Monitoring of river channel morphodynamical changes in the zone of bridge piers

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Abstract

Waterways that flow under bridge crossings are subject to changes in channel geometry on a regular basis. The scale of the changes can sometimes overwhelm estimated changes in the design process. The most usual concerns in relation to bridge design are; bearing capacity and the durability of the bridge construction and foundations, the optimum route or line of the bridge and other parameters regarding the safe construction, while the detrimental effects of water flow are sometimes neglected. This paper places particular emphasis on the problems of morphodynamical changes of the river channel in the immediate vicinity of the bridge piers. The theoretical background to the process of global and local river-bed erosion is initially presented. This is followed by an overview of new technologies for the survey of hydraulic and river channel changes in the area of interaction of river flow, sediment routing and bridge piers. The method of Acoustic Doppler Current Profiling (ADCP) for hydraulic surveys together with the methodology of hydrographic surveying using specialized multi-beam sonar are presented. Two case studies of hydraulic surveys and bridge scour analyses are presented. The fist study shows the deterioration of stability of Jakuševac bridge piers in Croatia due to significant river bed changes during a 20 year period. The second study shows collapse of the Malahide viaduct in Ireland due to the bridge pier stability problem and the subsequent remedial action on the bridge construction repair. Finally, a critical review of current engineering practice is given. The importance of giving more attention to the problem of constant river channel degradation is stressed, especially for locations were the degradation process may cause significant material damages or even death or injury of the general public.

Keywords: bridge scour, weir, railway, ADCP, multibeam

1 Introduction

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 channel (global erosion), or blocking of the discharge profile. In alluvial channels, local erosion occurs in places where the flow pattern is disrupted due to the influence of a submerged structure like a bridge pier. 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. Modern devices, based on satellite positioning and ultrasonic measurements help us to collect high quality information for forecasting the stability of the river channel.

In everyday practice there are numerous examples of problems caused by the deepening of the channel. Two case studies are chosen to illustrate the type of technical problems that can occur. The first example is the significant tilting of a pier of the Sava-Jakuševac bridge near Mičevec in Zagreb, Croatia on the night of March 30, 2009, during the passing of a flood wave in the Sava channel. The second example is the collapse of 30m of the 160m Malahide railway viaduct in North Dublin, Ireland due to the partial erosion of the tidal weir on which the viaduct was constructed. The railway bridge in Malahide over the Broadmeadows Estuary collapsed on August 21, 2009.

The global stability of the river channel is dependent on the sediment load discharge regime. The dynamics of bed load greatly affects the stability and shape of the channel, and bed-load transport equations are founded on different bases. The mechanism of bed-load movement differs between gravel bed and sand bed channels. In gravel channels the influence of the bed forms is not so prevailing, and bed roughness is related mainly to the surface roughness. 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.

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. This can result in intensive scouring of material from the channel bed, aided by high turbulence. 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 $(Qs)_{in} = (Qs)_{out}$, being inversely proportional to the sediment particle diameter. Most investigations of the local erosion phenomenon were conducted to determine the effect on bridge piers.

2 Sava-Jakuševac bridge (Croatia)

On March 30, 2009, at 22.30 hours, on the arrival of a freight train, the stability of the bridge structure failed, resulting in deformation of the bridge span and railway track.

Figure 1. Influence of global and local erosion on the Sava river channel in the profile of the bridge "Jakuševac" during 20-year period.

Degradation of river bed in the upper reaches, including the Sava River in the area of Jakuševac 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 (10), for example in some locations the level of the riverbed has been lowered by 5m. 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. At the moment of bridge collapse, the water level in the Sava River was high, with high discharge and flow velocities, which in combination with the static and dynamic loading imposed by the moving train led to instability of the bridge structure and the tilting of the pier into the scour hole.

2.1 Hydrographic and hydraulic survey of the river reach

Data on the river channel bathymetry upstream and downstream of the bridge location were collected and processed by the Hydrosweep integrated module for the processing of the multibeam echo sounder data. As the bridge is positioned on the river bend, flow velocities are higher on the concave side, i.e. on the side of the pier S2, and the unit sediment discharge and riverbed erosion are more emphasized on this side (Fig. 2). 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.
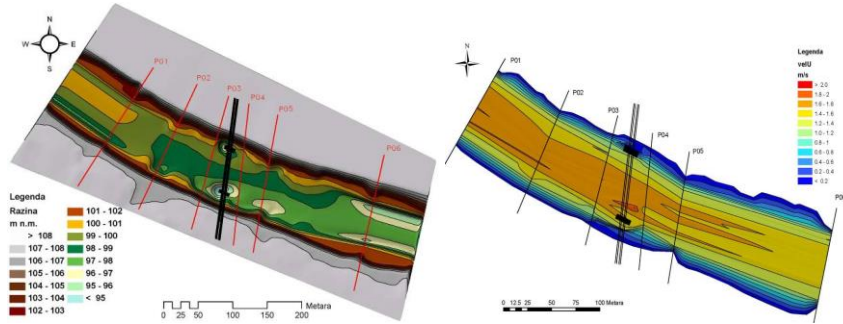
Figure 2.   Measured bathymetry and flow velocity field in the bridge zone.

2.2 Theoretic estimate of local 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 undercutting depth d_s may be written as:

$$d_S = f\left[\begin{array}{l} \text{Flood flow}\,(\rho, v, V, y, G, g), \quad \text{Bed sediment}\,(d_{50}, \sigma_g, \rho_s, V_c), \\ \text{Bridge geometry}\,(B, b), \quad \text{Time}\,(t) \end{array} \right]$$

where: ρ = water density, v = cinematic 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 in the channel, 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 d_s around the pier in the range from 3.86 to 8.40 m. The empirical equations used were subjected to sensitivity analyses (Fig. 3) 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. 3) 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.
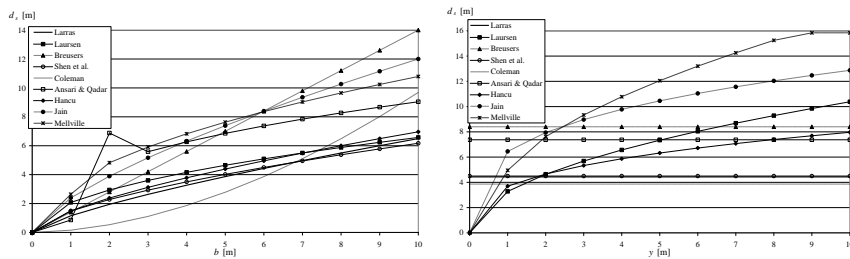
Figure 3. Dependence of local scour depth d_s on **a)** change of pier width b at constant water depth; **b)** change of water depth y with constant pier width.

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. 2, Fig. 3).

3 Malahide viaduct (Ireland)

A 160m twelve span railway bridge crosses the Broadmeadows Estuary north of the town of Malahide and is part of the main Dublin–Belfast intercity railway as well as providing a rail link for Dublin city commuter trains. Eleven masonry piers were constructed on a tidal weir of approximate trapezoidal cross-section to provide the support structure for the reinforced bridge decks. The original weir, built in 1845, was founded on up to 25m of estuarine sand and silt and the construction method was one of displacement of weak material using rock quarried locally. The original design was inherently unstably and unconsolidated and consequently throughout its history, settlement and erosion of the weir required repair works of varying scope and repairs and levelling to the bridge deck was continuous. An historical account of major works on the bridge and the weir is given in [4], with detailed presentation of methodologies and various improvements and remodelling during 150 years of the bridge history.

The collapsing of the railway bridge is the result of combination of two effects viz. partial erosion of the weir armouring over a long time period, and subsequent undermining of one of eleven bridge piers in a relatively short time period.

Hydrodynamic forces associated with high spring ebb tide flows finally washed away a 30 m wide section of the weir. This left an opening in the weir through which an estimated peak ebb tide discharge of 100 m³/s flowed with water flow velocities of up to 6m/s. At this stage there was a potential risk of further erosion and collapsing of the remaining bridge structure and weir.

3.1 Hydraulic analyses of the weir

The basic purpose of hydraulic analyses was determining of the overflow characteristics of the historic weir and its influence on water levels in the estuary for the entire range of tidal wave, and testing of the overflow characteristics of the new design of the weir, which should be roughly similar to those of the historic weir. A hybrid model was made, consisting of:

1. Collecting of data on weir and bridge geometry, estuary bathymetry, hydrological and hydraulic parameters.

2. Construction of physical models in the hydraulics laboratory of University College Cork, Ireland, for the purpose of determining of flow characteristics of the historic weir, hydraulic characteristics of the designed weir, design of armouring, obtaining of parameters for calibration of 2D mathematical models and getting the insight into the causes of collapsing.

3. Elaboration of the mathematical model in Faculty of Civil Engineering, University of Zagreb, by using the numeric model Mike 21.

4. Process of hybrid modelling by calibration and adjustment of physical and mathematical models for a series of hydrological scenarios.

3.2 Physical models

A number of 1:80 scale 3-D models of the existing and proposed reinstated weir and a 1:40 scale 2-D mobile bed model were constructed in the laboratory, using Froudian laws of similarity [5].

A 3D physical model of the historic weir was used to obtain data on flow patterns and distribution of flow velocities prior to the bridge collapse to help identify the collapse mechanism. Modified geometries for a new improved and more stable construction were tested in the model tank. The model of the historic weir was also used to establish the discharge curve during a ebb-tide wave, which will be maintained for the improved weir, in order to maintain the same environmental conditions in the Broadmeadows tidal Estuary which has a number of Environmental designations including NHA, SAC and SPSA for bird wildlife. Tests on 3D physical model included flow variation and measurement of corresponding water levels and velocities.

Morphodynamic 2D physical model was used for designing of the weir and selection of the type and size of its armouring. Versions of armouring types included gabion mattresses and rock armouring. The scale of 2D physical model was 1:40. The model was used for simulation of extreme ascending and descending tidal waves.

A Mike 21 model of Broadmeadows Estuary was calibrated and verified by the analysis of water levels, flow velocity and discharge. For water levels and velocity, comparison was made between results of the mathematical model, measurements on 2D and 3D physical models, and field observations. Discharges were compared between results of the mathematical model and measurements on 3D physical model. In order to be able to compare results of

physical models to results of mathematical models, the same boundary conditions were used in simulations.

The physical 3D model of the historic weir showed very high flow velocities between bridge piers, exceeding 5 m/s in nature, located directly downstream from the piers. The flow over the weir also proved to be exceptionally turbulent, in particular between bridge piers, where a hydraulic jump was formed between piers Nº 4 and 5. The general conclusions were that historically flow velocities were too high between the bridge piers and this combined with the action of the hydraulic jump produced instability of the weir rock armour. A comparison was made of water levels and velocities obtained along control points from 2D and mathematical model for various steady state boundary conditions. The comparison of results for steady state flow (Fig. 4) shows a comparatively good match of water levels and velocities, when the mathematical model assumes the value of the Manning coefficient of $n = 0.10$ m$^{-1/3}$s.
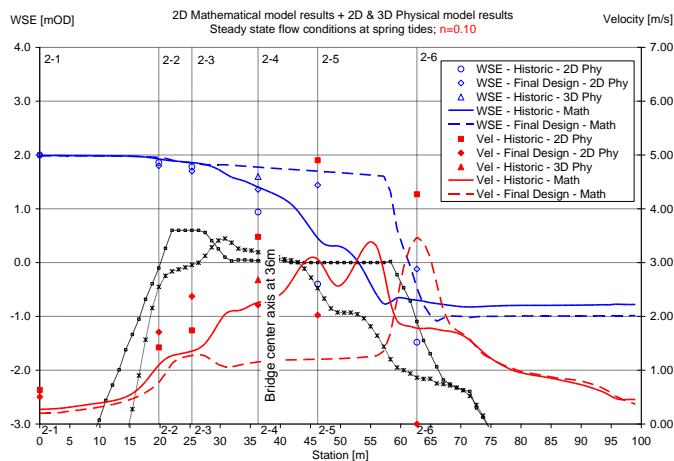
Figure 4. Comparison of model results for the historic and design weir

The final geometry of the proposed improved weir was derived from a hybrid model involving the interaction of physical and mathematic models. In the improved weir, the proposal consisted of a series of trapezoidal channels repeating in all spans between piers. The flow velocity and flow pattern between the piers have been considerably reduced and equalized (Fig. 4). The location of flow acceleration and increased hydrodynamic forces has been moved almost 16m downstream from bridge piers on the ebb-tide. Flow equalization is also noted in comparative results of 2D and 3D physical models and in the mathematic model for steady state. Water velocities are reduced to approximately 1.1 m/s between bridge piers.

4 Conclusion

Dynamical changes of the alluvial river channel are a natural process determined by a number of factors. Often this phenomenon is not given enough attention during the bridge design process, which may result in poor design with potential for instability or even bridge collapse. Engineering estimates of channel changes requires knowledge of physical processes and good quality data as the basis for developing mathematical and/or physical models. Factors affecting the channel dynamic process change with time, and the design conditions, for which the technical solution has been derived, alter as well. Moreover, the changes of the river channel stability factors are very difficult to detect and difficult to control. Therefore it is very important to monitor changes of the river channel and determine whether they are in accordance with predictions or not. Present state-of-the art techniques allow reliable and rapid collecting of the data on changes in the river, related either to channel geometry or to hydrological and hydraulic parameters. In combination with strong computer support it is possible to assess more reliably the dynamics of morphological changes in the river and to find out for each individual case whether the bridge structure or equivalent hydraulic structure is exposed to potential risk by such changes.

Reference

[1] Abbott, M.B. et al, Numerical modeling of free-surface flows that are two-dimensional in plan, Proceedings of a symposium on Predictive Ability of Transport Models fir Inland and Coastal Waters, Academic Press, 1981.

[2] Bekic, D., Numerical Modeling of Estuary Hydrodynamics, Master's Thesis, University of Zagreb, Faculty of Civil Engineering, 2005.

[3] Danish Hydraulic Institute, MIKE21 Hydrodynamic module, Scientific Documentation, 2003.

[4] Doyle Oliver, Mahahide-2 Article (2) IRSS, Vol 20, No 143, Oct 2000.

[5] Hamill L., Understanding Hydraulics, 2nD Edition, Published by Palgrave 2001.

[6] IPCC 4th Assessment report, 2007.

[7] Melville, B.W., Coleman, S.E.; Bridge scour, Water Resources Publications, 2000.

[8] Natural Environmental Research Council, Flood Studies Report, Vols 1-V, NERC, 1975.

[9] Petan, S., Horvat, A., Padežnik, M., Mikoš, M., Globevnik, L., Brilly, M., Gravel barsampling along Sava River, Proceedings of the XXIVth Conference of the Danubian Countries, Bled, Slovenia, 2008.

[10] Samoupravna vodoprivredna interesna zajednica grada Zagreba, Vodoprivredna Zagreba 1980-1990, Artjus, 1990.

[11] Yalin, M.S.; River Mechanics, Pergamon Press, 1992.

[12] Tomczak, M. and Godfrey, J.S.: Regional Oceanography: an Introduction, Pergamon, Oxford, 1994. Also available at http://www.es.flinders.edu.au/~mattom/