ICE JAMMING STUDIES AND EFFICIENCY OF PROTECTIVE MEASURES ON THE LENA HYDRAULIC MODEL AT LENSK

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ABSTRACT

Results of the hydraulic modeling of the jam formation on the Lena river scale model at Lensk are presented in this paper. Regularities of the formation of the water surface longitudinal profile within the river reach under study in relation with the ice jam location to the town, ice volume and water discharge are investigated in the experiments using the ice substitute material. Ice jam stability by various by various obstacles for ice run at various water discharge and means of the artificial impacts on the ice jam formation is evaluated. After – effects of the premature destruction of the ice accumulation and forms of the breakthrough wave, in case of the channel with the free of ice and unbreaked ice surfaces are identified.

INTRODUCTION

Catastrophic floods on the Lena river at Lensk in 1998 and in 2001 in particular caused great damages. Though Lensk is being constructed after the floods on a more elevated site and a dyke is being built around the town there is still a danger of water overflow in case of water level in the river close to the highest one of 1% probability of exceedence (Rozhdestvensky et al., 2003). This causes a necessity of more detailed studies of reasons and conditions for extreme floods, improvement of methodology of such floods prediction and development of new technologies to affect ice jamming and to mitigate a possible damage. It was attained in 2003 at the State Hydrological Institute by making numerous laboratory experiments on ice jam formation and on efficiency of protective measures using a big scale hydraulic model of the study reach. A theoretical analysis and statistical processing of observation data from the ROSHYDROMET hydrological network, were also made.

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MODEL STUDIES AND ANALYSIS

Similarity criteria were observed on the model during studies; these criteria made it possible to recalculate model values of different characteristics of the process to field values. These studies provided a solution of several problems. Firstly, the process of water surface profile was studied on the specified river reach at different sites of ice jamming relative to Lensk, water discharges and ice volume contributing to ice jamming; conditions of water overflow across the dyke crest were estimated. Secondly, a stability of ice accumulation was investigated during ice storage at various obstacles at different water discharges and ways of artificial impact on ice jams to estimate efficiency of certain measures to affect ice jams. Thirdly, durations of ice jamming and formation of backwater prism were determined; assessment of the results of a premature ice storage destruction was made; the nature of water wave propagation after its break through the ice jam down the river free from ice and in case of undisturbed ice cover as well as individual ice floes was estimated. The latter problem also envisaged clearing up of the efficiency of the water wave break-trough the ice jam as a means of an active human impact on the ice coverage of the river and getting information on possible (or impossible) water overflow across the dyke around Lensk if an artificial ice jam is created at Polovinny Island upstream Lensk (Fig. 1). About 80 experiments were made to study the above problems.

The model was calibrated on the basis of data on field water surface slopes measured during channel surveys at mean water discharge of 2500 cu. m/s and water level of 153.22 m (Baltic System) at Lensk. As maximum water levels caused by ice jams were in a good agreement with the observed data, it gave ground to assume that processes simulated on the model were adequate to natural processes.
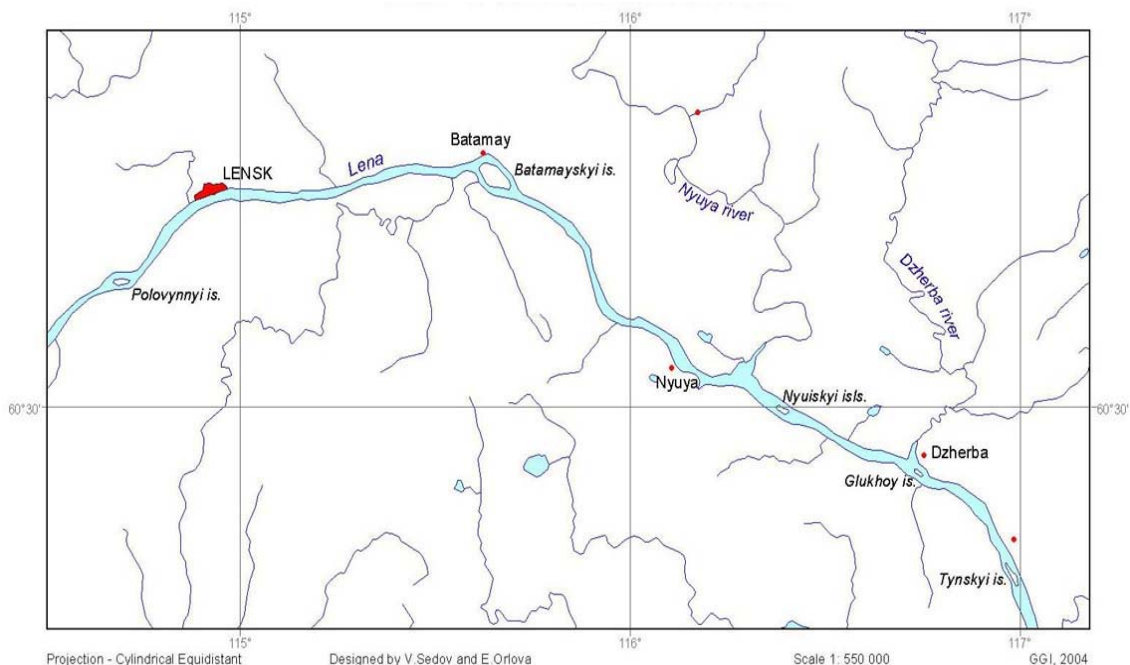

Fig 1. Map of the Lena River at Lensk

Water flow in the channel was simulated with the account of two conditions, i. e. equality of field and model Froude numbers $Fr = idem$ (criterion of dynamic similarity) and the provision of Reynold's number values exceeding its critical value $\mathrm{Re}_m \succ \mathrm{Re}_{cr}$ (criterion of cinematic similarity).

Proceeding from the Froud equation, with the account of geometric (horizontal and vertical) scales of the model the following scale multipliers were derived for a recalculation of model values of different characteristics of water flow and channel into their field values:
1000   for lengths and widths
250   for elevations and depths
250000 for cross-section areas
15.81   for flow velocity
63.25   for time
0.25   for slope.

The basic condition followed during ice modeling was as follows:
$\rho_i / \rho_w = idem$, where: ρ_i is natural ice density; ρ_w is water density. Taking into account that natural water occurs in the channel and on the model the above ratio shows that densities of natural ice and ice imitator on the model are similar.

Other ice properties (strength, plasticity, etc.) could not be simulated on the model.

Sheets of white polyethylene of mean density of 0.93 g/cm^3 were used as ice imitator on the model; its density varied within 0.92-0.95 g/cm^3. This material is often applied for ice processes simulation and the obtained results give grounds to assume that it is a good ice imitator. Density variations within the above limits make no trouble because the natural ice density is subject to variations, too, during spring warming in particular.

Polyethylene square plates with lateral sides of 5, 10 and 20 cm and 0.5 or 0.6 cm thick were used during the experiments, which corresponded to the size of ice flows of 50x50 m, 100x100 m and 200x200 m in area and ice thickness of 1.25 m and 1.5 m.

Ice fractions used during the experiments were based on the analysis of video film about ice drift on the Lena river. Ice floes size was selected to reproduce a situation resembling natural ice drift. Ice floes of 5x5 cm (70% of the total number of ice floes) were taken with water discharges within 3000-8170 m^3/s. Ice floes of 10x10 cm made 30% of the total number of ice floes. During the experiments with water discharges of 12000 m^3/s and 22900 m^3/s the following percentage was accepted for ice flows of different sizes contributing to the ice drift: 5x5 cm – 60%, 10x10 cm – 30%, and 20x20 cm – 10%.

Ice-conveyance capacity on the channel at the sites of ice jamming was tested for four water discharges (3000 m^3/s, 8170 m^3/s, 12400 m^3/s and 22900 m^3/s). The following methodology was applied. When the required water discharge was attained a layer of ice was delivered to the river reach upstream Lensk. When the required ice mass was distributed over the water surface, the clutching device was taken away and a free

downstream motion of the ice layer began. The whole process of ice floes drifting and a subsequent ice jamming were fixed by a camera and video camera; thus it was possible to follow and analyze the processes many times.

Twenty combinations of basic factors were reproduced on the model. Time of the experiment was preliminary estimated from the data on real ice jams observed on the study Lena reach. Ice jam duration at Lensk never exceeded 4 days during the whole period of hydrological observations. Proceeding from this duration, every experiment continued until the backwater level attained its extreme level, without rising any longer. Thus, the obtained duration of the experiment appeared to be close to field data being one more indicator of a good agreement between model and natural processes. The following methodology was applied during the experiments. The required water discharges and marks of free water surface (for the case of a channel free from ice) were fixed on the model. Then, the ice cover was produced within the reach of Batamaisky Island (either at its upstream extremity, or at its downstream extremity, or 50 km far from the hydrological station at Lensk). This ice cover was imitated by a polyethylene sheet of an appropriate thickness. The coastal facet of the sheet corresponded to the river bank shape. As a result, the mechanism of ice jamming was discovered qualitative by; quantitative assessments were made for backwater levels in different initial situations, for intensity of backwater level rise, and for changes in water surface profiles up to extreme position in finally produced ice jams.

It was noted that ice reefing initiated at the edge of the undisturbed ice cover is spread quite intensively upstream the river which was the result of constant compression of ice due to shoves. As a result, the multi-layer accumulation of ice is transformed into a one-layer cover. As the distance between the ice cover edge increases upstream, ice reefs and number of layers in ice accumulation tend towards decrease, though they are still great.

On the basis of data on water levels produced by ice jams and appropriate water discharges, $Q = f(H)$ curves are plotted for three positions of undisturbed ice cover edge (Fig. 2). According to Fig. 2, a double increase of ice volume causes the rise of water levels by 3 m and higher within the range of water discharges from 8000 m³/s to 23000 m³/s; in the upper part of the curve the water level rise equals 5 m. Powerful ice jams at Lensk accompanied by high water level rise and flooding of the floodplain in the left and right banks are formed in case of high water discharges produced by ice jams and in case of great ice volumes contributing to ice jam formation. The location of the ice jam may be different. But the highest water level at Lensk up to the level mark of 174.2 m (BS) was caused (according to the experiments) by the ice jam produced by ice volume of 0.2 km³ at water discharge of 22900 m³/s and the position of the undisturbed ice cover edge at the upstream extremity of Batamaisky Island (Fig. 3). If water discharge equals 8170 m³/s and ice volume equals 0.2 km³, the water level is high in the river but it does not exceed the dyke crest at the elevation of 170.17 m (BS). But at the same volume of ice mass, water discharge of 22900 m³/s and the ice jam formed at Batamaisky Island the town is flooded.
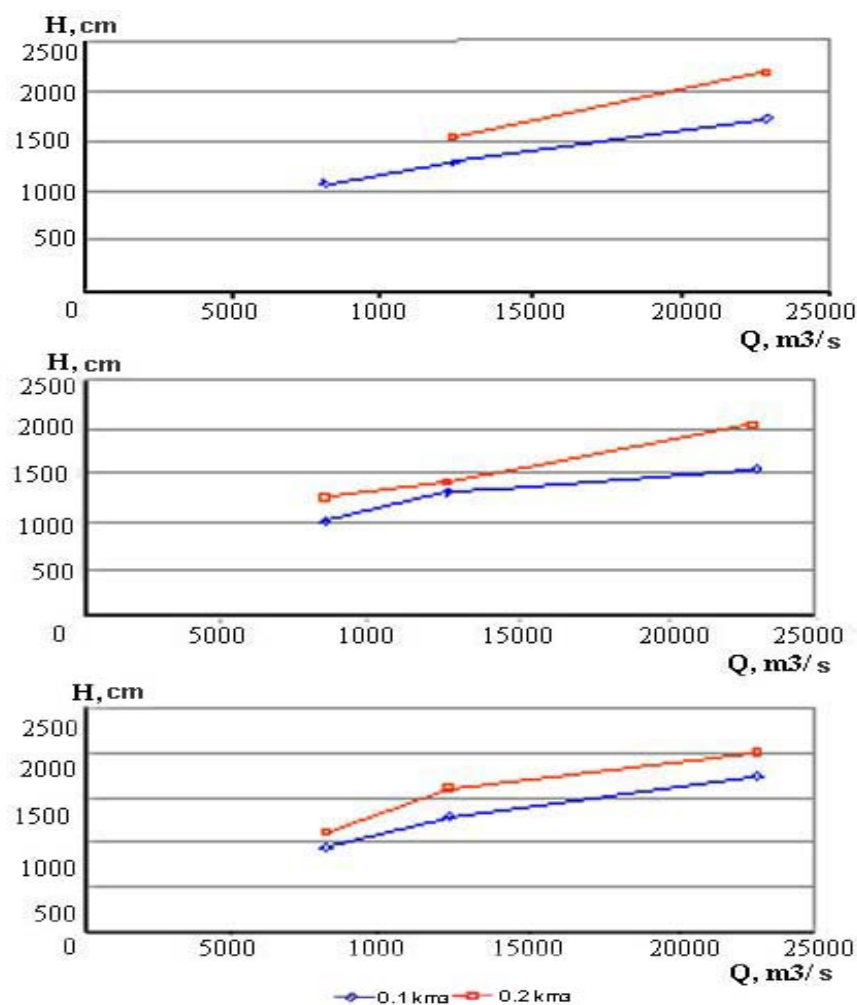
Fig. 2. Stage – Discharge Curves Q= f (H):
a - Upper edge of Batamaisky Island*; b* - Nail of Batamaisky Island;
c - 50 km downstream Lensk.

Assessments made on the intensity of water profile changes in time lead to a conclusion that the maximum increment of water level is observed during the first day of ice jamming and varies from 2 m to 5 m.

The following protective measures were simulated on the hydraulic Lena model:
- control of water discharges at the reach of channel separation into arms at Batamaisky Island;
- decrease of ice cover strength by ice cutting into different fragments of various shapes;
- creation of artificial ice jam at Polovinny Island.

The channel separated into two arms at Batamaisky Island is the most probable site for ice jamming. Meanwhile, this is the site where rocks are spread close to the channel bottom. Therefore, channel dredging, its straightening and widening at the sites of channel contraction are too costly; therefore, water discharges were controlled only by blocking the left arm.
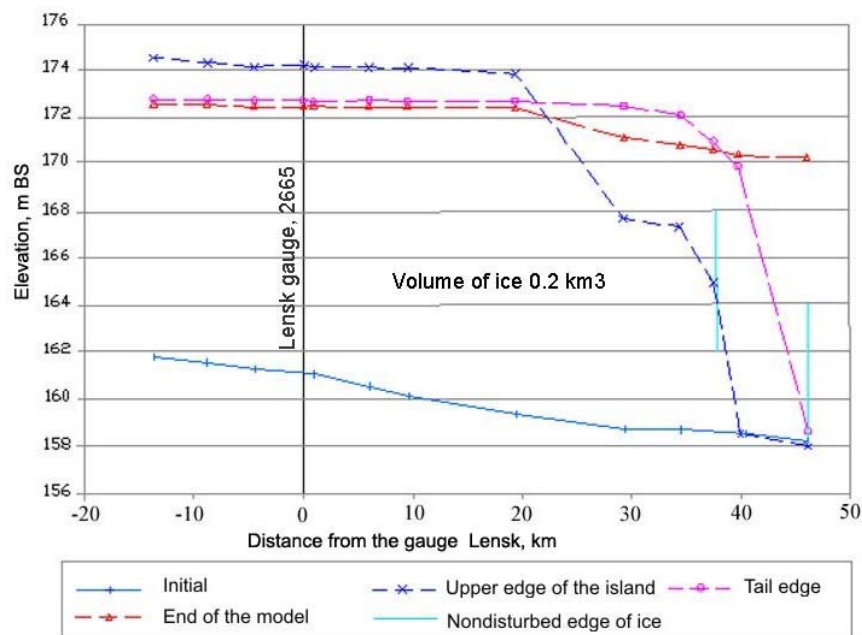
Fig. 3. Water Level Profiles of Water Level on Hydraulic Model of the Lena River Under Ice Jams Formed at Different Locations of the Ice Cover Edge and Q = 22 900 m³/s

Experiments show, that ice accumulated in the right arm comes into motion and flows downstream. After some time, however, mother ice jams are formed in the right arm because of ice accumulation at the river bend to the left and at the upstream extremity of Batamaisky Island. A positive result was not achieved in spite of almost doubled water availability in the arm, increase of its depth and higher flow velocities. It means that probably specific features of channel morphology (meandering, contractions and shoals) produce more effect on ice motion but not the amount of water in the channel. As channel morphology cannot be changed in this particular case, channel changes are not recommended protective measures against ice jams.

Ice jam destruction by explosions has been practiced in the Lena river during several years. This is used in extreme situations when there is a danger of flood damage for population. Appropriate experiments were made on the model to imitate explosions from the surface and under ice. These explosions were simulated mechanically by making square stamps 5x5 cm and 10x10 cm, which corresponded to 2500 m² and 10000 m² under natural conditions. It was assumed that an explosion within such areas would make holes and would move ice accumulation downstream, where the river is free from ice or where ice cover is not thick. On the model these holes were made by sudden pressing onto the stamps in case of surface explosions or by a rapid pulling them out in case of explosions under ice cover. Such «explosions» were made across the downstream edge of the ice jam and along it.

Surface explosions appeared to be useless because ice floes at the head of ice jam fill the channel up to its bottom and simultaneous explosions across the river do not cause ice motion. When explosions under ice were imitated across the channel, many ice floes

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were thrown away and water areas free from ice were formed. But the whole stability of ice jam was not disturbed. Explosions under ice made along the profile were more effective, water was released through the ice jam and caused water level fall. The so-called «drainage path» was formed in the ice jam after such explosions making an intensive water diversion from the ice jam.

Explosions, however, are extremely dangerous for the environment. Therefore, it is more reasonable to cut the ice cover into different fragments during the period of a complete ice coverage. A series of experiments was made in hydraulic flumes to determine the most applicable shapes of ice cover cutting. The most effective variant was tested on the space hydraulic model. The idea was to cut the ice cover into diamond-shaped and triangular pieces and to make slots in the ice along the banks; the cut ice field might be affected by water flows through these slots and move them downstream. The right arm at Batamaisky Island is curvilinear and slots were curvilinear, too. In the left arm the slots were rectilinear and parallel to each other. Ice fields composed of such fragments were kept afloating by special sticks. Coastal slots were held by other sticks with metal pins inserted into openings in the pins. Then, an ice drift was simulated upstream and the drifting ice came into contact with the model fragments.

Gradually, these fragments moved downstream; the drifting ice followed them. At the sharp turn to the left (in the right arm) triangular and diamond-shaped fragments were subject to self-jamming resulted in ice accumulation. After some time, the right arm was blocked. The same situation was observed in the left arm a bit earlier. Thus, even the most effective cutting of the ice cover did not produce desirable results. It is possible to cut the ice cover into smaller fragments (may be twice smaller) but this would make the preparatory protective measures too costly.

Under the influence of the flowing water ice fragments join together again and can freeze-up in case of air temperature fall. Therefore, it is better not to cut ice into fragments but to make narrow trenches in the ice cover and fill them with sodium chloride to get an eutectic mixture with the constant temperature of ice melting of – 21.2^0 C thus decreasing the ice cover strength.

In (Faiko, 1972) it is noted that a reliable protective measure against an ice jam to make an artificial ice jam on the river upstream the place to be protected. Therefore, a removable dam was made on the hydraulic model at the downstream extremity of Polovinny Island. It initiated an ice jam on the ice cover in front of which an ice jam was to be formed. Considering the morphology of river channel and floodplain within Polovinny Island, the water level upstream the artificial ice jam was raised to the mark of 167.0 m (BS). The experiment was repeated several times by releases of water mixed with ice to water areas free from ice and to water areas with ice floes. The results of these experiments demonstrate a perspective use of this method to protect Lensk against flooding.

Then, the artificial ice jam was exploded; a water wave rushed through the ice jam, rapidly reducing in height; therefore, at the initial water level of 167.0 m (BS) at the artificial jam near Lensk the wave crest was at the level of 165.0 m (BS) at water

discharge of 22900 m^3/s, which was 2 m lower than the crest of the dyke around Lensk. The positive result is most probable when the channel downstream is free from ice.

Considering different projects to protect Lensk against ice jams, it is quite reasonable to turn to the problem of dyke reconstruction by making it at least 0.5 m higher than the water level observed in 2001. To avoid negative effects for the town (worse air circulation in the town, its greater separation, etc.) if the dyke is higher, this additional part of the dyke may consist of separate shields connected with the main dyke by special joints and placed horizontal on the dyke crest in case of a favourable situation. When the situation is dangerous for the town, the shields are to be raised and fixed vertically by special supports; the vertical sides of the shields are to be connected by rubber seals to avoid leakage, Of course, there may be other alternative measures to protect the town.

CONCLUSIONS
The following measures against ice jamming were simulated and studied on the scale hydraulic model:
- control of water discharge on the reach of channel branching at Island Batamaisky 40 km downstream Lensk;
- decrease of ice cover strength by cutting it into pieces of different shapes;
- creation of an artificial ice jam 20 km upstream Lensk.

The results of the experiments show that the artificial ice jam upstream Lensk is most promising measure to measure Lensk against overflow.

The use of fore casting data on the maximum water levels caused by ice jams would greatly reduce the cost of anti-jamming measures and increase its efficiency.

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