Experimental study of deformation and stability of dams built of phosphogypsum under seismic impacts

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Abstract. The article presents the results of experimental studies of the model behavior under seismic influences. The conditions for ensuring the seismic resistance of phosphogypsum dams were investigated and established by testing the models on a vibration platform. The purpose was to study the deformability and stability of slopes of a given configuration built of phosphogypsum and to substantiate the possibility of using phosphogypsum to construct enclosing dams of sludge tanks located in seismic regions. The tests were conducted on small-scale models on a horizontal vibration platform in laboratory conditions. The methods of research using the vibration platform and the accepted modeling parameters were discussed. Dihydrate phosphogypsum with an optimal moisture content of 22-23% was used to construct the models. In total, 2 groups of prototypes were tested; they differed from each other only in the slope ratio. Models of the 1st group were tested without water. Models of the 2nd group were tested after wetting their materials to an average of 32 - 40%. To do this, water was filled in into the tank to the crest level, and the models stayed in this state for a week. Each model in both groups was tested for dynamic impacts with an earthquake intensity of 6-9 points. As a result of the studies on the seismic stability of dam fragments made of phosphogypsum, it was established that the enclosing dams of sludge tanks (built from phosphogypsum with optimal moisture content and its layer-by-layer compaction up to 1.25 g/cm^3, when the slope ratio was no steeper than m=3), have the necessary seismic resistance during earthquakes with an intensity of 7 -9 points. Based on the generalization of the data of model studies, the diagrams of the acceleration distribution in the height of the models were obtained. The diagrams of the acceleration distribution in height obtained in the experiments indicate the amplitude attenuation of the model vibrations from the base to the crest zone.

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1 Introduction

Industrial waste- phosphogypsum is formed in the production of phosphorus mineral fertilizers. The problem of using phosphogypsum on an industrial scale remains unresolved; therefore, the need for their storage in special storage facilities continues to hold[1]–[4]. It should be noted that even if this problem gets a positive solution, the need for storage will not disappear. It will be necessary to store this raw material in intermediate storage facilities until the development and implementation of a waste-free technological chain, considering the complete utilization of phosphogypsum. To create dumps of phosphogypsum, it is necessary to alienate large areas, sometimes even arable land.

To increase the efficiency of using land allotted (in vast areas) for sludge tanks, the building up of storage facilities in height becomes a practice. Local soils are used for the construction of secondary dams of the built-up sludge collectors. Using waste materials for constructing primary and secondary embankment dikes leads to a noticeable reduction in the cost of building storage facilities. Recently, phosphogypsum has been introduced into the practice of building sludge collectors as a building material, from which enclosing dams and other storage elements are erected; however, the overwhelming majority of such storage tanks are located in non-seismic zones. The possibilities of using phosphogypsum to construct dams for hydro-dumps considering a seismic factor were limited by the poorly understood behavior of load-bearing structures built of phosphogypsum during strong earthquakes. In this regard, the study of these issues seems to be relevant and has great scientific interest and practical importance.

Theoretical and practical studies devoted to the physical, mechanical, and dynamic properties of phosphogypsum, filtration processes, slopes of enclosing dams stability, creation of new designs of anti-filtration screens of sludge collectors, methods of erecting and building up enclosing dams in height were reflected in scientific works of such researchers as T.Z. Sultanov [5, 6], K.D. Salyamova and A.A. Yangiev [7], H. Fayziev [2], [3, 8, 9], R.R. Sharipov and S. Sayfiddinov [10, 11], N.A. Kutepova [12] and others.

Studies of the seismic resistance of earth dams are conducted by theoretical and experimental methods. Among the theoretical methods, one can mention the study in [7]. As for the experimental methods, research methods using a seismic platform and centrifugal modeling have become widespread. Krasnikov N.D. [13], Sharapova O.N. [14] and others conducted experiments on a vibrating platform, and many researchers were engaged in the method of centrifugal modeling [15–18],[19–22], [23].

We have studied the seismic resistance of phosphogypsum dams by testing the models on a vibration platform.

2 Methods

A fragment of the enclosing dam of the hydraulic dump was taken as the initial full-scale object, the diagram of which is shown in Fig. 1. The following conventional signs were used: H is the height of the fragment; L is the length of the fragment along the crest; B is the width of the fragment at the base; b- is its width along the top at the dam crest level; m is the slope ratio. On the front side, the fragment is limited by the slope of the dam; on the other three lateral sides - by vertical transversal planes; on the top - by the dam crest surface; and on the bottom - by the base of the fragment. Models must comply with the following requirements: geometric similarity of the structure and the model, similarity of foundation conditions, and similarity of external impacts [24]. However, it is impossible to comply with all the similarity conditions in practice; therefore, it is necessary to use the methods of approximate modeling.

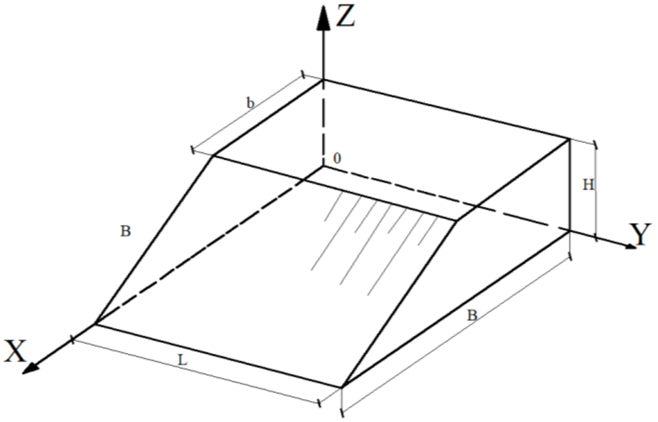


Fig. 1. Fragment of full-scale dam

The experimental studies of models on a vibrating platform are based on the theory of mechanical similarity developed by A.G. Nazarov [24]. Because in these experiments, it is impossible to comply with the conditions for modeling the accelerations of gravity, the initial premise of modeling volumetric forces is the equality of accelerations in the full-scale object and the model. Other conditions for converting quantities in dynamic processes are determined based on the indicated premise. Although this approach is approximate, it is possible to set up experiments and obtain sufficiently reliable research results [24].

The full-scale fragment of the dam taken is characterized by the following overall dimensions: H = 15 m, L = 60 m, b= 45 m, and B = 45-105 m, depending on the change in the slope ratio in the range of 0-3.5. Natural material – phosphogypsum - in the body of the dam fragment is characterized by the following values: optimum moisture content $W = 22 - 24\%$; the density of the dry phosphogypsum skeleton $\rho_d = 1.23 - 1.25\, {}^{g}/_{m^3}$; the angle of internal friction φ=30-35^0; specific cohesion of the material C = 0.03-0.05 MPa; normal modulus of elasticity E = 0.9-1.2 MPa; Poisson's ratio ν = 0.39-0.41; filtration coefficient K = 0.01-0.02 m/day [25].

Soils of the II category (semi-rocky soils) are taken as a basis of the full-scale fragment; seismic vibrations are set by the following parameters: prevailing periods T_0 = 0.3-0.6 s; duration of seismic impacts no less than 0.5 A_{max} (where A_{max} is the maximum amplitude of vibrations in any of the values considered - displacement, velocity or acceleration) τ_0= 10-15 s; displacement and acceleration of soil vibrations during earthquakes of the following intensities see in the table 1 below [26].

Table 1. Displacement and acceleration of soil vibrations during earthquakes

I (point)	6	7	8	9
U_0(cm)	0.15-0.3	0.3-0.6	0.6-1.2	1.2-2.4
ω_0 (cm/s^2)	25-50	50-100	100-200	200-400

Considering the specific possibilities of setting up experiments, the modeling scale was taken to be 30, so we determine: α = 1: 30 ≈ 0.033, where α is the similarity factor for linear dimensions. Therefore, for the model of the dam fragment, we have the following overall dimensions: H′ = 50cm; L'= 220 cm; b′= 50 cm; B′ = 50-220 cm, depending on the change in m′ in the range of 0-3.5.

To ensure the similarity of the material properties of the model, the following conditions must be met:

$\rho'=\rho$ is density of the materials; $E'=E$ is elastic moduli;
$\varphi'=\varphi$ is the angle of internal friction; $\nu'=\nu$ is Poisson's ratio;
$c'=c$ is specific cohesion; $\kappa'=\kappa$ is filtration coefficient.

To ensure the similarity of seismic effects and ongoing dynamic processes in the models, the following conditions must be met:

$\omega_0' = \omega_0$ is acceleration of vibrations; $\vartheta_0' = \sqrt{\alpha}\vartheta_0$ is vibration velocities;
$U_0' = \alpha U_0$ is displacements, offset; $t_0' = \sqrt{\alpha}\, t$ is current time;
$T_0' = \sqrt{\alpha} T_0$ is vibration periods; $S'= S$ is volumetric forces;
$\sigma' = \alpha\sigma$ is stresses in the material; $\varepsilon' = \varepsilon$ is relative strains.

According to these equations, the parameters of the model base vibrations should have the following values: periods of vibrations T_0'= 0.06-0.11 s, duration of impacts τ_0'= 1.83-2.75 s, displacement and acceleration under dynamic impacts of various intensities.

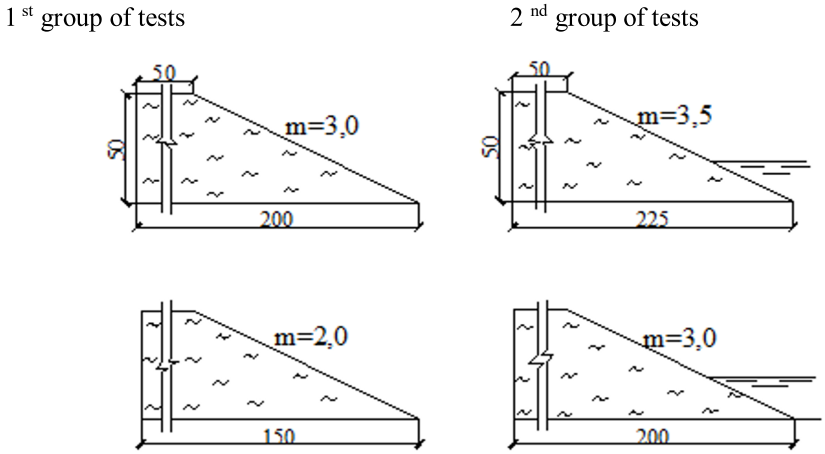
3 Results and Discussion

A metal tray rigidly fixed to the vibrating platform was filled with the prototype material. Dihydrate phosphogypsum was used to construct the models, with the optimal moisture content of 22-23%. The material of the models was poured in layers of 10 cm and compacted with a manual rammer to ρ_d' =1.24-1.25 g/cm^3; the remaining properties of phosphogypsum were characterized by the following parameters: φ'=32-33^0; c'=0.035-0.04MPa; ν'=0.38-0.39; K'= 0.01-0.015 m/day.

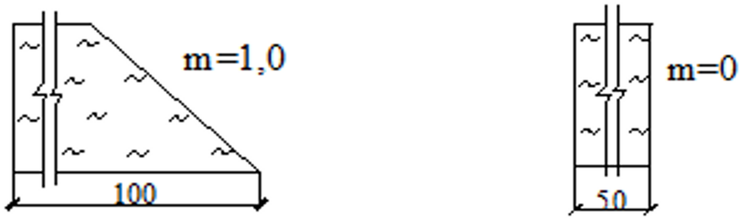
In total, 2 groups of prototypes were tested, including 4 and 2 models, respectively, the diagrams of which in cross-section are shown in Fig. 2. They differed only in the slope ratio. Models of the 1st group were tested without water. Models of the 2nd group were tested after wetting the materials to an average moisture content of 32 and 40%. To do so, water was poured into the tank to the crest level, and the models stayed in this state for a week.

Both groups' models were tested for the dynamic impact of 6-9 points' intensity. The total number of experiments was 30, of which 24 tests were conducted in the ordinary mode, and 6 tests were conducted in the resonance mode.

Calibrated vibration measuring devices OSP-2M were used to register vibrations; they recorded data at two points in three mutually perpendicular directions and at one strain gauge, recording the data in the longitudinal direction.


1 st group of tests
2 nd group of tests

1 st group of tests



Fig, 2. Diagrams of transverse profiles of models tested on seismic platform (dimensions are given in cm).

Measurements of vertical and horizontal displacements of the models at 9-point intensity were done using a sliding ruler with an accuracy of ± 1 mm. The appearance of landslide phenomena on the slopes was stated by examining the condition of the crest zone and the slope's surface after each test. The locations of instrumental observation points are shown in Fig. 3.

The following problems were set for these studies:

1. determination of the numerical values of the parameters of natural vibrations of prototypes;
2. identification of dynamic response of models under different frequencies of external impacts;
3. the establishment of diagrams of the distribution of vibration intensity at the height of the prototypes

In all the experiments conducted, a general tendency was observed towards a certain decrease in the periods of the natural vibrations of the models with an increase in the intensity of the impact. This phenomenon could be explained by an increase in the density of the material of the models and, consequently, an increase in their rigidity. However, it was not possible to establish an unambiguous dependence T′= f(ω′).

Recording the vibration level in the crest zone of the models under different frequencies of impacts showed a certain increase in amplitude with an increase in the frequency of vibrations. A similar picture of the vibrations of the models was observed at the mid-slope level.

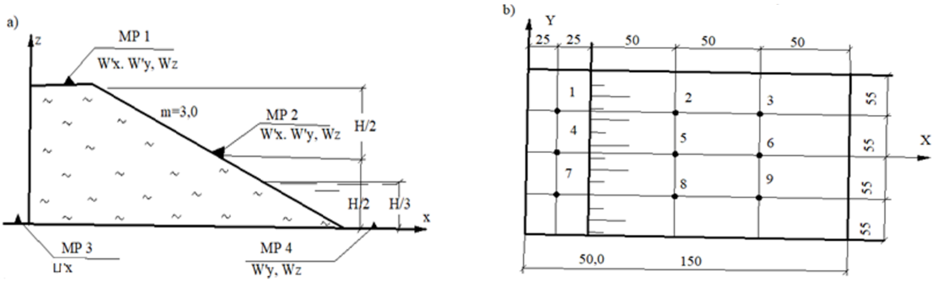


Fig. 3. Placement of measuring points for studying the dynamics of models (a); placement of surface marks for studying seismic deformations of models (b)(dimensions are given in cm)

The graphs of changes in u' for all three directions of vibrations depending on the change in f' are given in Fig. 4.

Analysis of the dynamic responses of the models of both groups shows that with an increase in the impact intensity, the amplitudes of vibrations of the models gradually attenuate. For example, the ratios of the averaged values of the amplitudes of the crest vibrations along the X-axis to the corresponding vibrations of the model base are: at 6-point intensity -0.63; at 7point intensity -0.52; at 8 point intensity -0.41 and 9 point intensity -0.3. This process of decreasing amplitudes is also observed at the mid-slope level, i.e., at 0.5H'. The resulting diagrams of the acceleration distribution in height of the models are shown in Fig. 5, where the numbers in the circles indicate the intensity of the impacts in points.

The observed decrease in the amplitude of vibrations of the models with an increase in the impact intensity can be explained by a noticeable manifestation of the nonlinear properties of phosphogypsum [16]. A significant influence of this factor was also noticed in special experiments related to the sample testing in the resonance zone. The effect of nonlinear properties was expressed in the fact that the ratio of the vibration amplitudes in the crest zone to the vibrations in the base in the resonance zone in all experiments did not exceed 1.2. At the same time, as is known, in earth dams and dikes, the level of vibrations of the crest zone compared with the base is several times higher. True, here, too, the influence of nonlinear properties of soil materials on a decrease in the values of the vibration amplitudes observed in another zone of deformation of materials is noted.

The averaged data of measurements of the crest deformations of the models (absolute values and relative values) under influences of various intensities are presented in Fig. 6 as graphs.

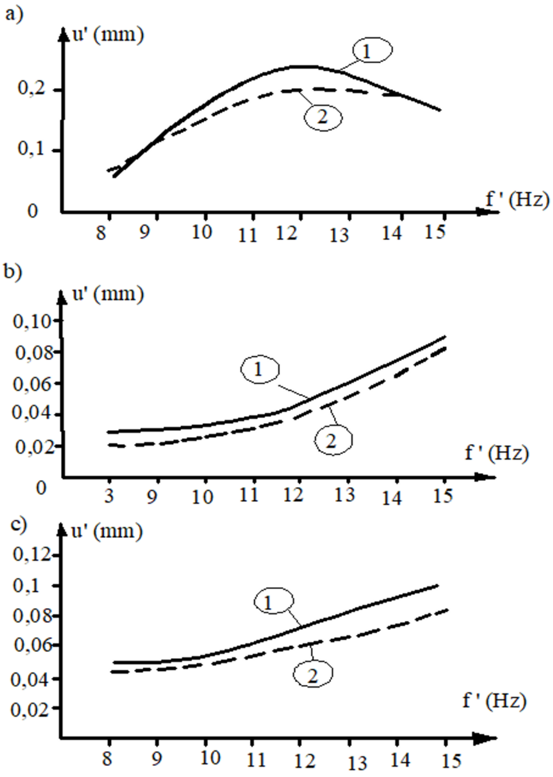


Fig. 4. Dependences of vibration amplitude of models on frequency: a) along the Z-axis, b) along the Y-axis, c) along the X-axis. 1 is on the crest; 2 is on the mid-slope level.

The results of the experiments show that the seismic deformations of the 1st group models begin to occur mainly at the 8 point intensity. This can be seen from the graphs of the crest model settlement in Fig. 6. No significant influence of the change in the slope steepness on the deformation values of the models was observed. Even in the model with a vertical slope (m = 0) under 9-point intensity impact, only spalling fractures of the upper part of the crest appeared, but no loss in stability of the samples was observed. In the models of the 2nd group, seismic deformations appeared at 7-point intensity impacts. Moreover, the steepness of the slope from 3.5 to 3 and a slightly higher moisture content of phosphogypsum in the second model led to the loss in slope stability at a 9-point impact. This was manifested in the partial liquefaction of the phosphogypsum of the slope and the re-laying of the material with a slope ratio of 1: 4.5 ÷ 1: 5.0. In this case, the maximum crest settlement reached 37% of the initial height H′ of the model.

According to the test data of models composed of phosphogypsum with a moisture content of no more than 23%, the following empirical dependence of the seismic settlement of the dam body on its height and the earthquake intensity, set by the seismicity coefficient K_c, was obtained:

$$\Delta = 0.13\ HK_c^2 \tag{1}$$

where Δ and H have the same dimension.

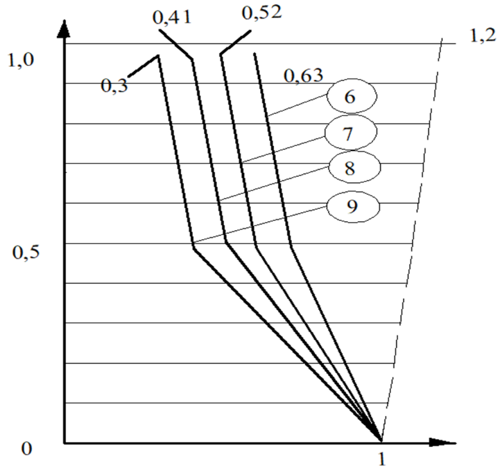


Fig. 5. Generalized diagrams of acceleration distribution in the height of models

Fragment diagramCrest settlement

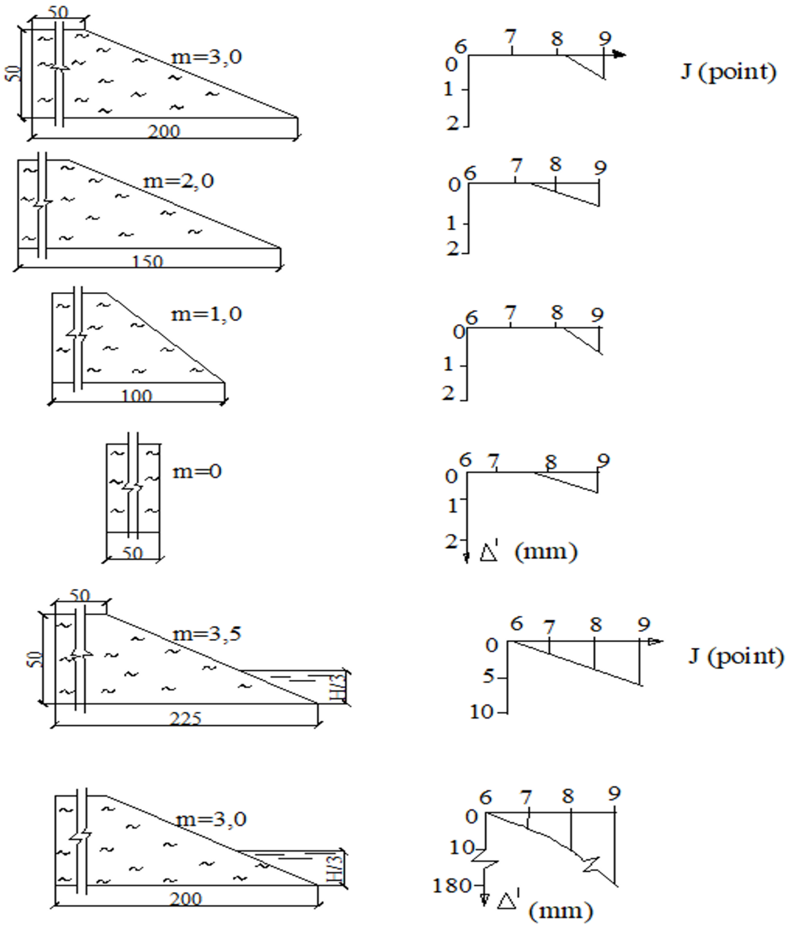


Fig. 6. Averaged data on model crest deformations under impacts of different intensities.

4 Conclusions

Based on the generalization of the experimental data, the following conclusions can be drawn, which give a general idea of the seismic resistance of the dams built of phosphogypsum dihydrate.

1. Embankment dikes of hydraulic dumps, built of phosphogypsum with optimal moisture content and its layer-by-layer compaction up to 1.25 g/cm^3, at the slope ratio no greater than m = 3, have the necessary seismic resistance against earthquakes of 7-9 point intensity.
2. Analysis of the amplitude-frequency response of the models showed that they are nonlinear objects. This nonlinearity is displayed by the dependence of the prototypes' periods of natural vibrations on the excitation load's intensity.
3. Under the effect of nonlinear properties of phosphogypsum, the vibration accelerations in the height of the models decreased from the base to the crest.
4. It was established that the settlement of wetted slopes is significantly greater than the settlement of dry slopes, and this process increases with an increase in slope steepness.

5. Based on the generalization of the data of model studies, the diagrams of the acceleration distribution in the height of the models are described by the following dependence:

$$K_c(Z) = K_c\,(1 - C\frac{Z}{H}) \qquad (2)$$

where H is the maximum height of the dam; Z is the ordinate of the point in height; C is a factor equal to 0.37 for 6 point intensity, to 0.48 for 7 point intensity, to 0.59 for 8 point intensity, and to 0.7 for 9 point intensity.

6. The diagrams of the acceleration distribution in height obtained in the experiments, as a whole, indicate the attenuation of the amplitudes of the model vibrations from the base to the crest zone.

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