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Environmental and Hydro-Engineering Problems on Georgia's Black Sea Coast and the Ways of their Solution

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Abstract. *The main results of studies of sea water pollution, geomorphological, hydrotechnical and environmental problems currently existing in the estuaries of the Rioni and Inguri rivers of the Black Sea coast of Georgia are presented in the article. These problems arose after the transfer of the final 7-km part of the Rioni River to another channel, and at the mouth of the Inguri River they were caused by a change in flow after the construction of the high arch dam of the Inguri hydroelectric power station. Mathematical models for solving these problems are constructed. Some engineering measures are proposed to prevent geomorphological changes.*

Keywords: *environment, mathematical model, pollution, rehabilitation, waves.*

1. Introduction

In the nearest future, the ancient maritime gateway – the city of Poti and its bordering territory – will be declared the free trade zone. In Anaklia, near the mouth of the Enguri river, it is planned to construct a large port on the eastern Black Sea coast of the Caucasus. A successful implementation of these projects directly depends on the correct assessment of hydro-engineering, geo-morphological and environmental problems which have emerged in Georgia's Black Sea coastal regions.

In Fig.1, the red circles mark the cities and settlements where the Georgian participants of the ICME and the SRNSF projects carried out activities since 2013 till 2017.

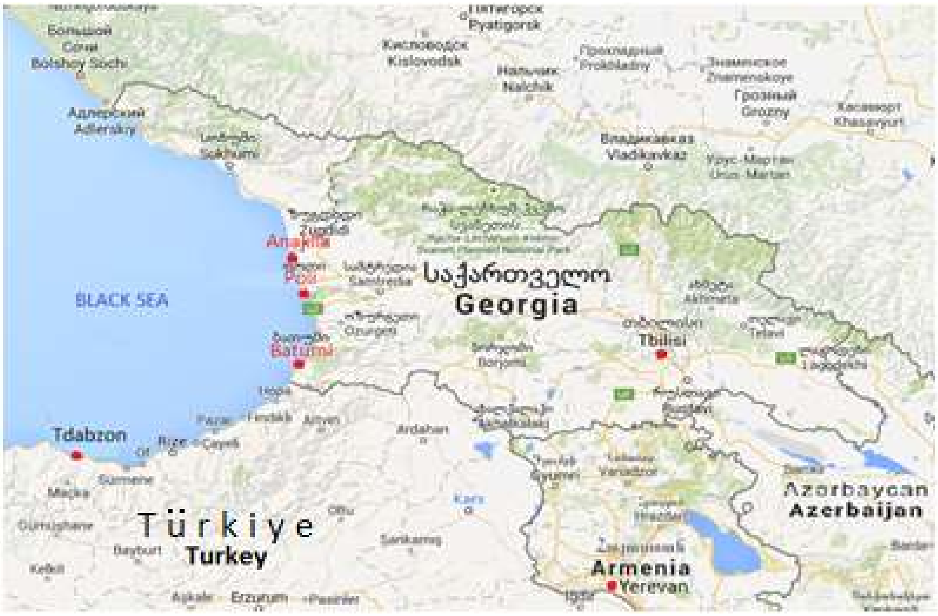


Fig. 1. Map of the eastern coast of the Black Sea

Large-scale geo-morphological changes of the coastline of the city of Poti began after 1939 when the Rioni river course was completely diverted to the north of the city (Fig.2). This event prevented the town from dangerous flooding processes, but, on other hand, it produced an irreparable deficiency of coast generating alluvia. The coastline of Poti was catastrophically washed out by sea waves and reduced by hundreds of meters. On the sea shore of Poti many protection walls and engineering structures were constructed; a huge quantity of concrete blocks, broken stones and boulders were thrown, but these measures were incapable to stop the intensive process of sea shore erosion, which became even more intensive after putting into operation the cascades of the Gumati and Vartsikhe power plants. Thus, the solid alluvia amount of the Rioni river reduced from 2.07 million m^3 to 1.35 million m^3 per year.

Moreover, the diversion of the Rioni river to the North created problems for navigation because of siltation of the entrance channel of the Poti sea port, which was caused by northwest storms and sea currents. The removal of sediments from the port entrance channel is very costly and every year the Poti port administration has to spend hundreds of thousands of dollars on this work.

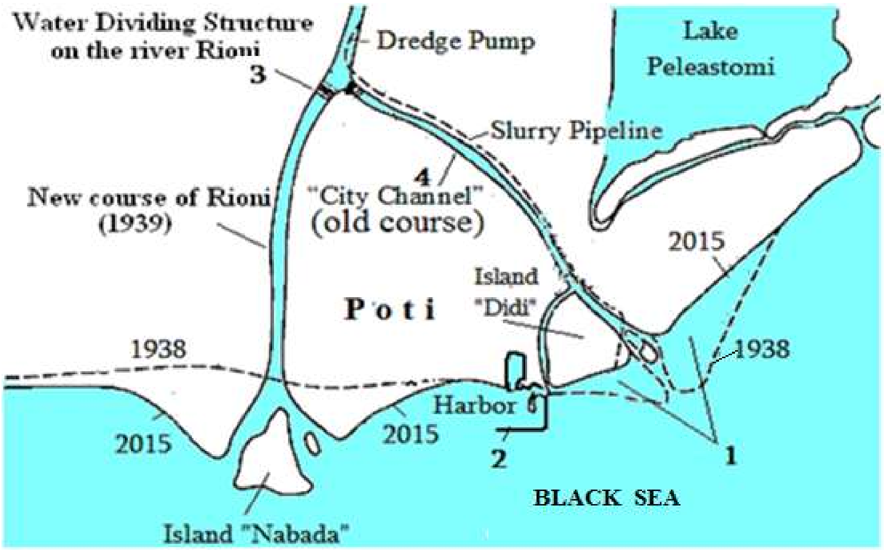


Fig. 2. Situational map for environmental and hydro-engineering problems of the Poti region. 1– washed-out Poti coastline; 2 – entrance channel of the Poti port; 3–water dividing dam on the Rioni river; 4 – bed and outlet of the Poti City Channel

To restore the washed-out sea coast of Poti, in 1959, the dam with a regulator (sluice) was built across the Rioni river, on the 7th kilometre to the northeast of Poti. Its purpose was to divide the river flow so that some part (≈ 500 m^3 /s) of the river discharge would go back to the former riverbed (the so-called City Channel) in order to compensate for the alluvia deficit (600 thousand m^3 per year). However even the discharge of 250 m^3/s produced the flooding because of the city channel siltation and the deformation of the channel outlet by sea waves (which occurred during the low water period). To protect the city from floods, the channel was enclosed with dams; two water collectors and a pumping station were built. However, these measures failed to provide the required water discharge rate. That was why in the 80s of the past century, in order to reconstruct the washed-out sea shore of Poti, the pulp feed-line was erected along the city channel to transport inert materials from the Rioni river basin to the sea coast. But this feed-line soon went out of order and for various reasons was not restored.

With a lapse of time, the downstream wall and the apron of the Rioni water dividing dam got essentially destroyed and the dam itself faced destruction. In 2006, it was partly rehabilitated by temporary measures. However, these measures did not take into account the operation regime of the regulating sluice and therefore disregarded problems of the restoration of the sea coast of Poti.

Thus, the water dividing dam with a regulating sluice failed to meet its purpose to deliver alluvia to the sea coast.

This brief historical information clearly shows how topical it was to carry out scientific investigations of hydro-engineering and environmental problems existing in the Poti region and to propose such engineering measures that would facilitate to a maximal extent the restoration of the Poti coastline and protect the port of Poti from the inflow of river alluvia.

2. Main Part

1. Some Results of Sea Water Quality Studies in the Poti and Anaklia Coastal Areas

For the problems in the Poti region as shown by the numbers in Fig. 2, hydrological and meteorological observation data, topographic and bathymetric maps and other materials were prepared and processed. Several expeditions were organized to carry out field observations in the river mouths and coastal areas of the sea towns of Western Georgia.

100-120 water samples were taken during the four-year period. The water samples were analyzed at the Laboratory Test Centre in Poti and hydro-chemical laboratory in Tbilisi. 2500 tests of 18 pollution ingredients were run. This number of tests was quite sufficient for the data statistic processing. Water samples were taken from selected locations, including the points at the sections of the watershed dam of the river Rioni and in the Enguri mouth in the Anaklia region. The statistic processing included both our test data and the data previously collected by hydrological stations in the 70-80s. The correlation coefficients and regression equations were obtained. Calculations showed the existence of a clear and obvious correlation: with water discharge and mineralization (the correlation factor is $r \approx 0.93$); between the coli-index and the water discharge ($r \approx 0.63$); between the nitrate concentration and the discharge ($r \approx 0.34$) and between the coli-index and the nitrate concentration ($r \approx 0.89$) (Gagoshidze and Khatiashvili, 2015). Averaged results of hydro-chemical, biogenic and bacteriologic analyses are given in Table 1.

Table 1

Averaged Values of Sea and River Water Samples from the Poti and Anaklia Regions

Hydro-chemical, biogenic and bacteriologic characteristics		Sites and dates of taking sea water samples			
		Poti, Lake Paleastomi merges with sea	Sea water near Poti. lighthouse	Sea water near Poti Port	Anaklia. Enguri river mouth
Hydro and bio - chemical	PH	8.5	8.7	8.0	8.8
	BOD_5 mgo_2/l	2.6	3.8	2.9	3.7
	Dissol. Oxygen	8.8	7.6	7.4	8.9
Basic ions, (mg/l)	HCO	62.2	100.1	76.8	100.2
	Cl	7350	8525	7840	8405
	SO_4	735	1210	805	735
	Ca^2	252	253	225	282
	Mg^2	714	640	575	714
	Na	5355	5390	5200	5290
	Ka	220	200	185	220
Biogenic elements, (mg/l)	NH_4	-	-	-	-
	NO_2	-	-	-	-
	NO_3	0.1	0.1	0.1	0.1
	PO_4^3	1.2	2.2	1.2	27
Micro elements	Fe, mg/l	<0.05	<0.05	<0.05	<0.03
	Mn, μg/l	-	-	-	-
others	Oil products, mg/l	0.2	0.9	0.4	0.08
	ε-coli, 1/l	5736	4420	6720	5536

2. A Brief Description of Mathematical Models

For the solution of problems which existed in the Poti and Anaklia regions, and also of general problems of coastal hydrodynamics the following numerical and analytical mathematical models were developed.

2.1. Numerical simulation of lithodynamic processes in the entrance channel of Poti port. Engineering measures against the channel siltation

The list of engineering problems that exist in the water area of Poti port can be seen in the "Google Earth" internet picture (Fig. 3).

Fig. 3. "Google Earth" picture of the Poti port water area.
1 – Port entrance channel intensively silted by alluvia transported from the mouth of the Rioni river;
2 – Location of the deep-sea canyon where sediments delivered from the City Channel are lost;
3 – Recommended construction of the sediments retaining pier.

The problem of protection of the entrance channel and the internal water area of Poti port against siltation was studied (Fig. 4). The mathematical model of entrance channel siltation and the algorithm of numerical solution of the resulting problem were developed. To solve the problem, the finite element method and the Crank-Nicholson scheme were used (Horikawa, 1988; Saghinadze, 2013). Numerical experiments showed that the sedimentation rate was 0.7-0.8 m/year.

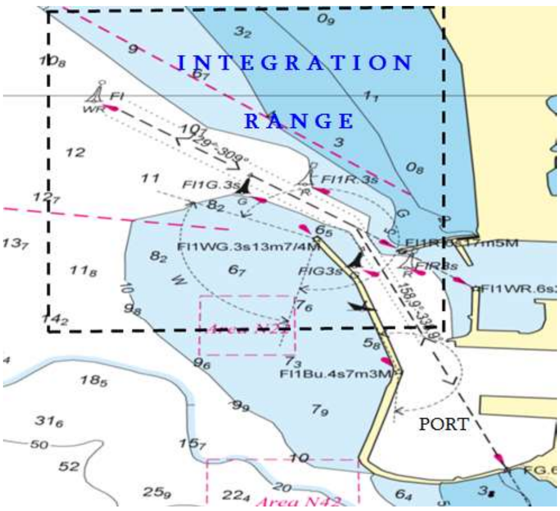


Fig. 4. Integration range of the mathematical model for the entrance channel of Poti port (shown by the dotted line)

2.2. Refraction of waves on coast slopes of arbitrary steepness

The classical problem of wave refraction over the coast with an arbitrary angle of slope was solved in the cylindrical coordinate system by the means of direct and asymptotic methods. After choosing a basis function $f = \cosh kr(\theta + \theta_0)$ (Gagoshidze, 1991), where k is a variable wave number satisfying exactly all boundary conditions (as distinct from the Berkhoff (1976) basis function) and averaging the wave equations by the direct Kantorovich method (1933) with respect to the polar angle θ, we derive a one-dimensional evolutionary equation of Schrödinger type which is asymptotically solved by the WKB method (Nikiforov and Uvarov, 1984) for an arbitrary angle α_0, $0° \le \alpha_0 < 90°$, between the wave crests on the deep water and the shore line. Without the phenomenological use of the laws of geometrical optics, solutions explicitly dependent on a slope angle of the coast are obtained. They are quite close to the existing numerical realizations of exact but highly complicated mathematical solutions.

The WKB solution of this problem enables us to easily determine the three-dimensional field of velocities and to construct the refraction picture of the wave surface near the coast having an arbitrary angle θ_0 of slope to the horizon varying from $0°$ to $180°$.

This solution, in particular for a vertical cliff, almost fully agrees with Stoker's particular but difficult solution (Stoker, 1957). Moreover, it is shown for the first time that our Schrödinger type evolutionary equation leads to the formation of the so-called "potential wells" if the angle θ_0 of coast slope to the horizon exceeds $45°$ while the angle α_0 given at infinity (i.e. at a large distance from the shore) between the wave crests and the coastline exceeds $75°$. When the angle between the wave crests and the shore line is $\alpha_0 < 75°$, the wave crests do not break for an arbitrary coast slope.

This theoretical result expressed in terms of elementary functions is well consistent with experimental observations and with lots of aerial photographs of waves in the coastal zones of the oceans (Berkhoff, 1976; Hodgins et al., 1985).

2.3. Peculiarities of long waves on stationary currents

Possible approaches to the linearization of a system of basic equations of long waves on stationary flows (Lamb 1932; Nekrasov and Pelinovsky 1992; Voinich-Sianojentsky, 1972) of arbitrary depth are discussed. The accurately fulfilled linearization of this system makes it possible to obtain the following one-dimensional differential equation for long wave disturbances (Gagoshidze, 2013):

$$\varphi_{tt} + 2U_0\varphi_{xt} + \left(\frac{3}{2}U_0^2 - gh\right)\varphi_{xx} + U_{0x}\varphi_t + \left(3U_0U_{0x} - gh_x\right)\varphi_x = g\left(U_0h\right)_x - \frac{3}{2}U_0^2U_{0x}, \tag{1}$$

where $U_0(x)$ is a given stationary component of the stream velocity; $\varphi(x,t)$ is the function which is an analogue of the velocity potential of wave disturbances; $h(x)$ is the variable depth of water in a statically undisturbed state; g is the gravity acceleration; t is the time; the x -axis is superposed on the undisturbed free surface.

For the classical problem of motion of long waves on flows of constant depth (h) and velocity (U_0) this equation leads to the following formula for the phase velocity of a long wave:

$$c = U_0 \pm \sqrt{gh - \frac{U_0^2}{2}} \; , \tag{2}$$

where the sign “$+$” before the square root corresponds to waves directed along the flow and the sign “$-$“ to waves directed against the flow. Relation (2) is essentially different from the classical Lagrange formula :

$$c = U_0 \pm \sqrt{gh} \tag{3}$$

and enables us to formulate the criteria of formation of a hydraulic jump which is a blocked wave, as well as the formation of rolling long discontinuous waves in chutes without using the momentum change equation. In particular, (3) implies that waves cannot move against the flow, i.e. $c = 0$ when $U_0^2 = gh$ or when the Froude number is $Fr_0 = U_0^2 / gh \geq 1$, whereas (2) implies that $c = 0$ when $Fr_0 \geq 2/3$. Along with this, according to (2), the wave blocking condition precedes the wave destruction condition $Fr_0 \geq 2$ for which the subroot expression in (2) becomes negative. In that case, the oscillation frequency takes a complex value and the solution brings to the Helmholtz instability.

Thus, in the framework of result (2), we can give a good explanation of the fact confirmed by experiments (Chertousov, 1962) that near the unit value of the Froude number or, speaking more exactly, when $\frac{2}{3} \le Fr_0 \le 2$, the hydraulic jump, which is actually a blocked long wave, is the so-called undular hydraulic jump. A perfect hydraulic jump occurs only for $Fr_0 > 2$, while for $Fr_0 < 2/3$ a long wave freely moves against the flow, i.e., a flow of large depth (a long wave) overlaps a calm flow of small depth without wave destruction.

Considering a hydraulic jump as a blocked long wave, we derive from formula (2), without using the momentum equation, a simple formula for calculating the conjugate depths of a hydraulic jump:

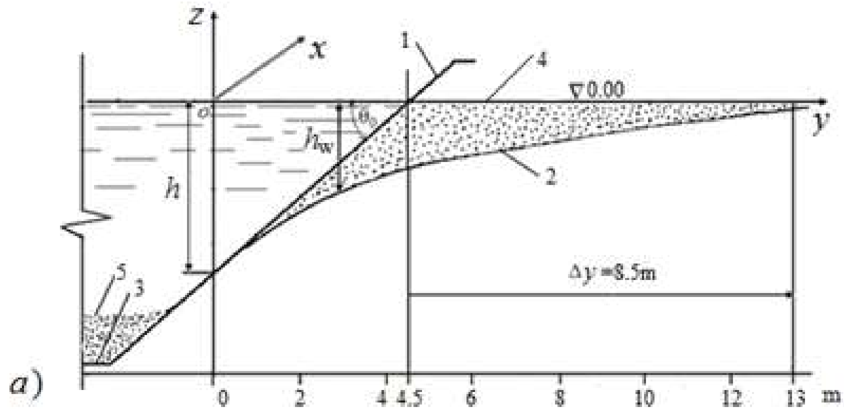
$$\frac{h_2}{h_1} = \sqrt{\frac{3}{2}\frac{U_1^2}{gh_1}} \approx 1{,}225\sqrt{Fr_1} \tag{4}$$

which, as different from Belanger's formula commonly used in the hydraulics courses, is applicable both to “an undular hydraulic jump” and to “a perfect jump”.

2.4. The action of longitudinal waves on bank slopes

Longitudinal waves are the dominating ones in open maritime and navigation river channels. The quantity of exact solutions is limited only to a few particular cases (Constantin, 2001; Jonson, 2005) which are difficult for practical use. Our solution is based on the application of the Galerkin-Kantorovich direct method (Kantorovich and Krilov, 1962) to three-dimensional linear equations of wave hydromechanics written in the cylindrical system of coordinates.

Using the obtained relations and estimating the stability of the bank slope of a trapezoidal channel built of loose soil, we come to a conclusion that the wash-out of the bank slope of the channel by long waves leads to the concave shape, whereas relatively short longitudinal waves lead to the convex shape (Fig.5,a; b).



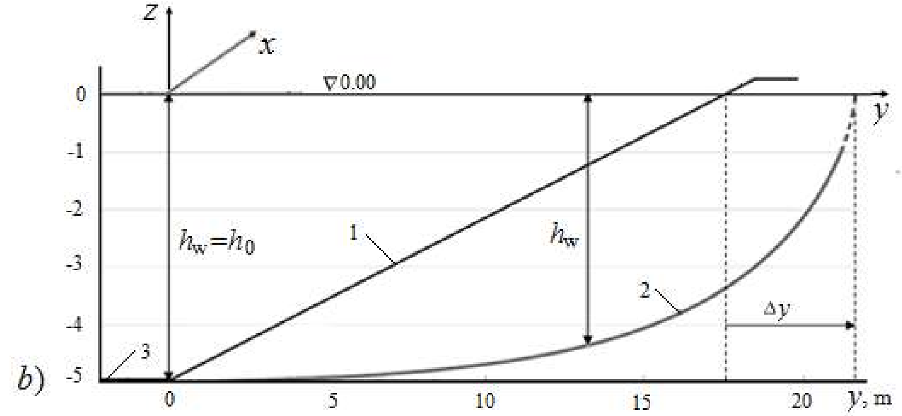


Fig.5. Typical configurations of the channel bank slope washed-out a) by the short and b) by the long waves: 1 – design contour of the coastal bank slope; 2 – washed-out coastal slope; 3 – channel bottom; 4 – washed-away gravel layer; 5 – settled gravel layer

2.5. Hydraulic calculation of storm drain and spillway collectors

The problem of interaction of sea and waste waters in river mouths and deep water outlets is one of the problems associated with the hydrodynamics of coastal regions. On the one hand, the salinity wedge (halocline) intrudes into the river inflows, non-pressure or pressure discharge structures over large distances, impedes with the exploitation of water-supply and sewerage systems of coastal settlements, stimulates load sedimentation and holm formation in stream canals, reduces the discharge capacity of collectors, creates threats of flooding of coastal territories, causes sea water pollution (which is especially dangerous for the Black Sea recreation zones of Georgia), etc. Accordingly, the practical importance of specifying the dimensions of salinity intrusions in inflow reaches and sewage collectors and studying the diffusion and range zone of impure water streams, which intrude into the sea from storm sewers and sewage collectors, is obvious.

At present, these issues have been more or less precisely studied for cases where the sea bottom has a gentle slope (Voinich-Sianojentsky, 1972; Ippen, 1966; Ghogheliani et. al, 2006). As for the Black Sea regions of Georgia, the slopes of inflow reaches and those the sea bottom are so steep that it is inadmissible to disregard them. The steep slopes of the sea bottom also determine the location and dimensions of a section through which waste water flows into the sea. It is practically impossible to place the end section of a spillway on the sea bottom, 13 km away from the shore, which is required by the normative documents. The problem of interaction of sea and waste water at inflow reaches is considered and formulae to calculate the maximum dimensions of a salinity wedge intrusion into bottom spillways are established (Kodua and Gagoshidze, 2014). These formulae foresee the end slopes of spillway bottoms which must be necessarily considered in hydraulic engineering construction, especially in the Black Sea regions of Georgia.

2.6. Hydrodynamic stability of streams in free-flow cylindrical conduit

In hydraulic engineering practice, the fact is well known and taken into account that for a nearly fully filled free-flow tunnel with a circular-cross section the water flows in a pulsating manner, i.e. the flow is unstable. Such a phenomenon also occurs, for example, when emptying a bottle, but no mathematical confirmation has so far been found for it. The estimate of the flow stability is obtained for two limiting cases: when the conduit of circular cross-section is nearly fully filled with water and when it is nearly empty, i.e. the water flow in the conduit has a small depth as compared with the radius of the water conduit (Gagoshidze, 2015).

Wave equations written in the cylindrical system of coordinates x, r, θ, where the x-axis coincides with the axis of the conduit; r is the radius vector, θ is the angle counted off from the equatorial plane of the conduit upwards (with sign "+") and downwards (with sign "-") are simplified by neglecting the change of the polar angle $(\frac{\pi}{2} - \theta)$ in the limiting case when the flow free surface is of small width (Fig. 6a; b).

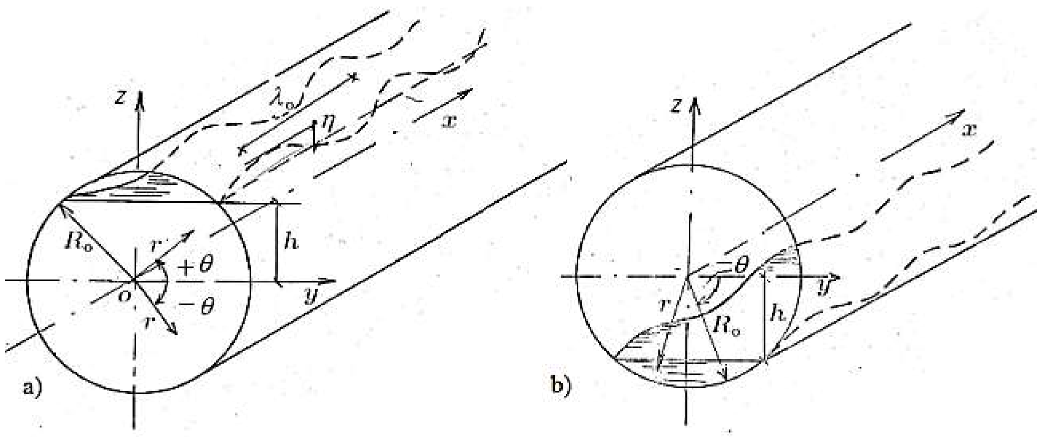


Fig. 6. Cases of non-pressure flow in circular cylindrical conduits: a) – nearly full filling; b) – almost empty round-cylindrical conduits. R_0 is the conduit radius; h is the distance between the horizontal axis and the water level

As a result of this simplification the Helmholtz equation for the wave potential reduces to a Bessel equation not depending on the polar angle θ and its asymptotic solution $(R_0 \approx h)$ gives $\sigma = kU_0 \pm i\sqrt{gk \tanh k(R_0 - h)}$ for the wave disturbance frequency σ in nearly fully-filled round-cylindrical conduits. Here k is the wave number, U_0 is the stationary water flow velocity, i is the imaginary unit. In the other limiting case with $R_0 >> h$, i.e. for round-cylindrical conduits with a small water depth, σ is expressed by an ordinary relation.

In the first case, the complex expression for σ indicates the occurrence of Helmholtz instability of wave disturbances independently of a velocity value of the stationary water flow. This result fully agrees with the results of thorough experimental studies of Chanishvili (1947), according to which the occurrence of flow instability in gravity-flow conduits of large diameter does not depend either on the flow velocity or on the presence of an air layer between the water free surface and the conduit vault – this instability always appears when the conduit is filled up to 92-93% of its height (diameter).

In the other limiting case the wave motion in a conduit of circular cross-section with a small water depth is always stable.

3. Laboratory Studies of the Action of Waves on the Pollution Spread

These experiments were mostly qualitative in nature, and their main goal was to identify the effect of waves on the distribution of impurities entering the sea from both the deep sewer outlet and from the river inflow. The experiments showed that short waves contribute to an increase of the pollutant concentration near the coast, while long waves on the contrary diminish it by carrying pollutants into the sea depth. Along with this, vertical and horizontal jets of impurities get strongly bent under the action of waves. It would be highly desirable to continue experimental and theoretical research in this direction.

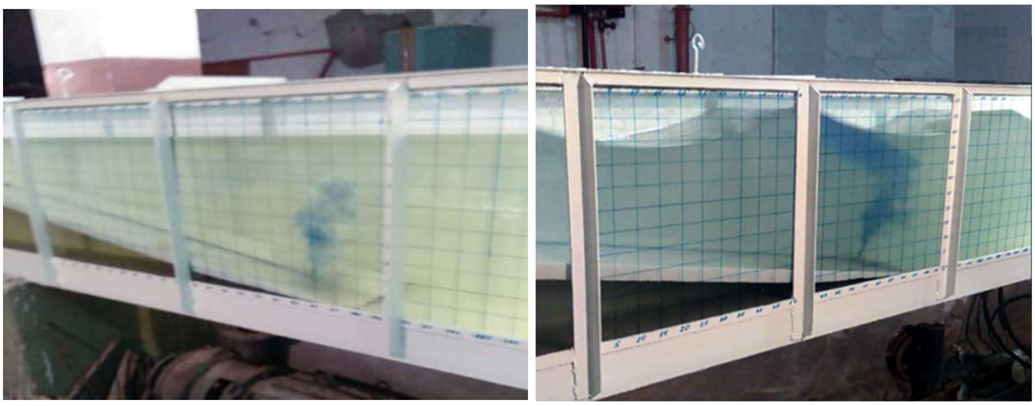


Fig. 7. Photos of laboratory study effects of waves on contaminants arriving from the deep sewage outlet

4. About the Reasons of Destruction of the Downstream Pool of the Water-Dividing Dam on the Rioni

As mentioned above, the downstream pool of the dam of the water-dividing structure built in 1959 (Fig.8) got destroyed with the lapse of time and there appeared a threat of failure of the dam itself. This threat is still persisting (Figs. 9, 10) .

Fig.8. The water dividing dam on the river Rioni. 1– Dam;
2 – Gateway regulating the water supply from the river Rioni to the City Channel.

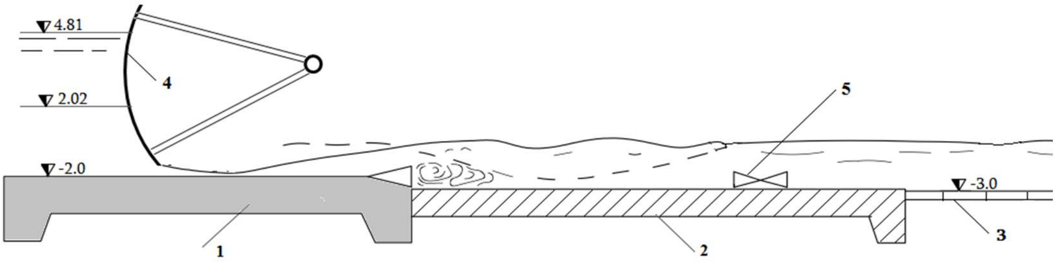


Fig. 9. Longitudinal section of the initial location of the apron slab and downstream apron of the dam: 1 – spillway foundation; 2 –Rehbock dentated apron; 3 – downstream aprons; 4 – segmental gate; 5 – Rhebock sills. The dotted line shows the undesired mode of upper and lower pools conjugation for a Rioni water discharge of 200-300 m^3/s.

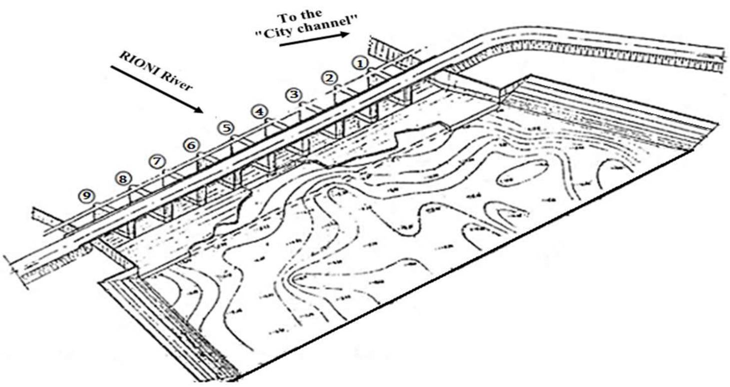


Fig. 10. Destructions contour in the downstream pool of the dam
of the Rioni water dividing structure

The cause of destructions in the downstream pool was estimated on the basis of the two postulates:

a) In easily washed-out river beds, in the calm regime (the Froude number is $Fr<1$), a maximum depth of wash-out coincides with the depth of the uniform flow determined by means of the Chezy formula depending on a slope of the river free surface in the river mouth;

b) This maximal depth occurs at the distance from the spillway outlet over which the velocity of the submerged jet drops to the uniform flow velocity in the river mouth. These distances (X) of maximum depth were estimated by us on the basis of G. Abramovich's relation for a turbulent waterlogged stream (Kiselev, 1972)

$$X=\frac{h_0}{0.08}\cdot\left(0.48\cdot\frac{V_0}{V_{bot}}-0.145\right), \tag{5}$$

where h_0 and V_0 are respectively the depth and the velocity of the stream in the spillway outlet section; V_{bot} is the velocity of the river uniform flow in the downstream pool of the dam which is determined according to the postulate b.

This approach almost accurately reflected the maximum depth of the channel washout and the coordinate of their distances from the section of the jet outlet, which are given in the drawings prepared in 2006.

Our studies showed that the causes of destruction of the downstream pool of the water-dividing dam on the Rioni lie in the gross errors made in the dam design stage in 1958. Of these, here we note the following:

a) The apron slab and downstream apron were located at a high elevation of –3 m which is only by 1 m below the spillway surface level.

b) The dimensions of the monolith apron slab (20 m in length, 1.2 m in thickness) and the downstream apron (40 m in length, the slab dimensions are $2\times2\times0.4$ m) were designed without taking into account dynamic loads from the upstream side: during intermediate discharges of the Rioni (up to 600 m^3/s), they experienced vibrations which were additionally intensified by the absolutely excessive Rehbock dentated apron and which led to their complete failure and to the threat of destruction of the dam itself.

All the measures taken by various design and construction companies in the 80 s to prevent wash-out processes and destructions of the downstream pool of the dam which we will not list here turned out ineffective and even on the contrary aggravated these processes. Only the temporary measure designed and carried out in 2007 and consisting in placing Maccaferri gabions up to the elevation of –5 m should be regarded as the most justified.

3. Conclusion

Ways of Solution of Hydro-Engineering, Geomorphological and Environmental Problems in the Poti Region

For the capital rehabilitation of the downstream pool of the water-dividing dam we propose to erect a new apron slab 30 m long and 1.5 m thick (Fig.11) in front of the spillway. The slab surface should be located at a level of -5 m (i.e. 2 m below the spillway surface) and should be smooth. The slab end part must rest on metal sheet piles (5) driven up to an elevation of -15 m and equipped with bulwark. In addition, cavities existing under the spillway and apron slab must be grouted with cement or filled with sandbags (2,7).

For the restoration of the washed-out sea coast of Poti, it is necessary to clean the city channel bed and increase its capacity; to repair the sluice to consider possibilities of the pulp feed-line rehabilitation and construction of a alluvia-retaining barrier along the underwater canyon located near the southern pier of the Poti port.

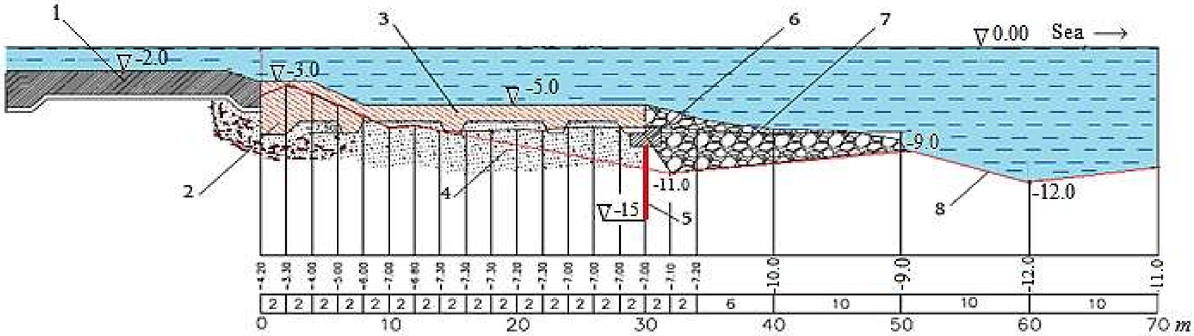


Fig. 11. Recommended structure for the capital rehabilitation of the downstream pool of the water dividing dam: 1 – spillway; 2 – cementation of earth cavities; 3 – apron slab; 4 – gravel pillow; 5 – metal sheet-pile wall; 6 – bulkhead; 7 – sandbags; 8 – river bottom (2005)

The operation regimes of the sluices of the water dividing structure were elaborated. The main principle of these regimes consists in the following: the sluices supplying water in the City Channel open only when a sea storm is of magnitude not higher than 3 (since only in this case alluvia transported to the City Channel participate in the restoration of the beach). When a sea storm exceeds magnitude 3, the sluices must be closed (since in the case of open sluices alluvia are carried away into the sea depth and do not contribute to the restoration of the Poti beach).

Engineering measures for preventing the Poti port from siltation were worked out taking into account variants of the reconstruction and extensive development of the Poti port as shown in the Fig.12 (Saghinadze, 2013).

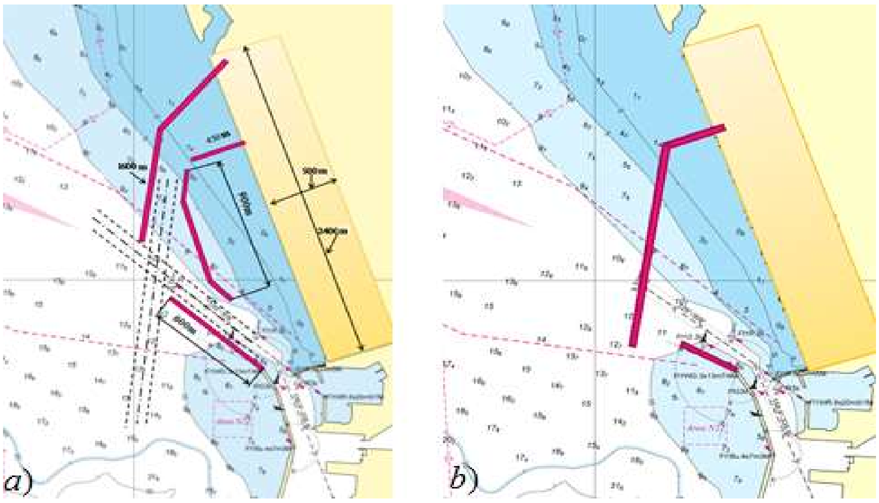


Fig. 12. Variants of extensive development of the Poti port studied and evaluated in terms of navigational safety: a) variant with a bilateral entrance in the Poti port; b) variant with a single entrance.

In conclusion, we note that the same studies should be conducted in other regions of the Black Sea coast of Georgia, in particular, at the mouth of the Chorokhi River, the flow of which is regulated by the HPP cascades in the Turkish territory.

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