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Combined method for calculating the total erosion of channels composed of easily erodible grounds

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Combined method for calculating the total erosion of channels composed of easily erodible grounds

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Abstract. Riverbed processes on rivers composed of easily eroded soils differ in intensity. Therefore, deformation calculation methods are needed that take into account the characteristic features of such rivers. These features can be taken into account by introducing into the composition of the initial equations of dependencies reflecting the features of the alluvial regime and the nature of deformations. To this end, based on the analysis of existing empirical dependencies and actual data of the total erosion below the Takhiatash hydro unite (Amu Darya River, Uzbekistan), the structure and type of dependence of the transporting capacity of the stream on the main parameters of the channel and the morphometric dependence of the width of the stable channel on the average depth were selected. The proposed combined calculation method is based on the theoretical equations of deformation (Saint-Venant) and the equation of fluid motion (Bernoulli) and empirical dependencies for determining the average turbidity of the flow and the width of the channel. With the use of these equations, the calculation of the total erosion below the Takhiatash hydrounite on the Amu Darya River was carried out. Comparison of the calculation results and the actual data showed their satisfactory convergence. The proposed method can be applied to calculate channel deformations on rivers composed of easily eroded soils when regulating the flow of retaining structures.

1. Introduction

The dynamics of the channel flow or the channel process in rivers is a complex physical phenomenon, the nature of which has been studied in some detail [1,2,3,4]. The nature of the course of these phenomena is influenced by a set of factors. The main channel-forming factors are the hydrological regime [5,6,7], alluvial mode (turbidity) [8,9], topography (structure of the river valley) and geology (composition and content of soils composing the bottom and banks of the riverbed) [10]. Climate change also has a significant impact on the riverbed process [5,11]. The riverbed process proceeds especially intensively on rivers composed of easily eroded soils [12,13]. The nature of channel deformations changes as a result of anthropogenic action, after the regulation of the flow by water support structures – dams. In the in the upstream of the hydrounite, the processes of siltation of the reservoir begin due to a decrease in flow rates and, accordingly, the transporting capacity [14,15]. In the downstream of the hydrocomplex, the predominant type of channel processes is the general erosion [16,17,18]. Channel deformations (channel reshaping) arising as a result of riverbed processes on rivers have various impacts on the environment, on the life of the population in coastal areas, and on the operation of structures. Siltation of the upper stream leads to a decrease in the useful capacity of the reservoir, complicates the operation of culverts [12]. General erosion in the downstream of the hydrofacility leads to a decrease in water levels in the river (thereby worsens water intake conditions)

[19], to planned washouts of the riverbed banks. Intensive general erosion of the riverbed can even lead to deterioration of the working conditions of hydraulic structures for stability.

Therefore, the issues of calculation and prediction of channel deformations in conditions of flow regulation are relevant and the purpose of the research is to improve the method of calculating deformations of channels composed of easily eroded soils. To achieve this goal , it is necessary to solve the following tasks:

- to analyze the existing methods for calculating the total erosion in the downstream of waterworks and evaluate the possibility of their application for calculating the deformations of channels composed of easily eroded soils (like the Amu Darya River);
- select the initial basic formulas that take into account the main features of the riverbed process on rivers composed of easily eroded soils;
- to calculate and compare the results of the calculation according to the proposed methodology with the full-scale data of the general washout (verification).

The object of the research is the methods for calculating the total erosion of channels stacked with easily eroded soils. The subject of research is the general erosion on the Amu Darya River (Uzbekistan).

Despite the large number of available methods for calculating the total erosion after river flow regulation, there is no universal, generally accepted methodology. This is due to the complexity of the riverbed process and its dependence on many factors that it is not possible to take into account. Especially difficult is the calculation of the total erosion of riverbeds composed of easily eroded grounds [1,3,4].

All existing calculation methods can be separated:

1) hydrodynamic (theoretical) methods that are based on solving a system of equations of a suspended channel flow in a deformable channel [2,10,13,14,15].

2) hydromorphological (empirical) methods are based on the correlation of hydromorphological dependencies between the hydraulic characteristics of the flow, the morphometric characteristics of empirical channels[4,16,21,22,23].

A separate group is represented by methods based on geoinformation systems [24,25,26].

According to the rigor of the theoretical justification and the reflection of the physical essence of the phenomena that determine the channel processes, the methods of the hydrodynamic direction are more preferable. But the solution of the system of basic equations presents serious, and in some cases insurmountable difficulties in view of the considerable complexity of the process of channel transformations and its dependence on a large number of factors. Theoretical calculation methods are more preferable with the available complete initial data and the uniformity of fluid movement over a relatively short period of time. Empirical methods have an advantage in conditions of relative non-obviousness and for a longer period.

2. Methods

The methodology of the conducted research consists in the application of general scientific research methods within the framework of comparative, logical and statistical analysis, as well as through the analysis of structure and dynamics, graphical interpretation of calculation results, etc. The general scientific method consisted in the analysis of literature on the research problem, generalization, comparison and systematization of empirical and theoretical data. Theoretical (analysis, synthesis, generalization) and empirical (results of field observations, methods of mathematical processing) methods were used.

The proposed method uses the basic equations of theoretical methods, which are supplemented by empirical dependencies. The application of empirical dependencies in theoretical equations is not entirely correct. But it is the empirical hydromorphological dependences that give good convergence for the conditions of the Amu Darya River.

All the main hydrodynamic methods are based on the solution of Saint-Venant differential equations and the differences relate mainly to one or another approach to their solution (a set of analytical and graphical techniques), the assumptions used to close the system of initial equations, recommendations for determining sediment flow, etc. Therefore, when calculating the channel deformations in the lower reaches of the Takhiatash hydrocomplex, the Saint-Venant equations were used as the main basic equation.

1) The channel deformation equation has the form (the Saint-Venant equation):

$$\frac{\partial P}{\partial s} = \gamma \frac{\partial \omega}{\partial t} \ , \qquad (1)$$

where, $\partial\omega/\partial t$ is the change in the cross-section of the riverbed over time;
P is the flow rate of sediment;
γ is the specific gravity of sediment.

2) The equation of fluid motion (Bernoulli equation) [1]:

$$\frac{1}{g}\frac{\partial(\alpha_{\omega} v)}{\partial t} + \frac{\partial}{\partial s}\left[\frac{\alpha_0 v^2}{2g} + y\right] + \frac{\alpha_s v \rho_s q_s}{\rho_{\omega} g \omega} = -i_f \qquad (2)$$

where, y is the mark of the free surface of the water, m; v is the flow rate m/s; ω is the cross-sectional area m^2; α_ω and α_s are flow adjustments that take into account the uneven distribution of local sediment concentrations and velocities over the living section; $\alpha_0=2\alpha_{0\omega} - \alpha_\omega^2$,$\alpha_{0\omega}$ — adjusting the amount of movement; ρ_s and ρ_ω are densities of sediment and water material, respectively, kg/m^3; i_f is the friction slope.

3) Empirical morphometric dependence of the width of the riverbed on the average depth (the formula is of great importance for riverbed composed of easily eroded grounds):

$$B = \kappa h^{\alpha} \qquad (3)$$

where B is the width of the riverbed along the edge, m; h is the average depth, m; k and α are empirical coefficients.

To clarify the coefficients in the morphometric relationship formula for the conditions of regulated flow, statistical processing of data on the Samanbai hydropost (Amudarya River, Uzbekistan) for various years of operation of the hydrounite was used, i.e. data were taken for one alignment, but for a wide range of expenses and for a long time. The following results were obtained:

a) for a period of intense erosion. Statistical calculations used data for the period 1974-1979. The coefficient “k“ varied from 500 to 100 depending on the year (in1974 k=135, in 1975 k= 250, in 1976 k= 300, in 1977 k= 380, in 1978 k= 290, in 1979 k= 330, the average for the entire period 1974-1982 k=320); the power indicator " α “ was equal to 0.4 . Thus, all the values of the dependence B=f(h) during this period were in the region of two curves $B = 500 \cdot h^{0.4}$ and $B = 100 \cdot h^{0.4}$.

b) for the period of stabilization of the channel process. In statistical calculations, data from the hydrometeorological service for 1992-1993 were taken, since it was during these years that the deformation of the channel in the second period was calculated. The value of the coefficient “k” varied from 500 to 100 depending on the flow rate (at Q < 400-600 m^3/s k = 170, and at Q>400-600 m^3/s k = 460), the power indicator "α" = 0.1. That is, the values of the dependence B=f(h) for this period are in the field of curves $B = 500 \cdot h^{0.1}$ and $B = 100 \cdot h^{0.1}$. Thus, the power-law indicator in the morphometric dependence “α“ was equal to 0.4 for the period of intensive erosion (1974-1982), and 0.1 for the period of stabilization of the channel process (1992-1993). The interval within which the values of the coefficient “k” change both for the second period and for the period intensive erosion is the same (500 - 100).

4) sediment flow equation [12,16]:

$$\mu = K_1 \frac{v^m}{(ghw)^n} \qquad (4)$$

μ is the average turbidity of the flow corresponding to its transporting capacity, kg/m^3; *v* is the average flow velocity, m/s; *h* is the average depth, m; *w* is the average median fall diameter, m/s; *k* is the proportionality coefficient; *m,n,a* are the degree indicators determined by according to empirical data;

When choosing a formula for determining sediment flow, it is necessary first of all to take into account the factor of flow clarification as a result of flow regulation by a retaining dam. The importance of this factor in the calculation of deformations was emphasized above. After the river is regulated, the water enters the lower stream clarified (especially during the initial period of operation of the hydrounit). I.e., the stream is "underloaded" with sediments. The process of replenishing the flow with sediments to the conveying capacity occurs at a considerable length of the downstream. There are a huge number of formulas for determining the conveying capacity of the flow and flow rate of solid sediments. This is due to the fact that the movement of sediments is an extremely complex process, depending on a huge number of both natural and random factors. Therefore, there is no universal formula suitable for any rivers. Each formula is valid for specific field or experimental conditions under which the research was conducted, which is taken into account by the empirical proportionality coefficients present in the formulas. The dependence of the type (4) was chosen, in which the conveying capacity of the flow depends on the main hydraulic parameters of the channel. It is this type of dependence that shows the best convergence with full-scale data for the conditions of the Amu Darya River.

As a result of statistical processing of hydrometric data on the Samanbai located directly in the lower reaches of the Takhiatash hydrounite, the following dependencies were obtained.

For a period of intense erosion (1974-1982):

$$S_{aver} = 0.113\frac{v^{1.5}}{(ghw)^{0.5}} \qquad (5)$$

For the period of stabilization of the riverbed process (after 1982):

$$S_{aver} = 0.039\frac{v}{(ghw)^{0.33}} \qquad (6)$$

The joint solution of equations (1)-(4) leads to an equation of the form:

$$\frac{\partial z}{\partial s} + F_1\frac{\partial z}{\partial t} = -F_2 \qquad (7)$$

where

$$F_1 = \frac{-(k^{m-1}(gw)^n h^{m\alpha-\alpha+m+n-2})\gamma(\alpha+1)}{K_1 Q^{m+1}(m\alpha+m+n)g}(gk^2h^{2\alpha+3}-(\alpha+1)Q^2)$$

$$F_2 = -\frac{(1+m)kqh}{Q(m\alpha+m+n)} + \frac{(1+m)kq(\alpha+1)Q}{(m\alpha+m+n)gk^2h^{2\alpha+2}} - \frac{Qkq}{gk^2h^{2\alpha+2}} + \frac{Q^2n^2}{k^2h^{2\alpha+2m_1+3}}$$

Equation (7) is solved by an auxiliary system of canonical equations of the form:

$$\frac{ds}{1} = \frac{dt}{F_1} = \frac{dz}{-F_2} \qquad (8)$$

$$\begin{cases} \Phi_1 = \int F_1 ds = t + C_1 \\ \Phi_2 = -\int F_1 / F_2 dz = t + C_2 \end{cases} \qquad (9)$$

where C_1 and C_2 are arbitrary functions of independent variables *s* and *t*. C_1 and C_2 are found by graphoanalytical method. Numerical integration using closed-type Newton-Cotes quadrature formulas was used to calculate the values of F_1 and F_2. Knowing the values of C_1 and F_1, which are determined for predefined marks of deformations *z*, it is possible to determine the value of the time interval for which this deformation will occur:

$$\begin{cases} t = \Phi_1 - C_1 \\ t = -\Phi_2 - C_2 \end{cases} \qquad (10)$$

By specifying the values of deformations, it is possible to use formulas (9) to find the time interval during which this deformation occurred and, based on them, to plot the change in the values of deformations in time z (t) and the change in the area of deformation in time $\omega(t)$.

3. Results and discussions

To calculate the total washout, an algorithm and a calculation program in the language "Turbo Pascal 7.0" have been developed. The calculation of the total erosion during the period of intensive erosion (1974-1982) was carried out. The initial data and calculation results are presented in Table 1.

The results of the deformation calculation obtained during the processing of data on Samanbai and Kyzyljar hydraulic posts according to the proposed method and the resulting curve of actual deformations are presented graphically in the form of the relation $\Delta\omega = f(t)$ in Fig.1. Visual analysis and comparison of curves shows that the calculated curve does not differ significantly from the curve of actual deformations, and in general, corresponds to the course of channel deformations along the Samanbai in the period under review. But, unlike the curve of actual deformations, the calculated curve does not take into account seasonal deformations and deformations caused by the water content of the year, and is, to some extent, an average curve of actual deformations.

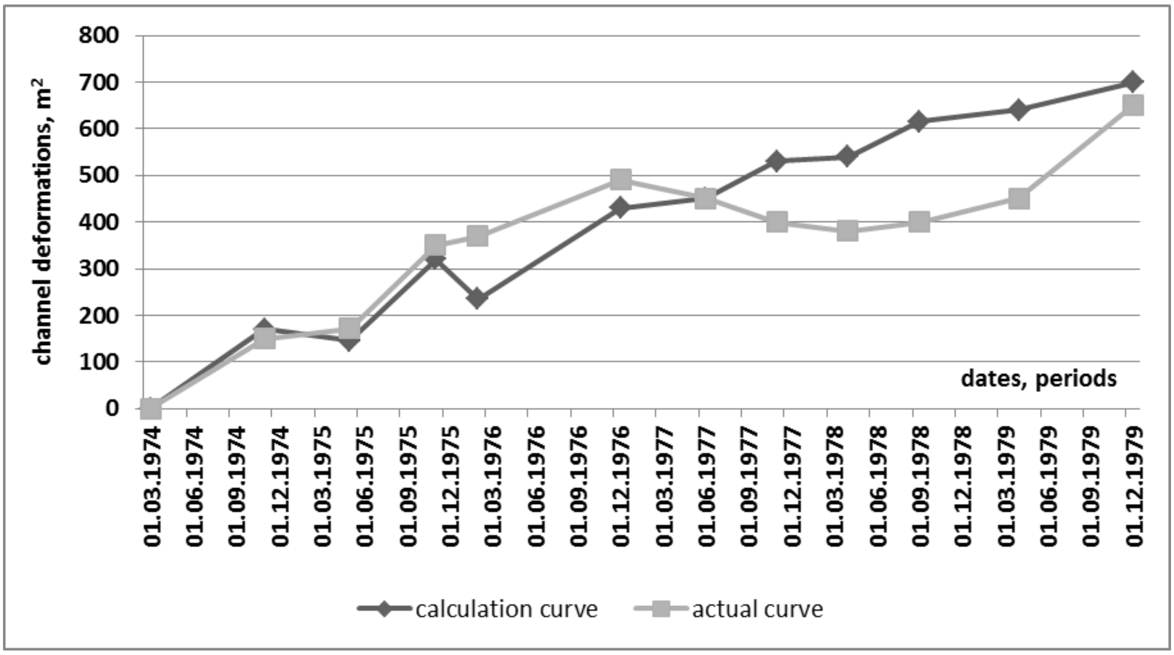

Figure 1. Calculated and actual curves of channel deformations

This is explained by the fact that for the entire calculation period, a general formula was chosen to determine the sediment consumption (5), although, in fact, in low—water years, the actual sediment consumption is less, and in high-water years - more than defined by formula (5). So, 1974 and 1975 were low-water years, i.e. the actual sediment consumption in these years is less than the calculated one calculated by this formula. Accordingly, the values of the actual deformations are greater than the calculated ones. 1978 was a high-water year, and the volumes of actual deformations are decreasing (some siltation occurs), the actual sediment consumption this year is greater than the calculated one, this explains the large discrepancies in the deformation curves this year.

Table 1. Results of calculation of deformation during intensive erosion (1974-1979)

Calculated period	initial data: line 1 Q_1 h_1 B_1	line 2 Q_2 h_2 B_2	transporting capacity S_{aver} kg/m^3	hydraulic size, w, mm/s	"α" / "K"	Time x10^5 s	received results: roughness coefficient	Δz m	Δw m^2
04.03.74 - 15.11.74.	310 2.15 190	280 1.50 230	1.075	2.5	0.4 / 135	221	0.048	0.62	170
04.03.74 - 13.05.75.	230 1.90 160	200 1.35 195	1.760	1.9	0.4 / 170	376	0.058	0.45	145
04.03.74 - 03.11.75.	375 2.00 210	335 1.60 200	0.870	1.9	0.4 / 190	526	0.045	0.84	320
04.03.74 - 20.02.76.	320 2.00 190	290 1.50 180	0.748	2.6	0.4 / 200	620	0.048	0.60	235
04.03.74 - 10.12.76.	430 1.90 240	330 1.60 180	0.957	2.6	0.4 / 240	873	0.043	0.95	430
04.03.74 - 06.06.77.	385 1.75 230	290 1.45 170	0.827	1.6	0.4 / 250	1027	0.045	0.94	450
04.03.74 - 02.11.77.	415 1.70 255	320 1.50 180	0.860	1.6	0.4 / 270	1156	0.044	1.02	530
04.03.74 - 8.04.78.	375 1.60 245	290 1.50 170	0.785	1.5	0.4 / 265	1300	0.045	1.08	540
04.03.74 - 29.09.78	455 1.70 260	375 1.65 170	0.806	2.5	0.4 / 270	1443	0.043	1.18	615
04.03.74 - 19.04.79.	430 1.60 260	365 1.65 175	0.762	2.0	0.4 / 275	1618	0.043	1.21	640
04.03.74 - 29.12.79.	445 1.60 270	385 1.70 175	0.795	2.0	0.4 / 280	1839	0.043	1.30	700

Comparison of the calculation results with the actual data of the total erosion in the lower reaches of the Takhiatash hydrocomplex on the Amu Darya River showed good convergence. The discrepancies between the calculated and actual curve as a percentage for the entire period under review amounted to no more than 5% (the maximum deviations in some periods are 20-25%).

4. Conclusions

1. Based on a comprehensive analysis of existing methods for calculating channel deformations, the basic initial equations for calculating the total erosion of bed on rivers composed of easily eroded soils were selected: the deformation equation, the equation of fluid motion, the dependence for determining the transporting capacity of the flow and the hydromorphological dependence of the connection of the width of the channel with the average depth (this dependence plays an important role, since for the channels of folded easily eroded soils are characterized by intensive planned deformation).

2. Comparison of the results of the deformation calculations using the proposed method with the full-scale data showed a fairly good convergence, taking into account the complexity and uncertainty of the change in the parameters of the phenomenon under consideration. Thus, this method allows us to determine the general trends in the development of the general erosion of channels composed of easily eroded soils during flow regulation and can be used for their quantitative assessment.

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