Trajectory of sediment deposition at the bottom of water intake structures of pumping stations

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Abstract. The study of the causes and patterns of sediment deposition at the bottom of water intake structures of pumping stations, the negative impact of sediments on the efficiency of their operation is one of the important measures taken to improve the efficiency of the water recovery system. The issues of studying the determination of the deposition rate and the trajectory of solid particles at the bottom of structures were analyzed, and the main shortcomings and shortcomings in determining the parameters of particle deposition were identified. An equation is proposed that allows determining the trajectory of solid particles deposition taking into account their concentration in the flow, the main properties (density, geometric parameters) of particles and water flow, as well as the design dimensions of the pump station's advance chamber. The obtained calculated results based on the proposed equation were verified by the results of the study of deposits at the bottom of the advance chamber of the operating pumping station, which showed that the spread of the obtained data does not exceed 7...12 %. At the same time, the smallest particles settle at the end of the pre-chamber in the water suction zone. The obtained data showed the possibility of using the proposed equation to determine the trajectory of sediment particles deposition at the bottom of water intake structures of pumping stations.

1. Introduction
Reclamation pumping stations often have to pump water flows with solid particles exceeding the norm, the main reasons are a high degree of turbidity in the source or an increase in the amount of solid particles caused by the processes of erosion of the supply channel. Silt particles begin to settle as a result of a sharp decrease in the flow rate in the pump station's pre-chamber and form a thick muddy deposit, which leads to changes in the flow structure leading to the water intake chamber, the energy characteristics of the pumps and the amount of water being pumped. To take measures to prevent these negative consequences, it is necessary to know the laws of sediment deposition at the bottom of the water intake structure in order to achieve a state of sediment minimization.

It is known that the deposition of solid particles occurs after the water flow rate in the structure decreases to the minimum speed, when the particles, under the influence of known physical properties
and water flow, begin to sink down to the bottom of the structure. In a water stream containing solid particles, you can see two vertical layers and observe the process of their deposition: the first layer is relatively transparent, and the lower layer has suspended particles and is located at a certain depth where the particles settle. The particle moves horizontally with the speed of water flow, and also falls vertically down with the speed $v_z$. As a result of adding two directions of the velocity vector, the particle subsidence has a certain trajectory. The values of the pulsation velocities (longitudinal and transverse) that occur in the lower part of the structure during particle subsidence are equal to zero or less than the value of the hydraulic fineness. For this reason, solid particles begin to sink to the bottom of the structure [1–8].

It is important to determine the following parameters in the development of measures to prevent the occurrence of turbid sediments.

a) granulometric composition of solid particles;
b) distribution of solid particles on the surface of the structure by granulometric composition;
c) dimensions (area, thickness and volume) of turbid sediments;

To determine the above parameters, we briefly consider the theoretical basis of sedimentation of turbid particles.

The problem of subsidence of solids moving in a liquid stream has been considered in many studies [2, 5–14].

In these studies, the deposition of solid particles in a liquid medium has been shown to be related to the following factors.

a) the hydrodynamic structure of the flow and the values of the various forces acting on the particles (resistance, gravity, Archimedes and other forces), other forces mean the Magnus force, which leads to transverse migration of small particles [1].

b) the interaction of particles. In cases of high turbidity, their concentration has a large effect on the sedimentation rate of the particle. Each particle creates a certain amount of velocity and pressure field around itself. If two particles are close to each other, hydrodynamic, gravitational effects occur between them. As a result, the particles interact with each other, collide, and can even coalesce to form a single particle. This of course depends on the flow rate and the specific dissipation of energy [1, 7, 9, 12].

c) distribution of particles by size, shape and construction area. Large particles are submerged at the beginning of the structure, and small particles are submerged at the end. When the shape of a particle is different, the force of resistance acting on it, the Archimedean force, is also different, and this affects their rate of subsidence [3, 4, 15–23].

d) the law of subsidence of particles depends on the properties of the flow (viscosity, density, surface gravity, etc.).

e) if in some cases there is some excitatory cause for the motion of the particles, the diffusion of the particles must also be taken into account [15].

f) it is necessary to take into account that the sedimentation process of solid particles in general has a stochastic nature. This situation is determined by the fact that the shape and size of the particles are different, they sink in the gravitational field at different speeds, in some cases have pulsating motions, their concentration varies.

Therefore, in each particular case, it will be necessary to take into account the above facts and select the most important influencers from them.

The sinking process of a single particle in a stream moving at a small value velocity has been sufficiently studied. Several equations have been proposed that take into account the motion of this particle, its mass, density, weight, Archimedean and resistance forces.

Of these, the empirical formula for determining the settling velocity of a spherical turbid particle is given in [16].
where \( \nu_c \) is the kinematic viscosity coefficient of the flow, \( \rho_s \) is the particle density, \( \rho_c \) is the water flow density, \( d \) is the average particle diameter.

This formula, according to the authors of the [16] work, is a universal formula that gives results close to the results of experimental studies among all similar formulas.

The settling velocity in the slow-moving stream of the above-mentioned solid particles is obtained for single, spherical particles. If the particles in the stream are not spherical and their concentration is large, the values of the sedimentation rate will change. In such cases, additional coefficients are added to the values of particle sinking speed

\[
V_3 = \frac{1}{2} \left( \sqrt{\frac{36 \cdot \nu_c}{d}}^2 + 7.25 \left( \frac{\rho_s - 1}{\rho_c} \right) d \cdot g - \frac{36 \cdot \nu_c}{d} \right) \tag{1}
\]

here \( V_{3s} \) - sedimentation rate of spherical particles,

\( V_3 \) - is the rate of settling of a non-spherical particle, the values of the coefficient \( K_l \) are determined depending on the shape of the particle [7].

The sedimentation rate of a particle is greatly affected by their concentration in the stream [1,12,13]. The amount of particle concentration in the flow leads to the formation of forces of interaction between them, in the "cramped" state there is a sinking mode, gravitational coagulation of particles (large particles catch small particles) occurs [8].

According to [1], the interaction of particles occurs when the \( l_i \) distance between them is less than the particle size of \( l_i < d \), \( l_i \approx 80 \cdot d \sqrt{\rho_c / C_m} \), where \( C_m \) is the mass concentration of turbid particles.

The interaction of particles with each other is sufficiently studied in [26, 27, 28, 36, 37] the dependence between the deposition rates of a single spherical particle and particles with a high concentration is shown in the following figure [1].

\[
\frac{V_3'}{V_3} \approx (1 - \phi)^n \tag{3}
\]

where \( V_3' \) - is the deposition rate of particles with a high concentration,

\( \phi \) - volume concentration of deposits, \( n \) - density coefficient.

In [18], the results of experimental studies were analyzed and it was proposed to determine the average statistical value of \( n \) with the following dependence

\[
n = 1.75 - 1.25 \cdot \phi^{8.5} \tag{4}
\]

In the classical design of an advance chamber, that is, when the flow is moving at a certain slope and its cross-section is constantly expanding, it is of great importance to determine the main zone of particle deposition.

Studies to determine the trajectory and length of sediment particles [4,19] have shown that particles of the same size and density sink to the bottom of the structure in accordance with the normal Gauss law, and the average length of particle deposition is determined by

\[
L_{av} = \frac{Q_{uv} \cdot h}{W} \tag{5}
\]
where $h$ is the depth of particle placement, $\mathcal{G}_{av}$ is the average water flow rate, $w$ - is the hydraulic particle size (the rate of particle fall in standing water).

Analysis of the laws of sedimentation of solid particles in a very slow water flow shows that this equation has the following disadvantages.

a) the value $L_{av}$ is not affected the degree of particle concentration;
b) this expression is intended for a rectangular structure without a slope;
c) the particle settling rate is assumed to be equal to its hydraulic size.

2. Methods
Consider the movement and deposition of solid particle $A$ in the pump station's advance chamber (Fig. 1).

This particle travels a distance $dx$ in the horizontal direction under the action of the water flow velocity $\mathcal{G}_x$ in time $dt$. In addition, under the influence of gravity, the particle moves down vertically at a speed of $V_z$. In this case, we assume that the value of the pulsation velocities in the flow is zero. Therefore, if we consider the direction of motion of the particle in the plane as $dx = \mathcal{G}_x \cdot dt$ horizontally and as $dy = \mathcal{G}_y \cdot dt$ vertically, the trajectory of the particle is represented by equation

$$dy = \mathcal{G}_y \frac{dx}{\mathcal{G}_x} \quad (6).$$

In this case, the value of $\mathcal{G}_x$ can be determined by the water flow rate.

$$\mathcal{G}_x = \frac{Q}{\omega} = \frac{Q}{bh + mh^2} \quad (7)$$

where, $b$ is the width of the advance chamber, $H$ is the water depth, and $m$ is the slope coefficient.

Taking into account $\mathcal{G}_y = V_3$ and using (6) and (7), we can write the following

![Figure 1. Flow diagram of a solid particle in the pump station's advance chamber](image)

In this case, the value of $\mathcal{G}_x$ can be determined by the water flow rate.
\[ \vartheta = \frac{Q}{\omega} = \frac{Q}{bh + mh^2} \]  

(7)

where, \( b \) is the width of the advance chamber, \( H \) is the water depth, and \( m \) is the slope coefficient.

Taking into account \( \vartheta = V_3 \) and using (6) and (7), we can write the following

\[ \omega \cdot dx = \left( \frac{V_3}{Q} \right) dy \]  

(8)

The value of \( \omega \) from this expression is defined as follows (Fig. 1)

\[ \omega = b \cdot h + m \cdot h^2 \]

So we can write the value of \( \omega \) as follows

\[ \omega = x^2(2\tan \alpha \cdot \tan \beta + m \cdot \tan^2 \alpha) + x(b_1 \cdot \tan \alpha + 2h_1 \cdot \tan \beta + 2m \cdot h_1 \cdot \tan \alpha) + bh_1 + mh^2 \]

here, \( A = 2\tan \alpha \cdot \tan \beta + m \cdot \tan^2 \alpha \); \( B = b_1 \cdot \tan \alpha + 2h_1 \cdot \tan \beta + 2m \cdot h_1 \cdot \tan \alpha \); \( \omega_1 = b \cdot h_1 + m \cdot h_1^2 \) then we get the equation of the following form

\[ \omega = Ax^2 + Bx + \omega_1 \]  

(9)

Substituting (9) into (8) and integrating the result, we can obtain the following equation

\[ A \frac{x^3}{3} + B \frac{x^2}{2} + \omega_1 x = \frac{Q}{V_3} y + C \]  

(10)

Given that \( x=0 \) when \( y=0 \) and \( C=0 \), equation (10) looks like this

\[ y = \frac{V_3}{Q} \left( A \frac{x^3}{3} + B \frac{x^2}{2} + \omega_1 x \right) \]  

(11)

In this equation, we use equation (1) to determine the particle settling velocity \( V_3 \). However, since this formula is the sedimentation rate of a spherical single particle, we include the coefficient \( K_3 \) in equation (11), which takes into account the effect of the non-spherical shape of the particle and its concentration.

\[ K_3 = K_1 \cdot K_2 \]  

(12)

where \( K_1 \) is the coefficient for the indeterminate shape of the particles, \( K_2 \) is the coefficient taking into account the concentration of the particles.

Hence we write (11) in the following form

\[ y = \frac{V_3 \cdot K_3}{Q} \left( A \frac{x^3}{3} + B \frac{x^2}{2} + \omega_1 x \right) \]  

(13)
3. Results and Discussion
As an example, we present an equation that determines the trajectory of solid particles in the pump station’s advance chamber with an initial width \( b=3.0 \) meters, water depth \( h_1=2.5 \) meters, slope \( i=0.2 \), slope coefficient \( m=1.5 \), expansion angle \( \beta=22.50 \), which has the following form

\[
y = \frac{V_3 \cdot K_3}{Q} \left( \frac{0.242}{3} x^3 + \frac{5.407}{2} x^2 + 16.87 x \right)
\]

\( V_3 \) - we determine the value under the following conditions: particle diameter \( d=0.25 \cdot 10^{-3} \), density \( \rho=2000 \) kg/m\(^3\), kinematic viscosity coefficient of water flow \( v_c =1.006 \cdot 10^{-6} \). Under these conditions, the value of \( V_3 \), calculated by formula (1), is 0.026 m.

We calculate the value of \( K_3 \) under the following conditions: Assume that the particle concentration is \( \varphi=15\% \). In it, we determine the value of \( K_3 \) based on the results obtained on the basis of experiments conducted by the study. Such results emphasize the need to determine the exponent \( n \) in equation (3) by formula (4).

So, \( n = 1.75 - 1.25 \cdot \varphi^{0.5} = 1.74 \) and \( K_3 = (1-0.15)^{1.74} = 0.75 \) also \( K_3 = K_1 \cdot K_2 = 0.66 \cdot 0.75 = 0.495 \).

Using this method, it is possible to determine the trajectory and places of deposition of particles of different diameters and densities observed in different zones of the advance chamber.

We will examine the results of the calculation using the proposed equation using the example of the advance chamber of the M-II-2 pumping station in the Kashkadarya region. Length avancurar pumping station is 36 meters, the bottom of the 29-metre stretch horizontally, the remaining 7-metre plot has a slope of \( i=0.5 \) (Fig. 2). The expansion angle of the sides of avancurar \( \beta=17^0 \), the slope coefficient \( m=1.5 \) and the width of the input portion \( v_1 =3.0 \) m, water depth \( h_1=1.95 \) m, water flow rate \( Q = 7.8 \) m\(^3\)/s. This water flow rate corresponds to a water velocity of 0.675 m/s (in the entrance part of the pre-chamber).

**Figure 2.** Schematic of the M-II-2 pump station advance chamber
1 - advance chamber (avancamera); 2 - solid sediments; 3 - water intake chambers.
In the horizontal part of this advance chamber, that is, at \( \tan \alpha = 0 \), we calculate the trajectory of solid particles settling. In this case, equation (13) looks like this
\[
y = \frac{V_3 \cdot K_3}{Q} \left( x^2 \cdot h_1 \cdot \tan \beta + \omega_1 \cdot x \right)
\] (14)

This equation can be written in the following form under the given conditions
\[
y = \frac{V_3 \cdot K_3}{Q} \left( 0.596x^2 + 11.55x \right)
\] (15)

We assume the values of \( V_3 \) and \( K_3 \) on the basis of the above conditions, ie \( K_3, d=0.25 \cdot 10^{-3} \), for cases \( K_3=0.66, V_3=0.029 \) m/s.

Based on the results of the calculations, it was found that particles with a size \( d=0.25 \cdot 10^{-3} \), a density \( \rho =2200 \) kg/m\(^3\), and an indeterminate shape fall to the bottom of the advance chamber at a distance of 33.8 meters.

When analyzing the fractional composition of samples taken from the advance chamber of the M-II-2 pumping station, particles with a size of 0.25...0.3 mm were found, which occur at a distance of 25...37 meters from the entrance of the advance chamber (interval between sections b-b and c-c, Fig. 2.). Particles larger than 0.3 mm settle more between sections a-a and b-b, at a distance of 16...24 meters from the entrance of the advance chamber. The difference between the results of calculating the deposition distance according to equation (15) and the actual results of deposition of solid particles of other sizes is 7...12%.

4. Conclusions

1. It is established that in the advance chamber of pumping stations, accepting the value of the particle fall rate equal to the value of their hydraulic size leads to unacceptable errors in determining the particle deposition trajectory.
2. It is expedient to determine the trajectory of particle subsidence taking into account the turbid concentration, size, shape and density of the particles.
3. A new method and equation for determining the trajectory of the movement of solid particles in the advance chamber of reclamation pump stations was proposed.
4. The difference between the results of calculations performed on the proposed new equation and the actual results of sedimentation of solid particles is 7...12%, and this equation can be used to determine the trajectory of solid particles in the advance chamber of pumping stations.

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