

# RESEARCH on EROSION OF CONSOLIDATED and semi-consolidated SOILS BY HIGH SPEED WATER FLOW

Guy Berthault<sup>1</sup>, A.B.Veksler<sup>2</sup>, V.M.Donenberg<sup>2</sup>, A.V.Lalomov<sup>3</sup>

<sup>1</sup> 28 boul.Thiers, 78250, Meulan, France.

<sup>2</sup> Vedeneyev Russian National Research Institute of Hydraulic Engineering (VNIIG), St.-Petersburg.

<sup>3</sup> Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of Russian Academy of Science (IGEM RAS), Moscow.

Estimation rate of erosion of consolidated soils is an important practical problem in design, building and exploitation of hydrotechnical constructions. It also has very significant importance in the field of sedimentology for reconstruction of hydraulic conditions of paleobasins.

Analysis of existing methods applied to estimate the onset of consolidated soil erosion caused by water flow shows that the methods now in use provide a certain knowledge of conditions under which erosion of cohesionless (sandy, pebble gravel) and cohesive (clay, sandy loam, clay loam) consolidated soils starts under impact of a flow the speed of which does not exceed 2.5 – 3.5 m/s [1–3].

The data on interaction of flows running over rock and semi-solid rock channels were used only in theoretical considerations related to the effect of both rock block sizes and conjugated fractures dissecting rock mass on the critical erosion velocity responsible for the beginning of the erosion process [4].

Experimental evidence of the obtained results turned out to be presented by fragmentary and accidental field data usually of a roughly approximate nature with no information on hydraulic conditions, i.e. on velocities and depths of the flows involved in erosion process [5–7].

Similarly, the field data do not allow us to evaluate conditions of destruction of rock channels and formation of erosion pools in lower pools of by-washes of large dams, since the researcher knows only the end result, that is, the outline and depth of erosion pools after the flow impact has already taken place [8,9].

Besides, specific conditions of channel erosion under falling flow action essentially differ from the conditions of soil erosion produced by water mass moving over the soil surface.

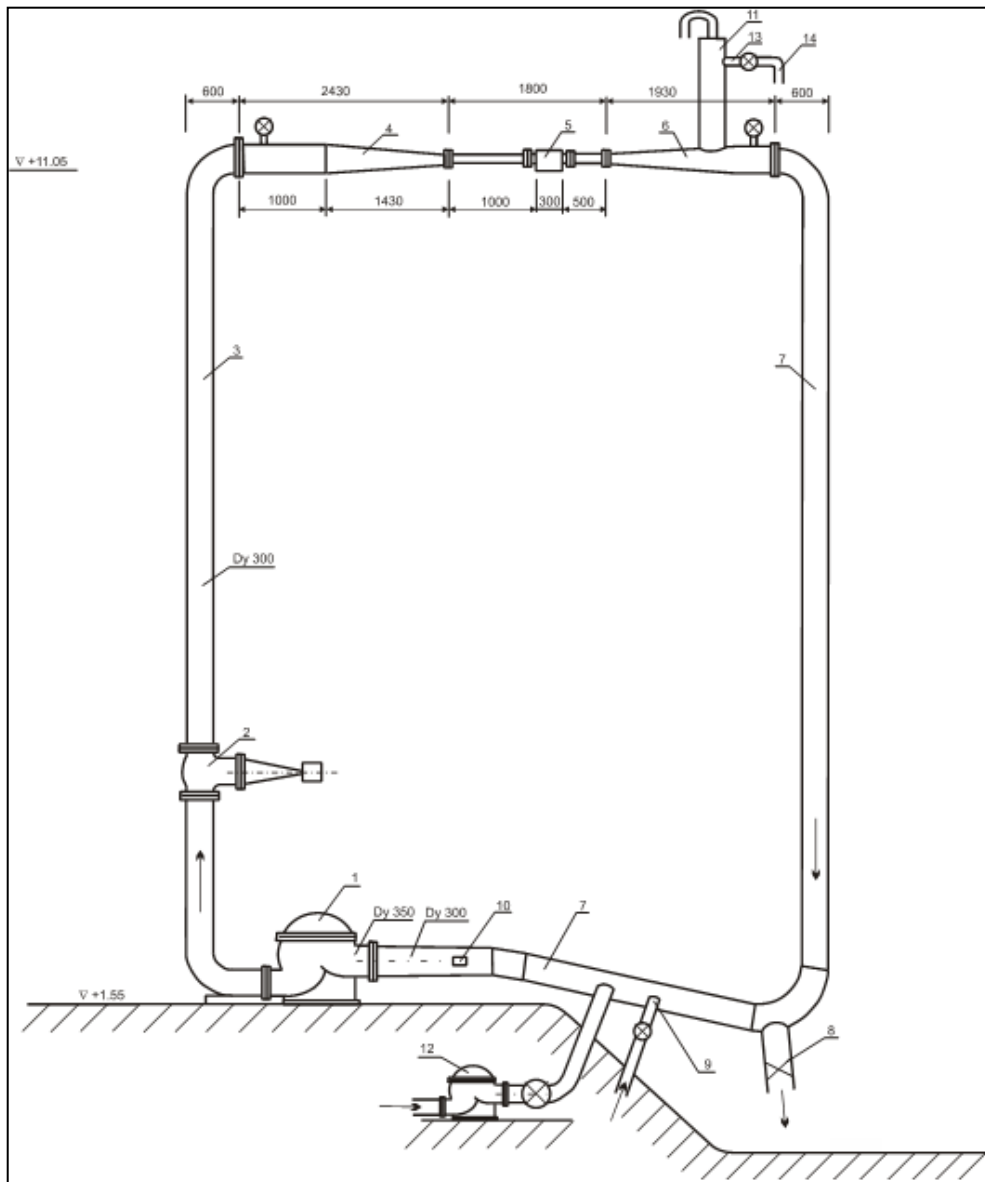
Scientific findings of the work are connected with an attempt to determine erodibility for some types of consolidated (semi-solid) rocks under impact of high-speed flow moving over their surface.

So as to perform scientific experiments on erodibility of consolidated soil under impact of the high-speed water flow a closed loop circulation hydraulic high pressure pipe system has been designed and built; the installation is provided with a right-angled cross section of 29.5 cm<sup>2</sup> where an average flow speed can reach 27 m/s.

The installation is a closed hydraulic system located in a vertical plane (Fig. 1), which consists of: 200 kw pump unit - 1 (1D1250-636); pressure pipeline with electrically driven control valve – 2 water supply pipe – 3 front transition area - 4 (confuser); working area - 5 of the installation; back transition area - 6 (diffuser); return pipeline -7 outlet branch to discharge water from the system – 8 feed pipe to fill the system – 9 device to measure and control water discharge -

10. An expansion unit –11 is installed within the back transition area 6 to provide vacuum braking action.

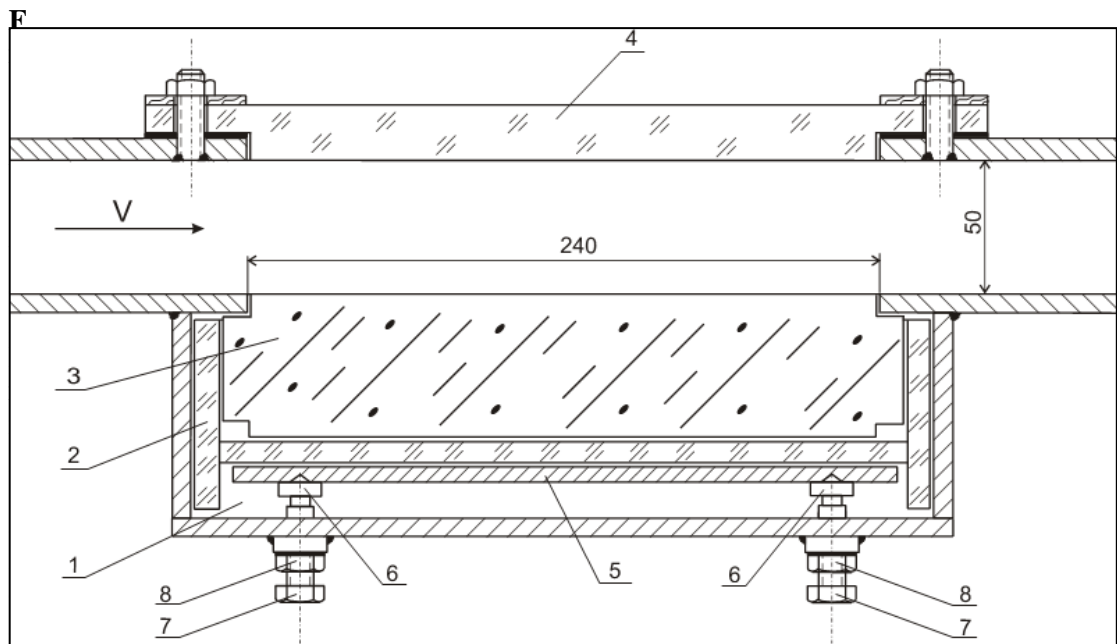
Working area 5 of the installation is a pipe of rectangular section of 290 mm in width and 50 mm in height. A symmetric rectangular cut-out 240 mm long and 200 mm wide is made in the middle of the working area (Fig. 2); a holder for a container with a researched sample is located under the cut-out. The surface of a researched sample is set flush with the bottom and the lower surface of watch window set flush with the top of the working area of the pipe. When carrying out experiments the water discharge in the closed hydraulic system was measured with a portable ultrasonic flow-meter-counter “VZLET PR”. Water flow velocity within the working area was calculated by water discharge according to the flow-meter readings and cross-section square in the working area.



**Fig.1. Schematic view of the installation for soil erosion rate research.**

1- pump; 2 – control valve; 3 – water supply pipe; 4,6 – transition areas; 5 – working area of the installation; 7 – return pipeline; 8 – outlet branch; 9 - feed pipe to fill the system; 10 - device to measure and control water discharge; 11 - expansion unit; 12 – auxiliary pump; 13 – branch pipe; 14 – hose to discharge cooling water into the reservoir;

Horizontal dimensions are given in mm, vertical dimensions (marks) – in m.



**Fig.2. Working area of the installation.** 1 - chamber of working area, 2 - container, 3 - sample tested, 4 – inspection window, 5 - elevating plate, 6 - centering bush (4 pieces), 7 – hold-down screws (4 pieces), 8 - safety nuts (4 pieces). Dimensions are given in mm.

Soils for experiments were collected on the banks and slopes of the Tosna river valley (Leningrad region). A total of five semi-solid rock separations were selected: three separations of limestone and two of sandstone which were used to make the samples fit the size of the chamber of the installation working area.

The basic physical and mechanical characteristics of researched soils as established by the personnel of the VNIIG laboratory of Engineering Geology and Permafrost Study are given in Tabl.1. According to classification of GOST 25.100 - 95 [10] all samples are classed as rock type, though V.D.Lomtadze's classification given in the textbooks for high school education [11] suggests that samples 1 and 4 are referred to as semi-solid type and samples 2, 3, 5 – as rock type.

The greatest compression strength is shown in sample 5 - calcareous fissure-free dolomite (it also has the greatest mineral density, least porosity and greatest rock density). The least strength in sample 4 – weathered, brown, glauconitic sandstone.

Sample 1 is fissured, light grey, obolus sandstone which only slightly differs in its strength properties from sample 3; the latter is rosy-grey dolomitic limestone with rare large pores. Sample 2 is rosy-grey, dolomitic limestone which is intermediate in its strength properties between samples 3 and 5.

Tabl.1. Physical and physico-mechanical properties of consolidated soils from the valley of Tosno – river (Lower Ordovician)

No of sample	Consolidated soil	Mineral density, $\gamma, g/cm^3$												
			Density of soil $\delta, g/cm^3$	Total porosity, n%	Open (communicating) porosity $n_{open}, \%$	Velocity of longitudinal wave $V_{P(XY)}, m/s$	Velocity of transverse wave $V_{P(Z)}, m/s$	Coefficient of anisotropy $K_a = \frac{V_{P(XY)}}{V_{P(Z)}}$	Compressive resistance along Z-axis, $R_{c1}, MPa$	Dynamic coefficient of Poassone, $\mu_D$	Dynamic modulus of elasticity $E_{D(Z)}, MPa$	$\delta, g/cm^3$	Water absorbing W, part of unity	Coefficient of soaking $K_S = \frac{R_{c2}}{R_{c1}}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Light-grey fissured obolus sandstone	2,65	2,46	7,2	4,0	3130	3310	0,95	20	0,15	12300	2,50	0,016	0,65
	Fissure-free zones					4470	5100	0,88	60		29200			
2	Pink-grey dolomitic limestone	2,75	2,63	4,4	4,0	5260	5070	1,04	60	0,24	27700	2,67	0,015	0,75
3	Pink-grey dolomitic limestone with large rare pores	2,73	2,49	8,8	6,0	5380	5170	1,04	65	0,24	27300	2,55	0,024	0,60
4	Weathered brown glauconitic sandstone	2,65	2,23	15,9	5,0	2920	2650	1,10	15	0,20	6800	2,28	0,023	0,46
5	Calcareous fissure-free dolomite	2,88	2,81	2,5	2,0	6110	4730	1,29	90	0,26	25000	2,83	0,007	0,84

Notes:

1.  $V_{P(XY)}$  – Velocity of longitudinal wave along stratification in horizontal direction;  $V_{P(Z)}$  – Velocity of transverse wave across stratification in vertical direction;
2. Data in the columns 3, 11 are obtained from reference book for analogue soils; column 10 – from correlation connection  $R_c = f(V_p)$ , column 15 – from correlation connection  $K_p = f(n)$  for analogue soils; the other columns are compiled from experimental data;

Erodibility of soil samples under impact of water flow was estimated visually and determined instrumentally as a difference in their masses before and after the experiments. In this case two methods of weighing were used:

- Weighing a water-saturated sample, i.e. a method of "wet" weighing;
- Weighing a sample dried to stabilization its mass either in conditions of an air-dry state (at room temperature and humidity), or in an electric drying box - a method of "dry" weighing.

In using the above "wet" weighing method the sample was first soaked in a vessel with water (provided that the sample had been in an air-dry state before the experiment) and was then placed in the container.

Weighing was carried out with a laboratory electronic balance "Shinko AJ-12KCE" (Japan) with the value of a scale division of 100mg.

In experiments 1÷16 at the same time as the method of "wet" weighing, the method of "dry" weighing of the samples reduced to a stabilized air-dry state was used in the following cases: sample 2 - after experiment 2, sample 5 - after experiment 4, sample 3 - after experiments 6, 13, 14, 15, sample 1 - after experiment 8, and sample 4 – after experiments 12 and 16.

Beginning with experiment 18 the only method used was the "dry" weighing method applied to the samples being dried in the electric drying box. At the first stage a preference was given to the "wet" weighing method (experiments 1÷16). It was thought that a sample first soaked for 1.5÷3.0 days at a pressure close to atmospheric pressure  $p = p_a$ , would be completely saturated with water, and its water-saturation would not change during the experiment. However, already the first experimental results argued against this assumption: the mass of samples after experiment was increased due to additional water-saturation under pressure  $p$ , which was essentially higher than atmospheric pressure  $p$ , and came up to about 3atm. in the chamber of the installation working area. This gave rise to the development of additional research on determination of dependence of water absorption per time under pressure and water loss after experiment. Obtained results permits development of a special method of calculation, which allows transformation of "wet" weighing results to "dry" weighing results. An absolute weighing error for the "wet" weighing method is  $\Delta w = \pm 5.0g$ .

The method of "dry" weighing is simple; it does not demand subsequent processing and can be used both for air-dry samples and for the samples which have been dried in the electric drying box. In this case the sample, as such, is weighed.

The only thing to be considered with heating a sample in the electric drying box is a dependence of its mass on temperature of heating. Usually the heating of sample in the electric drying box was carried out up to 68÷76°C and some times - up to 80-90°C. When a sample was allowed to stand overnight in the switched-off cooling-down electrical drying box the mass of the sample increased at the expense of the absorption of atmospheric moisture coming in the electric drying box through an opening for the thermometer. The difference of masses of the cooled down and heated up sample was, as a rule 1.5÷2.0g.

Information about the main characteristics of the experiments and the results obtained is shown in table 2. Results of the experimental series 16 and 17 are excluded from the table: because of technical problems the velocity of flow was not determined correctly.

Each sample of soil for testing has two flat surfaces which can be exposed to water flow impact. One of the surfaces was designated as side "A", another – as side "B" (column 2 of table 2). The

mass of sample 4 only changed once when it had broken apart at the first interruption of experiment 9 and then the parts were glued together by adhesive (plitonit) before experiment 16, so the mass and volume of the sample became different from those before experiment 9. A change of mass was taken into account in the later series of experiments. The sample 1 was glued by adhesive (plitonit) from the beginning of experiment.

Table 2. Basic characteristics, conditions and results of experiments

No of experiment	No of the sample and side	Dry initial mass (g)	Mass of the dry sample after experiment before stabilization (g)	Velocity of the flow (m/s)	Duration of the experiment (hours)	Loss of mass of dry sample ( $t^{\circ} = 18^{\circ}\text{C}$ )		Intensity of erosion $I = \Delta G / (\text{TF})$
						Visual	By weighing $\Delta G$ , (g)	
1	2	3	4	5	6	7	8	9
1	2;A	6759.8	-	25.9	13.2	No	-	0
2			6760.0	25.9	9.3		0	0
3	5;A	6571.3	-	25.8	8.2	No	-	0
4			6570.8	25.6	7.3		0	0
5	3;A	6631.2	-	26.0	8.0	No	-	0
6			6631.2	25.9	10.0		0	0
7	1;A	6322.9	-	25.8	13.5	Yes	(1.8)	2.78
8	1; B	-	6318.2	25.8	21.7	No	(2.3)	2.21
9	4;A	4802.8	-	22.5	10.5	Yes	(108.4)	215.08
10			-	17.3	15.0		(19.0)	26.39
11			-	10.9	16.0		(20.7)	26.95
12			4650.0	7.8	17.5		(4.7)	5.60
13	3;B	6613.6	6613.8	25.7	9.0	No	0	0
14	3c;A	6589.6	6589.5	25.9	5.7	No	0	0
15	3c;A	6589.6	6589.5	26.0	17.3		0	0
18	4к; A	4674.5	4673.0	5.5	18.0	No	1.5	1.74
19	1; B	6317.2	6315.1	25.9	18.0	No	2.1	2.43
20	4k; A	4673.0	4671.5	13.2	18.0	No	1.5	1.74
21	1; A	6315.1	6313.1	25.9	16.0	No	2.0	2.60
22	4k; A	4671.5	4669.0	19.6	18.0	Yes	2.5	2.89
23	1; A	6313.1	6311.2	23.8	18.0	Yes	1.9	2.20
24	4k; A	4669.0	4668.0	8.4	18.0	No	1.0	1.16
25	1; A	6311.2	6309.9	19.2	18.0	No	1.3	1.50
26	3c; B	5897.8	5891.2	20.1-25.8	18.0	No	6.6	7.84
27	3c; B	5890.9	5891.2	20.1-25.8	18.0	No	0	0

Notes: Values of  $\Delta G$  in brackets (column 8) were obtained by indirect way with wet weighing and coefficient of correction.

Sometimes changing in mass  $G_0$  during the experiments could not be caused by scouring of a sample; in other words, other factors were involved. In particular, sample 3 varied in mass three times:

- when removing sample 3 from the chamber of the installation working area after experiment 6, a sample fragment of 17.6 g in mass broke off; therefore initial mass and volume of this sample in experiment 13 respectively decreased in comparison with experiments 5 and 6
- before experiment 14 an artificial roughness was created on surface "B" of sample 3 by drilling hollows of 8-10 mm across and 4-6 mm deep spaced at regular intervals 30-40 mm over all surface "B", so the initial mass and volume of sample 3 in experiments 14 and 15 became less in comparison with their values in experiment 13;
- before experiment 26 one more artificial change in mass and volume of sample 3 was made by cutting its base on side "A" at an angle of about  $2.5^\circ$  and as a result the sample could be set in such a way that side "B" was inclined at the above angle to the bottom of the working area, with the depth of the flow decreasing downstream within the working area.

Artificial roughness on the surface B and inclination of the surface should result to increasing of erosion of the limestone. However, erosion was not observed in both cases. Erosion obtained by dry weighting in the series 26 loss of weight  $DG=6.6g$  was not confirmed by visual observation of the surface. Addition series 27 that repeat condition of series 26 confirmed absence of erosion. Apparently, result of series 26 could be explained by insufficient drying of the sample before series 26. Moisture in the laboratory also could exert influence on the weight of the sample after drying in electric box. It could have significant influence on the obtained dry weight (column 8 of table 2). This is obvious from the experiments with samples 2 and 3 (dolomitic limestone) and sample 5 (calcareous dolomite). In all the series of experiments visual erosion of the surface was absent, whereas in the results of series 1, 2, 13 and 27 an increase in the mass up to 0.3g was registered. The single reason could be absorbed water, because addition of the ground is excluded completely.

In the series 3, 4, 14 and 15 registered loss of weight was 0.5g for dolomitic limestone and 0.1g for calcareous dolomite. Visual observation did not confirm the erosion, so we believe that the loss is the result of changing of moisture in the samples, therefore in these series we took  $DG=0g$ .

Interpretation of the results of the weight of eroded samples of sandstones 1 and 4 is more difficult. The texture of the samples did not allow a reliable conclusion of erosion by visual observation. Therefore we did not use the correction on different moistures to determine  $DG$ , taking into account that it results in higher dispersion of the resulting data. In experiments 19 and 21, with the sample dried in the drying box before and after each experiment, the loss of mass of the sample from its both sides with the same flow velocities as in experiments 7 – 8, turned out to be practically identical: 2.1g - for side "B" (experiment 19) and 2.0g - for side "A" (experiment 21). Besides, there were no observable traces of erosion for evaluation.

This fact was taken into account in interpreting the results of series 7 and 8 that had the same conditions as series 1. In these series of experiments the loss in mass of sample 1 was 4.7g. By visual evaluation it was entirely attributed to erosion of a thin ( $\approx 0.5$  mm) layer of adhesive (plitonit) on the side "A" in experiment 7. The mass of eroded adhesive (plitonit) was assumed to be  $DG_{plit} \approx 0.6g$  with  $\rho = 1.5g/cm^3$  and with the area of erosion spot  $F \approx 7.5cm^2$  being taken on the basis of measurements of the spot. With this in mind the loss of "dry" mass of sample 1 in experiments 7-8 should be accepted as  $DG = 4.1g$ . Proceeding from this fact, the researchers

decided to distribute the corrected loss in the mass of sample 1 (experiments 7 – 8) proportionally to the time of action of the flow on the sample side facing this flow and to accept:  $DG = 1.8\text{g}$  (experiment 7),  $DG = 2.3\text{g}$  (experiment 8), with a slightly increased share of the mass loss for experiment 7 because in this case the erosion had been observed visually. Calculated value of  $DG$  is shown in parenthesis.

The results of measurements of mass loss in all experiments involving sample 1 were plotted against relevant flow velocities  $DG = f(V)$  (Fig. 3) to allow determination of the critical erosion velocity (non-eroding velocity) for the sample ( $V_{kr} \approx 11.0\text{ m/s}$ . in this case).

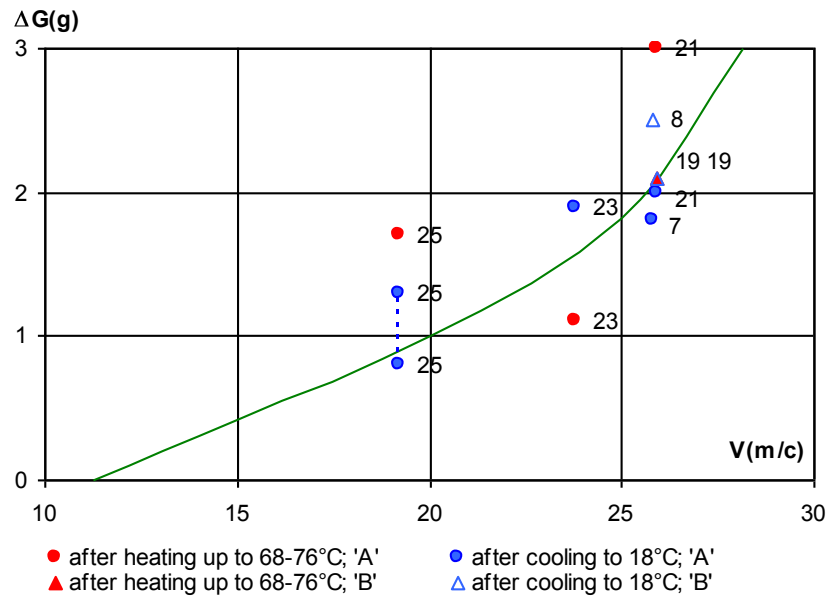


Fig.3. Dependence of loss in mass  $\Delta G$  of sample 1 on flow velocity  $V$ .  
7, ..., 25 - numbers of experiments

Visual examination showed that small inclusions of light sandstone (apparently more friable than the base rock) were subjected to scouring on side "A" of sample 1. The general area of the inclusions accounted for about 7 - 10 % of the area of side "A". Scouring of these inclusions became especially noticeable when the deepening that was formed was bordered by almost vertical edges.

To observe changes in topography of a sample surface during a single experiment was only possible in rare cases. As a rule, scouring was possible to detect only after several experiments conducted on a sample where the same side was exposed to the flow.

So, even with the large mass loss in the series of experiments 9–12, the visual examination of surface "A" (sample 4) showed traces of erosion only after 3 hours of experiment 9, sure confirmation by photo fixation appears after 25 hours of experiments (after series 10). Summary loss of dry weight of 152.8g was registered in experiment 12 of the final series. Determination of intermediate losses was obtained from wet weighting with corresponding correction. These corrections were determined by numerous wet and dry weighting of the samples before and after the series of experiments. Calculated corrected results in the table 2 are in brackets. The most loss was obtained in series 9 under a velocity of 25.8 m/s. The loss of mass decreased approximately fivefold in experiment 10 and 11 and - more than 20-fold in experiment 12 in



comparison with experiment 9. Such distribution of erosion of sample 4 (experiments 9 – 12) can be explained by the following factors:

1. In natural conditions the separation of sandstone (used for sample 4) had been exposed to the atmosphere which mostly affected the more friable surface layers of rock of high porosity, thus, more and more decreasing its strength and structural integrity.
2. The strength and integrity of surface layers of the sample were also decreased by cutting the sample to the sizes of the container and window in the bottom of the installation, but in this way some parts of the sample layers weakened by the effect of atmospheric factors, had been cut off.
3. Sample 4 was first exposed to the impact of water flow in experiment 9, with flow velocities being the greatest in a series of experiments 9 - 12.
4. In the middle of experiment 9, sample 4 broke in two and in the crack there were many small fragments squeezed by the crack edges. Some fragments fell to the bottom of the container. As the small fragments were washed away from the crack the larger fragments got more degrees of freedom and were also little by little washed away by the flow. The washing-away of the fragments could occur in any experiment at random fashion because the removing of the container from the installation for the purpose of weighing made the fragments more free from squeezing caused by the crack sides and so the fragments could get rearranged.

All these factors explain the following related phenomena: a high erosion rate of the friable surface layer of sample 4; decrease in the erosion rate as this layer was washing out and the more pressed layer of rock happened be in its place; accidental washing-away of the fragments squeezed in the crack in the experiment with smaller flow velocity. Thus the general law of dependence of sample mass loss on flow velocity characterizes the decrease in erosion rate with reducing flow velocity.

The results of all experiments carried out with samples 4 and 4k are given with respect to the uniform frame of reference  $\{V, DG\}$  in Fig. 4. The points on the graph evidently fall into two groups:

- 1) Points of experiments 9 - 12 and experiment 18 fit well into this group being characterized by increased erosion rate of the sample attributable to the above mentioned factors;
- 2) Points of experiments 20, 22, 24 with the erosion rate many times less than the rate in the above item.

The relationship  $DG = f(V)$  yields a continuous curve for each group of points; the top curve illustrates erosion of the friable surface layer, and the lower one shows erosion of the stronger monolith of sample 4. Significant dispersion of the frame points for the upper curve is the result of the random process of washing away of broken fragments. Before the curves were constructed experiment 18 with sample 4k (Fig. 4) had been automatically classified among the second group of experiments, and the assumption had been made that the deviation of result of experiment 18 from the points of this group reflected the difference within the limits of sample mass stabilization at different conditions of sample drying: before the experiment - air drying and after the experiment - drying in the electric drying box. This assumption was proved not to be valid: the sample, being soaked after drying in the drying box on the termination of experiment 18, was dried in air and the value of its "air-dry" mass practically was equal to the mass after drying in the above box.

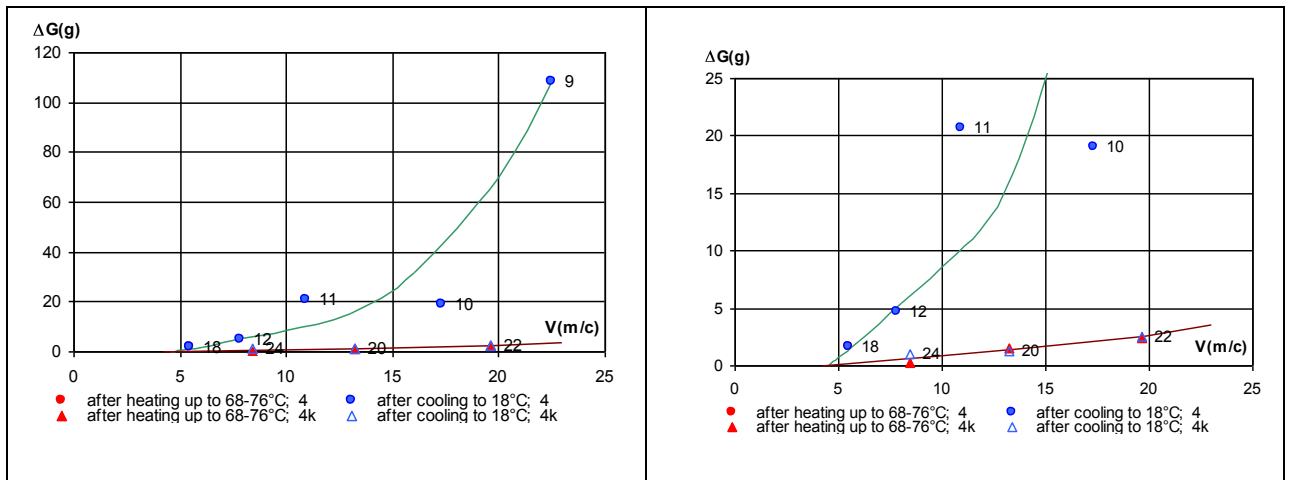


Fig.4. Dependence of loss in mass  $\Delta G$  of sample 4 on flow velocity  $V$  (a), the bottom part of the graph is shown also on a larger scale (b) 9, ..., 22 - numbers of experiments.

After making graphical representation of the experimental data (Fig. 4), it became clear, that the process of erosion of the friable layer from surface "A" of sample 4 (more precisely - sample 4k) began and ended within experiment 18, and this experiment should be placed in the first group of experiments.

The curves  $DG = f(V)$  in both groups of experiments are seen to converge to point  $V \approx 4.5$  m/s with  $DG = 0$ . This average flow velocity is a critical erosion velocity (non-eroding velocity)  $V_{cr}$  for sandstone of sample 4. This velocity characterizes equilibrium between effects of water flow on strong layers of sandstone and resistance forces of these layers.

### Conclusions

The results of the experiments lead to the following conclusions:

1. Limestones (samples 2 and 3) and dolomitic monoliths are resistant to eroding action of water flow with velocities up to 26m/s. Taking into account variation of the velocity of 5%, it is possible to conclude that upper non-erosive velocity is about 27.5 m/s.

Summary duration of the flow action was 22.5 hours for sample 2 in series 1 – 2; 18 hours for sample 3 in series 5 – 6 and 13 – 15; 36 hours for sample 3 in series 25 – 26; 15.5 hours for sample 5 in series 3 – 4.

Artificial roughness on the surface of limestone (sample 3) and inclination of the surface against flow did not increase erosion of the sample.

2. Sandstones could be eroded under relatively small velocities of affected flow. Minimal erosive velocity varies within wide limits depending upon the mechanical properties of the rock. For

fissured obolus, sandstone the velocity is about 4.5 m/s, for weathered glauconitic sandstone – about 11 m/s.

The experiments show that erosion of sandstones significantly depends upon weathering and fracturing. Weak zones of samples are eroded first; after erosion activity gradually decrease.

3. Relatively high erosion resistance of monolith in comparison to interblock binding F shows that rocks begin with destruction of ties between separate blocks and washing-out of the blocks from erosion zone with velocities less than minimal erosion ones for monolithic rocks[12 – 14].

Experimental research of erosion of limestones and dolomites which are not of highest erosive resistance with high velocity flow confirmed the block mechanism of erosion of rock massifs.

## REFERENCES

1. Recommendations on forecasting of transformation of river-beds beneath of hydrofacilities. SO 34.21.204-2005// RAO EES of Russia. VNIIG, 2006.
2. Mirtshulava Ts.E. Foundations of physics and mechanics of river beds. St.-Petersburg, Hydrometeoizdat, 1988.
3. Parteniades, E. Erosion and deposition of cohesive minerals // River mechanics. V.2. Edited and printed by prof. H.W.Shen. Ch.25, p.91. Fort Collins, CO, USA. 1971.
4. Akhmedov T.H. Erosion of rock river beds. Alma-Ata: Nauka Publ., 1982.
5. Vovkushevsky V.I. Reasons and forms of damages of spillway of Bolshoi Karaganda reservoir. Hydrotechnical building. 1947. No.6.P.16–19.
6. Tokarev I.I. Experience of building of dam on weathered rock basement. Hydrotechnical building, 1952. No.10. P. 18-21.
7. Khapaeva A.K. Model and natural data of erosion beneath of hydrosystem spillway. Transactions of VASKHNIL. Moscow: Koloss. 1969. P.146–154.
8. Ribeiro A.A., da Cunha L.V., da Silva D.P., Lemon F.O. Erosion in concrete and rock due to spillway discharge // Ninth International Congress on Large dams. R.19. Vol.11. Istanbul, 1967.
9. Riquois, M. Praff, Savey et d'autres. Problems poses par l'exploitation et l'entretien des organs d'evacuation des barrages // Neuvieme International Congress des Grandes Barrages. R.28. Vol.11. Istanbul, 1967.
10. GOST 25100-95 "Soil Classifications".
11. Lomtadze V.D.. Engineering geology. Engineering petrology, "Nedra", Leningrad.1970.
12. Rubinstein G.L. Local erosion of rock channels beneath hydrosystems. Transactions of VNIIG, 1997. V.230: Hydraulic, part 1, pp.314 – 326.
13. Shvaistein A.M. spillways of foreign hydrofacilities with high concrete dams. Leningrad: Energiya. 1973.
14. Gureev A.M. Engineering geology characteristics of rock fundament and its estimation concerning to erosion of high velocity water flow // Proceedings of co-ordination conference on hydrotechnics. Vol.52.Leningrad: Energiya. 1969. P.552–565.