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

Khamidxon Fayziev 1, Takhirjon Sultanov 2*, Lobar Mambetova 2, Ravshan Sharipov 1, Javlon Yarashov 3

1 Tashkent Institute of Architecture and Civil Engineering, Tashkent, Uzbekistan
2 Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan
3 Tashkent State Pedagogical University, Tashkent, Uzbekistan

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. Diaryhydrated 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 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/cm³, 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 vibration from the base to the crest zone.
1 Introduction

The study of seismic resistance of phosphogypsum dams has been a subject of scientific interest and practical importance. Recent studies have focused on the physical, mechanical, and dynamic properties of phosphogypsum, which is used in the construction of secondary dams of the built-in practice of building sludge collectors as a building material, from which enclosing dams are formed in the production of phosphorus mineral fertilizers.

The problem of using phosphogypsum on an industrial scale remains unresolved; therefore, it is necessary to develop new designs for anti-earthquake bearing structures. The possibilities of using phosphogypsum in the construction of secondary dams of the built-in practice of building sludge collectors as a building material, from which enclosing dams are formed in the production of phosphorus mineral fertilizers.

The options for storing phosphogypsum in large areas, sometimes even arable land, will be necessary to alienate large areas, sometimes even arable land. Phosphogypsum is formed in the production of phosphorus mineral fertilizers and is used to construct construction of secondary dams of the built-in practice of building sludge collectors as a building material, from which enclosing dams are formed in the production of phosphorus mineral fertilizers.

2 Methods

The methods of approximate modeling have become widespread. We have studied the seismic resistance of phosphogypsum dams by testing the models and building up enclosing dams. Models must comply with all the similarity conditions in practice; therefore, it is necessary to use the foundation conditions following requirements: geometric similarity of the structure and the model, surface similarity of the enclosing dam of the hydraulic dump was taken as the initial full fragment of the enclosing dam of the hydraulic dump was taken for analysis. The following convention on the top of the fragment is limited by the slope of the dam, on the bottom by the base of the fragment. Models must comply with the similarity conditions: H – height of the fragment; L is the length of the fragment along the horizontal axis; A – area of the fragment. The ratio of the model to the real object: H’/H = L’/L = A’/A = k. Models were tested on a vibration platform, and many researchers were engaged in the method of centrifugal modeling and building up enclosing dams.
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: \( H = 15 \text{ m}, \ L = 60 \text{ m}, \ b = 45 \text{ m}, \ B = 45 - 105 \text{ m}, \) depending on the change in 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 \( \rho_d = 1.23 - 1.25 \text{ g/cm}^3 \); the angle of internal friction \( \phi = 30 - 35\,^\circ \); specific cohesion of the material \( C = 0.03 - 0.05 \text{ MPa} \); normal modulus of elasticity \( E = 0.9 - 1.2 \text{ MPa} \); Poisson's ratio \( v = 0.39 - 0.41 \); filtration coefficient \( K = 0.01 - 0.02 \text{ m/day} \) [25].

Soils of the II category (semi-rocky soil) are taken as a basis of the full-scale fragment; seismic vibrations are set by the following parameters: prevailing periods \( T_0 = 0.3 - 0.6 \text{ s} \); duration of seismic impacts no less than \( 0.5 A_{\text{max}} \) (where \( A_{\text{max}} \) is the maximum amplitude of vibrations in any of the values considered - displacement, velocity or acceleration) \( \tau_0 = 10 - 15 \text{ s} \); displacement and acceleration of soil vibrations during earthquakes of the following intensities see in the table 1 [26].

<table>
<thead>
<tr>
<th>I (point)</th>
<th>( U_0 ) (cm)</th>
<th>( \omega_0 ) (cm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.15 - 0.3</td>
<td>25 - 50</td>
</tr>
<tr>
<td>7</td>
<td>0.3 - 0.6</td>
<td>50 - 100</td>
</tr>
<tr>
<td>8</td>
<td>0.6 - 1.2</td>
<td>100 - 200</td>
</tr>
<tr>
<td>9</td>
<td>1.2 - 2.4</td>
<td>200 - 400</td>
</tr>
</tbody>
</table>

Considering the specific possibilities of setting up experiments, the modeling scale was taken to be 30, so we determine: \( \alpha = 1: 30 \approx 0.033 \), where \( \alpha \) is the similarity factor for linear dimensions. Therefore, for the model of the dam fragment, we have the following overall dimensions: \( H' = 50 \text{ cm}; \ L' = 220 \text{ cm}; \ b' = 50 \text{ cm}; \ B' = 50 - 220 \text{ cm}, \) depending on the change in \( m' \) in the range of 0 - 3.5.
\[ \rho' = \rho \text{ is density of the materials} \]
\[ \varphi' = \varphi \text{ is the angle of internal friction} \]
\[ v' = v \text{ is Poisson's ratio} \]
\[ c' = c \text{ is specific cohesion} \]
\[ k' = k \text{ is filtration coefficient} \]

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

\[ \omega_0' = \omega_0 \text{ is acceleration of vibration} \]
\[ \vartheta_0' = \sqrt{\alpha} \vartheta_0 \text{ is vibration velocities} \]
\[ U_0' = \alpha U_0 \text{ is displacements, offset} \]
\[ t_0' = \sqrt{\alpha} t_0 \text{ is current time} \]
\[ T_0' = \sqrt{\alpha} T_0 \text{ is vibration periods} \]
\[ S' = S \text{ is volumetric forces} \]
\[ \sigma' = \alpha \sigma \text{ is stresses in the material} \]
\[ \varepsilon' = \varepsilon \text{ is relative strains} \]

According to these equations, the parameters of the model base vibration should have the following values: periods of vibration \( T_0' = 0.06 - 0.11 \text{ s} \), duration of impacts \( t_0' = 1.83 - 2.75 \text{ s} \), 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 \( \rho_d' = 1.24 - 1.25 \text{ g/cm}^3 \); the remaining properties of phosphogypsum were characterized by the following parameters:

\[ \varphi' = 32 - 33^0 \]
\[ c' = 0.035 - 0.04 \text{ MPa} \]
\[ v' = 0.38 - 0.39 \]
\[ K' = 0.01 - 0.015 \text{ m/day} \]

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.
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 a unambiguous dependence $T' = f(\omega')$.

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

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.
The intensity of impacts, the amplitudes of vibrations of the models gradually attenuate. For example, the ratios of the averaged values of the amplitudes of crest vibrations along the X-axis to the corresponding vibrations of the model base are: at 6-point intensity - 0.63; at 7-point 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. 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 $H'$. 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:

$$\Delta = 0.13 H K_c^2$$

where $\Delta$ and $H$ have the same dimension.

Fig. 5. Generalized diagrams of acceleration distribution in the height of models. Fragment diagram Crest settlement.
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:

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

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.

References


