11 Impact of Morphodynamical Changes on the Bridge Stability: Case Study of Jakuševac Bridge in Zagreb

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11.1. Introduction

When watercourses are regulated, riverbed morphology changes in comparison to the natural state of the watercourse; it is shortened and, therefore, causes greater longitudinal slope and concentration of the river flow energy. Due to greater longitudinal slope, river velocity as well as riverbed shear force are locally higher causing changes in the riverbed morphology. When hydrodynamic force reaches its critical value and disrupts the balance of forces keeping the particles on the river bottom in place, the particles are lifted from the bottom and transported downstream. After a while they settle again thus influencing the morphological development of the riverbed.

Under critical flow velocity conditions in riverbeds with movable bottoms, rivers and channels adapt their riverbed shape to the boundary conditions and mold a natural flow and bed-load transport [13]. The shape of a river valley is a result of fluvial erosion and is influenced by hydrodynamic forces which act on non-coherent material in riverbeds. The stability of a river channel is dependent on the regime of sediment load discharge. If the natural balance of sediment discharge is disrupted, the result is deepening of the riverbed (global erosion), river bank erosion and even discharge profile obstruction can occur. In addition to global erosion, local scour can occur in places where the flow pattern is disrupted due to the influence of a submerged structure like a bridge pier. A significant hydraulic structure in the river usually reduces the local discharge profile, causing backwater effects and disruption of the flow pattern. The flow lines are elongated and concentrated along the solid contour, resulting in increased velocity and unit discharge, as well as increase in local shear stress. Aided by high turbulence, this can result in intensive scouring of material from the channel bed. Although structures may be inherently strong enough to withstand water forces their stability may be endangered by transportation of the material in the channel. The process of channel deepening in the zone influenced by the structure is finalized when equilibrium conditions are established, i.e. when the quantity of sediment entering the scour hole and sediment removed from the scour hole become equal $(Q_s)_{in} = (Q_s)_{out}$. Most investigations of the local erosion phenomenon were conducted to determine the effect on bridge piers.

In hydrotechnical engineering, the need to evaluate river behavior in altered conditions, caused primarily by anthropogenic influence, is extensive. The occurrence of such influences must be foreseen, and their possible impact on the river channel must be estimated, followed by the design of appropriate measures to protect the structure or ensure the stability of the river channel. Considering bed-load transport is never exactly determined and depends on hydrological and hydraulic flow parameters, the amount of transported bed-load as well as transport distance cannot be precisely defined. While selecting methodology for the sediment discharge estimation, care must be taken with regard to the appropriate theoretical equations, and verification by on-site measurements is required. The most accurate methods in determining the creation and movement of riverbed bed-load in a watercourse are in-situ bed-load and hydrological-hydraulic flow parameter measurements. Modern devices, based on satellite positioning system and acoustic measuring devices are used to collect high quality information for forecasting the stability of the river channel.

11.2. Case Study: Sava Jakuševac Bridge

Intensive riverbed degradation over many years causes damage to structures built in riverbeds. Every structure is designed to withstand conditions relevant at the time of construction, with appropriate safety factor. When the conditions change, the balance of forces affecting the structure is disrupted. The balance can be affected by changes in the hydrological regime of the river, global erosion and local erosion around the structure or a combination of these changes. Flood events cause greatest damage and disruption of the stability of the bridges spanning over rivers. Harmful effects to the structures are various, the most significant being the local washing away of the riverbed material in the area around bridge foundations (abutment and pier foundation erosion). Loss of bridge stability due to erosion is considered to be the result of inadequate criteria used during bridge design and insufficient field analysis of erosion on the built structures. Influence of flow forces is more emphasized when the riverbed is not oversaturated with bed-load. Degradation of river bed in the upper reaches, including the Sava River in the area of Jakuševac is a natural phenomenon. However, the gradient of changes is heavily influenced by a human factor. More specifically, the following parameters have caused the acceleration of the process: reduction of sediment inflow due to construction of dams and weirs in upstream reaches; increased tractive force due to increased longitudinal slopes as a result of shortening of the river course by regulation works; increase of water depth during flood waves due to flow concentration in the channel, without natural floodplains and gravel excavation from the riverbed.

At the end of 1981, on the reach of the Sava River between the stations of HEPP Podsused and Zagreb, significant problems appeared regarding continuous and reliable supply of the necessary amount of cooling water to the thermal power plant 'Termoelektrana – Toplana Zagreb' (TE-TO Zagreb) (rkm 696+400). That was the first time the TE-TO Zagreb plant needed to be shut down due to the low Sava River water level and inability to supply the necessary amounts of cooling water. This incident announced the existence of significant changes in the hydrological regime of the Sava River. Extremely low water levels of the Sava River at the pumping station, causing shut downs of the TE-TO Zagreb plant during 1982, became increasingly frequent and urgent improvements had to be made in order to ensure the necessary amounts of cooling water during low water periods. Research results showed a submerged weir in the riverbed, functioning as a temporary barrier, to be the best solution to the problem of ensuring necessary water level for unhindered functioning of water pumps and stabilization of the riverbed upstream from the barrier weir cross-section. First submerged weir in the Sava riverbed was built in 1983.

Part of the Srednje Posavlje flood protection system, designed and partially constructed after the 1964 Zagreb flood, is the Sava-Odra flood relief canal. The Jankomir overflow located at rkm 710+100, acting as the flood relief canal's starting point was designed to activate when the river discharge reaches 1900 m^3/s. However, in the period from its construction in 1979 until 2000, lowering of the Sava riverbed on the overflow location amounted to 2m [6] and additional 70cm in the last 10 years. Under these new circumstances, the overflow activates only when the river discharge reaches 2350 m^3/s and not 1900 m^3/s, which was originally the maximum allowed discharge. The downstream reach of the river is therefore exposed to influences which dramatically exacerbate the already negative riverbed erosion process. According to the discharge measurements conducted by the DHMZ (Croatian Meteorological and Hydrological Service), the overflow should have been activated 9 times in the period between 1979 and 2006. In fact, it was activated only 5 times: twice in 1979 and once in years 1980, 1990 and 1998 [10].

In everyday practice there are numerous examples of problems caused by the deepening of the riverbed. Case study chosen to illustrate the type of technical problems that can occur is the significant tilting of a pier of the Jakuševac bridge near Mičevec in Zagreb, Croatia (rkm 693+100). The railway bridge Jakuševac is an example of a loss of bridge stability caused by global and local erosion, aided by extreme hydraulic conditions. On March 30, 2009, during the passing of a flood wave in the Sava channel when a freight train was crossing the bridge, the bearing structure of the bridge lost its stability and resulted in a deformation of the bridge structure and tracks. Tilting of the pier was caused by the superposition of two influences: disruption of the global riverbed stability leading to considerable lowering of the riverbed compared with the time the bridge was designed and constructed, and the appearance local scour in area around the bridge pier.

This paper presents the effects of anthropogenic influences on the morphological development of the Sava River, based on the observed characteristic stages collected from the Zagreb and Bundek gauging stations over a number of years. Field surveys have been conducted to monitor development of scour hole with respect to time after bridge collapsed. Analyses of theoretical estimation of scour depth have been made and compared with actual development of scour hole measured through field surveys for verification purposes.

11.3. Hydrological Indicators of Morphological Changes

The Sava River stage and discharge readings at the Zagreb gauging station, situated at rkm 702+800, and the Bundek gauging station, situated at rkm 699+700 were used in this paper. Available data was collected and originally processed by the DHMZ. Annual mean stage and discharge values were calculated for low, mean and high waters, depending on the duration curve. This type of measurements has been available since 1926 for the Zagreb GS and for the Bundek GS since 1967.

The time line is divided into two periods: one spanning over the 1925-82 period and the other covering the period between 1983 until today. These two periods were chosen for two reasons, both having a great impact on the hydrological regime of the Sava River. One reason was the afore mentioned construction of the weir at the TE-TO Zagreb location (rkm 696+400) in 1983, and the other was the occurrence of a long dry period on the territory of the Republic of Croatia after 1980 [14]. In 1983 a unique limit was accepted since dry years added to the first time period could not significantly affect the homogeneity of the data [10].

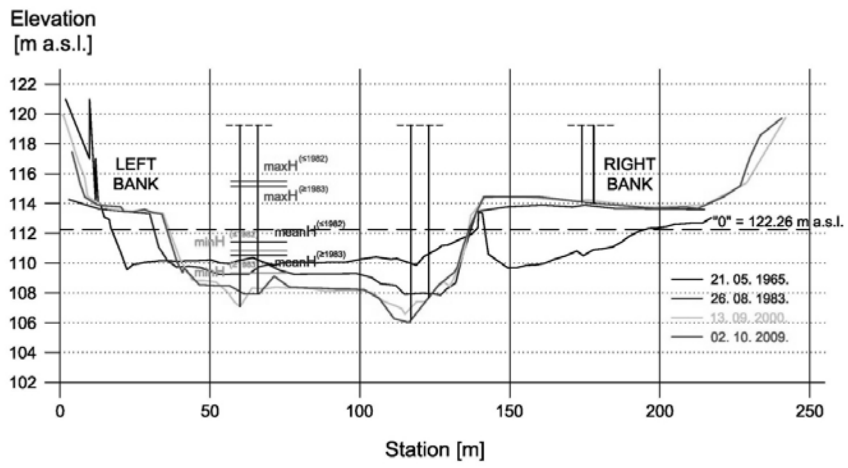

Fig. 1. Cross section of Sava riverbed at Zagreb GS with characteristic stages

Beside measurements of morphological changes and hydraulic flow parameters in a control profile, lowest annual stage trend is the best indicator of morphological changes. Observing stage and discharge values at river profiles over a number of years provides an insight into the trends of hydrological parameters as well as the ground for drawing conclusions on the morphological development of the riverbed on the observed river reach. The following figures show trends in annual maximum, minimum and mean stages at the Zagreb GS and Bundek GS.

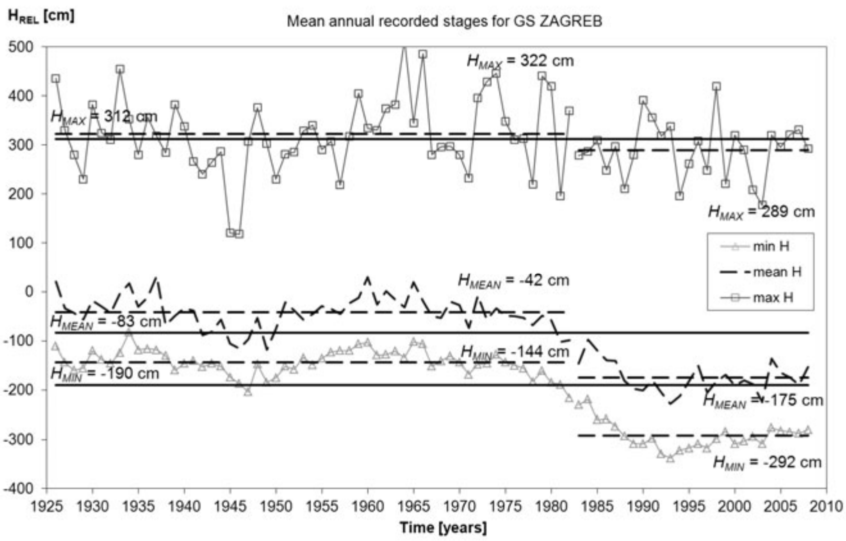

Fig. 2. Characteristic measured stages for the Zagreb GS

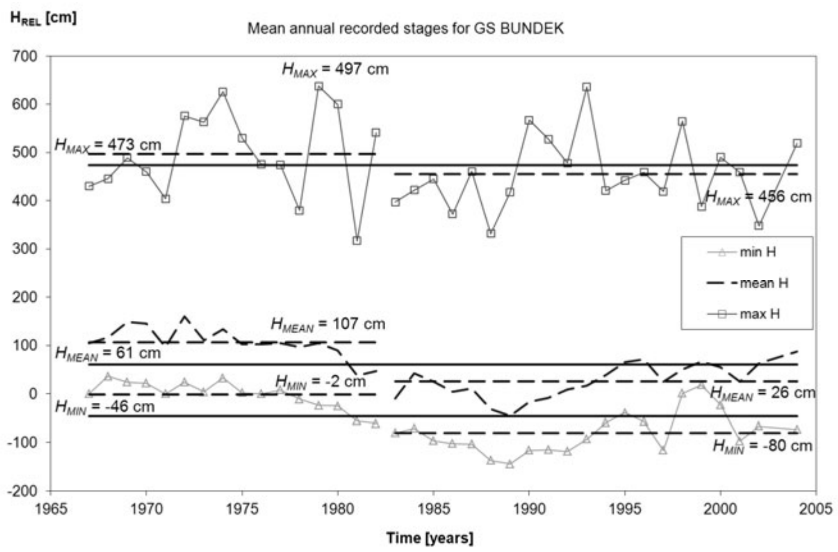

Fig. 3. Characteristic measured stages for the Bundek GS

Fig. 2 and Fig. 3 show two main stage trends: one that lasted until 1983 and is characterized by equable values of mean annual stage for minimum, medium and maximum stages, and the other, which started in 1983 and is still present today. There was an abrupt decline in characteristic annual stages in the period between 1982 and 1986, followed by a period of stage stabilization. Stabilization of the hydrological regime was accomplished by construction and continuous maintenance of the weir at the TE-TO Zagreb location on the Sava River. There was a significant decline predominantly in minimum and mean annual stages caused by riverbed degradation (Fig. 1). The decline in minimum and mean stages amounted to approximately 140cm at the Zagreb GS, whereas at the Bundek GS the stages lowered for approximately 80cm. Riverbed degradation did not significantly affect the regime of annual maximum stages which lowered for 40cm at both stations. The effect of riverbed degradation would probably have been more visible had the weir not been built. The average value of the annual mean stages in the period following the weir construction is 31cm lower than the mean value of the annual minimum stages before building the weir and, therefore, shows significant changes in the hydrological regime.

Although characteristic mean stage values are a good indicator of morphological riverbed changes, they are not sufficient to complete the picture of the Sava River hydrological regime. This would require constant observations of changes in discharge regime. Right before the weir construction a dry period started [15], which manifested itself in lower discharge of the Sava River (Fig. 4). Annual mean discharge for the period after 1983 fell by 15%, from 325 m^3/s to 275 m^3/s, whereas the mean value of the annual minimum discharge fell by 21%, from 87 m^3/s to 69 m^3/s.

The analyses show riverbed degradation not to be the only cause of a declining trend in characteristic stages. Although deepening of the riverbed is cause of concern, declines in characteristic discharges of the Sava River in Zagreb are equally important. Measures for erosion protection exist and can be implemented as required, but on the other hand, there can be no influence on natural forces which supply the discharge and that should be also taken into consideration. Analyses of hydrological indicators show that they cannot be only indicator for reliable representation of riverbed degradation, because they don't include discharge information. Continuous stage measurements have to be supplemented with periodic bathymetry survey of riverbed, and detailed survey around submerged structures.

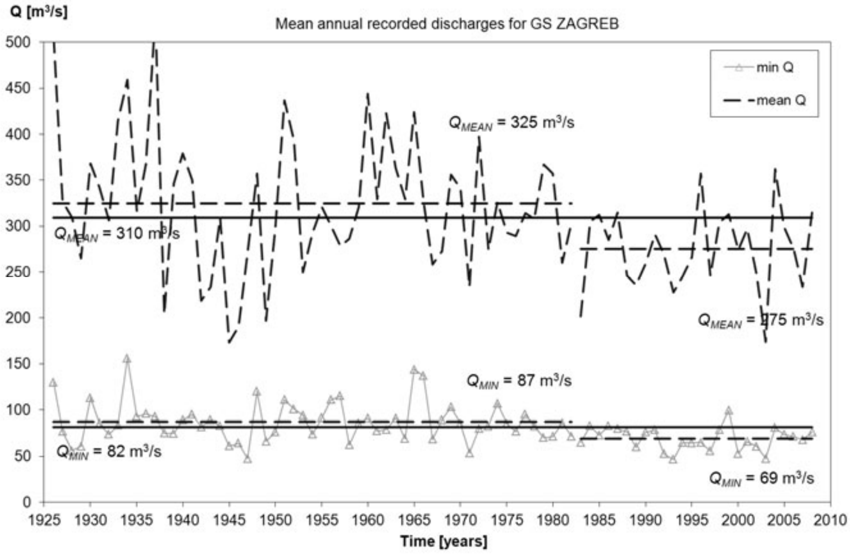

Fig. 4. Characteristic discharges at the Zagreb GS

11.4. Bathymetry Survey

Degradation of river bed in the upper reaches, including the Sava River in the area of Mičevec is a natural phenomenon. However, these changes are greatly influenced by the human factors which accelerated the degradation process: (a) reduction of sediment inflow due to construction of dams and weirs in upstream reaches; (b) increased tractive force due to increased longitudinal slopes as a result of shortening of the river course by regulation works; (c) Increase of water depth during flood waves due to flow concentration in the channel, without natural floodplains; (d) gravel excavation from the riverbed.

Due to advanced global erosion of the channel, the riverbed was considerably lower in relation to the level at the time of bridge design and construction: in the period between 1985 and 2009, the riverbed lowered by about 5–6 m (Fig. 5). The position of the bridge piers in the river channel caused additional bed lowering due to local erosion directly along the upstream walls of the piers, resulting in further river channel deepening by additional 5m. This local scour caused the removal of a part of the foundations under bridge piers and the stability of the bridge was severely reduced, as total scour in the area around the pier compared with the time the bridge was designed was approximately 10 m.

During 2009, in the period between April and October, The Faculty of Civil Engineering in Zagreb (Water Research Department) in collaboration with the Faculty of Geodesy (Department of Hydrography), conducted hydrographic surveys of the Sava River bathymetry. Geodetic and hydrographic surveys included monitoring of the morphologic changes measurements collected and processed by the Hydrosweep integrated module for the processing of the multibeam echo sounder data. The area covered by hydrographic measurements stretches over 2 ha and encompasses the area to the north and south of the Jakuševac bridge, totaling 200 m in length, including the river bank and the Sava River inundation area. Measurements were conducted at six control cross-sections, three upstream and three downstream from the bridge. The following parameters were measured at each profile: flow velocity profile, flow area, free flow width, stages and discharge.

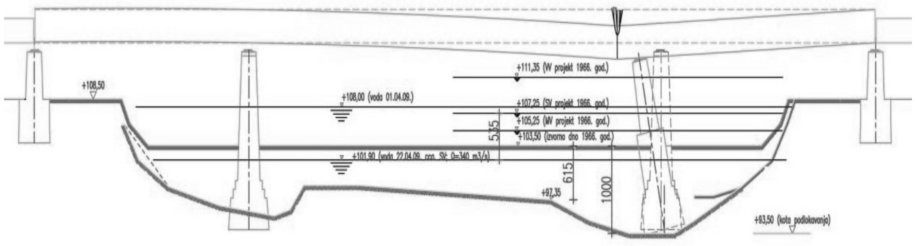

Fig. 5. Influence of global and local scour in the Sava riverbed on the Jakuševac bridge profile over a 20-year period

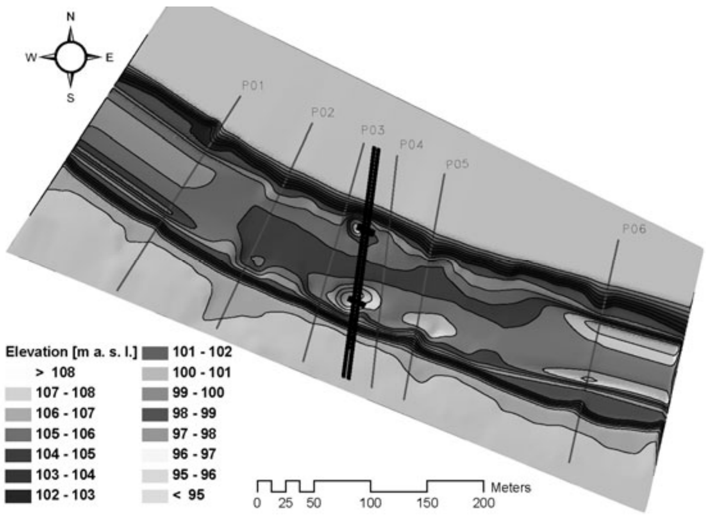

Fig. 6. Measured bathymetry in the bridge zone

It may be seen that the depth of the scour hole formed in the pier zone is greater than 4 m in relation to the mean level of the channel bed at both piers, and that the hole is more or less uniform. This means that, at this stage, local erosion has reached its maximum, and that it is in the state of temporary equilibrium until the entire river channel is additionally deepened under the influence of global erosion. The flow velocity field in the observed section of the river and around the bridge piers was obtained by monitoring velocity profiles. As the bridge is positioned on the river bend, flow velocities are higher on the concave side, i.e. on the side of the south pier and the unit sediment discharge and riverbed erosion are more emphasized on this side (Fig. 6, Fig. 7).

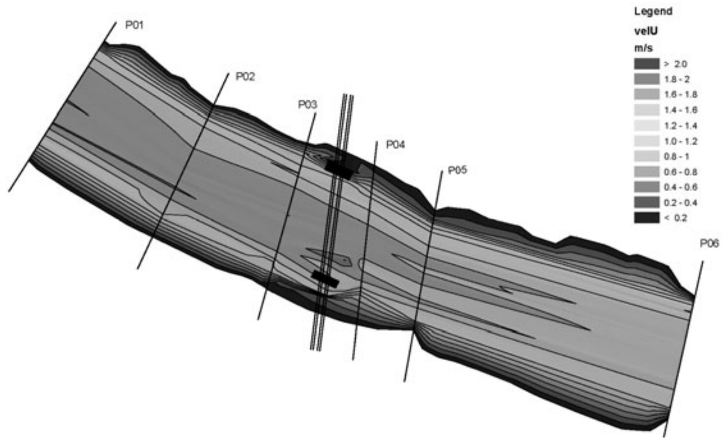

Fig. 7. Measured flow velocity field in the bridge zone

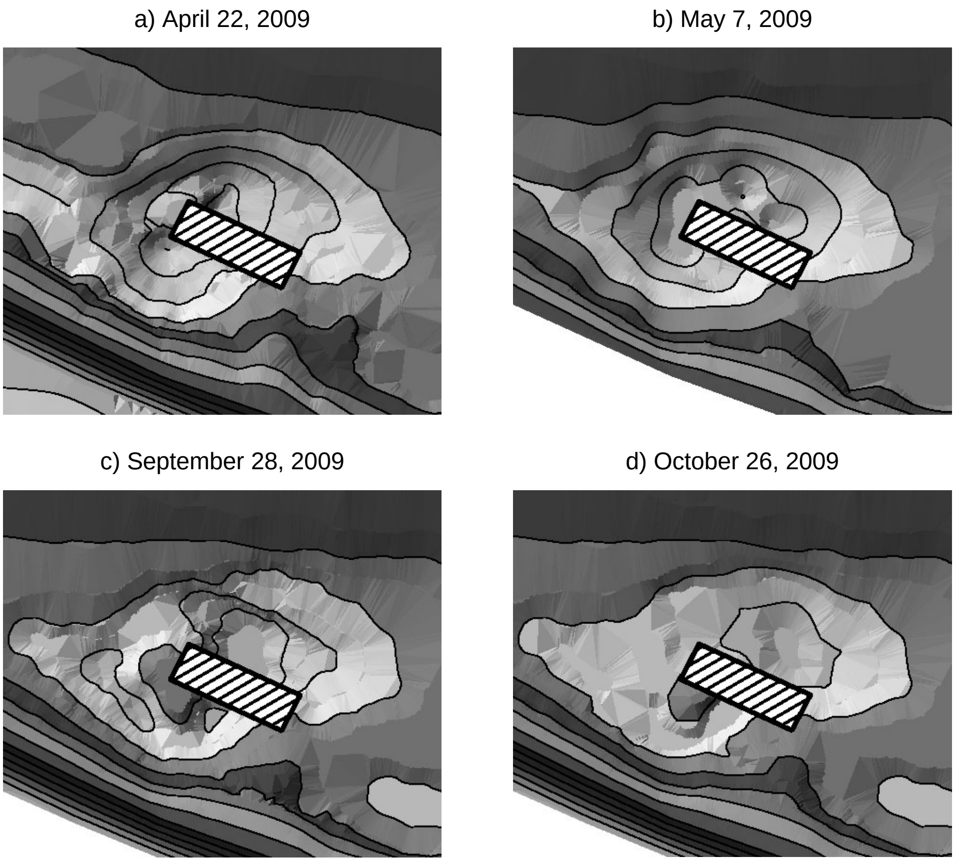

Fig. 8. Development of scour hole under south pier

Field surveys were conducted four times during the monitoring of scour hole development following the bridge collapse: on April 22 and on May 7. As a consequence of tilting of the pier into scour hole, stability of bridge was endangered. In order to temporary slow down scouring process under the pier, railway authorities decided to fill scour hole with bags of gravel. Field surveys were conducted during and after filling of scour hole, on September 28 and October 26, respectively (Fig. 8).

11.5. Theoretical Estimation of Scour Depth

The estimate of the final depth of local scour around the pier is given by empirical equations derived by a number of authors. To get a good quality estimate of scour depth, the methodology of the following authors were utilised: Melville, Larras, Laursen, Breusers, Shen, Coleman, Ansari & Qadar, Hancu and Jain.

Parameters influencing the scour depth d_s may be written as:

$$d_S = f\begin{bmatrix}\text{Flood flow}\,(\rho,\nu,V,y,G,g),\ \text{Bed sediment}\,(d_{50},\sigma_g,\rho_s,V_c),\\ \text{Bridge geometry}\,(B,b),\quad \text{Time}\,(t)\end{bmatrix} \tag{1}$$

where:
- ρ – water density,
- ν – kinematic viscosity,
- V – mean flow velocity,
- y – mean flow depth,
- G – parameter describing the influence of transversal flow distribution and form of channel cross-section,
- g – gravity acceleration,
- d_{50} – mean particle size of the riverbed material,
- σ_g – standard deviation of particles distribution in the channel,
- p_s – sediment density,
- V_c – critical flow velocity for moving of channel bed particles,
- B – foundation width,
- b – width of pier.

In the calculation, hydrological values measured on the observed section were used, as well as empirical coefficients dependent on the pier geometry. Empirical equations gave the values of local scour depth ds around the pier in the range from 3.86 to 8.40 m (Fig. 9). The empirical equations used were subjected to sensitivity analyses for two most influential parameters, i.e. mean flow depth y and pier width b.

It may be seen that the increase if local scour depth with unit increase of pier width is approximately the same for all equations. This is an important fact because erosion of the channel bed in the zone of the bridge caused uncovering of the caisson, which is wider than the pier, and consequently the erosion potential was increased at this point. It may be seen from the graph (Fig. 10) that some of the equations do not take into consideration the flow depth at all, assuming that for a given pier width there is a final local scour depth which will be achieved regardless of the conditions in the river.

It is also apparent that the equations fall into two groups; one group for actual conditions in the observed section of the Sava river gives the mean value of local scour depth d_s = 4.7 m, and the other group gives d_s = 7.7 m. The total mean value of local scour depth of all equations gives the value of d_s = 6.0 m, which corresponds to actual measured depth of the scour hole at the southern pier of the Jakuševac bridge (Fig. 5, Fig. 6).

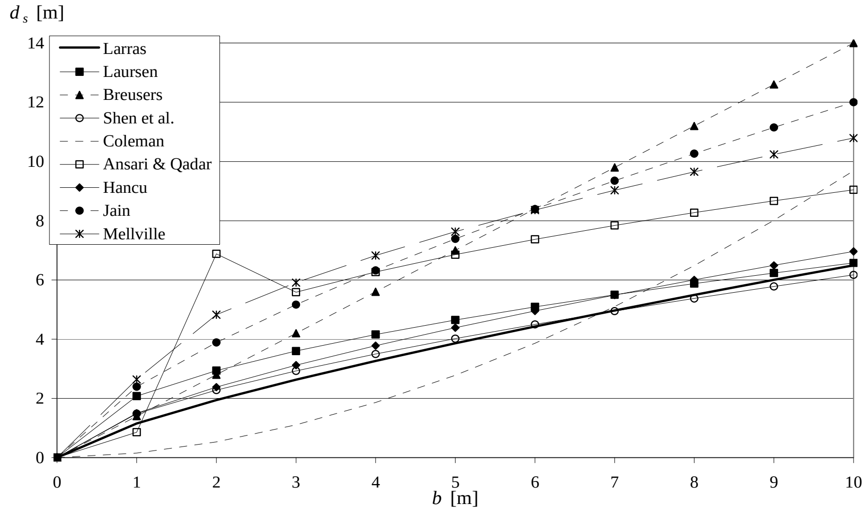

Fig. 9. Dependence of local scour depth d_s on change of pier width b at constant water depth

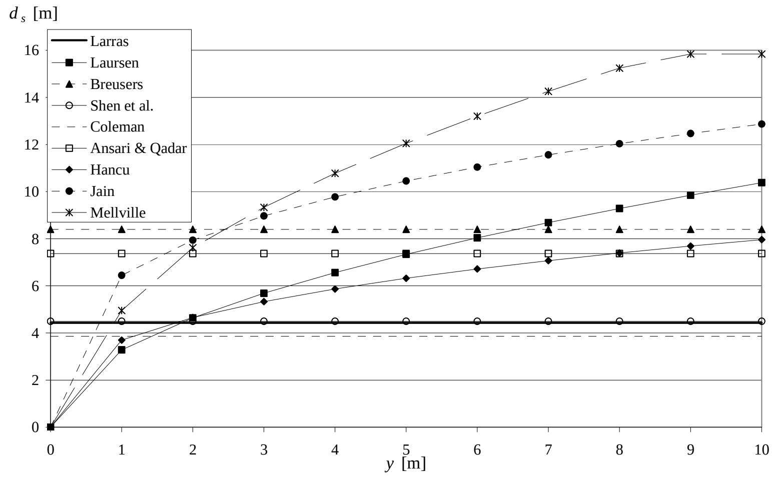

Fig. 10. Dependence of local scour depth d_s on change of water depth y with constant pier width

11.6. Conclusion

To become aware of natural events, one often needs to suffer their consequences, and they are usually of catastrophic proportions, causing human losses and material damage. In order to react on time and undertake improvements or reconstructions of the endangered structure, continuous surveys of physical phenomena trends in nature are needed. In this paper, as in the ones done by other authors in the past, annual minimum and mean stage trends at gauging stations in the Zagreb area of the Sava River have been analyzed. Although stages are a good indicator of the changes in the riverbed morphology, they are not an independent physical value since they directly depend on the amount of discharge coming from the upstream catchment area. Conclusions based solely on stage measurements are not accurate and it is necessary to concurrently conduct discharge measurements as well. Lack of monitoring causes lower awareness about the problems relating to structures in riverbeds, which in turn may lead to grave consequences, such as the accident at the Jakuševac railway bridge in Zagreb. Advances in information technology, particularly in the field of acoustic equipment which operates on the basis of Doppler effect, simplify and speed up the methodology of measuring stream flow and riverbed bathymetry. In accordance with this, monitoring of hydrological parameters at more important river sections, where there are bridges and other building structures, should be completed with discharge measurements and cross-section profile geometry.

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