Stability of dam slopes of phosphogypsum sludge collectors

Takhirjon Sultanov¹, Khamidkhon Fayziev², Elyor Toshmatov¹ and Ilkhomjon Zokirov¹

¹Department of Theoretical and Constructional Mechanics, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan.
²Tashkent Institute of Architecture and Civil Engineering, Tashkent, Uzbekistan

E-mail: tohir-zs@mail.ru, toshmatov.elyor@bk.ru

Abstract. The results of calculations of the enclosing dam stability of phosphogypsum sludge collectors are presented in the paper. The stability calculations were carried out according to the “RUZO” program; they are based on the method of circular-cylindrical sliding surfaces under the action of basic and seismic loads. The main objective of this work is to determine the minimum safety factors for dam slopes of a given transverse profile under known loads and characteristics of the dam body material. To develop a rational profile of collector dams, 9 options of design models of the structure and its base were considered. The body of the enclosing dams of collectors of considered options consists, as a rule, of two elements: the primary floodwall built of earth materials, and secondary dams constructed according to a different build-up schemes from stored materials. Secondary dams are constructed from stored phosphogypsum by the method of layer-by-layer filling and compaction. The calculations showed that in all considered schemes the minimum safety factors under the action of basic and seismic loads are higher than the standard values. The maximum permissible values of the slopes are established with an allowable margin of safety, thus, the stability of dam slopes in all considered options of the phosphogypsum collector is ensured under basic and special combinations of loads.

1. Introduction

In the process of phosphoric mineral fertilizers production, industrial waste - phosphogypsum is formed. For each ton of main production, depending on the raw materials used (apatite or Karatau phosphoric flour) there are from 4 to 7 tons of waste, respectively. There are over 52 countries in the world, on the territories of which there are similar dumps with a total volume of phosphogypsum of the order of 5.6–7.0 billion tons [1]. For example, 52 million tons of phosphogypsum are accumulated in the dumps of Tunisia (Gabes), 100 million tons - in Spain (Huelva), 150 million tons - in Brazil, and more than 200 million tons - in the USA (Florida). The data in CIS countries are: in Ukraine - 33.2 million tons; in Kazakhstan - 22 million tons; in Russia, more than 200 million tons; in Turkmenistan - 6.6 million tons; in Belarus - 13.1 million tons; in Lithuania - 7.7 million tons. About 55.2 million tons of phosphogypsum are stored in dumps in our country. Dumps of these wastes occupy significant areas of land, they look extremely unsightly and have a negative impact on the environment.
As is well known, the issues of processing and disposal of phosphogypsum on an industrial scale remain unresolved. Consequently, production waste generated at chemical plants will be stored, as before, in collectors and storage devices of various types.

One of the effective ways to reduce the cost of sludge collectors and increase their service life is the use of phosphogypsum for the construction of primary and secondary dams. For the construction of dams, local earth materials are usually used. Special studies of the properties of phosphogypsum wastes from the phosphorus-containing mineral fertilizers production conducted in recent years [2-5] showed that they are quite suitable for the construction of dams of hydraulic fills. Moreover, they are also suitable for the construction of dams in seismically active areas [6-13].

The study and development of constructive schemes for hydraulic fills, their build-up over height and various measures to eliminate flooding of dams, as well as testing technological methods for constructing dams from phosphogypsum in natural conditions, allowed us to successfully implement the results of these studies in design and construction of hydraulic fills at a number of chemical plants in our republic (in Samarkand, Almalyk) as well as in the CIS countries: Cherepovets and Krasnodar (Russia), Sumy (Ukraine), Dzhambul (Kazakhstan) and others. Similar experience has also been gained in a number of foreign countries: the USA, France, Romania, Sweden and other countries [1,2,12-15].

Despite the certain successes achieved in research, the issues of improving designs, calculation methods and the technology of erecting sludge collectors with enclosing dams made of phosphogypsum are still not generalized, and the necessary regulatory and methodological documents are not available. In this regard, the studies of these issues seem relevant and present scientific interest and great practical importance.

2. Methods
In calculation practice, there are still no exact methods for determining the stability of slopes for any form of the sliding surfaces of failure sections. Existing methods consider imbalance either along a curved surface or along a broken surface. The hypothesis of a round cylindrical sliding surface is based on the study of landslide phenomena, which make it possible to establish that the form of the failure surface of earth homogeneous masses is close to circular-cylindrical one. Slope sliding on flat surfaces is most often observed in soils with very different physical-mechanical properties within the slope, and when there is a weak soil at the base of the layer.

A number of methods includes a combination of already described ones [16]. The most widespread method in computational practice is the method of circular-cylindrical sliding surfaces. This method is the most acceptable one for calculating the slope stability of a phosphogypsum collector.

According to the structure, the hydraulic fills can be of fill-in and alluvial types [16]. In the first case, the enclosing dams are erected to the full design height and the waste accumulation occurs continuously until the collector is completely filled. In the second case, dams are erected in tiers with a gradual build-up of the collector to the full design height. The construction and operation of the hydraulic fills occur alternately, i.e. practically simultaneously. Obviously, the alluvial fills have more complex structural schemes and complex technological conditions of construction than the fill-in ones. This can be seen, for example, from a comparison of the cross sections of hydraulic fills, the schemes of which are shown in figure 1, a. In order to develop a rational profile of the dam collectors, based on the results of the slope stability assessment, various height build-up schemes were considered, the main ones [2,12] being: internal (I), central (C) and external (E) ones. In specific conditions, combinations of these schemes can also be used, such as: internally central (IC), centrally internal (CI), externally internal (EI), centrally external (CE) and internally central (IC); the schemes are given in figure 1, b.

Based on the conditions of ensuring the overall stability of hydraulic fills at the most compressed dam profiles, for the indicated 9 schemes, the minimum values of external (outer) slopes ratio of the dams (m_e) were calculated.

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The body of the enclosing dams of collector in the considered options, as a rule, consists of two elements: the primary floodwall built of earth materials, and secondary dams constructed according to a different build-up scheme from stored materials. The bodies of the primary and secondary dams are protected by screens and in calculations accepted as non-saturated ones. The bases of the collectors consist of undeformable bedrock and are also in an unsaturated state. Secondary dams are constructed from stored phosphogypsum by the method of layer-by-layer filling and compaction. In order to prevent the entry of contaminated water from the hydraulic fill into the base soils and to exclude the flooding of the enclosing dams, the anti-filtration screens are arranged along the bottom of the collector bowl and internal slopes of the dams. In addition, to reduce the depression curve in the zones adjacent to the dams, annular drainages are provided along the bottom of the internal slopes of the dams. For the dehydration of phosphogypsum deposits, systematic or reservoir drains are arranged along the collector bottom, which to some extent reduce the hydrostatic pressure of water on the screens. The clarified waters from the surface of the hydraulic fill and filtering waters from the drainage system are removed with special devices used for these purposes.

The body of the secondary dams is assumed to be homogeneous, the phosphogypsum deposition in the hydraulic fill occurs without fractionation over the entire volume of the collector. Full height of the hydraulic fill is 50m; the height of the primary dams is 10m and secondary dams - 3.33m.

The calculated values of the indices of physical-mechanical properties for the elements of the collector dams are given in table 1.
Table 1. Calculated values of enclosing dam material

| Collector elements | Material      | $\rho_{d_{i}}$ t/m$^3$ | $\phi$, degree | $c$, t/m$^2$ |
|--------------------|---------------|------------------------|----------------|-------------|
|                    |               |                        | wetted         | Water-saturated |
| Primary dam        | Loamy soil    | 1.7                    | 22             | 22          | 0.75        | 0.75        |
| Secondary dam      | phosphogypsum | 1.26                   | 32             | 26          | 4.0         | 2.0         |
| Hydraulic fill     | phosphogypsum | 1.0                    | 32             | 26          | 4.0         | 2.0         |

The purpose of the calculation is to determine the minimum safety factors for dam slopes of a given transverse profile under known loads and characteristics of the dam body material. The calculations are conducted under basic and seismic loads of an intensity of 7.8 and 9 points. The phosphogypsum collector generally refers to the constructions of the II-class of solidity with the following values of the safety factors:
- under basic loads $K_{e} = 1.15$;
- under basic and special loads $K_{e} = 1.05$.

Stability calculations are carried out for a one-dimensional problem, when considering a unit thickness along the dam length.

Stability calculations of the slopes of collector dams were carried out according to the “RUZO” program developed by the Kharkov Vodokanalproekt together with the VNII VODGEO [17].

Four formulas are included into calculation formulas of the “RUZO” program, three of them are based on the Terzagi scheme, accounting the effect of filtration forces with varying accuracy: according to the method developed in the VNIIG named after Vedeneev, according to Terzagi scheme, according to Nichiporovich and Fedorov, as well as according to the Chugaev method of "weight pressure". The program provides for the simultaneous calculation of safety factors by all four formulas.

In the numerical solution, the sliding triangle is divided into a series of elementary columns. The expression for $K_{e}$, summarizing the formulas introduced into the “RUZO” program, can be written as follows:

$$K_{e} = \frac{1}{r} \sum M_{act}$$

where, $r$ - is the radius of the sliding surface; $\Sigma M_{act}$ - are the total moment of volume and surface forces acting on the sliding triangle; $G$ - is the weight of the i-th elementary column $\Delta b_{i}$ taking into account water, the sliding area with a slope $\alpha_{i}$;

$$N_{i} = \gamma h_{b} \Delta b_{i} \frac{\alpha_{i}}{\cos \alpha_{i}}$$

is the resultant hydrodynamic pressure on the sole of the i-th element in conditions of steady filtration; $U_{i}$ - is the resultant of excess pore pressure along the sole of the i-th element; $\mu$, and $\nu_{i}$ are the coefficients that reflect in the accepted methods an account for interaction between the elements of the solid and liquid phases, respectively.

Their values are summarized in table 2.

Calculations of the stability of slopes were carried out on a computer using the “RUZO” program with directed search for the center of the most dangerous sliding surface as applied to the I.F. Fedorov formula, in which the hydrodynamic effect for the steady state filtration was taken into account in the most strict form. The results obtained by the method of "weight pressure" were used for comparative...
purposes to preliminarily establish the range of variation of $K_e$ considering the interaction forces between the elements.

### Table 2. Coefficient values

| Coefficients | Calculation methods according to |
|--------------|----------------------------------|
| | K. Terzagi | I.V. Fedorov | A.A. Nichiporovich | R.R. Chugaev |
| $\mu_i$ | 1 | 1 | 1 | $1/\cos\alpha_i$ |
| $v_i$ | $\cos^2\alpha_i$ | $\cos\alpha_i \cos\theta_i \cos(\alpha_i - \theta_i)$ | 1 | $\cos^2\alpha_i$ |

The total moment of active forces $\Sigma M_{act}$ entering the denominator of the formula, can be represented as

$$\Sigma M_{act} = \Sigma M_Q + \Sigma M_S$$

where $\Sigma M_Q$ - is the total moment from loads corresponding to static conditions of the structure operation (gravity, hydrostatic pressure of water from the upstream slope); $\Sigma M_S$ - is the total moment from seismic loads within the sliding triangle.

In modern design practice, seismic inertial loads are calculated according to the spectral method adopted in «ShNK 2.06.11-04 (Building Code)» and taken into account as calculated static loads applied to the test slope. It is assumed that structures that are the systems with many degrees of freedom undergo elastic displacements along the normal components of various modes of vibrations under the action of seismic loads.

The spectral method allows us to set the maximum values of seismic forces for each of considered modes of vibration. The resulting seismic forces are found as the root-mean-square values of the sum of the forces acting according to the given modes of vibrations. So, the method gives an estimate of the sought for loads by their upper limit.

Ignoring the nonlinear properties of materials, the seismic values turned out to be unreasonably high, especially at the level of the dam crest. New standards partially take into account this circumstance; nevertheless, even with them, the excess of seismic loads on the crest (with respect to the structure base) reaches 2.6 times.

This difference in the intensity of dam body vibrations does not correspond to the actual distribution of seismic accelerations along the height of the structure and does not confirm the survey data of the behavior of more than two dozen dams in Central Asia that underwent repeated earthquakes of 6-8 point intensity [18-20].

As shown by experimental studies of the earthquake resistance of earth dams, conducted by the method of seismic and explosive impacts with an intensity of 7-10 points on the model of the Nurek dam 6.3 m high, on full-scale fragments of a number of dams 4.5-7 m high, the parameters of seismic vibrations over a height significantly differ from the normative ones [18]. The generalized dynamic coefficient varies within $1 \leq \mu(z) \leq 2.0$. Therefore, both normative and actual diagrams $\mu(z) = 2.0$ are accepted as the basis of our calculations.

When calculating seismic loads to verify the stability of slopes according to ShNK 2.06.11-04, it is recommended to use design accelerations at $a_{kj}^p$ points of "k" structure

$$a_{kj}^p = A_k k_2 \sqrt{\sum_{i=0}^{n} \left( k_\nu \beta \eta_{kj} \right)^2}$$

where $A_k$ - is the coefficient whose values are taken in accordance with the calculated seismicity of 7, 8, 9 points - 0.1; 0.2; 0.4; $k_1$ - is the coefficient that takes into account permissible damage to buildings and structures, and equals to 0.25; $k_2$ - is the coefficient that takes into account structural solutions of buildings and structures and equals in this case to 1; $k_\nu$ - for earth structures with
seismicity of the construction site of 7 and 8 points it is 0.7; for the seismicity of 9 points it is 0.65: \( \eta_i \) is the coefficient of the i-th mode of vibration; \( \beta_i \) - is the dynamic factor of the period.

The dimensionless diagram of the acceleration distribution over the structure height calculated by formula (3) is used in slope stability calculation; seismic force is obtained by multiplying the corresponding acceleration by the soil weight at a given point in the section.

### 3. Results

**Calculation of slope stability under the action of basic loads.** In calculations, 3 basic and 6 combined schemes of dam build-up of phosphogypsum hydraulic fills are considered. It is assumed that the build-up is made of phosphogypsum. The properties of phosphogypsum are given in table 1. Since the options of collectors of external, internal-external and central-external build-up are similar in design of external slopes, the number of combinations considered is reduced. The results of calculating the slope stability under calculated slope ratio are given in table 3.

| Options | Slope ratio | Calculation Method |
|---------|-------------|--------------------|
|         | K.Terzagi   | I.V. Fedorov       | A.A. Nichiporovich | R.R. Chugaev |
| I       | 3.0         | 1.795              | 1.801              | 1.754        | 1.857        |
| C       | 2.0         | 1.971              | 1.971              | 1.971        | 2.054        |
| E, IE, CE | 1.8     | 1.944              | 1.944              | 1.944        | 2.036        |
| IC      | 2.0         | 1.837              | 1.837              | 1.837        | 1.914        |
| CI      | 2.5         | 1.814              | 1.814              | 1.814        | 1.869        |
| EI      | 2.5         | 2.046              | 2.046              | 2.046        | 2.09         |
| EC      | 2.0         | 1.971              | 1.971              | 1.971        | 2.054        |

According to this table, the degree of stability under basic loads for all schemes of collector build-up was much higher than the normative one. However, according to the results of these calculations, it is difficult to evaluate the most stable scheme, due to the various ratio of external slopes adopted in them. For example, the maximum value of the safety factor 2.046 was obtained (option VIII) at a slope ratio of 2.5, and \( K_e = 1.944 \) for options III, V, VIII at \( m = 1.8 \).

In terms of stability, the most economical option is considered to be the one that provides the smallest ratio at similar standard value of the safety factor.

To determine the most economical profile of the corresponding stability with a minimum slope ratio and to compare the options, stability calculations of the maximum permissible slope were performed.

An analysis of the methods used in the “RUZO” program showed the highest validity of the Terzagi method. Considering its widespread use in calculation practice, it was adopted for further calculations, the results of which are given in tables 4, 5.

| Options | Build-ups |
|---------|-----------|
| I       | C         | E, IE, CE |
| IC      | CI        | EI        | EC        |
| \( m^\delta \) | 1.34 | 1.10 | 1.05 | 1.15 | 1.22 | 1.15 | 1.10 |
| \( k_c^\delta \) | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 |

From table 4 it can be seen that the least limiting values of slope ratio are obtained for the III, V, VII options according to central or external build-up scheme and the greatest values are obtained for options with an internal build-up scheme.

**Calculation of slope stability under the action of basic and seismic loads.** The stability test was performed for seven options of dam build-up schemes at seismic intensity of 7, 8, 9 points. The
calculation takes into account the change in seismicity coefficient over height, established on the basis of experimental studies (Table 5).

**Table 5. Distribution of seismicity coefficients over the structure height**

| Intensity points | 7  | 8  | 9  |
|------------------|----|----|----|
| At the base level| 0.023 | 0.06 | 0.10 |
| At the crest level| 0.05 | 0.10 | 0.20 |

The minimum safety factors $k_e$ of the external slope of the collector dams at their estimated ratio are determined in calculations. For the options under consideration, the calculation results are summarized in Table 6.

**Table 6. Results of slope stability calculation**

| Options          | Slope ratio | Minimum safety factors at |
|------------------|-------------|---------------------------|
|                  |             | 7 points | 8 points | 9 points |
| I                | 3.0         | 1.597    | 1.438    | 1.200    |
| C                | 2.0         | 1.774    | 1.642    | 1.438    |
| E, IC, CE        | 1.8         | 1.767    | 1.649    | 1.447    |
| IC               | 2.0         | 1.663    | 1.519    | 1.232    |
| CI               | 2.5         | 1.644    | 1.523    | 1.215    |
| EI               | 2.5         | 2.63     | 1.478    | 1.137    |
| EC               | 2.0         | 1.774    | 1.642    | 1.428    |

4. **Discussion**

Calculations show that in all considered schemes the minimum safety factors under the action of seismic loads are higher than the standard values. The maximum permissible values of slope ratio are established with an allowable safety factor. The calculation data are given in Table 7.

**Table 7. Maximum permissible values of slope ratio**

| Options          | $k_e$       | Maximum permissible values of slope ratio at |
|------------------|-------------|---------------------------------------------|
|                  |             | 7 points | 8 points | 9 points |
| I                | 1.90        |          |          |          |
| C                | 1.40        |          |          |          |
| E, IE, CE        | 1.30        |          |          |          |
| IC               | 1.36        |          |          |          |
| CI               | 1.56        |          |          |          |
| EI               | 1.85        |          |          |          |
| EC               | 1.35        |          |          |          |

Thus, the stability of dam slopes in all considered options of phosphogypsum collector is ensured under basic and special combinations of loads.

5. **Conclusions**

1. The external slope ratio of the secondary dams of hydraulic fills for the selected build-up scheme is taken based on stability calculations on the effect of basic loads, and in seismic areas on the effect of special loads. The obtained values of the slope ratio should not be less than the maximum permissible values given in Tables 4 and 7.
2. The performed calculations show that under the earthquakes up to 7 points in magnitude, the internal (I), centrally internal (CI) and externally internal (EI) options are the optimal ones, while in
the areas with high seismic activity, the most optimal options are external (E), internally external (IE) and centrally external (CE). The most optimal option of the buildup is determined by the analysis of technical and economic indices.

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