L, %	Plasticity index, I_p, %
0.6	16.5	26.1	55.4	1.4	19.9	21.1	1.2

The geological cross-section of the dam at Sta 0 is shown in figure 3.

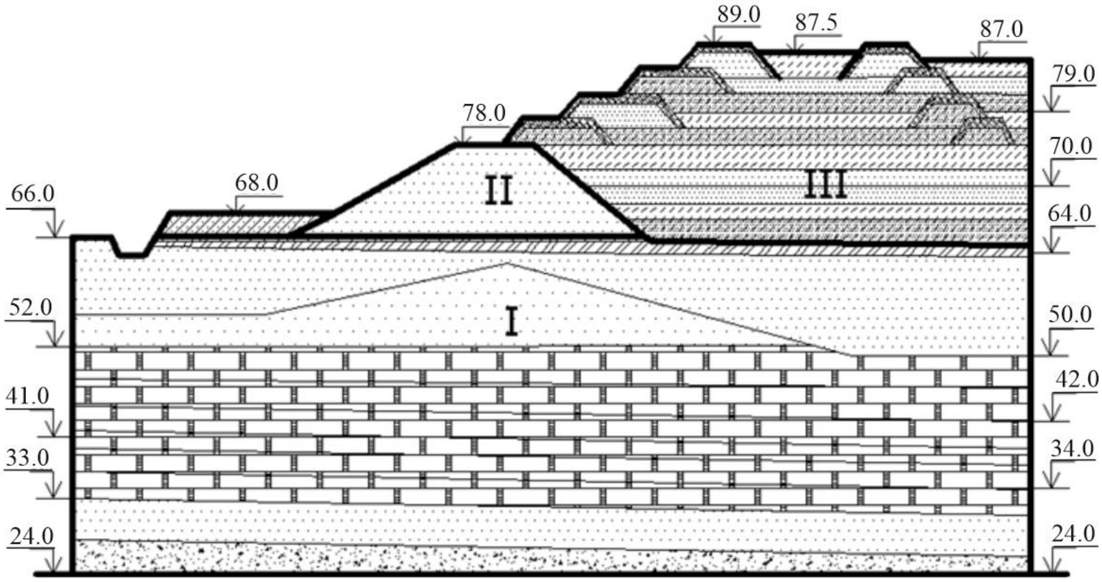

Figure 3. Geological section 1-1 of the dam at Sta 0 (vertical scale enlarged): I – dam foundation, II – primary dams built from alluvial sands of the tailings pond basin, III – dam built from tailings layers.

When conducting blasting operations, longitudinal and transverse vibrations propagate from the epicentre of the explosion in rock formations. Therefore, the dynamic impact of explosions during rock development in the Dnipro Ore Management quarry on specific objects located at various distances from the explosion site was investigated. The seismic effect of blasting operations is assessed using a dynamic characteristic such as vibration acceleration.

There are several methods for determining the radial vibration acceleration of soil particles from the centre of the explosion. We considered several of the most well-known methods.

The maximum vibratory acceleration of soil particle displacement at the measurement point, according to V.G. Afonin, is determined by the formula [17]:

$$a = 6.4\omega \cdot (2.50 - 1.50)\left(\frac{\sqrt[3]{C}}{R}\right)^{2.5} \quad (5)$$

where C is the weight of the charge, kg; R – distance to the explosion site, m; ω – frequency of oscillations, *Hz* (for calculation, ω = 0.3 Hz is assumed); (2.50-1.50) – coefficient adopted depending on engineering and geological conditions.

Since the city of Horishni Plavni is built on category II soils (fill soils consisting of fine sand and sandy loam with admixtures of organic matter, crushed stone, and construction waste of heterogeneous composition), we accept a coefficient of 2.25 in formula (5) for seismic properties.

Another method, determining the vibration acceleration of soil particles in the radial direction based on experimental data by S.V. Medvedev, which was used in design practice [17]:

$$a = 6.4 \cdot K_v \omega \sqrt{\frac{g}{\rho b_1 \tau}} \left(\frac{\sqrt[3]{C}}{R} \right)^{1.5} \tag{6}$$

where K_v is an empirical coefficient, m; ρ is soil density, kg/m^3 (accepted for each plot based on engineering and geological research data); g is acceleration due to gravity, m/s^2; τ is soil oscillation period (based on field studies, accepted as 0.25 – 0.3 s); b_1 is wave propagation velocity, m/s (determined according to [18]).

Using the proposed methods, soil vibration acceleration was calculated depending on the distance to the explosion site in the quarry.

It is also possible to calculate soil vibration acceleration using the finite element method. Vibration acceleration at the foot of the dam at a distance of 4500 m from the explosion site has been calculated (figure 4).

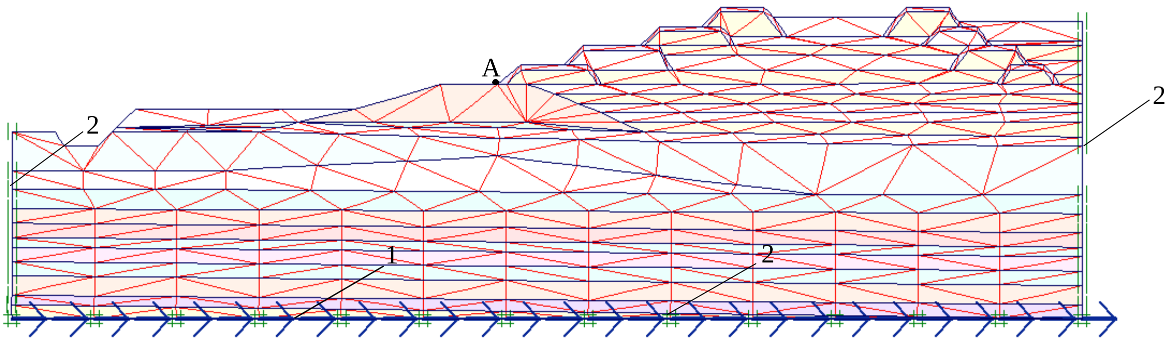

Figure 4. Calculation diagram for calculating the vibration acceleration of the tailings dam at Poltava Mining and Processing Plant: 1 – direction of seismic load; 2 – ties [19].

At the first stage of calculation, a 65×220 m calculation scheme was constructed, including a cross-section of the tailings dam at PC 0 in sections I-II together with the foundation [20]. Characteristics are assigned to each selected element that makes up the dam and its foundation. Next, a mesh of finite elements is formed by dividing the calculation scheme into elements. Boundary conditions are assigned by imposing constraints on the calculation scheme. In the lower part, there is a rigid clamp (horizontal and vertical movements are restricted), and at the vertical boundaries of the calculation scheme, the constraints restrict movement only horizontally. Vibration acceleration is determined at the point where the study was conducted (marked as point A on the calculation scheme).

To assess the accuracy of the calculation of soil vibration acceleration at the foot of the dam, the calculation scheme was divided into 50–1000 elements. The calculation was performed with 250 iterations.

The most excellent convergence between the calculated and measured values of vibration acceleration is observed when the calculation scheme is divided into 100 finite elements (4% discrepancy). It is not advisable to perform calculations when dividing the calculation scheme into 500 – 1000 elements, because the results obtained from the calculations are overestimated compared to the measured values (error up to 52%). Therefore, it is advisable to calculate the vibration acceleration of an earth dam by dividing the calculation scheme into 50–250 elements without losing accuracy.

2.3. Peculiarities of measuring dynamic soil characteristics

To assess the reliability of any calculation method, the method of comparing the calculated dynamic characteristics of the soil with the measured value at the same test point was used [21,22]. The dynamic characteristics of the soil following seismic impact from explosions were measured using a Vibrometer B107 (figure 5). A metal probe, attached to an accelerometer sensor via a threaded connection, was used to measure vertical soil vibrations. The metal probe was inserted into the soil at the test point, while the accelerometer sensor remained on the soil surface in a vertical position. To measure horizontal vibrations, a metal rod (reinforcing rod, 10 mm in diameter) 300 mm long was driven into the ground, with 100 mm of the rod protruding above the soil surface. An accelerometer sensor was attached to the reinforcing rod in a horizontal position using a magnet. Initially, trial measurements of horizontal and vertical soil vibrations were carried out at the points under study. As a result of the first stage of measurements, the points and directions of vibration registration most characteristic of this dynamic process were identified. It was determined that horizontal vibrations exceeded vertical ones, i.e., the primary focus was on studying horizontal soil vibrations.

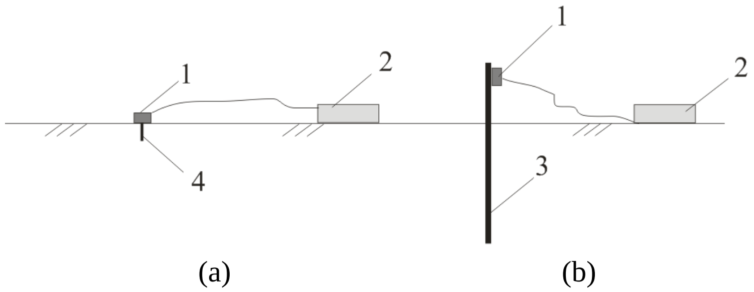

Figure 5. Diagram of sensor installation for measuring:
a) vertical; b) horizontal soil vibrations: 1− accelerometer sensor;
2 – vibrometer B 107; 3 – stake (reinforcing bar); 4 – probe.

Measurements of dynamic characteristics at the foot of the tailings dam were carried out at PK0 at a distance of about 4500 m from the explosion site. Five measurements were taken. The average of the measured maximum vibration acceleration values was 0.0154 m/s², which corresponds to 3 points on the MSK scale, indicating that vibrations were felt by some people who were aware of the explosion.

The graph of soil vibration acceleration at point A at the foot of the tailings pond at a distance of 4500 m from the rock blasting site, calculated using the finite element method, is shown in figure 6. The maximum value of soil vibration acceleration is 0.016 m/s^2, observed 0.96 seconds after the explosion.

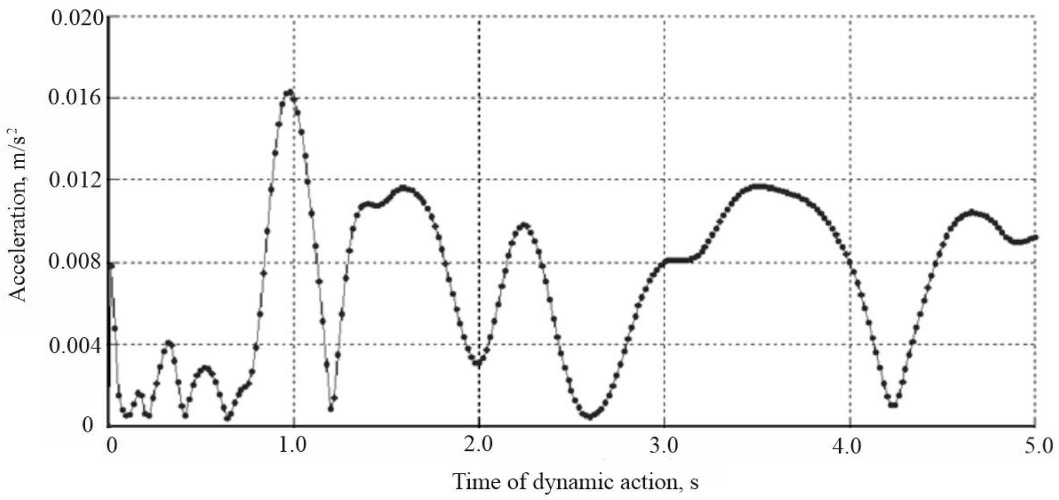

Figure 6. Graph of soil vibration acceleration at point A at the foot of the tailings pond, 4500 m from the blast site.

3. Results and discussion

When calculating by V.G. Afonin's method, the ground vibroacceleration at the dam's base would be 0.010 m/s². However, measurements of ground oscillations conducted at a distance of 4500 m from the blast site near the tailings dam yielded an average vibroacceleration value of 0.0154 m/s², which is more than 1.5 times higher than the theoretically obtained value.

The convergence of the results obtained using S.V. Medvedev's method (formula 6) is more accurate, yielding an obtained value of 0.017 m/s².

The vibration acceleration value obtained through mathematical modelling using the finite element method most accurately corresponds to the values obtained experimentally. The deviation of the obtained value of 0.016 m/s^2 does not exceed 4%.

4. Conclusions

The dynamic characteristics of building foundations and structures were studied using real seismic impacts as examples. The source of the impact was the use of explosives for rock development by JSC "Poltava Mining and Processing Plant". The object of analysis, located about 1000 m from the quarry (4500 m from the epicentre of the explosion), was the tailings dam of the Dnipro Ore Mining and Processing Plant.

The comparison method was used to verify specific calculation methods. The essence of the process was to compare the calculated dynamic characteristics of the soil with the actual measured value at the same control point. Measurements of the dynamic characteristics of the soil caused by the seismic impact of explosions were carried out using a B107 vibrometer.

It has been established that vibration accelerations calculated as a result of modelling the "tailings storage facility – foundation" system using the finite element method give better agreement with the measured values than the vibration acceleration values obtained using known techniques. The difference between the obtained results and the experimental values is within 4%. That is, the determination of soil vibration acceleration from the seismic impact of explosions can be performed by modelling the "structure-foundation" system using the finite element method.

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