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On the Probable Technical Reasons of the Devastating Flood in 2015 in Tbilisi

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ABSTRACT

The analysis of the possible technical reasons, which contributed catastrophic results of the flood on the Vere river 13.06.2015, which can become basis for the preventive actions in the case of repeating a similar extreme phenomenon in the future is carried out.

Key words: river Vere, flood

Preface. The river Vere is a typical mountain river with more than 40 km long gorge, about 1500 m water level difference and average yearly water flow Q $\approx$ 1m^{3}s^{-1}. The river is considered as one of the most dangerous in East Georgia due to frequent recurrent floods characterized by two orders of magnitude greater water flow than the average yearly value. The permanent complex meteorological-hydrological observations on the river flow regime include a period of more than half a century [1,2]. Besides, there are quite complete data on individual devastating floods, which occurred between the end of the 19th century and the second half of the 20th century. Usually, floods used to occur in the lower part of the Vere gorge near the boundary of Tbilisi city. In the Soviet period the flood zone was the area between the two tunnels (underground tubes) constructed in the first half of the last century. The first tube, which is nowadays situated under the Tamarashvili Highway, was 108 m long. The other tube was significantly longer, $l \approx$ 700 m. It occupied the natural bed of the river Vere before the junction with the river Mtkvari. Before 13.06.2015 night, for a long time, the flood taking place on 04.07.1960 was considered as the heaviest one. According to various assessments the flood was caused by the $h \approx 100$ mm precipitations, which fell during two and half an hour. According to approximate assessments, during this time period, the maximum water flow in the Vere bed could be $Q \approx$ 260 m^{3}s^{-1} [3]. According to our assessments the water flow in the closed bed of the river Vere during the night of 13.07.2015 was probably the same as the one of the 04.07.1960 flood [4]. However, the result of the last one appeared much disastrous due to human life losses and enormous material damage.

Like other mountain rivers of Georgia the bed of the river Vere is curving. It is quite deep in its upper part and considerably wide in the lower part. There are numerous springs on the either sides of the Vere Gorge. The dry ravines, also met here, turn into gutters during precipitations. In the areas of Tbilisi the surface and underground waters of the city also join the river Vere. Therefore, in the case of intense precipitations the lower, part of the Vere gorge turns into a fairly large catchment basin. Consequently, there could be no doubts that changing the bed of the river could be followed by negative consequences. After constructing the part of the high-speed highway in 2010 in the lower part of the gorge, the river Vere appeared partially contained in the artificial closed bed consisting of several tunnels joined by open sectors. Therefore, the geometrical properties of the natural bed corresponding the orography of the gorge, was significantly changed. It is probable that the first changes in the natural flow of the river Vere, which took place during the Soviet period, changed the parameters of the river bed and it could eventually affect the consequences of the flooding on 04.07.1960. The new closed bed of the river Vere, instead of two, has seven tunnels with general length of 2100 m. The two tunnels, which had been constructed earlier, were partially elongated and as a result, nowadays the first tunnel is $l \approx$ 360 m and the other is $l \approx$ 1200 m long.

Figure 1 shows a scheme of modernized old and new tunnels. The tunnels are placed along the natural bed of the river, from the Tamarashvili Highway to the junction with the river Mtkvari. The tunnels are complex structures made of concrete and corrugated steel sheets at straight sections. At curved sections the steel sheets are replaced with reinforced concrete. At cross section the tunnels look like a semicircular arch, which rests on a flat concrete base.

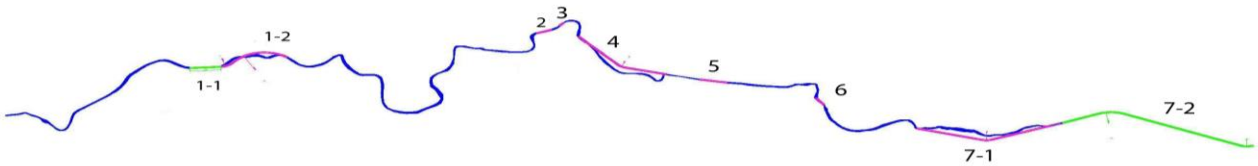

Fig. 1.

Scheme of modernized old (green sections) and new tunnels (red sections)

Specification of the construction made of corrugated steel sheet. The theory of the construction of water supply canals states that arched tunnels and bridges constructed from corrugated steel have a sufficiently high seismic stability. Therefore, according to their technical and economic characteristics, they are almost as stable as structures made of stone, reinforced concrete or metal. Moreover, large water pipes made of corrugated steel have some advantages over concrete ones due to technological simplicity and less labour-intensiveness for construction and installation works. It is known that one of the advantages of arched tunnels and bridges made of corrugated steel is their ability to gradually fracture, i.e. soft bedding in case of considerably strong and prolonged tremors. Therefore, in poor countries like Georgia, corrugated steel structures are usually used for hydraulic facilities in seismically active regions. Obviously, this quality is important, as far as according to the current seismic zoning map, the territory of Tbilisi belongs to the earthquake zone of intensity VIII motion. However, it should be noted that after earthquakes with intensity VII-VIII, restoration of arched tunnels and bridges constructed from corrugated steel is is not recommended [5-7]. Consequently, after such earthquakes they must be completely disassembled. Corrugated water pipes are often used under bridges crossing narrow rivers and ravines. However, they should not be used for hydrotechnical objects in regard to mountain rivers with fairly long closed riverbeds. Despite this, the structure of the closed and sufficiently long arched tunnels of the river Vere was made of corrugated steel sheets. In particular, the total length of the tunnels of the closed channel was 46% of the original length of the natural river bed between the Tamarashvili highway and the river Mtkvari.

The security problem of the closed channel of the river Vere. A project of any potentially dangerous civil engineering object, including large hydraulic structures, should contain an analysis of probable negative consequences of the construction. According to generally accepted rules, it is necessary to take into account the changes in external conditions that arise during the construction and operation of the structure. Any problem should be considered, evaluated and reflected in concluding of opinions of official responsible persons. It is obvious that the project of the section of the high-speed highway in the gorge of the river Vere could not be an exception to this rule. Moreover, its safe operating required the minimization of the real threat seen not only from the history of the river Vere, but also from the data obtained of detailed observations during half a century. It was probably assumed that the closed channel, in addition to the transport problem, could also solve the flood problem in the lower part of the Vere gorge. However, it seems that mistakes were made during the design process, the reason of which is disregard of the factor of the hydraulic resistance in the tunnels having corrugated inner surfaces. As a result, the closed riverbed turned into an even greater danger than the historically known river Vere. Proceeding from such a vision of the reason for the development of the events, we cannot agree with the widely spread opinion that the devastating flood on 13.06.2015 was caused by anomalously heavy precipitation. Firstly, after different estimates, an explicit amount of precipitation height has not been established so far. Secondly, it was well known about the frequent occurrence of very heavy floods in the Vere gorge. Therefore, when designing a closed channel, it was necessary to a priori consider the dangers that could arise in case of severe weather conditions. Due to the constant threat of flooding, it was obviously not reasonable to use such constructions that could reduce the capacity of the closed channel. It would be quite likely that there would be retrospective data on the 04.07.1960 flood in order to assess the degree of danger potentially threatening the urbanized gorge of the river Vere. There were also valuable data on series of floods that occurred in the subsequent period of time. First of all, it was quite possible to estimate how much the capacity of the new tunnels of the closed channel corresponded to the full load of the modernized first tunnel. As it is shown below, most likely the damming occurred not only before the first tunnel, but also in front of other tunnels. An important proof in favour of such an assertion is the fact that the water from the dam formed on Svanidze Street did not flow over the Tamarashvili highway. Consequently, this highway was a watershed, dividing the gorge into two parts. Therefore, we can assume that the flooding beyond the watershed began independently from the reason of damming of the first tunnel. For this, e. g, it was sufficient that water flow in any of the tunnels was reduced due to the increase in hydraulic resistance, and also because of the drain of urban storm water in the lower part of the gorge. As it is known, on 04.07.1960, flooding occurred in front of both tunnels.

Hydraulic resistance in the tunnels of the closed channel. It seems that during the design process of the sector of the high-speed highway in the Vere gorge, increase in the hydraulic resistance of tunnels of the closed channel under severe conditions was underestimated. Indeed, there was a physical reason for a sharp decrease in water flow, which was associated with the corrugated structure of the inner surface of the tunnels. The negative effect could also intensify due to the critical curvature of the new segment of the first tunnel, the length of which increased more than twice after modernization. According to the prevailing opinion, the cause of the devastating flood was precipitation of exceptional intensity, as well as trees, brought by the water flow and accumulated in front of the inlet of the first tunnel. However, it seems that such an explanation is insufficiently substantiated. Undoubtedly, the inlet of the first tunnel for some time was actually partially blocked that contributed to the flooding in Svanidze Street. However, it is especially noteworthy that from here the water did not flow over the Tamarashvili Highway, which turned out to be a watershed. After some time, the inlet of the first tunnel was released. Therefore, the previously partially blocked tunnel could not operate at its maximum throughput. Besides, there was a flood also in the area between the outlet of the first tunnel and the inlet of the last one. As far as the first tunnel was partially blocked, this could hardly have been caused only by the additional flow of water from urban drains and precipitation in the area of this part of the Vere gorge. Indeed, according to rough estimates, the area of the bottom of the gorge is $S \approx 3*10^5$ m^2. The catchment area corresponding to this part of the gorge is about an order of magnitude larger. Taking into consideration that on 13.06.2015 the precipitation height was $h \approx 100$-150 mm, then an additional volume of water, beyond the watershed, could be $V \approx (3\text{-}4.5)10^5$м^3. Such an amount could accumulate during 2.5-3 hours. This corresponds approximately to the flow rate of water $Q \approx$ 25-30 m^3 s^{-1}, which is about 10% of the estimated throughput of the first tunnel. However, the first tunnel was partially blocked for some time, and consequently its capacity was lower than the design one. Therefore, in spite of the additional volume of water received from the gutter, in the case of sufficiently effective operation of other tunnels (especially the last one), floods in the lower part of the gorge were unlikely to have occurred. At least, here the water could not rise by 15 m or more. In fact, the water rose to such extent that the tunnels were below its level. Therefore, even if this estimate of the amount of the flooded water is understated, this factor could not raise the water level so high if the capacity of the tunnels was at a sufficient level. Moreover, in design calculations the maximum value of the water flow in a closed channel was $Q \approx$ 260 m^3 s^{-1}, which fully corresponds to emergency situations. However, we need additional facts for proving our opinion. Thus, below is a brief qualitative analysis, the basis of which is the hydrodynamic theory of turbulent water flow in rough pipes.

Modelling of the closed tunnels. It is well known that the coefficient of hydraulic resistance in a circular pipe depends on the characteristic value of the Reynolds number and also on the curvature and roughness of the inner surface of the pipe. There must be a similar dependence for all natural and artificial channels, including tunnel water pipelines. Therefore, using the hydrodynamic similarity method, it is possible to correctly model the hydraulic resistance of a water channel of any shape. Consequently, it is possible to accurately determine the characteristic value of the coefficient of hydraulic resistance of the tunnels of the closed bed of the river Vere. To do this, it is necessary to approximate the closed channel (i.e., any of the tunnels) with a circular cross-section curved rough pipe. Obviously, such an analogy, both for a separate tunnel and for a closed channel as a whole, is physically fully justified. The analogy between a tunnel with a corrugated inner surface and a rough pipe is also evident. It enables to determine the coefficient of hydraulic resistance, the key parameter on which the flow of water in any water pipe depends. The main determinant of the degree of turbulence in the water flowing in the pipe is the dimensionless parameter, the Reynolds number $R_e = \frac{\bar{u}D}{\nu}$, where $\bar{u}$ is average water flow velocity, D is the pipe diameter, ν is kinematic viscosity of water. Therefore, for the closed channel of the Vere, the linear characteristics of which is the constant hydraulic radius of the tunnels, the speed of the river flow determines the characteristic value of the Reynolds number.

It is known that inner surface of smooth pipes may become rough over time due to deposits of solid impurities in water. It is established that among the different types of roughness, in regard to reducing the fluid flow rate, corrugated roughness is the most negative factor. It is obvious that the corrugated steel surface of the closed channel is highly similar to the wavy-rough inner surface of a water pipe. The degree of flow turbulence in the tunnels of the closed channel must increase due to the roughness of the corrugated surface. In harsh conditions on 13.06.2015 this should have an effect on the fluid flow. Besides roughness, in the curvilinear sections of the tunnels, the hydraulic resistance must have been further increased due to the action of centrifugal forces. However, according to our estimates, exactly the corrugated surface was the main reason for the decrease in throughput rate in the tunnels of the closed channel.

Negative effect of roughness in water pipes was noticed long ago. This effect was modelled in numerous experiments, among which the laboratory experiments carried out by Prof. I. Nikuradze in the 30s of the last century are the most popular [8-10]. These researches determined that among the various types of roughness on the inner surface of water pipes, undulating roughness causes the maximum decrease in fluid flow. According to physical similarity, the analogy of the corrugated steel surface of the closed river Vere and undulating rough surface of water pipes is obvious. It is known that for different hydrotechnical objects the permissible relative roughness can vary within the limits of 0.2%-7% [7]. This parameter is the relation of the characteristic height of roughness to the radius of a pipe, or to the characteristic linear dimension of the cross-section of a water channel of any other shape. The existence of a sufficiently wide range of permissible relative roughness values at hydrotechnical objects of various purposes is caused by practical reasons, e.g., an ambiguous dependence of hydraulic resistance on the linear parameters of water pipes was established, and the Reynolds numbers were also obtained from the turbulence regime of the water flow. In the case of a water channel of a pipe shape, such an ambiguous parameter is the length. It is characteristic of the well-known Hagen-Poiseuille formula, which determines the flow of laminar fluid in a circular pipe. In this formula, the pressure gradient also enters as the main determinant. A special modification of the Hagen-Poiseuille formula is used for turbulent flow. The correctness of its use depends on the flow turbulence regime. The degree of turbulence, in addition to the level of the tube load, is also affected by the roughness of its internal surface. The longer the roughened tube, the lower the upper limit of the interval of subcritical values of the relative roughness. Intensification of flow turbulence, i.e. the transition from the initial stage to an increasingly developed turbulence, will be reflected in an increase in the characteristic value of the Reynolds number. However, in case the throughput of a smooth analogue of a pipe approximating the water supply considerably exceeds the volume of incoming water, the upper limit of the permissible relative roughness of the inner surface of the water pipe can be increased to 7%. Taking this qualitative fact into account, let us return to the closed channel of the river Vere, the characteristic diameter of which is $D \approx 8$ m. According to [1-3] in the lower part of the Vere gorge at the time of high-water flow, the average flow velocity is $\bar{u} = 3.5\ \text{ms}^{-1}$. Consequently, the Reynolds number in case of full load of the closed channel can reach $R_e \approx 2 * 10^7$ value. Therefore, according to the range of permissible relative roughness values, the minimum theoretical height of the absolute roughness, which can have an effective influence on the hydraulic resistance of tunnels of the closed channel, is equal to $k \approx 10$ mm. However, the actual height of the protrusion of the corrugated steel surface is $k = 150$ mm, i.e., it is more than an order of magnitude greater than the minimum theoretical value. Consequently, the relative roughness of the inner surface of the closed channel actually amounted to $\approx 4\%$. It is known that such roughness for some hydraulic structures, for example, irrigation canals, does not exceed the technically permissible limits. However, this is hardly acceptable for objects such as the closed tunnel of the river Vere.

Formation of the stagnation zone. It should be assumed that in emergency situations floods in a closed channel in the future can be caused not only by factors of roughness and curvature, but also other negative mechanisms. Obviously, roughness, under harsh conditions, in all sufficiently long tunnels of the closed channel will always contribute to the intensification of the turbulence and initiation of return flows. Therefore, we assume that the increase in hydraulic resistance to the critical level in the tunnels of the closed channel was one of the reasons that led to the disaster on 13.07. 2015. In particular, at the initial stage the flood zone formed in front of the first tunnel, the reason of which, in addition to the hydraulic resistance, was also partial overlapping of the inlet of the tunnel by various household objects and trees brought by the water flow. As a result, the flood zone gradually expanded and, according to oure estimates, a reservoir of volume /3.1-4.4/10^5 m^3 rapidly formed and was kept long enough along the entire length of Svanidze Street. Such a factor of mechanical damping, but to a lesser extent than before the first tunnel, was observed for a certain time also in front of the second tunnel. However, in our opinion, it is necessary to pay special attention to the fact that the section of the gorge between the first and second tunnel was dammed while the water flow in the first tunnel was diminishing.

Thus, it becomes obvious that the initial flood in the lower part of the Vere gorge occurred before inlet of the first tunnel. Then, regardless of the rapidly formed reservoir along the Svanidze Street, the areas in front of other tunnels were apparently also flooding. For example, after the first tunnel such a place could be the inlet of the second tunnel, or the inlet of the longest, the last tunnel connecting the Vere to the main river Mtkvari. Probably, it was the joint action of all local flood zones that resulted in heavy flooding. However, regarding the probability of possible repetition of severe meteorological conditions in the future, it seems that the discussion of the technical causes of the devastating 13.06.2015 flood should be supplemented with the fact that the river Vere has a sharp bend in front of the second tunnel (Photo 1).

Photo 1.

Therefore, it can be assumed that together with the negative effect of the hydraulic resistance of the tunnel, this place inevitably became one of the initial flood areas during the devastating flood. In the process of reconstruction of the closed channel, it was evidently noticed. Therefore, seemingly, to avoid danger in the future, guiding walls were placed in front of the inlet of the second tunnel. Photo *2* shows that this additional structure resembles a funnel, the purpose of which, according to the plan, is to direct the water flow towards the tunnel. The first segments of these guide walls are parallel to the tunnel. The other segments, having a length of about 5 m, form following angles with the axis of the tunnel: $\gamma \approx 20$ ° and $\delta \approx 30$ °. However, contrary to the assumption of the designer, who completed this upgrade, we believe that this design, under severe conditions, will only cause reduction in the water flow in the tunnel. The fact is that the guiding walls, located at such angles, will definitely create counter flows that will collide near the inlet of this tunnel. The intensity of the colliding flows will increase in proportion to the increase in the water level. A direct confirmation of this conclusion is *Photo 3*, which enables to estimate the degree of filling of the second tunnel during a fairly intense rain on 07.07.2017. On this day, the precipitation level was about 20 mm, i. e. not more than 20% of the precipitation that fell during the devastating flooding on 13.06.2015. This fact is quite noteworthy and certainly ought to be taken into account. Therefore, below we give a concise form of an explanation of the physical essence of the phenomenon, the emergence of which is obviously the result of an insufficiently thought-out technical solution.

Photo 2

In the hydrodynamic theory of ideal incompressible jets, several analytical solutions to problems associated with the formation of stagnant zones or, in other words, zones of liquid stagnation, are known. These solutions are generally ambiguous, as they depend on some free parameter [11]. In problems of collision of ideal jets, this parameter is usually the angle between the directions of straight and backward flows. The physical essence of the ambiguity of analytical solutions in the problems of jet collision is shown in *Figure 2*.

It corresponds to the particular case of a collision at a right angle of two liquid jets having equal intensities. As a result of the collision, there are two jets that are also at right angles, of the same intensity as the original jets. In the area of the convergence of all jets, a zone of water stagnation with a finite linear dimension is formed. It is obvious that only such a particular solution, corresponding to the idealized case, is single-valued from the view point of determining the direction of divergent jets. In case when converging jets have different intensities and collide at an arbitrary angle, then any analytical solution obtained within the limits of the theory of ideal jets will be ambiguous. Nevertheless, for example, in irrigation problems, such a drawback may not be a fundamental obstacle to numerical simulation of the collision of intersecting water flows.

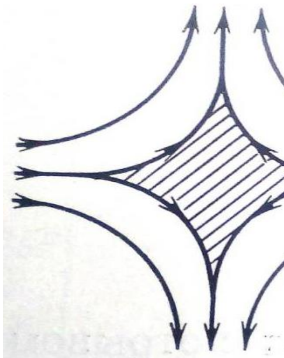

Fig.2

However, in the flat solutions obtained by the method of conformal mappings, the physical essence is, as a rule, concluded in the possibility of a thorough analysis of the asymptotic behaviour of the solution. An example of such an ambiguous solution is the mathematically indeterminate solution of the collision problem for two arbitrary jets A_1 and A_3, obtained in [12], which is schematically shown in Figure 3.

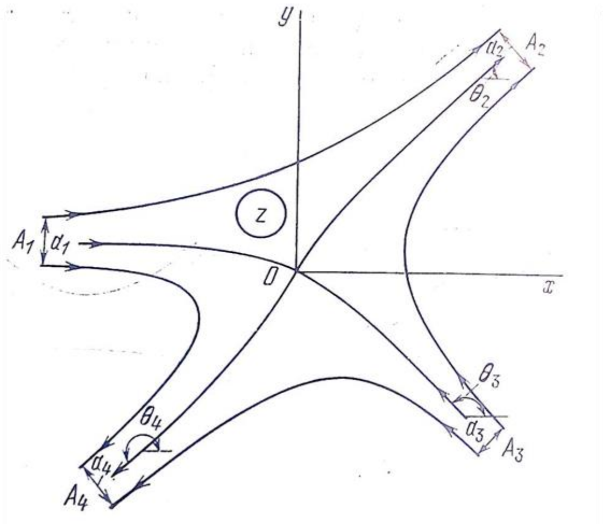

Fig.3

Several attempts to raise the practical value of this decision are known. In particular, it was substantially supplemented in work [13]. This synthesized analytical solution seems to be most suitable for simulating the flow before the second tunnel of the closed channel. In it, the problem of uncertainty was eliminated by estimating arbitrariness in the directions of the diverging jets A_2 and A_4, namely, the relation of the angle θ_2 to the angle θ_4 was established, which is a free parameter of the problem. Further, by the method of conformal mapping, having given values θ_2 and θ_4, for jets A_1 and A_3 colliding at the angle θ_3, with flows $\boldsymbol{Q}_1$ and $\boldsymbol{Q}_3$, the flows of the diverging jets $\boldsymbol{Q}_2$ and $\boldsymbol{Q}_4$ were determined. Thus, an analytical solution of the nonlinear system of equations of the coupling between the parameters of the straight and backward jets was obtained. Despite the fact that this solution is flat, it is convenient for analyzing the effect of water stagnation in front of the second tunnel. This requires angles γ and δ, as well as an analytically reasonable interval of the intensity ratio of the colliding jets. The main result of the approximate quantitative analysis is the following: the intensity of the water flow entering the tunnel will always be less than the sum of the intensities of the flows colliding at the inlet. Consequently, it is inevitable that this effect will be followed by a decrease in water throughput and formation of a stagnation zone in front of the tunnel inlet. It means that in the case of intense precipitation, the stagnation zone will rapidly widen in this area, which can lead to heavy flooding between the first and second tunnels. In particular, according to the estimates made on the basis of the topographic parameters of the Vere gorge, the volume of the rapidly formed reservoir in the indicated place on the night of 13.06.2015 was ≈ 1.6 10^5м^3.

Photo 3

Modelling of water flow in the closed bed. As it was said above, in order to prove qualitative assumptions corresponding to quantitative estimates it is reasonable to use a special modification of the Hagen-Poiseuille formula for the case of turbulent flow

$$Q = \pi R^2 \bar{u} \quad , \qquad (1)$$

where Q is the water flow in a circular pipe with radius R. Equation (1) also includes the average flow velocity, which is determined on the basis of the analytical expression [3-5]

$$\bar{u} = \sqrt{\frac{4R\Delta p}{\lambda \rho l}} \quad . \qquad (2)$$

This formula, together with the radius of the pipe, pressure drop Δp, length l of the pipe and water density ρ, obviously, also includes total hydraulic resistance λ. Namely, the total hydraulic resistance of tunnels of the closed Vere channel, by analogy with the resistance of a rough curvilinear model pipe, must be an additive value : $\lambda = \lambda_r + \lambda_k$, where λ_r is resistance, caused by curvature, λ_k is resistance connected with roughness. At the same time, the ambiguous dependence of the flow regime on the length of the tunnels should also be taken into consideration, as far as it makes the long closed channel a special hydrotechnical object.

To determine the value of the hydraulic resistance caused by the curvilinearity of the tube, one can use semiempirical formula

$$\frac{\lambda_r}{\lambda_0} = 1 + 0.075 R_e^{1/4} \left(\frac{R}{r}\right)^{1/2}, \qquad (3)$$

where, together with the Reynolds number, there is a hydraulic resistance of the smooth straight pipe, determined by expression

$$\lambda_0 = 0.0032 + \frac{0.221}{R_e^{0.237}}. \qquad (4)$$

In full load mode, the characteristic Reynolds number for the closed Vere channel is $R_e \approx 2 * 10^7$. Consequently, from formula (4) we will receive the following characteristic value of the hydraulic resistance of a smooth straight pipe $\lambda_0 \approx 0.73 * 10^{-2}$. Formula (3) includes relative curvature $\frac{R}{r}$, i.e., the correlation of the radius of the curved pipe to the radius of its curvature. According to the updated building codes and rules of the former USSR [7], which are valid up to the present day in Georgia, the permissible value of the relative curvature of waterworks depends on the value of the water flow rate and is limited by the maximum angular sector: $\varphi = 60^0$. As far as there is no available project of the high-speed highway section in open sources of information, we only indirectly estimate that in modernized first tunnel, which is the most curvilinear in the closed channel, the angular sector of curvature of the second segment does not exceed the maximum permissible value. In careful reasoning we can also assume that the flow velocity during the flood on 13.06.2015 reached the theoretical allowable value $V_{max} \approx 10$ мс$^{-1}$, determined both by indirect estimates and by the data of long-term observations. This limit value corresponds to the permissible relative curvature: $\frac{R}{r} \approx 0.17$, i.e., if $R_e \approx 2 * 10^7$, then from expression (3) we will receive $\frac{\lambda_r}{\lambda_0} \approx 3$. Therefore, since the absolute value of the coefficient of hydraulic resistance of a smooth pipe is $\lambda_0 \approx 0.73 * 10^{-2}$, for the coefficient of hydraulic resistance due to the curvature of the closed channel, we will have $\lambda_r \approx 0.022$ [4].

The coefficient of hydraulic resistance of a pipe with a rough inner surface, like λ_r, is also determined by semi-empirical formula [8-10].

$$\lambda_k = \frac{1.3}{ln^2\left(\frac{R}{k}\right)}. \qquad (5)$$

For the corrugated section of a closed channel the geometric roughness was $\frac{R}{k} \approx 26.6$, which corresponds to $\lambda_k \approx 0.12$. Thus, according to model estimates, during the devastating flood, the characteristic value of the total hydraulic resistance of the closed channel of the river Vere was equal to $\lambda = \lambda_r + \lambda_k \approx 0.14$.

To demonstrate mathematical correctness in estimating the degree of reduction of water flow in tunnels of a closed channel, let us consider two model pipes of different radii: R_1 and R_2. Let us consider that the first tube is smooth and rectilinear, the second is curved and rough. Let us suppose, having the same pressure gradients, the water flows in the pipes are the same. This assumption is physically justified in case of their full load under the condition of free gravitational flow of water. From the condition that the maximum water flows in the model tubes are equal, using expressions (1) and (2), we will have [4]

$$\frac{Q_1}{Q_2} = 1 = \frac{R_1^2}{R_2^2}\sqrt{\frac{R_1\lambda}{R_2\lambda_0}} = (\frac{R_1}{R_2})^{2.5}(\frac{\lambda}{\lambda_0})^{1/2}. \qquad (6)$$

This expression means that it can be satisfied only if the radius of the curved rough tube is much greater than the radius of the smooth one. Namely, as far as according to our estimates, the corresponding coefficients of hydraulic resistance are $\lambda_0 \approx 0.73 * 10^{-2}$ and $\lambda \approx 0.14$ we will have $\frac{R_2}{R_1} \approx 1.8$. It means that in order to meet the conditions of equal fluid flow in the model pipes, the area of the cross-section of the rough curved pipe must significantly exceed the area of the section of the smooth straight pipe $S_2 \approx 3.24 S_1$. In other words, the throughput of two pipes of the same cross-section having different geometry and the degree of roughness of the inner surface will be different. Therefore, if such pipes are connected and the first one is smooth and straight, then in the case of its full load, the second, curved and rough pipe will inevitably become partially locked. Consequently, if these pipes are not rigidly connected, a flood zone will appear before the second pipe. Regarding the closed channel of the river Vere, this means that in the extreme flow regime there could be a sharp difference in the flow of water, not only between the inlet and outlet of the closed channel, but also between individual tunnels. In any case, the inevitable outcome of this would be a flood in the lower part of the Vere gorge, which happened on 13.06. 2015.

Conclusion. The reason for the devastating flood on 13.07.2015 in the gorge of the river Vere was both natural and artificial causes. It seems that an anomalous natural phenomenon was added to a technical factor associated with structural deficiencies in a closed river channel, which is an integral part of the project of a high-speed highway section in the lower part of the Vere gorge. Therefore, in conditions of frequently repeated intense precipitation, the gorge remains a real threat for Tbilisi city for several reasons in the future, namely:

1. After the devastating flood, the closed channel was restored in its original form, though after modernization, guiding walls were installed in some places. According to the plan, they are to direct the water flow into the tunnels, in particular, the most problematic second tunnel. However, such a modernization, instead of a positive action, may reduce the throughput of the second tunnel;
2. In our opinion, in the design of the high-speed highway passing in the lower part of the Vere gorge, the possibility of a critical increase in the hydraulic resistance of a closed channel under severe conditions was not taken into account. The neglect of this factor was probably caused by the theoretically insufficiently developed design of the closed channel, which is a combination of several tunnels of considerable length, made of corrugated steel sheets and, partially, reinforced concrete. The curvature of the first tunnel, according to construction standards, is likely awkward. The total effect of the roughness factors of the corrugated inner surface and the curvature of the closed channel, according to our model estimates, could be extremely negative. As a result, there was a critical increase in the hydraulic resistance of the tunnels, leading to a partial closure of the closed channel of the river Vere. It turned out to be the probable cause of the great flood, which led to the well-known tragic consequences. Obviously, recurrence of anomalously intense precipitation is probable in the future. Therefore, since after the devastating flood on June 13.06.2015 the closed channel was restored without any changes, the negative factor associated with the hydraulic resistance may reappear.

3. The analysis of the possible technical reasons that contributed to the disastrous results of the flood on the river Vere on 13.06.2015 may become the basis for preventive actions in case of a repeat of such a phenomenon in the future. In particular, in conditions of periodically repeated intense precipitation, only external monitoring of the water level in the riverbed cannot provide a realistic forecast of the vulnerable situation. For this purpose, simultaneous observation of the water level at critical locations of the closed channel, in particular, before the first and second tunnels, is quite effective. In these places, so-called stagnant zones, which serve as an indicator of the formation of recurrent currents, may appear. Stagnant zones can form even in case of medium intensity precipitation. As to the factor of hydraulic resistance, it will fully manifest itself in the case of extremely intense precipitation, i.e. under the condition of the maximum load of the tunnels of the closed channel. Consequently, until a certain moment, the zone of stagnation will not cause the decrease in the flow of water in the tunnels. Moreover, local water stagnation in front of the first and second tunnels can reduce, or simply prevent flooding in the area between the second and the following tunnels. To eliminate heavy flooding of this area, it is also reasonable to install a special adjusting water gate under the road passing over the second tunnel across the Vere gorge.

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2015 წელს თბილისში მომხდარი დამანგრეველი წყალდიდობის შესაძლო ტექნიკური მიზეზები

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რეზიუმე

ჩატარდა ანალიზი მდინარე ვერეზე მომხდარი კატასტროფული წყალდიდობის ტექნიკური მიზეზების დასადგენად, რაც შეიძლება გახდეს საფუძველი პრევენციული მოქმედებებისათვის რათა მომავალში თავიდან იქნას აცილებული მსგავსი კატასტროფის გამეორება.

О возможных технических причинах катастрофического паводка в городе Тбилиси в 2015 году

З.А. Кереселидзе, И. Б. Хведелидзе, Г. В. Шергилашвили

Резюме

Проведен анализ возможных технических причин, способствовавших катастрофическим результатам паводка на реке Вере 13.06.2015, который может стать основой для превентивных действий в случае повторения подобного экстремального явления в будущем.