Seismic resistance of sludge collector enclosing dams erected from the waste product – phosphogypsum

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Abstract. The results of experimental studies of the model behavior under seismic effect in a centrifugal testing installation are given in the paper. The goal was to study the deformability and stability of slopes of a given configuration made of phosphogypsum and to substantiate the possibility of using phosphogypsum in erecting enclosing dams of sludge collectors located in seismic regions. The experiments on models are based on the centrifugal modeling method, which involves the change in gravity field of the model. The models were tested at a stabilized and unstabilized state of phosphogypsum. Models stabilization was achieved by centrifugation for 8-25 min. The model was considered stabilized when its deformation did not exceed 0.01 mm. In a stabilized state, a fragment of the dam slope made of phosphogypsum in a water-saturated state at a slope steepness m=2, m=3 and in a dry state at m=2 was investigated. In an unstabilized state, the models of dams made of phosphogypsum were studied in a water-saturated state with a slope steepness m=3, and a dam fragment at m=3 in a water-saturated state with horizontal and vertical sand drainage layers. As a result of studies of seismic stability of dam fragments made of phosphogypsum, the following was established: the overall stability of dams made of phosphogypsum (in a stable state) under seismic effect of up to 9-10 points is fully ensured both in a dry and water-saturated state. Horizontal and vertical interlayers increase the slope stability of the dam model made of phosphogypsum in a water-saturated state; the slopes were stable after a dynamic impact of 9 point even in unstabilized states. Drainage layers accelerate the consolidation of phosphogypsum, and this naturally increases the seismic resistance of dams.

1. Introduction
In the Central Asian region, of the greatest concern are the conditions of more than 300 dams aimed to regulation the water flow on transboundary rivers. Dams and other waterworks, built more than 30-40 years ago, due to their aging and reduced quality of operation, pose a serious danger to the population and facilities located in developed areas downstream the dams. Therefore, the compliance with design requirements, maintenance of hydrotechnical structures in good condition, ensuring the required level of reliability and maintainability is of paramount importance [1-3].

Over the past 70 years, more than a thousand accidents in large hydrotechnical structures have occurred in the world, the main causes of which are: cracks, destruction of slopes, settlement of the foundation of
earth dams and insufficient discharge capacity of spillway structures. World experience shows that timely prevention is much more economical and more effective than the elimination of the consequences associated with flood events and accidents on earth hydrotechnical structures. Therefore, the organization of monitoring and forecasting of possible emergency situations, the implementation of protective engineering and technical measures to increase the stability of earth dams come to the fore [4].

For the construction of dams, local soil materials are usually used. One of the main structural elements of the sludge collector are the enclosing dams. Special studies of phosphogypsum properties conducted in recent years have shown that they are quite suitable for the construction of sludge storage dams. Phosphogypsum is an industrial waste product in phosphate mineral fertilizers production. The problem of phosphogypsum utilization on an industrial scale remains unresolved, and because of this, the need for their storage in special collectors continues to be a pressing one.

To date, certain positive experience has been accumulated in the use of phosphogypsum for these purposes in the USA, France, Romania, Sweden, etc., and in our country. But the vast majority of such objects are located in non-seismic zones. The possibilities of using phosphogypsum for erecting dams of hydraulic fills in the presence of a seismic factor were limited due to little knowledge of load-bearing structure behavior during strong earthquakes. In this regard, the study of these issues seems relevant and presents both scientific interest and great practical importance.

2. Materials and Methods

The authors have studied seismic resistance of dams built from phosphogypsum by testing the corresponding models in a centrifugal testing installation. Theoretical foundations of the centrifugal modeling method were developed in the works of G.I. Pokrovsky, I.G. Fedorov, Nian Xiang et all [5].

In VNII VODGEO, Fedorov I.S., Melnik V.G., Teitelbaum A.I., Savvina V.A. using this method, have solved a large number of practical problems related to specific hydro-technical engineering objects to study strain, strength and crack formation in dams built from earth materials [6].

The method of centrifugal modeling was used by many scientists in solving various engineering problems: V.I. Wutzel, M.N. Goldstein, L.A. Popov, V.I. Shcherbina, T.G. Yakovleva, P.I. Averino, R.Kh. Basset, R.J. James, M. Mikasa et al [7-9].

The main principle of centrifugal modeling is that by reducing the geometrical dimensions of the structure while maintaining the basic properties of the materials, it is necessary to create large centrifugal forces in order to meet the equality of the concrete state of a full-scale structure and the model at similar points, i.e., \( \sigma = \sigma' \) (where \( \sigma \) are the stresses at some points of the full-scale structure, \( \sigma' \) are the stresses at similar points of the model) [10, 11]. Besides, in the model, the strain processes proceed, as in reality, in accordance with real laws between stresses, strains and time.

In order to achieve equal stresses under the above conditions and various absolute sizes of the systems, it is necessary that \( H \rho_s = \text{const} \), i.e., as \( H \) decreases, the particle density \( \rho_s \) of the structure material increases accordingly. This, as it seems, is easiest to achieve by replacing a lighter material with a heavier one. However, such a measure would be practically useless, since changing material, we would change not only their particle density, but also other properties, which would violate the conditions of complete similarity. In addition, the limits within which \( \rho_s \) could be changed are insignificantly small.

Thus, the value of \( \rho_s \) should be increased somehow differently. The following equality could be written [12]:

\[
\rho_s = \rho g \tag{1}
\]

where \( \rho \) - is the mass of the substance per unit volume (density); \( g \) - is the acceleration of gravity.

The value of \( g \) can be changed, causing inertial forces in this system. To do this, the system must be subjected to a motion with some acceleration \( i \), then the vector of total acceleration is obtained:

\[
a = g + i, \tag{2}
\]

\[
\rho_s = \rho \cdot a, \tag{3}
\]

where \( \rho_s \) is the volume force acting per unit volume of a given material in the total force field of inertia and gravity.
If the model is \( n \) times less than the full-scale structure (\( n \) is a modeling scale), then according to the above, the equality of stresses is achieved [13]:
\[
\frac{H \rho_a}{n} = \frac{n h \rho_a}{n} \quad \text{at} \quad H = \frac{n h}{n} \rho_a
\]
According to formulas (2) - (4), \( n \rho g = \rho a \) and therefore
\[
a = n \rho g \quad \text{as has been shown above in a different way, with formula (2).}
\]
So, the basic rule of the modeling (under the conditions considered) is that the volume forces that act on the model, should exceed as many times the force of gravity as many times the model is less than the full-scale structure.

When modeling any phenomena in a centrifuge tests, the linear dimensions are reduced by \( n \) times, i.e. [14].
\[
\frac{L}{\rho_n}, \quad \frac{H}{\rho_n}
\]
The area of the model of any body will be \( n^2 \) times less, and the volume will be \( n^3 \) times less than in a full-scale structure:
\[
S' = \frac{S}{n^2}, \quad V' = \frac{V}{n^3}
\]
The stresses at similar points of the model and full-scale structure are equal to each other \( \sigma' = \sigma \), as well as displacements \( \delta' = \delta \).

The value of total acceleration \( (a) \) from the conditions of considered force field in a centrifugal installation is:
\[
a = \sqrt{g^2 + \omega^4 R^3}
\]
and the necessary angular speed of centrifuge rotation to obtain the appropriate scale is:
\[
\omega = \sqrt{\frac{g}{R} \left( \frac{1}{n^2} - 1 \right)}
\]
All studies were carried out on a centrifugal installation created in the Institute of Mechanics and Seismic Stability of Structures of the Academy of Sciences of the Republic of Uzbekistan. The main installation parameters are as follows: maximum effective radius of rotation \( R_{ef} = 1.75 \) m, the maximum number of revolutions \( N_{max} = 160 \) rpm, the maximum modeling scale \( n = 40 \), the sizes of the carriages (internal) are 400x330x340 mm.

The models were carried out in a flat cartridge (seismoplotform), in the form of a rigid frame made of channel bar with side walls from organic glass. The internal dimensions of the cartridge are 250x190x145 mm.

The main measurements were carried out using surface and deep reference marks embedded in the model during its manufacturing. In some experiments, the model contours were fixed by sketching on tracing paper. The reference marks displacements were measured with a spitz-scale of 0.1 mm accuracy. Special reference marks were established at individual points of the model, the displacements of which were recorded during the experiments using selsyns of the BD-404A type, of 0.01 mm accuracy; the tests were conducted for the impacts of 8 and 9 points intensity.

To simulate the seismicity, the model located in the centrifuge carriage underwent an additional dynamic impact equal to the effect of a real earthquake on a field object. When considering this problem, the primary task was to establish the parameters that characterize the seismic impact.
As the basic criterion, the maximum acceleration $\omega$ is usually taken, acting on soil particles in the zone of the considered object under seismic wave propagation. Since acceleration is a vector, it is necessary to reproduce not only its value on the model, but also the acceleration direction in accordance with the full-scale structure.

Acceleration $\omega$ under seismic action is compared with a certain value that determines the stability and strength of the objects under consideration. Such a quantity is the acceleration $g'$, which replaces the acceleration of gravity $g$ on the model. Based on the laws of centrifugal modeling, we can write:

$$ g' = g \cdot n $$

(12)

To ensure that the model has the same conditions of stability under seismic impact as has the full-scale structure, the following requirement must be met [15]:

$$ \omega' = \frac{\omega}{g} $$

(13)

So,

$$ \omega' = \omega \cdot n $$

(14)

Acceleration $\omega$ in field conditions depends on the earthquake intensity, expressed in points. Besides acceleration, the seismic impact is characterized by a period of oscillations $T$, which can vary over a fairly wide range, with the main role being played by oscillations with periods from ten fractions to several seconds (0.1-5 s).

The third parameter of seismic impact related to the ones considered above is the amplitude $A$ [16]. If to assume that the seismic vibrations are sinusoidal in nature (harmonic vibrations), then the following equation can be written:

$$ \omega = \frac{4\pi^2}{T^2} \cdot A $$

(15)

Based on the condition of geometrical similarity

$$ A' = \frac{A}{n} $$

(16)

Based on equalities (14) and (16), we can determine the modeling scale of the oscillation period $T$. Using expression (15), we determine the oscillation period:

$$ T = 2\pi \sqrt{\frac{A}{\omega}} $$

then

$$ T' = 2\pi \sqrt{\frac{A'\cdot n^2}{\omega'\cdot n^2}} = \frac{T}{n} $$

(17)

Thus, the period of oscillations in the model should be $n$ times shorter than in the field object. If the models and the field objects are made of the same material, then longitudinal and transverse wave propagation in the field objects and in the models are the same. Consequently, the wavelengths equal to the strain propagation velocity, multiplied by the period of oscillations, in the model and in the field object are, respectively:

$$ \lambda' = c \cdot T' $$

$$ \lambda = c \cdot T $$

(18)

where $c$ is the strain propagation velocity.

So,

$$ \frac{\lambda}{\lambda'} = \frac{T}{T'} = n $$

(19)

This corresponds to the geometrical similarity of the model and field object and makes possible correct modeling in the conditions under consideration. Other conditions being equal, the seismic load on the structure is determined by kinematic parameters of the impact, so, it is very important to ensure kinematic similarity when studying the models in engineering seismology and earthquake-resistant construction.

The criterion of kinematic similarity in this case can be represented as:
where $A, A'$ are the oscillation amplitudes of the field object and the model; $T, T'$ are the periods of oscillation.

However, if this condition is necessary and sufficient for stationary vibrations, it is insufficient for modeling seismic vibrations at the same amplitudes and periods [1, 2], when, the dynamic effect of the impact is determined by the regularity $S_f(t)$, therefore, an additional condition for kinematic similarity in seismic stability studies should have the form:

$$\frac{A_t}{A'_t} = \text{idem}$$

Obviously, the dynamic similarity of the model to its field analogue is ensured if variable distributed forces identical in character and direction are applied to similar points of the model at similar times $t$ and $t' = t/n$.

3. Results

The tests of plane models of a phosphogypsum dam of 4 cm high were conducted with the upper slope steepness $m_u=3.0$ and the lower slope steepness $m_l=2.0$. Models were tested under stabilized and unstabilized states of phosphogypsum. Model stabilization was achieved by centrifugation for 8-25 min. The model was considered stabilized when its deformations did not exceed 0.01 mm. In a stabilized state, a fragment of the dam slope from phosphogypsum was investigated in a water-saturated state at $m=2$, $m=3$ and a slope in a dry state at $m=2$. In an unstabilized state, the dam models made of phosphogypsum were studied in a water-saturated state at a slope steepness of $m=3$.

Below the results of several test are given. In Fig. 1 the studied model is presented; it is a fragment of the upper part of the dam made of phosphogypsum. The dam was compacted to a density $\rho_d = 1.25 \text{ g/cm}^3$, then water was poured into the cartridge to a height of $1/3 N'$; after settling for 3 days, the excess water was drained. The process of phosphogypsum swelling was clearly traced in the dam to a height of $1/3 H'$. Therefore, the lower part of the slope was decompacted (softened) to $\rho_d = 1.15 \text{ g/cm}^3$.

The remote reference marks $P_1$, $P_2$, and $P_3$ were installed on the crest of the model and on the slope to monitor the strains throughout the experiment. Centrifugation was carried out on a scale of $n=40$. The acceleration time of the model was 5 minutes, i.e. the construction period in field conditions lasted 5 - 6 days.

![Figure 1](image)

**Figure 1.** Diagram of a model of dam fragment from phosphogypsum tested in a centrifuge for seismic effect (a), a record fragment of the oscillatory process (b) (record scale is 4.42:1), and a graph of the settlement change of the model over time during the test (c). 1 – a dam from phosphogypsum; 2, 3, 4 - crest settlement ($P_1$) and slope settlement ($P_2$ and $P_3$) after centrifugation with the application of seismic effect.

After reaching the rotation frequency corresponding to $n=40$ and the strain attenuation in the model under static load, the dynamic effect was reproduced for $n' = 1.4 \text{ s}$ at the following basic maximal parameters: amplitude $A' = 2.6 \text{ mm}$, frequency $\nu' = 31.8 \text{ Hz}$, period $T' = 0.0314 \text{ s}$, acceleration $\omega' = 10400 \text{ cm/s}^2$, which corresponded to a real earthquake $\omega = 0.26g$ in a scale of $n=40$ of (Fig. 1, b). It was assumed that in terms of acceleration and impact duration, this corresponded to 10 points intensity earthquake.
The basic strain of the model took place in the lower part of the slope (P 3) in both static and dynamic modes. This is explained by the fact that the lower part of the slope, when wetted to a height of 1/3 N′, swelled and decompacted (softened). On the graph $\Delta' = f(t')$ (Figure 1, c) it is clearly seen that after the strain attenuation under own weight of phosphogypsum, a noticeable jump occurred at the moment of seismic impact. The dynamic settlement $\Delta$ was 1.5 mm, i.e. approximately 3% of the model height. The total (static and dynamic) settlement was 4.6 mm, i.e. approximately 9.2%. The total settlement on the crest (P 3) and the upper part of the slope (P 2) was 1.25 mm and 0.75 mm, respectively, which is approximately 2.5% and 1.5% of the structure height.

A fragment of the dam slope made of phosphogypsum was tested for a seismic action without water (Figure 2a) with a slope steepness $m=2.0$, height 5.0 cm at a modeling scale of $n=40$. The density of phosphogypsum is $\rho_d = 1.25$ g/cm$^3$ at a moisture content of 10%. The parameters of the seismic effect on the fragment were set as follows: amplitude $A' = 2.65$ mm, frequency $\nu' = 31.7$ Hz, period $T' = 0.0315$ s, acceleration $\omega' = 10530$ cm/s$^2$. At a modeling scale of $n=40$, the acceleration at the field object is $\omega = 0.26g$ (Figure 2, b).

Figure 2, c shows the results of seismic action on a fragment. The dynamic impact of practically did not cause strain on a dry slope. The dynamic action caused a settlement on the fragment crest $\Delta'_g = 0.1$ mm, which is 0.20% of the structure height. The total settlement on the crest was $\Delta'_{g} = 0.3$ mm or 0.6% of the structure height, and the slope settlement was 0.2%.

![Figure 2. Diagram of a model of a dam fragment from phosphogypsum tested in a centrifuge for a seismic effect without water (a), a record fragment of the oscillatory process (b) (record scale is 4.15: 1), and a graph of the settlement change of the model over time during the test (c).](image)

In another test, a dam fragment of 5 cm high and of a slope steepness of $m=3.0$ with preliminary wetting was modeled without stabilization under dynamic impact at a modeling scale of $n=40$ (Figure 3, a). The parameters of seismic effect on the fragment were set as follows: amplitude $A' = 2.25$ mm, frequency $\nu' = 26.5$ Hz, period $T' = 0.0377$ s, acceleration $\omega' = 6240$ cm/s$^2$ or $0.15g$. A record fragment of the oscillatory process is shown in Figure 3, b. The time of dynamic impact is $\tau' = 1.5$ s, which corresponds to 60 s in field conditions. Thus, according to the impact duration, this corresponds to a 9 point earthquake.

Installation acceleration was carried out smoothly at a modeling scale $n=40$ for 5 min, after which the dynamic system was put into operation. As a result, a dam fragment was destroyed. Figure 3c shows the graphs of changes in the model settlement over time. The fragment crest sagged by $\Delta'_s = 16$ mm (by 15.7 mm after dynamic impact) which is 32% of the fragment height. The upper part of the slope (reference mark P 2) sagged by $\Delta'_s = 13.4$ mm (by 12.8 mm after dynamic impact) which is 26.8% of the model height. The lower part of the slope (reference mark P 3) sagged by $\Delta'_s = 10$ mm (by 8.2 mm after dynamic impact), which is 20% of the fragment height. In addition, it should be noted that all three reference marks have slid from their original position in horizontal direction: reference mark P 1 by 5.4 cm; reference mark P 2 by 5.6 cm; reference mark P 3 by 6.0 cm, which corresponds to 2.8%; 2.9% and 3.2%, respectively, of the fragment length.

Thus, the water-saturated (moisture-content after the experiment was $W=39\%$), unstabilized dam fragment of phosphogypsum with a slope steepness of $m=3.0$ turned out to be unstable after 9 point seismic impact.
The reason for this is the swelling properties of phosphogypsum upon wetting, resulting in (uncompaction) softening of the dam fragment from $\rho_d = 1.25$ g/cm$^3$ to $\rho_d = 1.1$ g/cm$^3$. Preventing the phosphogypsum to be compacted under its own weight, dynamic system was put into action and the slope, as is said, “drifted”. A slope fragment of a dam from phosphogypsum at $m=3.0$, 5.0 cm high (which corresponds to 2.0 m in field object) with a horizontal sand drainage layer 0.80 cm thick (which corresponds to 32.0 cm in field object) was studied at a modeling scale $n=40$ (Figure 4, a). The fragment was compacted to a density $\rho_d = 1.25$ g/cm$^3$, wetted to a height of 1/3 $N'$, settled for a day, after which the installation was accelerated for 5 minutes, which corresponds to 5.6 days in field conditions (construction period). Then, preventing the fragment from stabilizing under its own weight, a dynamic effect was applied for a time $\tau' = 1.5$ s. The parameters of the oscillation process were as follows: displacement $A' = 2.25$ mm, frequency $\nu' = 25.0$ Hz, period $T' = 0.004$ s, acceleration $\omega' = 5540$ cm/s$^2$, which corresponded to acceleration in field object. A record fragment of the oscillatory process is shown in Figure 4, b. Unlike the previous experiment, the slope was not destroyed, although the earthquake intensity, considering the impact duration, was 9 point as in the previous experiment.

Dynamic settlement of the model crest ($P_1$) was 4.7 mm or $e = 0.094$ (9.4% of the model height); dynamic settlement of the upper part of the model slope ($P_2$) was 1.3 mm or $e = 0.026$ (2.6% of the model height); dynamic settlement of the lower part of the model slope ($P_3$) was 0.9 mm or $e = 0.018$ (1.8% of the cross-section height).

The total settlement (stabilized and dynamic ones) on the model crest is $\Delta'_1 = 5.0$ mm or 10% of the model height; on the upper part of the slope $\Delta'_2 = 1.5$ mm or 3% of the model height; on the lower part of the slope $\Delta'_3 = 1.0$ mm or 2% of the model height (Figure 4, c).

A fragment of the dam slope made of phosphogypsum with vertical drainage layers was tested in a centrifuge for seismic effect (Figure 5, a). The slope steepness of the fragment is $m=3.0$, the height - 5.0 cm, the thickness of the interlayers -0.8 cm. The model was compacted to a density $\rho_d = 1.3$ g/cm$^3$, wetted to a height of 1/3 $N'$, settled for a day, after which an experiment was conducted. The installation was accelerated for 5 min to a modeling scale of $n=40$, then, preventing the fragment to be stabilized under its own weight, a dynamic impact was applied for $\tau' = 1.4$ s, which corresponded to $\tau = 56$ s in field object. The parameters of the oscillation process were as follows: displacement $A' = 1.65$ mm, frequency $\nu' = 26.6$ Hz, period $T' = 0.0376$ s, acceleration $\omega' = 4600$ cm/s$^2$, which corresponded to acceleration in field object. We believe that the earthquake intensity, considering the duration of oscillations, was 9 points. A record fragment of the oscillatory process is shown in Figure 5, b. As a result of the experiment, the model received strains, but was not destroyed. Figure 5, c shows the graphs of changes in model settlement over time during the test. The settlement as a result of dynamic impact on the model crest ($P_1$) was 4.3 mm, which is 8.6% of the model height; dynamic settlement of the upper part of the model slope ($P_2$) amounted to 1.1 mm or 2.6% of the section height; dynamic settlement of the lower part of the model slope ($P_3$) was 0.8 mm or 1.8% of the section height.

The total settlement on the crest (considering the construction settlement) of the model ($P_1$) was 4.3 mm, which is 8.6% of the model height; dynamic settlement of the upper part of the model slope ($P_2$) -1.3 mm or 2.6% of the model height; on the bottom of the slope ($P_3$) was 1.0 mm or 2% of the model height.

Two latter experiments have shown that drainage layers increase the slope stability of a dam from phosphogypsum in a water-saturated state. The slopes were stable after a 9 point dynamic impact, even in an unstabilized state. Drainage layers accelerate the consolidation of phosphogypsum, and this naturally improves the seismic resistance of dams.

4. Discussion

Experiments were carried out at displacements in the range $A'' = 2.25$-2.65 mm, an oscillation period $T''=0.0314$-0.04 s, and the impact duration time $\tau'' = 1.4$-1.7 s, which corresponds to $A= 90$-106 mm; $T=1.2$-1.6 s; $\tau=56$-68 s in field object (at a modeling scale of $n=40$) Of the above parameters, the displacement $A$ and period $T$ are close to the real values of earthquakes. The impact duration time $\tau$
exceeds that value during real earthquakes. We believe that this time margin will smooth out the errors and inaccuracies of the experiment.

The research results show that the total stability of dams from phosphogypsum (in a stabilized state) under seismic impacts of 9-10 points is provided both in a dry and water-saturated state. The slope collapsed only once, in testing a model from unstabilized and wetted material at a slope steepness of m=3 under a 9-point impact, with maximum settlement of the dam crest 32% compared to the initial height of the fragment model. The reasons for this were the swelling properties of phosphogypsum upon wetting, as a result of which the dam fragment was decompacted (softened) from $\rho_d = 1.25 \text{ g/cm}^3$ to $\rho_d = 1.1 \text{ g/cm}^3$. In all other experiments, the stability of dams was not violated. The research results show that the centrifugal modeling method can be effectively used to determine the strength and reliability of dams and levees built of fine-grained thixotropic materials under seismic effect. The prospects for the development
in this area are primarily associated with the improvement of devices that reliably model the parameters of dynamic effects in a centrifugal force field. The introduction of drain interlayers into the dam design has a favorable effect on the model stability.

5. Conclusions
As a result of studies of seismic stability of dams from phosphogypsum, it was found:
- The water-saturated (moisture-content after the experiment was W=39%), un-stabilized dam fragment from phosphogypsum at a slope steepness of m=3 turned out to be unstable under seismic impact of 9 points. The reason for this is the swelling properties of phosphogypsum upon wetting, as a result of which the dam fragment decompacted (softened) from $\rho_d=1.25\text{g/cm}^3$ to $\rho_d=1.1\text{g/cm}^3$.
- Seismic strain of dams made of phosphogypsum does not exceed 0.20% at a moisture content of 10-15%; 0.37% at a moisture content of $W = 30-35\%$ and 3% at a moisture content of 40-45% (in a swollen state).
- The total stability of dams from phosphogypsum (in a stabilized state) under seismic impacts of up to 9-10 points is fully ensured in both dry and water-saturated conditions.
- Horizontal and vertical layers increase the dam slope stability of the model from phosphogypsum in a water-saturated state, the slopes proved to be stable under dynamic impact of 9 points, even in unstabilized state. Drainage layers accelerate the phosphogypsum consolidation, and this naturally increases the seismic resistance of dams.

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