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Filtration and operational parameters determination of phosphogypsum sludge storage

Khamidkhon Fayziev[1], Takhirjon Sultanov[2], Elyor Toshmatov[2] and Akhrorbek Numonov[2]

[1]Tashkent Institute of Architecture and Civil Engineering, Tashkent, Uzbekistan
[2]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan

E-mail: tohir-zs@mail.ru, t.elyor85@mail.ru

Abstract. In phosphorus mineral fertilizer production, industrial waste is formed – phosphogypsum. As is well known, the issues of processing and utilization of phosphogypsum in an industrial scale remain unresolved. Consequently, the production waste generated at chemical plants is stored in various types of storage tanks. The currently used hydraulic storage method provides for the waste supply in the form of a slurry to the hydraulic dump plots one by one, their successive dehydration in the dump and the subsequent development of a part of the stored waste for the construction of the secondary dams. However, due to the low water-draining properties of phosphogypsum, it is not possible to ensure its dehydration to the required extent, in large volumes, and at the required time. This pattern is observed almost everywhere, especially in areas with high climate humidity. This circumstance significantly complicates the development of phosphogypsum in hydraulic dumps and in most cases leads to the impossibility of its implementation. Therefore, various designs of anti-filtration and drainage devices are provided in the sludge collectors to accelerate the process of dehydration of the phosphogypsum strata. This paper presents the results of a study of filtration processes in sludge collectors, and a method for calculating the filtration and dehydration of phosphogypsum at the initial stage of sludge collector operation with various designs of anti-filtration and drainage devices.

1. Introduction

In phosphorus mineral fertilizer production, industrial waste is formed - phosphogypsum [19]. As is well known, the issues of processing and utilization of phosphogypsum in an industrial scale remain unresolved. Consequently, the production waste generated at chemical plants is stored in accumulating tanks of various types [8, 16, 20].

In practice, the removal and storage of phosphogypsum are carried out in various ways: by road, conveyor transport in combination with cable cars and hydro-transport [7, 8, 14, 16].

Our research has shown that, in modern conditions, the most promising direction of increasing the efficiency of removal and storage of phosphogypsum is the use of hydro-dumps and waste hydro-storage when building up the storage units in height by building the enclosing dams from the stored materials. Bringing the height of the storage units up to 35-50 m allows storing 5-8 times more waste in the same areas. Due to the use of phosphogypsum, instead of local soils or other materials, when building the enclosing dams, it is possible to increase up to 25 to 50% the volume of build-up, depending on the build-up schemes and height.

The currently used hydraulic storage method provides for the waste supply in the form of a slurry by turns to the hydraulic dump plots, their consecutive dehydration in the dump, and the subsequent development of a part of the stored waste as a material for the construction of the secondary dams. However, due to the low water-draining properties of phosphogypsum, it is not possible to ensure its dehydration to the required extent, in large volumes and at the required time.

This pattern is observed almost everywhere, especially in areas with high climate humidity. This circumstance significantly complicates the development of phosphogypsum in hydraulic dumps and, in most cases, leads to the impossibility of its implementation. Therefore, various designs of anti-filtration and drainage devices were provided for in the sludge collectors to accelerate the process of dehydration of the phosphogypsum strata [11, 12, 13, 14, 15, 16, 21].

The balance of the sludge collector should be assessed in two stages: the initial stage when the sludge collector plots are filled-up bounded by the primary dam, and the subsequent one - when the collector is built up by erecting the secondary dams from the stored material. Moreover, the stage of the building-up is preceded by a stage of plot preparation, namely: the pond emptying and plot drainage to a moisture content suitable for filling-up the dams and normal operation of the mechanisms used in the dam construction.

This paper provides a methodology for calculating the balance at the initial stage of operation for storage with an impermeable screen (made of polymer film, asphalt-polymer concrete, etc.) above the screen drainage system (Fig. 1).

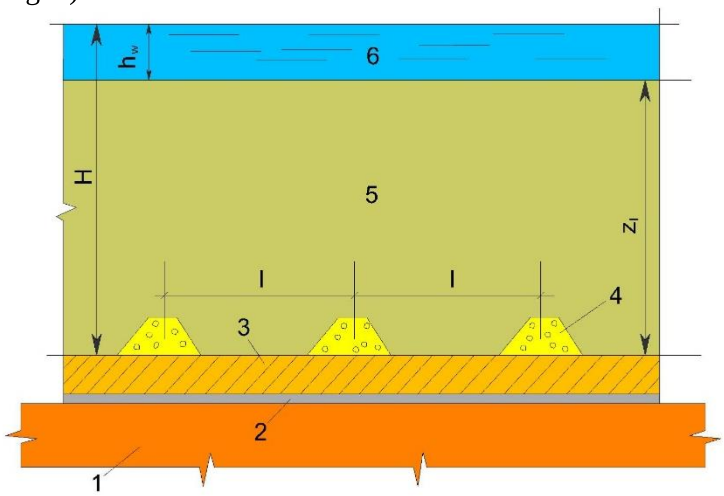

Figure 1. Filtration scheme in the hydro-dump 1-base; 2-film; 3-protective layer; 4-belt over-screen drainage; 5-deposits of phosphogypsum; 6-pond.

2. Methods

Methods for calculating the balance at the initial stage of sludge collector operation. During this stage, the operating mode of the hydro-dump is divided into two steps: the first, a pond is formed above the sludge layer of a certain predetermined depth; the second, this water depth in the pond is kept constant by means of spillways. From the moment the storage tank is filled, the solid fraction of the pulp settles in the storage tank in the form of a layer $z_1(t)$, the fluid is spent on filtration - $q_ф(t)$, part of it is drawn-off by drains - $q_{∂р}$ to form a pond h_0 (t) deep, at set maximum-permissible depth H_0 maintained constant by draining clarified water through spillways $q_0(t)$. Part of the fluid evaporates -$\varepsilon_и$ or is added in the form of precipitation ε_0 . The values of $q_ф$, $q_{∂р}$, q_0 represent the specific fluid flow rate per 1 m^2 of the plot area, and $\varepsilon_и$, ε_0 are the mean annual precipitation and evaporation moduli, determined from the meteorological data of the region in the m/day dimension [1].

To determine the parameters of filled storage screened with a polymer film - with a protective layer of dune sand, we would proceed from the following system of equations [1, 2, 4, 5, 6, 9, 10, 17]:

The mass conservation

$$q = \frac{dh_0}{dt} + \frac{dz_1}{dt} + q_{\Phi} + q_0 + \varepsilon \qquad \varepsilon = \varepsilon_u - \varepsilon_0 \tag{1}$$

the dynamics of solid suspension sedimentation

$$\alpha q = \frac{dz_1}{dt}\ ; \quad \alpha = \frac{c}{\gamma_2(1-n_1)}\ ; \quad \frac{c}{\gamma_2} = \frac{\eta_{w.c}\gamma^*}{1+\eta_{w.c}\gamma^*}\ ; \gamma^* = \frac{\gamma}{\gamma_2} \tag{2}$$

and filtration in the sludge layer

$$q_f = K_1 * \frac{h_0+z_1}{z_1} \tag{3}$$

where q—is the specific consumption of pulp, m/day;
c - concentration of solid particles in the pulp, kg/m^3;
K_1, K_0- coefficients of filtration of phosphogypsum and dune sand, m/day;
q_0 - specific value of clarified fluid discharge m/day;
γ, γ_2- specific gravity of water and phosphogypsum, kg/m^3;
n_1 - porosity of phosphogypsum;
$\eta_{w.c}$- weight consistency of the pulp.

Let us describe in detail the dependence of *c* on $\eta_{w.c}$. The weight consistency is the relation

$$\eta_{w.c} = \frac{G_T}{G_j} \tag{4}$$

where G_T G_j – are the weights of the solid and liquid fractions of the pulp.
Concentration C is determined by the relation

$$c = \frac{G_T}{V} = \frac{G_T}{V_j+V_T} \tag{5}$$

where V —is the pulp volume; V_j ,V_T are the volumes of the solid and liquid fractions of the pulp, respectively.
Let us express the values of V_j and V_T as follows

$$V_j = \frac{G_j}{\gamma}\ , \qquad V_r = \frac{G_T}{\gamma_2}$$

Substituting these expressions in (5) and, taking into account (4), we obtain

$$c = \frac{G_T}{\frac{G_j}{\gamma}+\frac{G_T}{\gamma_2}} = \frac{\eta_{w.c}\gamma\gamma_2}{\gamma\eta_{w.c}+\gamma_2}$$

Let us write C/ γ_2 in the form

$$\frac{c}{\gamma_2} = \frac{\eta_{w.c}\gamma^*}{1+\eta_{w.c}\gamma^*}\ ; \quad \gamma^* = \frac{\gamma}{\gamma_2} \tag{6}$$

So,

$$\alpha = \frac{\gamma^*}{(1+\eta_{w.c}\gamma^*)*(1-n_1)} \tag{8}$$

From equation (2) we have the dependence of the sludge layer change on time

$$Z_1 = \alpha \cdot q \cdot t \tag{9}$$

When determining the duration of formation of clarified water H_0 = 0.5 m deep above the phosphogypsum surface of the pond, there is no discharge of water, i.e. $q_0 = 0$. Introduce expression (4.9) into equation (3), and then into equation (1). The result is a homogeneous differential equation of the 1st order

$$\frac{dh_0}{dt} - (1-\alpha)\cdot q + \varepsilon + \frac{k_1 h_0}{\alpha q t} = 0 \tag{10}$$

This equation has a particular solution of the form

$$h_0 = C_1(t - t_H), \qquad C_1 = \frac{[(1-\alpha)q-\varepsilon-k_1]\alpha q}{k_1+\alpha q} \tag{11}$$

The level in the pond changes with time according to a linear law, t_H denotes the saturation time of the protective layer of dune sand at a thickness of m,

$$t_H = \frac{V_B}{Q_B}, \qquad V_B = m \cdot S_i \cdot n_0 \tag{12}$$

where V_B- is the volume of water used to saturate this layer;

$Q_в$ is the flow rate of the incoming fluid;
Q_n – is the slurry consumption;
n_0 is the porosity of the sand;
S_i is the storage base area.

The value of S_i for a plain sludge storage can be determined based on the volume of the storage tank V_i of a height Z_1. We reduce the entire tank to an equal-sized parallelepiped of the same height and the value is determined as the ratio

$$S_i = \frac{V_i}{Z_i} \quad \text{(I3)}$$

The value of S_i is necessary to obtain the specific flow characteristics - q_f , q_{dr} , q_0 in one dimension, which is convenient for comparison and construction of the calculation. To switch back to flow rates, the values of specific flow rates are multiplied by S_i.

Specific water consumption filtering through the thickness of the phosphogypsum at the changes in $h_0(t)$, i.e. at the first stage, is determined from relation (3) taking into account relations (9) and (11)

$$q_f = k_1 \cdot \frac{C_1(t-t_H)+\alpha qt}{\alpha qt} \quad (14)$$

In the second stage, at a constant water level in the pond

$$q_f = k_1 \cdot \frac{H_0+\alpha qt}{\alpha qt} \quad (15)$$

The flow rate of water discharged through spillway wells in the second stage is determined from equation (I) taking into account dependencies (9) and (15); i.e. we have

$$q_0 = (1-\alpha) \cdot q - \varepsilon - k_1 \cdot \frac{H_0+\alpha qt}{\alpha qt} \quad (16)$$

The duration of the operation of the sludge storage is determined using the dependence (4.9) as follows. For each plot of area S_i, we determine the specific values of the pulp flow rate

$$q_i = \frac{Q_n}{S_i}$$

(17)

To obtain the value of the flow rate of the filtration flow intercepted by the drainage system $q_{\partial \text{p}}$, we use the method of sequential change of stationary states (MSCSS) [2].

In the solution given by P. Ya. Kochina, the thickness of the water-saturated layer is assumed constant, and in our case it is taken into account in time $Z_1(t)$, which obeys dependence (9). Assume that the infiltration with constant intensity ϑ_{int} takes place over the area under consideration. There is a drainage device at point B (Fig. 2). At time points t and t + dt the drained areas are AED and A_1VD, respectively. Suppose that, according to the hydraulic theory of steady-state motion of groundwater with a constant infiltration rate, line AB is a parabola

$$Z^2=-Z_1^2x/\ell \, , \quad (18)$$

where ℓ is the length (AD), which changes in time, and Z_1 is the thickness of the aquifer (Aq). Then the flow rate of the considered flow per unit time is

$$q_{dr} = -k_1 Z \frac{dz}{dx} = k_1 \frac{z_1^2}{2\ell} \quad \text{(I9)}$$

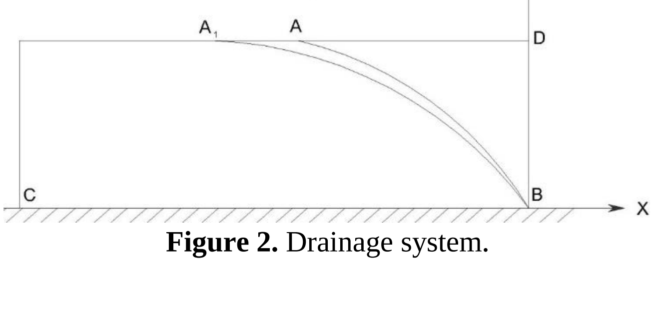

Figure 2. Drainage system.

The amount of water flown over a period of time dt from a part of the aquifer (phosphogypsum), ditched by drains is $q_{\partial p}dt$; on the other hand; it is equal to the change in area of AED (which is equal to $Z_1\ell/3$), multiplied by the phosphogypsum porosity n_1, added to the amount of fluid, taken by the surface AB due to infiltration. As a result, we have the equation

$$qdt = к_1 \frac{z_1^2}{2\ell} dt = \frac{n_1}{3} z_1 d\ell + \ell\vartheta_{int}, \qquad \vartheta_{int} = (1-\alpha)q_i - \varepsilon \tag{20}$$

This first-order homogeneous differential equation is reduced to an equation with separable variables by the substitution

$$\frac{\ell}{t} = u \tag{21}$$

of the form

$$\frac{udu}{u^2-\beta^2} = -2(1+\beta)\frac{dt}{t}, \beta^2 = \frac{A}{1+B}, = \frac{3k_1\alpha q_1}{2n_1}, \mathrm{B} = \frac{3\vartheta_{int}}{n_1\alpha q_i} \tag{22}$$

whose solution has the form

$$u^2 - \beta^2 = Ct^{-4(1+B)}$$

Then the solution to equation (20) with the initial condition
$t=t_н$, $\ell=0$ has the form

$$\ell^2 = \beta^2 t^2 + \frac{t_H^{4(1+B)} * t^{-4(1+B)}}{\beta^2 t_H^2} \text{ or } \ell = \sqrt{\beta^2 * t^2 + T_0 t^{-4(1+B)}} \ T = \frac{t_H^{4(1+B)}}{\beta^2 t_H^2} \tag{23}$$

Assume that

$$\ell = \beta * t \tag{24}$$

as at B >> 1, the expression t^{-4B} quickly tends to 0. This was checked for a specific hydraulic dump: the value of b was determined according to (22) at given characteristics of physical and mechanical properties of phosphogypsum.

Substituting ℓ into dependence (19), we have

$$q_{dr(f)} = k_1 \frac{z_1^2}{2\ell} = \frac{k_1 z_1^2}{2\beta t} = \frac{k_1(\alpha q)^2 t}{2\beta} \tag{25}$$

this value is half of the drain flow rate per one running meter of its length. The total discharge for the entire drain of length L from the phosphogypsum layer is

$$Q_{dr(f)} = q_{dr(f)} * L = \frac{k_1 z_1^2}{\beta t} * L = \frac{k_1(\alpha q)^2 t}{\beta} * L \tag{26}$$

The flow rate discharged by "n" strands of belt drain from the phosphogypsum layer represents the sum of the flow rates of individual drains of length

$$\sum_{i=1}^{n} Q_{dr(f)i} = \sum_{i=1}^{n} 2q_{\partial p(ф)i} L_i = \sum_{i=1}^{n} \frac{k_1(\alpha q_i)^2 t}{\beta_i} * L_i \tag{27}$$

To take into account the magnitude of the filtration flow intercepted by the drain from the protective layer of thickness m, which has a filtration coefficient K_0 and porosity n_0, we compose an equation similar to (20):

$$q_{dr(з)}dt = k_0 \frac{m^2}{2\ell} dt = \frac{n_0 m}{3} d\ell + \ell\vartheta_{int}dt, \qquad \vartheta_{int} = k_1 \frac{H_0 + \alpha * q * t}{\alpha * q * t} \tag{28}$$

The infiltration value entering the sand is equal to the water flow rate from the phosphogypsum layer into the sand layer. We consider it constant in a certain time interval dt, during which the flow gradient does not change.

Equation (27) is a homogeneous first-order equation and at the initial condition t = 0, ℓ = 0 has the solution

$$\ell = m\sqrt{\frac{k_0}{2q_f}\left[1 - exp\left(\frac{6q_f t}{n_0 m}\right)\right]} \tag{29}$$

Substituting ℓ into the dependence for $q_{dr(п)}$, we have

$$q_{dr(з)} = \frac{k_0 m^2}{2\ell} = \frac{k_0 m}{2}\left\{\frac{k_0}{2q_f}\left[1 - exp\left(\frac{6q_f t}{n_0 m}\right)\right]\right\}^{-\frac{1}{2}} \tag{30}$$

The total discharge for the entire length of the drain ℓ, from the sand layer is

$$Q_{dr(з)} = 2q_{dr(з)} \cdot L = k_0 m \left\{ \frac{k_0}{2q_f} \left[1 - \exp(-\frac{6qft}{n_0 m}) \right] \right\}^{-\frac{1}{2}} \quad (31)$$

The flow rate discharged by "n" strands of belt drain from the sand layer is

$$\sum_{i=1}^{n} Q_{dr(з)i} L_i = \sum_{i=1}^{n} 2q_{dr(з)} \cdot L_i \quad (32)$$

The total consumption diverted by the drains is

$$Q_{dr} = Q_{dr(f)} + Q_{dr(з)} \quad (33)$$

and the value of specific consumption of drainage water is

$$q_{dr} = \frac{Q_{dr}}{S_i} \quad (34)$$

Multiplying the value of q_0 by the corresponding area of the storage tank base, we determine the total flow rate of water discharged by the spillways Q_0. The sum of drainage and discharged water is the total amount of water used in the circulating water supply for the production of phosphoric acid Q_{pa}, i.e.

$$Q_{pa} = Q_{dr} + Q_o \quad (35)$$

To determine the decrease in the hydrostatic head on the anti-filtration screen, we will use the values of the specific flow rates of drainage water $q_{\partial \text{p}}$ and filtration flow $q_f = q - q_{dr}$.

Let us express the relative value of the averaged head h_a/H, the ratio of these quantities q_{dr} / q_f

$$\frac{q_{dr}}{q_f} = \frac{q_{dr}}{q - q_{dr}} = \frac{k_1(h_{cp} / z_1)}{k_1(H - h_{cp} / z_1)}$$

We have

$$\frac{h_{cp}}{H} = (1 - \frac{q_{dr}}{q_f}) \cdot 100\% \quad (36)$$

Next, we take the value of the relative distance between drains (ℓ/n) as the ratio of the distance between drains ℓ to the total thickness of the phosphogypsum layer z_1 and the water depth in the pond h0, h_0, H= h_0+z_1, and plot the change in the average head versus the value of the relative distance between drains.

From this graph, for any distance between drains ℓ and the amount of drains – *n* on the sludge plot, we can find the amount of the hydrostatic head reduction on the screen (in percent).

The stratal drainage is distinguished in the form of belts made of filter material (sorted fractions of coarse sand, crushed stone, gravel, ash, waste from coal and coke plants and other industries), and in the form of ceramic pipes with the dusting of one, two or three-layer filters.

They differ in discharge capacity. So, the following amount of fluid is discharged through a ceramic pipe with a diameter, determined by hydraulic calculations [3]

$$Q_{Tp} = k\sqrt{i} = \omega c \sqrt{Ri} \ , \lambda = \frac{64}{\text{Re}}, \ c = \sqrt{\frac{g}{\lambda}}, \quad C = \frac{1}{n_r} R^{1/6} \quad (37)$$

where K — consumption characteristic;
W - cross-sectional area;
α - coefficient of resistance along the pipe;
Re - Reynolds number;
g - gravitational constant;
C- Chezy coefficient;
n_r - roughness coefficient
R - hydraulic radius.

For ceramic pipes, $n_ш$ = 0.0I2. For a given the value of K is determined from Table 7.3, P.G. Kiselev [3].

Filter belt with filtration coefficient u, cross-sectional area F length L, gradient I and a platform is capable of discharging the following amount of fluid

$$Q_л = F \cdot u \cdot (\mathrm{I} + i), \quad \mathrm{I} = \frac{\Delta H}{L}, \quad \Delta H = h_0 + z_1 \tag{38}$$

3. Results and discussion

All obtained dependencies, h_0 (t), q_f(t), q_0(t) are valid for the case when the value of specific flow rate of the pulp is q> K_1, i.e. filtration with complete saturation of phosphogypsum pores takes place.

At q <K_1, filtration occurs at incomplete saturation. In this case, a pond of left water is not formed; all fluid is filtered into the drain. To obtain the value of the filtration flow rate, it is necessary to assume that h_0 =0, q_0=0 in the system of equations (I) - (3), and, taking into account (9), we obtain

$$q_f = (1 - \alpha)q - \varepsilon \tag{39}$$

If the discharge capacity of the drainage system is not sufficient and a part of filtration water accumulates in the thickness of phosphogypsum, then a pond will form over time. However, such a regime should be avoided and, therefore, it makes no sense to dwell on this case in detail.

According to the developed methods, the balance calculations of the sludge storage of the Chordzhou chemical plant were performed.

Based on the obtained values of q_f , q_{dr} of various ℓ and H, we plot the graphs of changes in the averaged head on the screen versus the value of the average distance between the drains for the screen protected by a layer of sand (curve 1) and by a layer of phosphogypsum (curve 2). Figure 3. shows both graphs.

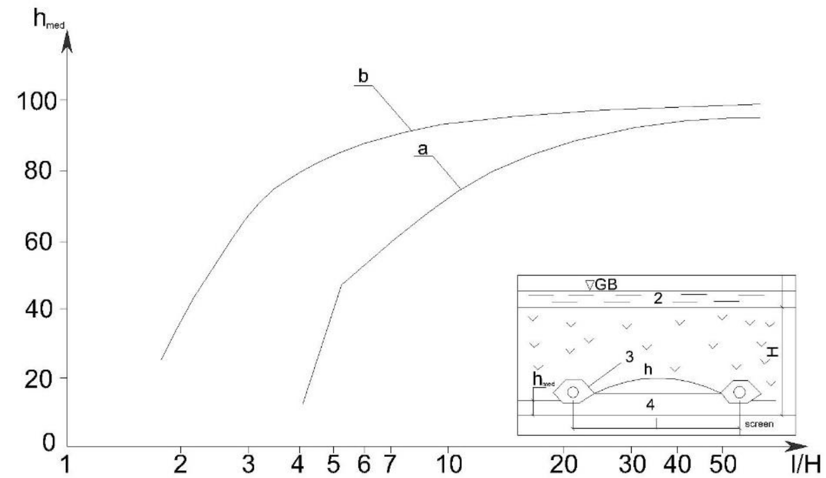

Figure 3. Graph of changes in the average head on the screen a) protective layer of sand; b) protective layer of phosphogypsum. 1 - phosphogypsum; 2 - pond; 3 - drains; 4 - protective layer.

As follows from the pattern of the curves, the residual head h is lower for a more permeable protective layer of the screen: at a large relative distance between drains (ℓ/H> 20) - a decrease in the head is 5%, at 10 <ℓ/H <20 – it is 10%, and at ℓ/H <10, the decrease reaches 50%. The head is completely reduced to 0 at ℓ/H = 3.7. For curve 2, this occurs at a value of ℓ / H = 1.6. Consequently, the screen film should be covered with a protective layer of material with a higher permeability than phosphogypsum, although the presence of a protective layer of phosphogypsum reduces the hydrostatic head on the screen.

As a result of calculations during the operation of sludge collector plots, the stage of filling the tank bordered by the primary dam, and the emptying stage, the following generalizations can be made:

- the specific consumption of the pulp must obey the condition q> k_1, i.e. exceed the filtration coefficient of phosphogypsum, which ensures the rapid formation of a pond of clarified water and its discharge through the spillways;

- drainage belts should be arranged at the edge of the dams, along the perimeter. In the future, when building a hydraulic dump, they are necessary to intercept the filtration flow, to prevent their seeping onto the slopes of the secondary dams, and the pond should be arranged closer to the center of the plot;
- for the drainage system of the 2nd plot and the second stage of the 1st plot, the most optimal is the 7th and 4th drainage belts, respectively. So, the drainage of a 15 m thick phosphogypsum with 7 drainage pipe belts takes 504 days, and with 7 belts in the form of a banquet, it takes 101.4 days.

4. Conclusions

Filtration processes in sludge collectors were studied and the methods were developed for calculating the phosphogypsum filtration in an impermeable screen (made of polymer film, asphalt-polymer concrete, etc.), above the screen drainage system and in a primary dam with slopes protected by an anti-filtration film screen.

The conducted studies have shown that for dehydration of phosphogypsum, the most acceptable design is a soil-film screen with systematic above-the-screen drainage, made in the form of a dump of belts from highly permeable filter materials. This design makes it possible to dehydrate phosphogypsum in a timely manner.

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