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SOLUTION OF RESERVOIRS' SILTATION PROBLEM FOR HYDROPOWER DEVELOPMENT AND COASTAL PROTECTION

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ABSTRACT: Georgia, as a seaside mountain country, faces three opposing issues: hydropower development, coastal protection, and flooding risks for riparian settlements and infrastructure. Present climate change will even more strengthen processes of beach abrasions. For study of silting prisms formation process and forecasting of the equilibrium channel on it, field natural experiment has been carried out on the small mountain rivers. The experiment showed that approximately for a year silting prism on some rivers closely reached its limited size and the equilibrium channel was formed. The silting prism in the tributaries, forms the sediment train that extended till the boundary of the top water level in the river. Length of train (L) is a function of the maximum flow discharge (QM), the deposit of runoff (R), diameter of bottom sediment (d) and initial inclination of riverbed (I). With the purpose of harmonious decision of all problems, eroded beaches periodically should be artificially filled by the river sediment, accumulated in the reservoirs. It's necessary to organize a system of the quarries in reservoirs.

Keywords: Accumulated Deposits, Equilibrium Channel, Mountain Reservoirs, Prism Train, Seashore

1. INTRODUCTION

High values of mountain reservoirs condition the construction of these facilities worldwide. However, at the selection of their location is ignored the threat possible catastrophic floods of the settlements. High values of mountain reservoirs condition the construction of these facilities worldwide. However, at the selection of their location is ignored the threat possible catastrophic floods of the settlements. In addition, in coastal zone causes heavy deficit along the beachmaker sediments.

Mentioned negative aspects are the result of the lack of corresponding knowledge. During designing, the project developers don't take into account rising of riverbeds.

Current climate change has strengthened processes of sea shore abrasions and mountain reservoir sedimentation. According to the National Communications of Georgia to the UNFCCC [1], [2] the trend of change in the mean annual air temperature, precipitation and the moistening regime were estimated between the times: 1955-1970, 1990-2005 and 1986-2010. The increment of temperature and precipitation in West Georgia appeared to vary in the range of 0.2-0.4°C and 8-13%, respectively, while in East Georgia the relative values were found to be 0.6°C and 6.0%.

Research on reservoirs worldwide was dedicated to study of sedimentation, monitoring [3], balancing [4], ecology, sustainability [5], comparative analysis [6] and assessment [7]-[11], methodology [12], management [13] and modeling [14], [15] of reservoirs, dynamic of silting prism [16], [17], avoiding the effect on the Environment and catastrophic water floods [18], [19], Dam-Breach Hydraulic Analyses [20], [21], investigation on the hydraulic conductivity and physical properties of silt [22], identification of vulnerable areas to floods in rivers [23], as well as hydro-regime of Caucasus reservoirs [24], etc.

In scientific literature, currently the emphasis is placed on silting processes taking place in headrace of water reservoirs, since this issue was not examined before. Particular interest is focused on interest in accumulative processes running in the headrace is caused by the fact that without study of these processes is impossible to identify settlements and infrastructure caught in the zone of catastrophic water floods and assess appropriate risks. Another important reason is that mentioned negatives appear in the middle phase of operation, while dramatic and sometimes tragic nature they take only after expiration of reservoirs' lifetime.

Because of the fact that the study of silting prism i.e. sediments accumulated in reservoirs and equilibrium channel formation processes and their parameters for acting water reservoirs is complicated, expensive and longstanding process, expected negatives are completely ignored during the selection of location for reservoirs. This problem is not highlighted in sufficient volumes, neither in Georgian, nor in foreign scientific-technical literature. Respectively, interests and safety of population domiciled aren't taken into account when selecting their location. Herewith doesn't occur determination of volumes and fractional composition of accumulated sediments and assessment of risks of seacoast degradation, caused by lack of sediments. Due to the same reason are not elaborated the methods of avoiding or adaptation of these negatives.

Natural experiments are the highly effective means for assessment of solid material accumulation and variations of bed processes in mountain reservoirs and tributaries and for filling the lack of knowledge. For these purposes must be created artificial reservoirs, where will be possible to carry out an integrated study of silting prism and equilibrium channel formation processes for less than two years, to determine functional relations between their parameters and hydrological hydraulic characteristics of the river. Obtained results allow us to elaborate recommendations on avoidance and adaptation of mentioned negatives.

2. STUDY AREA & RESEARCH METHODS

Research area covers Georgia's mountain reservoirs and sea coastal zone (fig.1). The studies were conducted in the following directions:

- Method of Natural experiment on small artificial reservoirs;
- Field method for a long-operated reservoirs (operating for several decades);
- Methods of Mathematical statistics.

Fig. 1 Location of Study Area

For spatial-temporal study of silting prism and equilibrium channel formation process, the method of Natural experiments was used. We have selected three small rivers: Ru and Ruchula from the southern slope of the Great Caucasus Range – tributaries of the Rioni river (Racha region) and Vere from the northern slope of the Small Caucasus Range – tributary of the Kura river (near Tbilisi city). On these rivers were constructed one meter height dams. A flooded sections of the rivers were covered by the network for stationary observation on the riverbed deformation. This network covers part of the reservoir and mouth of tributaries. Measurement of silting prism and its train (continuation of silting prisms above the normal level) was made taking into account the frequency of floods and freshet of tributaries.

Field studies were carried out on long operated reservoirs: Gumati (constructed at the Rioni River in 1953, West Georgia), Sioni (at the Iori River, 1963, East Georgia), Jinvali (at the Aragvi River, 1986, East Georgia), using a GPS-receiver Leica GS08. This apparatus is connected to a network of the National Agency of Public Registry and provides a high precision of geodetic measurements throughout the country.

For analysis of obtained results were used the methods of mathematical statistics (least square method) and differential calculus. Approbation of calculation results were implemented at Gumati, Sioni and Jinvali reservoirs.

3. RESULTS AND DISCUSSION

At this time the most part r(≥70%) of river deposits and solid materials formed due to reservoir's coast deformation. This accelerates the sedimentation of reservoirs. Herewith, prism formation occurs simultaneously, but with different rate in reservoir and riverbed.The phases of silting prism and train formation of the experimental rivers are shown in the table 1.

Table 1 Silting prism and train formation phases

Length of reservoir, m	Length of experimental part of riverbed, m	Inclination, ‰	Average annual water discharge, m^3/sec.	Measurement date	Silting prism length, m
River Ru					
1.45	4.5	34.5	0.002	07.07.15 18.11.15 05.04.16 29.05.16	0.0 2.1 2.4 4.4
River Ruchua					
2.5	6.0	17.4	0.6	20.08.15 25.08.15 28.08.15 05.03.16	0.0 3.0 3.0 4.5
River Vere					
7.5	45.0	5.3	1.45	07.08.15 17.09.15 24.09.15 27.11.15 09.03.16	0.0 11.0 13.0 15.0 20.0

By the results of natural experiments on the river Ru, the silting prism and its train has evolved so fast that it has become twice more than the reservoir's volume, as well as the length, compared to its initial state (fig. 2).

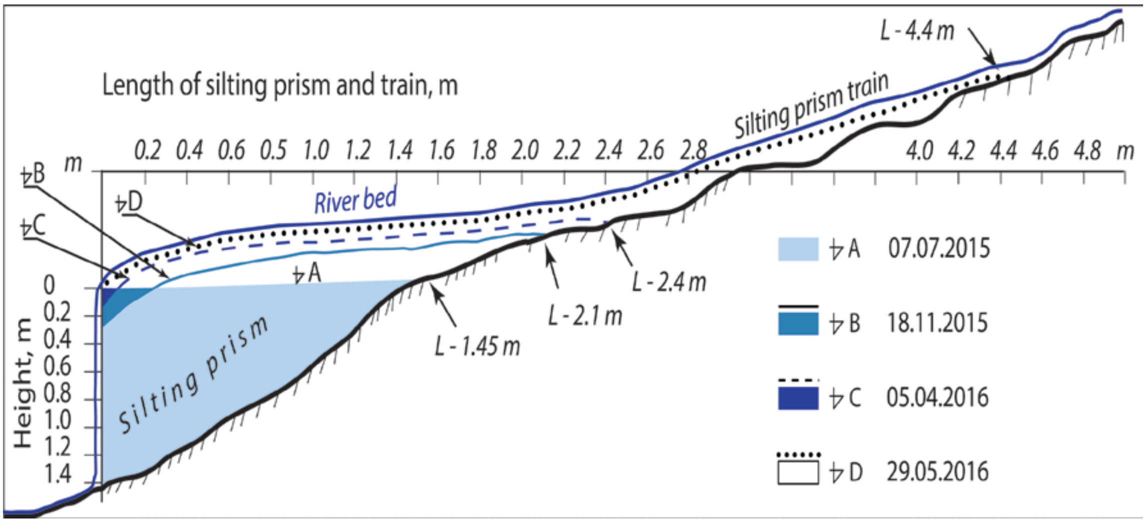

Fig. 2 Silting prism and train formation phases on the river Ru (by the natural experiment).

Sediment fractions (clay – fine sand), the hydraulic size of which in turbulent medium U≤1.0 m/sec, is transported by streams in the initial phase of operation through the whole reservoir and one part of them forms the layer with size corresponding to reservoir regulation type. The remaining part of such fractions (≥30%) not involved in prism formation, since it is transported by outlet water to the tailrace. Transportation of detritus (coarse sediments) in this phase to the tailrace occurs sporadically, during emergency water outlets.

In following phases the share and diameter of sediments transported from the reservoir gradually increase and reaches its maximum in the third phase of the operation. At the end of this phase silting prism reaches limit values of development and is formed as accumulation terrace, on which equilibrium channel is developed by tributaries.

Development of silting prism and train becomes especially active, when coarse-fraction sediment (d≥10 mm), which is precipitated in the zone of flood curve, forms crests. This accumulative formation has the form of beach ridge (falls), which slope exposed towards dam is sharper than the bench – slope formed in tributaries. Such crest gradually increases in height, comes close to the dam and when reaches it, silting prism volume and equilibrium channel length will become equal to their limit values.

The experiment showed that the sediment discharge (R kg/sec.) is divided into two components: coarse fraction (r_s kg/sec.), which is silted in the reservoir and the small fraction (r_u kg/sec.), which is taken out from the reservoir by the flow into the downstream.

$$R = r_s + r_u \quad (1)$$

The rate of silting prism growth is diminishing – average annual volume (r_s) of materials precipitated in reservoir and tributaries is the biggest in the initial phase of operation, afterwards it decreases in time in second and third phase and finally becomes equal to zero, when silting prism reaches its limit value.

$$\lim_{n \to T} r_s = 0 \quad (2)$$

Time distribution (r_u) of sediment transported from the reservoir is opposite to this process, it gradually increases and at the end of reservoir operation, i.e. after T time (in years) will become equal to the average annual volume (R) of sediments (r_u=R) and this sediment along with letting out water completely moves to tailrace:

$$\lim_{n \to T} r_s = R \quad (3)$$

Here, r_s and r_u are average annual volumes (m^3/year) of debris precipitated in reservoir and tributaries and sediments transported by the stream to tailrace, correspondingly, R is annual volume (m^3/year) of sediments brought by tributaries to the water reservoir, T – duration of reservoir operation time (years), while n=1, 2,…,T-1,T.

Equilibrium channel starts above the initial riverbed, at the height (h) of dam outlet. It follows silting prism surface and ends at the imaginary cross section, above which the river permanently keeps its natural ability of sediment transportation. Equilibrium channel length (L) and slope (I ‰) determine the value of silting prism surface area (F km^2) and by means of this parameter is possible to calculate F value in any phase of equilibrium channel development. The process of equilibrium channel forming occurred under the Erie low, which is very important for mountainous rivers.

$$d^3\gamma = Av^6 \quad (4)$$

Here, $d^3\gamma$ is the weight of the deposit, v – stream velocity (m/sec.), A – proportional coefficient.

Processes of silting prism and equilibrium channel formation proceeded with the rate corresponding to the ratio (W/V) of their useful capacity (W) and annual amount of sediments (V).

Silting prism consists of two growing part. First of them is a part formed right in the reservoir, and the second part is an accumulated in tributary channels, called as train. Growth of the latter causes rising of the riverbed that lasts until the silting prism its maximum limit, i.e. the volume after which accumulative processes in the headrace completely cease. In these conditions river has already a developed equilibrium channel on the surface of the silting prism, the parameters of which (length L and slope I) are so big that river is able to completely move deposits to the convey as transit.

Silting prism surface area (F) in limit state is represented by the plain inclined towards the dam, which begins from dam outlet. Its area significantly (sometimes f≥60%) exceeds the reservoir surface. It is extended in tributaries up to the cross section, to which reservoir's water flood curve reaches during floods and freshets. Silting prism bench sizes basically are depended on hydrological and hydraulic characteristics of tributaries [19]: bench length (L), dam outlet height (h), sediment diameter (d), maximum discharge of water and sediment (Q_m, R_m) and inclination of the bed located above the reservoir (I ‰):

$$L= f (h, Q_m, R_m, d, I\text{-}1) \quad (5)$$

At the same time equilibrium channel length is inversely proportional to the inclination of that river section (I‰), which is located above the reservoir. This fact means that the more riverbed is inclined, the shorter is equilibrium channel. According to experimental results, a length of the latter (L) doesn't exceed a double length of the reservoir (2l).

$$L \leq 2l \quad (6)$$

The experiment showed that the silting prism is a combination of two bodies, the first of which is formed in the reservoir (Wr), and the second one – above it and in tributary channels (Wt). Herewith, water flood risks for the population and infrastructure located above reservoir increase proportionally to the height of silting prism and its train. The more place is occupied by a train in the riverbed, the more higher is a probability of the river flowage. Consequently, the limiting volume of silting prism (Wp) is equal to the sum of the volumes of both bodies. The first of them is the reservoir's volume at the normal level; the second one is the volume of the body (Wt), which based on the surface of the limited prism (ABK). Height (h_1) of the body is a distance between the equilibrium channel and the initial position of the riverbed at the end (E) of the reservoir.

$$Wt = 0.33\, h_1 F_{ABK}, \quad h_1 = EF \quad (7)$$

Thus, $$Wp = Wr + 0.33\, h_1 F_{ABK} \quad (8)$$

A straight line is the simplest approximated form of equilibrium channel. When the river crosses a tectonic fault line its form comes closer to convex or concave curve. In this case it may be described by coordinates of the parabola, which begins from dam outlet and lasts up to above mentioned imaginary cross section.

Forecast based on calculations, made according to results of natural experiments in the near future (2025-2030 years) silting prisms and riverbed parameters will change by another 15-20% that creates a real risk of disaster for neighboring settlements. As a consequence the probability of catastrophic floods and related risks are so high that floods, which usually are repeated once in two decades (P≥5-10%), become a serious threat for population and environment.

Results of natural experiments are tested on Gumati (constructed in 1953), Sioni (1963) and Jinvali (1986) reservoirs, since silting prism and equilibrium channel are nearest to limited values (Fig. 3).

Fig. 3 Silting prism fragments (Jinvali reservoir)

Sediments accumulated during many decades in Gumati reservoir and in riverbed located above, much exceeds than the volume of the reservoir (40 million m^3) and reaches about 65-70 million m^3. These sediments have raised the Rioni riverbed level so much that it every year overflows its banks and submerges adjacent settlements and infrastructure. Territory adjacent to Sioni reservoir is in a more dangerous situation, since sediments precipitated above the reservoir (45-50 mln. m^3) already have raised riverbed by 3-5 meters.

Due to this fact Iori River several times overflows protective structures and heavily damaged riverine area, while it would seem that settlements are reliably protected by the dam. Almost 98% of Gumati reservoir is occupied by sediments (fig. 4), while Sioni reservoir already lost approximately 75% of volume. Both reservoirs are located in the active tectonic zone. As of 2015, the silting prism has changed riverbed parameters in these reservoirs (by 5-6 meters at Gumati and 2-3 meters at Sioni). Because of this, during the floods, rivers every year overflow their banks and do damage to the settlements, infrastructure and environment.

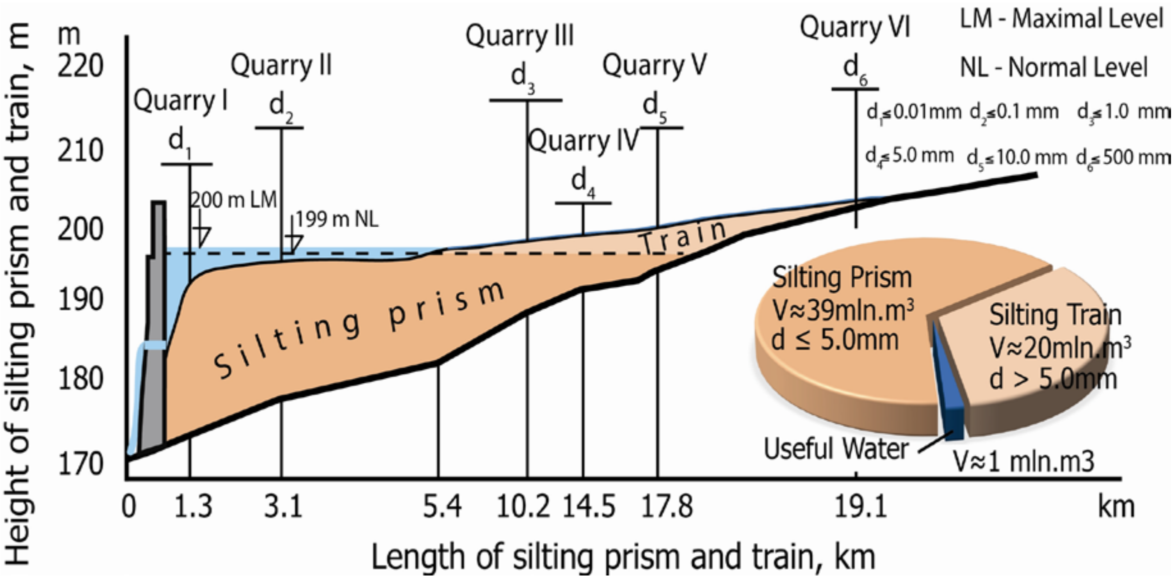

Fig. 4 Longitudinal section of Gumati Reservoir after 60 year exploitation

Silting prism and train of Gumati reservoir contain about 60 million m^3 beach-forming materials. Among them, about 60% are technically easily accessible and can be used to recharge of degrading coasts. Transporting of this material from Gumati to the seashore has been recommended by railway (Kutaisi-Poti), and after that by special courts along the coastline (fig. 5).

Fig. 5 Trajectory of sediments' transportation from Gumati reservoir to seashore

According to recent calculations, the annual volume of sediment, needed to prevent a coastal erosion along the seashore of Georgia, is about 0.4-0.45 million m^3 of beach-maker material ($d \geq 1$ mm). Even the stock of the solid material, accumulated only in Gumati reservoir, is sufficient to maintain coast of the country for at least 80-85 years.

Among the many ways to fill degraded beaches, using of silting material, removed from the reservoirs, is the most beneficial from the environmental and economic point of view.

In addition, as a result of periodic cleaning of the reservoirs, the useful volume of water in them will increase, that will contribute to efficient hydropower.

As a user of the proposed approach can be any mountainous country, with a high hydro power potential, where the rivers, flowing into the sea, are blocked by the reservoirs, for the reason of which coastal beaches are exposed to a sharp deficit of sediments.

4. CONCLUSION

Annual volume of material participating in the formation of silting prism and its train, wanes in time. Respectively, this is the most intense in the initial phase of reservoir operation and is negligible, when silting prism and equilibrium channel increases to the limit values.

Silting prism with limit value of volume completely covers reservoir and a part of a valley above it up to the imaginary cross-section. Its value is a sum of a reservoir's and train's volume.

Silting prism surface represents an inclined plane, which starts from dam outlet and lasts up to the beginning of the equilibrium channel.

The limit amount of silting prism more than 60% higher than the initial volume of reservoir. Therefore, the reservoir holds significantly more sediment than its volume is.

The most effective way to save the operating parameters of the reservoir and prevent deficiency of beach-forming material on the coast, is the creation of a quarry system in the reservoirs and the transportation of deposit to the seashore. This allows the solution of coastal protection and hydropower issues without the ecological damage and with some significant economic profit.

5. ACKNOWLEDGEMENTS

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