

CALCULATION OF TOTAL CHANNEL EROSION IN COHESIVE SOILS

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Annotation

This article highlights the main theoretical and practical issues of calculating general erosion processes in cohesive soil channels. The dynamics of flow saturation with particles and its dependence on flow velocity, sediment concentration, and the physical properties of the soil are studied. Integral consideration of parameters such as flow, topography, geology, and other channel-forming factors is included. The separation of soil under the influence of turbulent flow and the empirical relationships of this process are described. As a result of the research, mathematical models and calculation methodologies for assessing erosion processes in cohesive soils are proposed. The calculation of the free surface curve was carried out using nomograms based on the Hydoproject methodology. Hydraulic parameters of the channel were determined, and its profile was reconstructed based on this methodology.

Keywords

cohesive soils, channel erosion, turbidity dynamics, turbulent flow, mathematical modeling, empirical relationships, channel profile.

Introduction

Nowadays, the rational management and efficient use of water resources have become pressing issues. In particular, studying the general erosion processes in cohesive soil channels plays a crucial role in ensuring the stability of hydraulic structures. The impact of water flow on channel structures, the erosion resistance of

soil, and the analysis of hydraulic conditions are essential for improving the efficiency of channel operation and conserving natural resources.

Cohesive soil channels are widely distributed in nature, and the erosion processes occurring in them affect not only the stability of hydraulic structures but also the ecological condition of waterways. Therefore, this topic is not only relevant for scientific research but also has practical significance, playing a crucial role in developing strategies for water resource management.

Erosion of the channel and the saturation of the flow with suspended particles occur when the turbidity of the flow is lower than its transport capacity. This process takes place when the flow velocity within the channel is sufficiently high to either lift particles into suspension (in non-cohesive soils) or cause the detachment of aggregates (in cohesive soils). In sandy, non-cohesive soils, the resistance to particle erosion is primarily determined by their weight and the frictional forces between them. In cohesive soils, however, the primary factor ensuring resistance to erosion is the cohesive strength of the soil[1].

The erosion of cohesive soils occurs in the form of aggregates, with the detached fragments typically measuring around 3-5 mm[2]. The detachment of cohesive soil aggregates primarily results from the dynamic effects of turbulent flow[3]. This process depends on the bed velocities observed at the onset of deformation in the flow and the extent to which these velocities exceed the permissible bed velocities for the given soils[4].

A distinctive feature of cohesive soils is their ability to resist through tensile strength, which is conditioned by the structural bonds between particles[5]. The primary factor ensuring the strength of soils is the durability of these structural bonds.

The nature of structural bonds is highly complex and is determined by a combination of external and internal energy fields acting within the soil, primarily governed by molecular forces of electromagnetic nature.

As a first approximation, the ratio of the flow saturation velocity with suspended particles to the turbidity deficit can be expressed in the form of the following equation:

$$\frac{g_x}{\rho_{kp} - \rho_x} = \frac{\alpha(g_{\Delta\phi ak} - g_{\Delta a_{on}})}{\rho_x} \quad (1)$$

The saturation velocity of the flow can be expressed in the following form[4]:

$$g_x = \alpha(g_{\Delta\phi ak} - g_{\Delta a_{on}}) \frac{\rho_{kp} - \rho_x}{\rho_x} \quad (2)$$

Here $g_{\Delta\phi ak}$ – The bed velocity in the flow, m/s;

$\mathcal{G}_{\Delta a_{on}}$ – The critical bed velocity for erosion in the given soil, m/s;

ρ_{kp} – The amount of turbidity carried by the flow, kg/m³;

ρ_x – The amount of turbidity in the flow at a distance after the onset of erosion, kg/m³;

α – An empirical coefficient characterizing the length of flow saturation with suspended particles in the channel erosion process, which depends on the bed's strength properties.

Methods and Materials

The bed velocities are determined using the widely known formula by V.N. Goncharov, while the average critical velocity is calculated based on the formula by C.E. Mirtsxulava for cohesive soils[1].

The equation describing the dynamics of flow saturation with suspended particles for cohesive soils is based on the assumption of the channel's total erosion, derived from the following conditions and assumptions:

- The calculation is carried out under uniform conditions;
- The detachment rate of aggregates remains constant during a certain time interval Δt , based on the hydraulic parameters of the flow;
- The division of aggregates into fine fractions occurs over a relatively short distance on the path of saturation with suspended particles.

Consider a section of the flow with length dx , depth H , and width B . If the turbidity of the flow increases by $\frac{d\rho_x}{dx}$ per unit time, the amount of suspended particles entering the channel volume, $H \cdot B \cdot dx$, can be expressed through the following relation: [6]

$$dg_x = H \cdot B \cdot dx \frac{d\rho_x}{dt} = H \cdot B \cdot \mathcal{G} \cdot d\rho_x \quad (3)$$

If the flow has been saturated with suspended particles at a certain saturation velocity of \mathcal{G}_x m/s and the flow currently has a turbidity of ρ_x , with the flow area being $dx \cdot B$, the additional amount of suspended particles in the flow can be calculated based on the following formula:

$$dg_x = \rho_x \cdot \mathcal{G}_x \cdot B \cdot dx$$

alternatively, by substituting the value of \mathcal{G}_x from equation (2), we get:

$$dg_x = \alpha(\mathcal{G}_{\Delta\phi ax} - \mathcal{G}_{\Delta gon})(\rho_{kp} - \rho_x) \cdot B \cdot dx \quad (4)$$

by combining equations (3) and (4), taking into account: $d\rho_x = -d(\rho_{kp} - \rho_x)$

we obtain the following result:

$$-HB\mathcal{G}d(\rho_{kp} - \rho_x) = \alpha(\mathcal{G}_{\phi ax} - \mathcal{G}_{\delta on})(\rho_{kp} - \rho_x)B \cdot dx. \quad (4')$$

The result leads to:

$$\frac{d(\rho_{kp} - \rho_x)}{\rho_{kp} - \rho_x} = - \frac{\alpha(\mathcal{G}_{\varphi\alpha\kappa} - \mathcal{G}_{\delta on})}{\mathcal{G} \cdot H} dx \quad (5)$$

Let's integrate:

$$\int_0^{\rho_{kp}} \frac{d(\rho_{kp} - \rho_x)}{\rho_{kp} - \rho_x} - \frac{\alpha(\mathcal{G}_{\varphi\alpha\kappa} - \mathcal{G}_{\delta on})}{\mathcal{G} \cdot H} \int_0^l dx \quad (6)$$

$$x = 0, \rho_x = \rho_0, \quad x = l, \rho_x = \rho_l$$

here ρ_0, ρ_l – The turbidity at the corresponding inlet and outlet sections.

$$\frac{\alpha(\mathcal{G}_{\varphi\alpha\kappa} - \mathcal{G}_{\Delta gon})l}{\mathcal{G} \cdot H}$$

$$\rho_l = \rho_{kp} - (\rho_{kp} - \rho_0) \cdot l \quad (7)$$

In a flow with limited width, the depth should be replaced by the hydraulic radius in the equation. Equation (7) is the equation for the dynamics of flow saturation with suspended particles in cohesive soils, derived for uniform flow conditions[7]. Therefore, in the case of non-uniform flow, the flow is divided into separate sections along its length, with each section treated as uniform flow, and the calculations are carried out sequentially for each part.

Results and Discussions

In its most general form, the equation for the dynamics of saturation can be written as follows:

$$\frac{\alpha(\mathcal{G}_{\Delta\varphi\alpha\kappa(n)} - \mathcal{G}_{\Delta\delta on(n)})l_n}{\mathcal{G}_{(n)} \cdot H_{(n)}} \quad (8)$$

$$\rho_{l(n)} = \rho_{kp(n)} - (\rho_{kp(n)} - \rho_{l(n-1)}) \cdot l$$

here $\rho_{l(n)}, \rho_{l(n-1)}$ – The turbidity in the calculated and previous sections, kg/m³;

$\mathcal{G}_{(n)}, H_{(n)}$ – The average velocity in the calculated section (m/s) and h – the depth in the calculated section (m);

$\rho_{kp(n)}$ – The critical turbidity or the transport capacity of the flow in the calculated section.

Empirical coefficient α was determined through research on cohesive soils conducted at the ВНИИГ and М laboratory[8]. Based on the processing of experimental data, the following relation was obtained:

$$\alpha = 0,000175K \left(\frac{c}{\gamma_w \cdot h^*} \right), \quad (9)$$

here K – the coefficient characterizing the additional erosion of the bank. If $C < 0,12$ is in kg/cm^2 , in case $K = 1, 2 - 1, 3$, then $C > 0,12$ $K = 1$;

C – The average cohesion of the soil in the fully saturated condition (kg/cm^2);

γ_w – The bulk density of the soil, t/m^3 ;

h^* – The thickness of the soil layer, converted to 1 meter.

The transport capacity of the flow is determined according to X.Sh. Shapiro's formulas. For a single fraction, it has the following form:

$$\rho_{mpi} = \rho_{kp(n)} = K_i \cdot g_{cpak}^{0.7} \cdot U_b [l_n \left(\frac{W_i + 1}{W_i} - \frac{W_{i+1} - W_i}{U_b} \right)] \quad (10)$$

here K_i – The coefficient dependent on the fraction diameter;

U_b – The flow's capacity to saturate with vertical suspended particles;

i – The slope of the channel bed;

W, W_{i+1} – The minimum and maximum hydraulic dimensions of the given fraction.

The values of hydraulic parameters are determined according to the table by Goncharov V.N. The total transport capacity of the flow is calculated as the sum of the transport capacities of individual fractions[6].

Analysis of equation (8) shows that the primary factors determining the intensity of channel deformation are the flow velocity and the ratio of this velocity to the critical velocity for the given soil. These two factors account for the flow, topography, geology, and other parameters shaping the channel in an integrated manner.

Given the change in turbidity based on the sections calculated according to equation (8), the volume of eroded soil can be determined using the following formula:

$$W_{pazm(n)} = \frac{[\rho l_{(n)} - \rho l_{(n-1)}] \cdot Q \cdot t}{\gamma_{\text{об}}} m^3, \quad (11)$$

here Q – The flow rate over a time interval, m^3/s ;

t – The number of seconds in the selected time interval.

When selecting time intervals, the following factors must be considered: the hydraulic parameters of the flow are assumed to remain unchanged within the chosen intervals, which is not always true. Therefore, selecting smaller intervals reduces the average error. On the other hand, selecting very small intervals may result in deformations so small that they could be comparable to the error in the calculations. Furthermore, the choice of time intervals affects the number of calculation steps, and thus the labor costs of the calculations. Therefore, the

approach to selecting intervals should be rational but should not compromise accuracy.

The erosion depth for the calculated section can be obtained from the following expression:

$$h_{\text{разм}} = \frac{W_{\text{разм}(n)}}{B_{\text{ср}(n)} \cdot l_{(n)}} \quad (12)$$

Given the initial bed elevation of the channel, the erosion depth for each section can be determined by subtracting $h_{\text{разм}}$, and a new channel profile can be constructed. Once the new channel profile is obtained, the new free surface curve is calculated, and the new water depths are determined. Based on these new depths, the new velocities are calculated. These new hydraulic parameters will serve as the initial data for the next stage of calculations for the channel and flow [9].

In cohesive soils, the interaction between particles is carried out through hydration-ion-colloidal membranes, which are characterized by certain viscosity and mechanical strength, providing cohesion to the soils. The strength of cohesive soils increases as they dry.

The cohesion of cohesive soils is also related to the electrostatic attraction that arises from the interaction between soil particles charged with different types of charges or from particle-to-particle friction[10].

In some cohesive soils, the crystallization (solid) bonds formed during the precipitation of salts from new solutions play an important role in the soil's strength.

The compressibility of soils under constrained expansion conditions is reflected in the results of compression tests, which provide insights into their compression properties and the determination of compression.

The compressibility (consolidation) coefficient, the general deformation modulus YE_0 (kgs/cm²), as well as the settlement modulus, which indicates the amount of settlement in millimeters after applying a load R (kgs/cm²) to a 1-meter high soil column, serve as indicators of the soil's compressive capacity. For strongly compressible soils, the consolidation coefficient is greater than 0.1 m; for moderately compressible soils, it ranges from 0.1 to 0.01, and for weakly compressible soils, it ranges from 0.01 to 0.001 and less. N.N.Maslov classifies soils based on their compressibility.

Table 1

Classification of soils based on compressibility

Soil classification based on compressibility	Soil compressibility degree	P, kgs /sm ²	V, mm/min
0	Very rare	0,001	1

I	Weak	0,0001...0,005	1...5
II	Average	0,005...0,01	5...20
III	High	0,01...0,10	20...60
IV	Strong	0,20	60

The slow progression of the compaction process in clayey soils is conditioned by structural-adsorptive and structural deformations. Structural-adsorptive deformations refer to the changes occurring only in the water films at the points where particles are in contact, while structural deformations refer to the deformations related to the displacement of structural elements (particles or aggregates) relative to one another. Under the influence of loading, the total deformation of clayey soils results from the combination of reversible (elastic) and irreversible (residual) settlements.

The relative and absolute roles of structural deformations in the total deformation are significantly dependent on the soil density. It can be conditionally assumed that at 0.7, structural deformations dominate, while in denser soils, structural-adsorptive deformations dominate at values between 0.7 and 0.25.

The factors determining the compaction of cohesive soils are diverse and include texture, structural strength and consistency, mineralogical and granulometric composition, cation exchange capacity and the composition of exchangeable cations, the composition and mineralization of vapor solutions, and porosity.

In cohesive soils, since the erosion processes are irreversible, deformations increase with the increase in flow rate and remain unchanged with a decrease in flow rate. When calculating deformations, the maximum flow rate $Q = 320M^3 / c$ and the corresponding allowable velocities $g_{con} = 1,08M / c$, along with the actual velocities $g_{pak} = 1,4M / c$ at the channel bed, are considered.

The calculation begins with constructing the free surface curve. The channel is divided into sections, and the calculation of the free surface curve is carried out using nomograms based on the Gidroyekt methodology.

$$\Delta z = f\left(ng\sqrt{e}, H - \frac{\Delta h}{2}\right),$$

here Δz – The change in the water level at the upper part relative to the water level at the lower part;

H – The average depth of water;

Δh – The difference in bed elevation between the upper and lower parts;

g – The average flow rate of water per unit time.;

n – Softness coefficient.

The calculation is carried out from bottom to top. Once the curve of the free surface is constructed, the hydraulic parameters of the flow along the channel can be determined, and then the washings are calculated using the methodology described above.

To verify the accuracy of the calculation based on the given methodology, an alternative calculation was performed. This method is based on a logical estimate related to the assumption that the washing will continue unchanged in the channel. According to this estimate, the washing stops if such depths are established in the channel that provide the non-washing velocity. In this calculation, the time factor is not considered, but the final result must be correct – the new channel profile corresponding to the non-washing velocities. If the velocities should decrease from 1.4 m/s to 1.08 m/s, the initial depth should increase from 2 m to 2.9 m. However, the increase in depth slightly exceeds the permissible velocity, but this increase is very small, and we neglect it in our calculations.

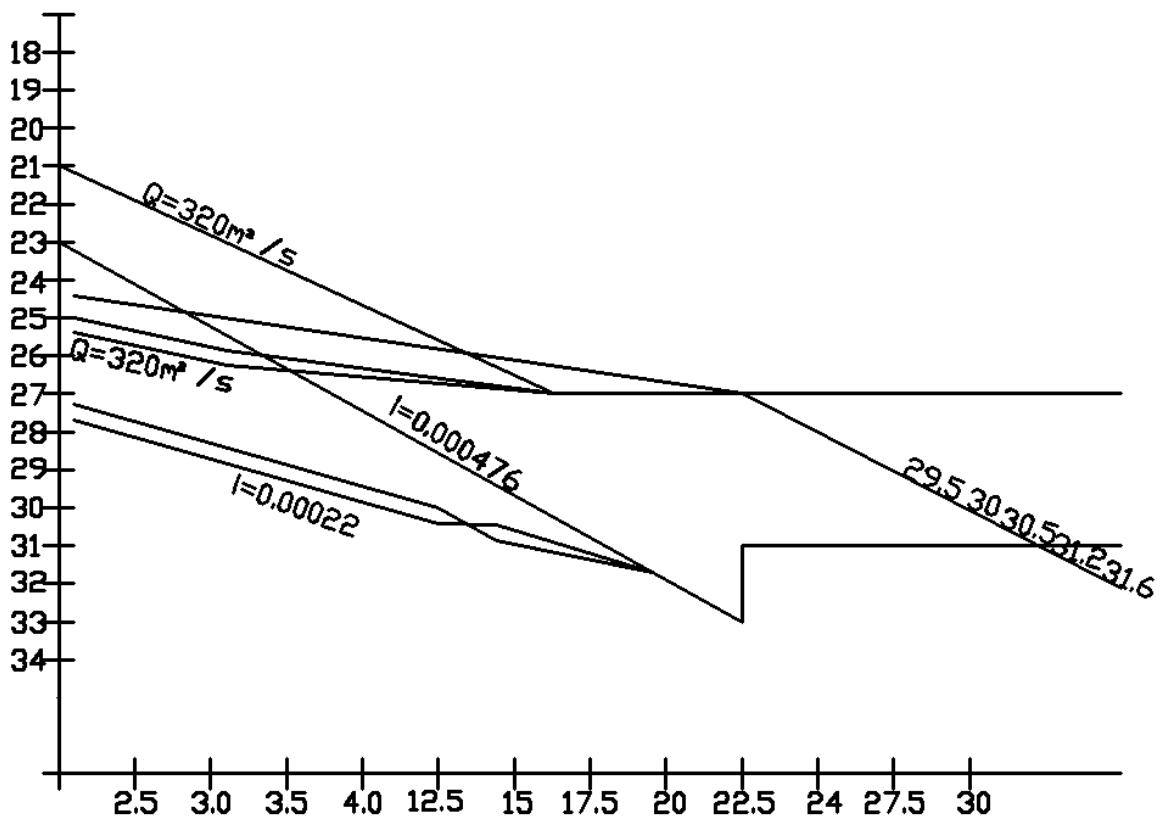


Fig. 1. Change in bed elevation along the length of the channel.

Conclusions

By considering the process as repetitive erosion, we transferred the 2.9 m depth through the calculations from section to section, adjusting the free surface curve at each stage. The final results were incorporated into the initial profile of the

channel (Figure 1), and the points obtained through the above-mentioned method were also placed here. The close results obtained from both methods are very convenient, as the allowable velocity method, while lacking the advantages of the first method (considering the erosion process over time), can serve as a confirmation of the accuracy of the calculations, as the final result leaves no room for doubt.

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