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The effect of flow velocity distribution on matter transport in a curved channel segment with the effect of moving ships taken into account

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Abstract. Ship transport produces a special type of bank waves, which have a specific effect on the boundaries of water bodies other than that of the wind-induced waves. In addition, the extent of frozen-bank erosion at a bend of river channel is determined by the entering flow velocity, which can increase in winter because of channel constriction due to freezing or ice jams and gorges. The accompanying vortices have a considerable effect on the flow velocity pattern.

1. Introduction

The formation and evolution of meanders can be simulated by both observation-based [1, 2] and physically based [3] models of bank erosion. The observation-based models assume the rate of bank erosion to be proportional to the near-bank flow velocity. The physically based models calculate the transport of bottom sediments and the rate of bank erosion to evaluate the retreat of channel bank line. In the latter case, the erosion factor in field models is empirical and fails to describe the erosion geometry in some channel parts containing natural meanders. Such models can be effective for predicting the long-term behavior of sinuous rivers [4, 5, 6]. Physical models are used to describe the rate of bank erosion in any places of a natural sinuous channel given the input data, including the velocity field, bank geometry, and the bank-forming material.

Another factor that has an effect on bank erosion is navigation period. The passage of a single ship causes a high wave collapsing on the bank, thus causing considerable erosion. To evaluate the strength of such waves and their effect on bank erosion, the major factors that contribute to the formation and propagation of ship-induced waves have been identified. The effect of ship-induced waves on a rectilinear bank has been discussed by many authors in the context of solving problems of hydroengineering construction and bank protection. The study [7] gives a method of spectrograms for determining additional components of ship waves which have not been examined before. The optical method of laser beams for determining the velocity field of ship-induced waves based on the comparison with a free surface was used in [8]. The effect of the shape of the ship, in particular, its bow, other conditions being the same, was described in [9]. The effect of flow parameters, taking into



account the critical velocity in a channel with a finite depth, on ship-induced wave propagation was described in [10]. Many authors calculated the ship trail with the use of accurate mathematical methods (for example, the method of asymptotic approximations) in [11] and the effect of wave interference at a large distance from wave source in the case of catamarans [12, 13]. These results have been supplemented by studies [14, 15].

In this study, we have made an attempt to develop a physical model of bank slope deformation in a channel bend and considered the main features of a curved flow with the aim to further apply it to permafrost zone conditions for the case of a channel constricted by freezing.

2. Materials and methods

The factual data were the results of laboratory experiments in the hydraulic laboratory of RUDN on a circular installation, which reproduces the flow motion in a curved channel. To indicate the erosion, the opposite slopes were marked by a thin layer of dyed (red) sand. Such studies were pioneer for the laboratory conditions.

The present-day literature on channel flow dynamics [16] gives a rigorous explanation of the formation of lateral circulations in a river flow. The formation of such circulations is attributed to the mechanism of the effect of the Coriolis acceleration transfer onto elementary water volumes in a flow through a pressure gradient caused by a lateral slope (and constant in the vertical direction) and the difference between the shearing stresses caused by the difference in vertical flow velocities at the sides of elementary water volumes. In a channel bend, the normal acceleration plays a role similar to that of the Coriolis acceleration.

A turn causes a redistribution of velocity over the vertical and horizontal directions in the flow cross section. Figures 1 and 2 show the directions of velocity vectors and flow lines in a curved flow obtained with FemLab software. Analysis [17] shows that, because of the transverse slope of water surface, the maximum velocity in the beginning of the flow shifts toward the inner (convex) bank. Within the curved segment, the exchange of momentum between the planar flow jets caused by transverse circulation results in a redistribution of velocities with the maximum velocity gradually shifting toward the external (concave) bank. At the exit from the curved segment, where the centrifugal force and the transverse slope have no effect, the vertical with a maximal velocity keeps at a continuation of the concave bank over a considerable distance.

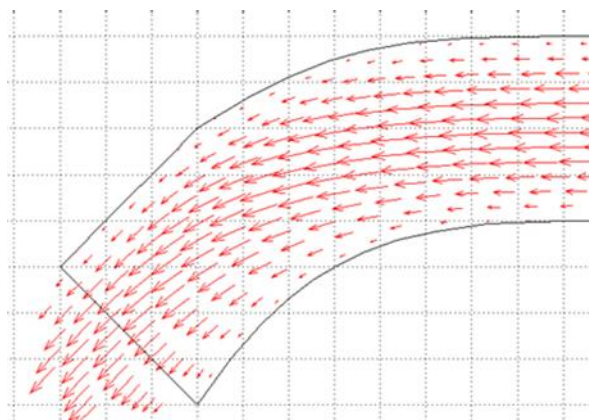


Figure 1. The directions of resultant flow velocity vectors at a bend.

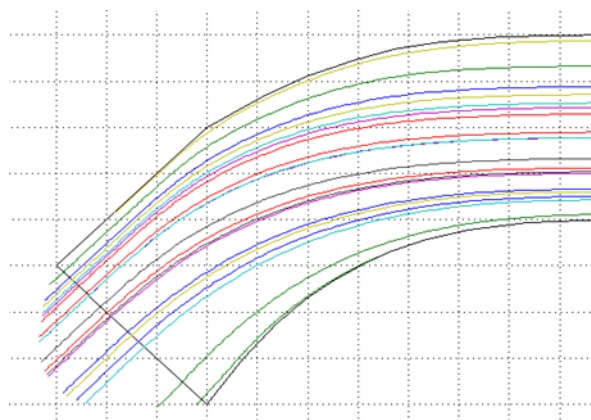


Figure 2. Flow lines (equal-velocity lines) in a curved flow.

To study ship-induced waves and their effect on permafrost bank deformations, *theoretical* studies of the conditions of formation and propagation of such waves were combined, in particular, with the flow approach angle taken into account, and the existence and preservation of the profile of bank dynamic equilibrium was analyzed.

The along-bank energy flow, generated by oblique waves, is a key advection mechanism of dissolved and suspended matter in the near-bank zone; it plays the main role in the formation of sediment flow along the bank. The length of the flow depends on the character of the bank-line contour and its width is determined by the scale of the width of the inshore zone within which the flow originates and from where it diffuses into nearby domains.

Longuet-Higgins [18] found a theoretical distribution of flow velocities for regular waves propagating at a small angle with respect to the bank in shallow water over a flat inclined bed. The coefficient of horizontal exchange (eddy viscosity) in an inshore with a monotonically rising bed was determined with the use of the relationship $\nu_l \sim gHT$, where H and T are wave height and period. This relationship shows that the flow velocity is directly proportional to the bed slope, which determines the dissipation rate, the sine of the wave approach angle, and the square root of the collapse depth, which largely depends on the initial wave height.

3. Results and discussion

Experiments were carried out to determine the erosion of the inner and outer banks in a circular flume (the inner radius of 35 cm and the outer radius of 75 cm). Organic admixtures in the material (sand) were used to visualize the surface velocity profile in the flow segment (figure 3).

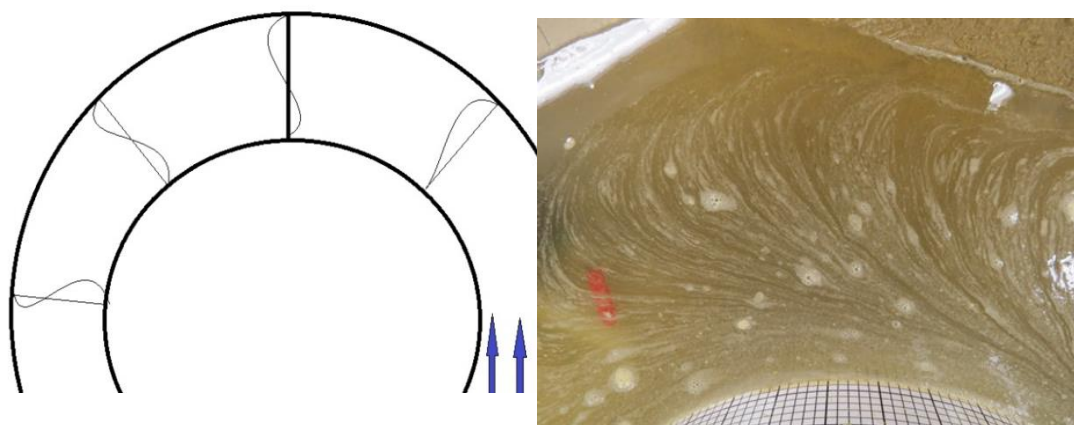


Figure 3. Velocity surface profiles in a flow in a bend (in a circular flume).

A counterflow with separate vortices was found to form at the inner boundary of the flow. With water removed, it could be seen that the effect of flow on different slopes was different---on the outer (concave) slope, at an above-critical flow velocity, distinct ridges had formed; while no ridges had formed in the inner slope, thus implying that the velocities on that slope were enough for erosion but not enough for ridge formation. The erosion of the lower part of the inner (dyed) slope was greater than that of its upper part, thus reflecting an increase in the velocity module with a constant gradient from the surface to the bed in this segment. All this allows a conclusion to be made regarding the character of velocity distribution in the curved flow (figure 4).

Flow transporting capacity in a bend

Thus, an increase in flow velocity in a bend inevitably causes, which has an effect on the character of transported sediments. V.K. Debol'skii [19] obtained a formula for the carrying capacity of water flow taking into account variations in ice content:

$$S_{tr} = 2.4 \times 10^{-3} \frac{U^3}{ghw}, \quad (1)$$

where S is flow transporting capacity, U is the average flow velocity, h is flow depth, w is the hydraulic size of unfrozen material. The countercurrent velocity on the slope at depth h is determined by the relationship:



Figure 4. Channel view before and after the experiment.

$$U = \frac{5\pi^2 H^2}{4TL \operatorname{sh}^2 kh} \sin \varphi \quad (2)$$

H is wave height and L is wave setup length.

In the general case [17], velocity distribution over flow width (in cylindrical coordinates) at the entry into a bend outlined by an arc of the circle, can be written as

$$v_{\theta} = \frac{1}{r} \sqrt{\int r^2 \frac{d(v_0^2)}{dr} dr} + c, \quad (3)$$

where r is the larger radius, v_0 is the vertically averaged velocity before the bend; v_{θ} is the corresponding velocity within the bend, θ is an angle measured from the beginning of the bend.

The constant c can be determined from the continuity conditions, i.e., from the equality of water discharge rate Q before the bend and within it:

$$Q = \int_{r_{in}}^{r_{out}} v_0 h dr = \int_{r_{in}}^{r_{out}} \frac{h}{r} \sqrt{\int r^2 \frac{d(v_0^2)}{dr} dr} + c, \quad (4)$$

where r_{in} and r_{out} are the radiuses of the convex and concave banks, respectively, h is the depth along the vertical.

Ship wave effect

As it has been proved in [20], the propagation velocity of the transverse waves that form at the motion of a ship is equal to the ship velocity. In [21], a relationship has been obtained for the angle at which ship-induced waves are propagating at the moment of their formation:

$$\theta = \frac{1}{2} \arcsin\left(\frac{4y}{V_c t}\right), \quad (5)$$

where V_c is ship velocity; t is time, y is the distance from the ship to the bank;

The domain of admissible arguments of arcsine is $-1 \leq \frac{4y}{ct} \leq 1$, or $t \geq \frac{4y}{c}$. It is starting from this time (not earlier) that the waves from the ship start reaching the bank.

Also, the approach angle of ship waves to a linear bank was calculated in [22]. In the case of a curved river segment, this angle can be found from the theorem of sines: the sides of the triangle are proportional to the sines of the opposite angles. In our case, the sides are the radius of curvature of the external (concave) bank R_{out} and the radius of curvature of ship trajectory R_{sh} (see figure 5):

$$\frac{R_{out}}{\sin(90+19^\circ 28')} = \frac{R_c}{\sin \theta} \quad (6)$$

Whence $\sin \theta = 0.94 \frac{R_c}{R_{out}}$

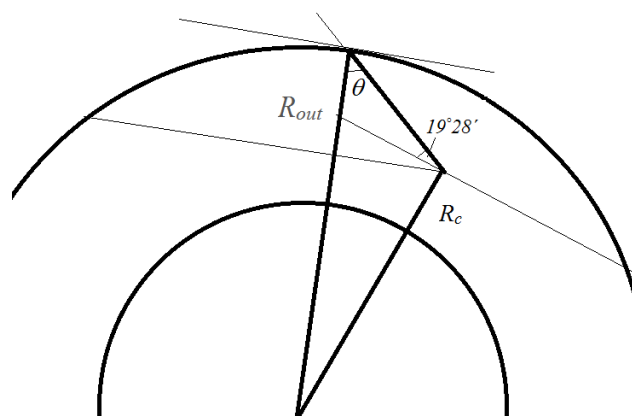


Figure 5. Calculation of ship wave approach to a curved bank.

As can be seen from the figure, the outer bank suffers the impact of ship waves in practically all cases, while these waves reach the inner bank along the frontal direction, though with a delay, with a part of their energy lost in their way.

4. Conclusion

Bank erosion in permafrost zone takes place because of the motion of the flow proper and the waves caused by ships.

A system of equations has been obtained for calculating the rate of erosion of a concave bank and the erosion plus aggradation of the opposite, convex bank.

The ship waves impact the outer bank in almost any case in the passage of the ship, while such waves reach the inner bank with a delay, with a part of their energy lost in their way.

In combination with the equation of erosion of frozen banks obtained before, a model has been proposed to describe the joint effect of a flow on curved banks, including in the process of rock thawing, and the impact of ship waves, depending on ship motion parameters.

The obtained formulas describe the velocities on stream surface and can be applied in the case of a laminar flow. In the case of an increase in the Reynolds number and the formation of vortex motion and countercurrents at the inner slope, the problem requires further studies and treatment.

Acknowledgments

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