Riverbed Scour Induced by Bridge Destruction

Affouillement local produit par la destruction des ponts

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ABSTRACT
This technical note is a contribution to riverbed scour analysis, presenting results of field investigations of scouring processes induced by sudden formation of underwater barriers. It describes a case study of the Danube river and three bridges at city of Novi Sad which were destroyed during NATO raid on Yugoslavia in 1999. Acting as submerged sills, the bridge debris strongly affected the river flow pattern, and caused large scale erosion of the riverbed. Two years after the event, an attempt is made to assess the morphological river response to new conditions, and the evolution of the riverbed toward its new equilibrium state.

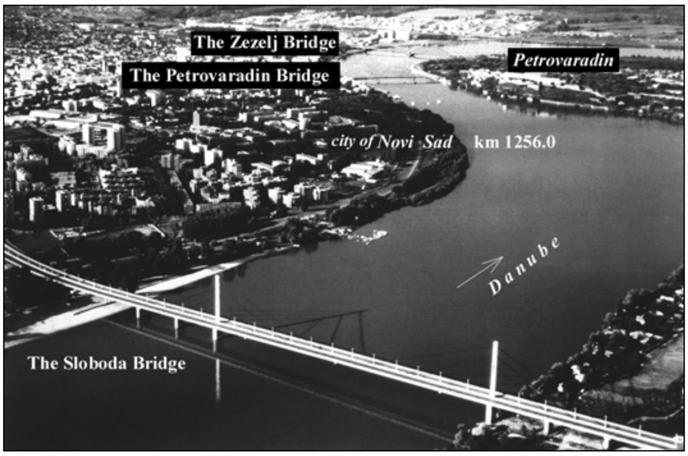
RÉSUMÉ
Cette note est une contribution à l'étude du problème d'affouillement local, décrivant un cas d'affouillement par soudain formation des barrières submergés. Is s'agit da la rivière Danube et trois ponts à la ville Novi Sad qui ont été detruits au cours de bombardement de la Yougoslavie par NATO en 1999. Agissant comme les seuils, les débris ont changé les caractéristiques d'écoulement menant au processus d'affouillement de très grande intensité. Deux ans après l'événement, un essai d'estimation de la réponse morphologique de la rivière est fait, aussi q'une analyse des résultats des sondages montrant l'évolution du lit vers son nouveau état équilibre.

Introduction

The riverbed scour phenomenon has been investigated for years, and there is an extensive literature on the subject, for instance [2], [3], [6] – [12]. The results, obtained from laboratory and field data, are principally used for proposing a formula for prediction of the equilibrium scour depth.
This note approaches the subject from a specific angle, describing large scale morphological changes in the Danube riverbed, induced by sudden formation of underwater sills, created of fallen bridges destroyed in the city of Novi Sad, in the course of NATO raid on Yugoslavia in 1999. No such event has been recorded anywhere in the past, nor had hydraulic engineers to cope with such an unplanned flow obstruction and its consequences. Two years after the event, efforts are made to assess the river morphological response in order to deal with cleaning up of this particular river reach and restore navigation.

The cause of riverbed scouring processes

Figures 1-3 depict the three bridges on the Danube in the city of Novi Sad (km 1252.90-1258.70), prior and after their destruction in April 1999. These bridges were of different types - suspension prestressed concrete, girder truss steel structure, and massive prestressed concrete arch structure. One consequence of their destruction was that the hydraulic engineers (however unfortunately) got a chance to study local scouring processes in a 1:1 field experiment.



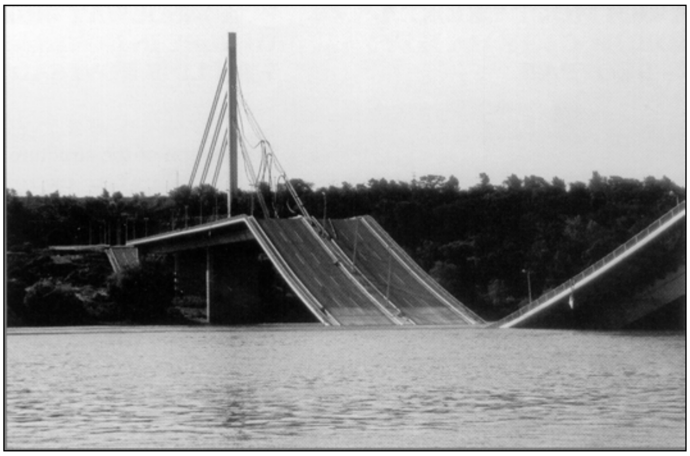


Fig. 1. Layout of bridges in city of Novi Sad prior to April 1999 (on the left) and the 591 m long Sloboda suspension prestressed concrete bridge (km 1257.60) after bombardment on April 4^{th} 1999 (on the right); the central span collapsed over the navigable waterway forming a V-shaped barrier, the lowest part of which is now covered with sand.

Fig. 2. The Petrovaradin bridge (km 1255) before destruction (on the left), and after destruction (on the right); its structure was K-type girder truss, with the central span of 130 m, and two minor spans 51 m.

Fig. 3. The Zezelj bridge (km 1254.17) prior to destruction on April 26^{th} 1999 (on the left), and at the end of 2001 (on the right); its prestressed concrete arch structure had 231 m and 180 m spans; in spite of numerous echo soundings, the exact position of arches lying on the riverbed is still unknown, but it is estimated that a 7 m high underwater sill has been formed along the entire cross section, radically affecting the flow pattern.

Qualitative assessment of riverbed scouring process

The reach of the Danube river in the city of Novi Sad (km 1252.90-1258.70) has been systematically monitored by echo soundings for navigation purposes in the past. It is known that for the last 25 years the riverbed has been in state of dynamic equilibrium.

In April 1999, the destroyed bridges formed submerged barriers on the riverbed, thus causing large-scale scouring immediately downstream from each bridge. The evolution of the riverbed was registered in several echo sounding campaigns, undertaken from April 1999 (immediately after bombing), to September 2001. Fig. 4 shows the hydrologic regime during the period of the most intensive riverbed morphological changes, one year after the onset of the scouring process.

Fig. 5 gives a comparison of riverbed morphology under stable, equilibrium conditions prior to April 1999, and in May 2000. It can be observed that the V-shaped sill, formed by the broken structure of the most upstream Sloboda bridge, caused a solitary sand bar in the central part of the channel, immediately downstream from the structure (cross section (1) in Fig.5 - (right)). The major current shifted toward the right bank, thus deepening this part of the channel for about 2 m on the average. A similar phenomenon was observed downstream from the second, Petrovaradin bridge, where 2 m high solitary sand bar (in respect to the original bottom) was formed in the central part of the channel (cross section (2) in Fig. 5-(right)). Generally depths in this sector increased for 4-5 m, endangering the stability of the left bank

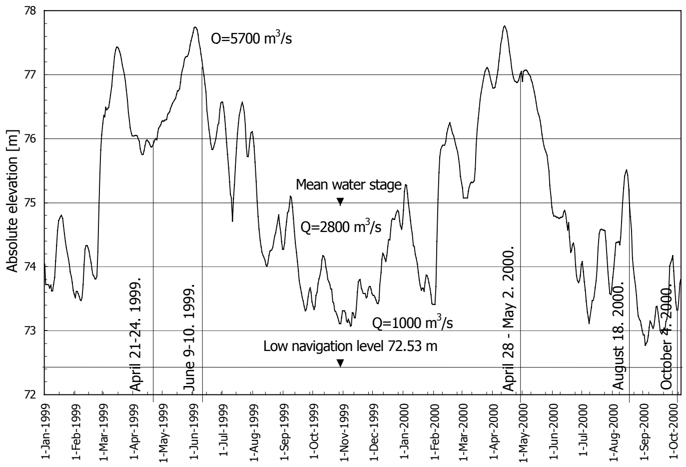


Fig. 4. Water stage hydrograph and dates of echo soundings
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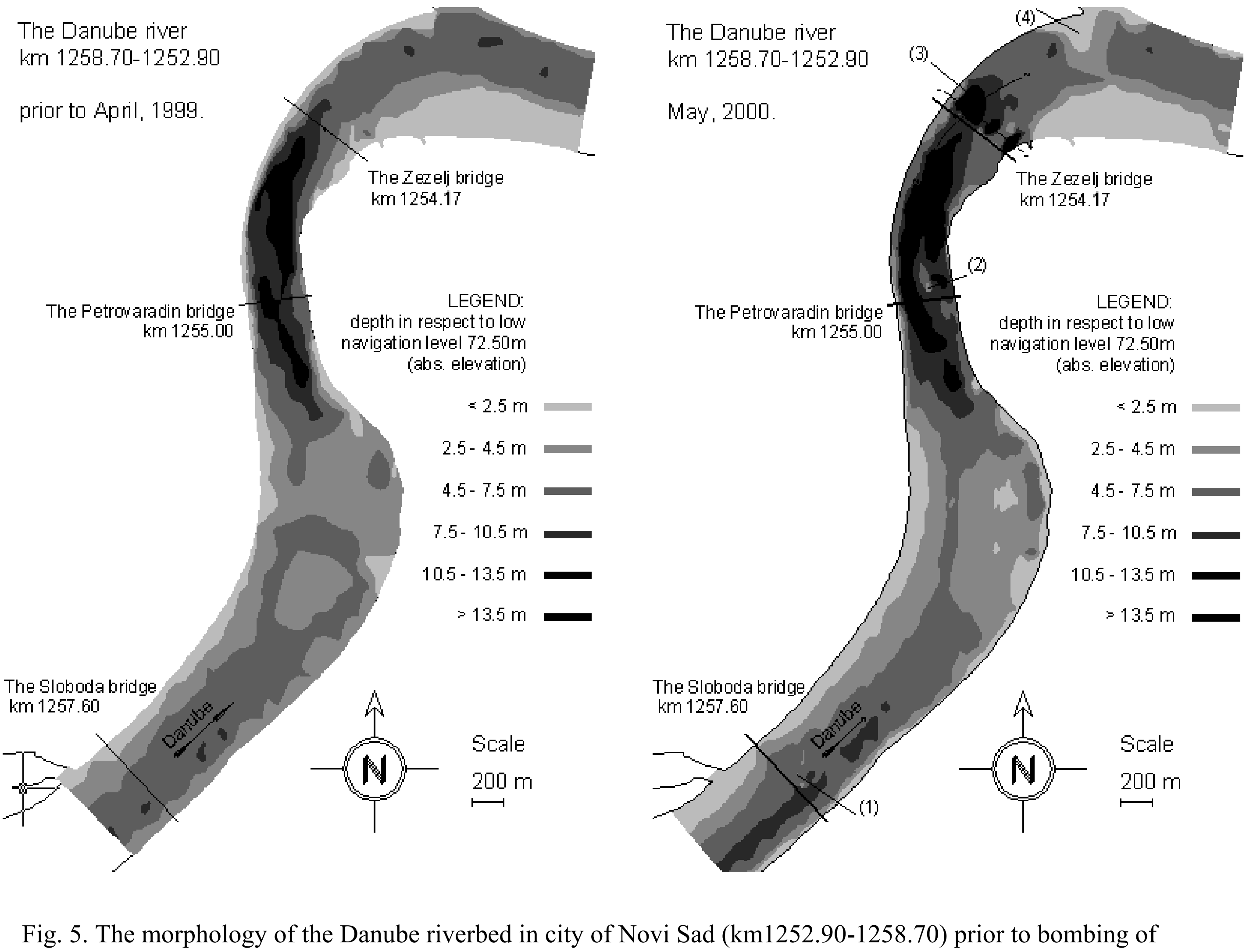

Fig. 5. The morphology of the Danube riverbed in city of Novi Sad (km1252.90-1258.70) prior to bombing of bridges and one year later [4].

However, the most intensive scouring process took place downstream from the Zezelj bridge, due to its massive arch structure, forming a huge underwater barrier. The exact alignment of the submerged arches is yet to be determined. (Camera use is restricted by high intensity of turbulence and sand concentration, while diver activities are limited due to high velocity currents).
Three large scour holes formed downstream from this bridge (cross section (3) in Fig. 5, Fig. 6). Their size is affected by a number of superimposed factors, such as: hydrologic regime, geometry of the sill, flow conditions, secondary effects of curvature, etc.

disturbed as well, the submerged bridge structures having induced accelerated flow zones (Fig. 7).
Echograms show that about 1 km downstream from the Zezelj bridge, a large transversal sand bar was formed by the eroded material (cross-section (4) in Fig. 5), and its dredging is prerequisite if navigation is to be restored. The riverbed morphological changes are intesified over a distance of about 40 km downstream from the city of Novi Sad. There is an increase of sediment loads and insufficient river transport capacity, causing development of sand bars, local changes of the flow course, and bank instabilities.

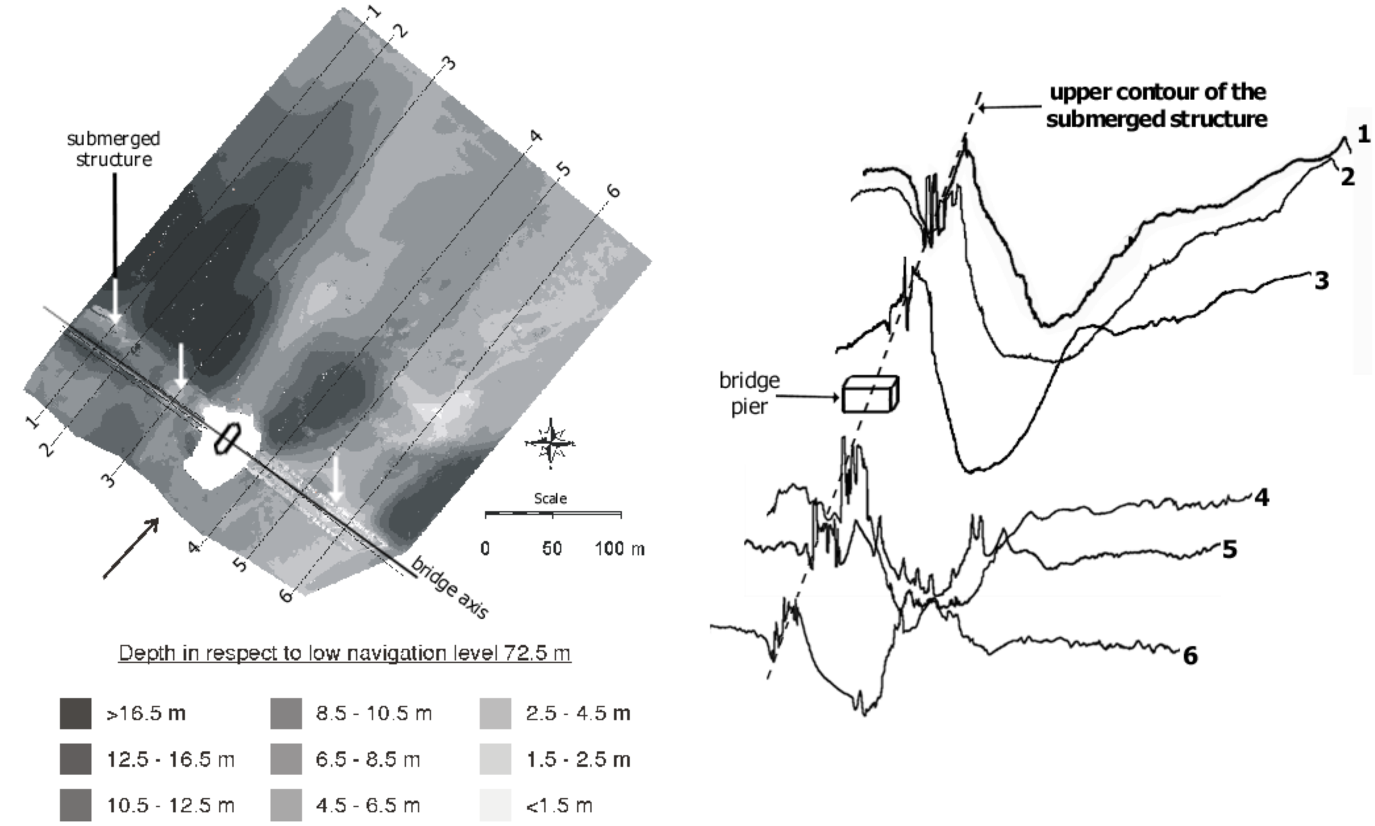

Fig. 6 Plain view of the scour pattern two years after the beginning of the process (on the left), and axonometric view of the longitudinal profiles (on the right); measurements were performed using multibeam echo sounder with approximately 9 points per square meter (Courtesy of Barthel & Sohn GmbH, Germany)

However, in this case the primary factor is the highly turbulent 3D flow generated by the sill.
The most recent and accurate scour pattern in shown in Fig. 6. The hole has reached its ultimate depth, all of the alluvial material - sand and gravel, has been washed away and the clay stratum has been reached; however, minor downstream translatory movement of the hole is still observed.
The maximal local water surface elevation difference caused by new riverbed bathimetry varies between 0.2 and 0.45 m (depending on discharge rate), which clearly indicates the intensity of the hydraulic disturbance at this particular location [4], [5]. This difference corresponds to a 10 km long river reach under normal, "natural" flow conditions. The velocity distribution along the channel is

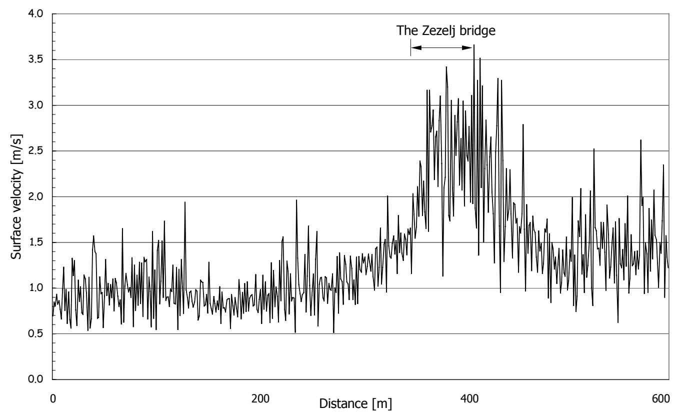

Fig. 7 Surface velocities measured along the longitudinal axis of the principal scour hole downstream from the fallen Zezelj bridge (Oct. 1999).

Quantitative assessment of riverbed scour

An attempt is made to quantify the scouring phenomenon. Fig. 8 shows the evolution of a cross section located 80 m downstream from the Zezelj bridge axis, with three distinct scouring holes.

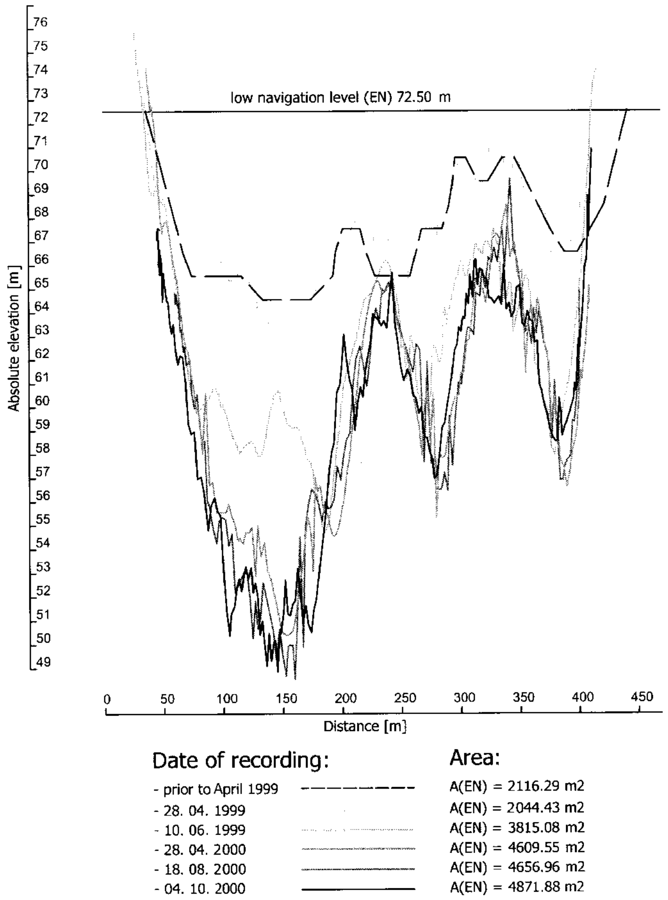

Fig. 8 The evolution of a cross section immediately downstream from the Zezelj bridge (km 1254.090).

Fig. 9 shows a typical echogram, taken along the longitudinal axis of the largest scour hole. Using such data, an empirical function for the temporal scour depth variation is proposed.

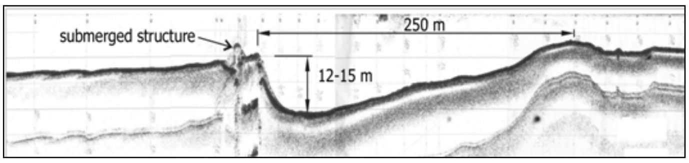

Fig. 9 Echogram showing the longitudinal profile of the largest scour hole in October 1999, six months after the onset of the scouring process.

It should be noted that the evolution of the scour depth was studied by many researchers in the past, considering various causes of erosion and boundary conditions.

Following the theoretical approach given in [2], [7], and [10], in this case the following expression is derived:

$$h_s / h_{se} = 1 - \exp[-3.5 (t / T)^{0.6}] \qquad (1)$$

where h_s is the scour depth, h_{se} is the equilibrium (terminal) scour depth, t is time, and T is the characteristic time representing the terminal stage of riverbed deformation, i.e. the time period required for a new equilibrium state to develop.

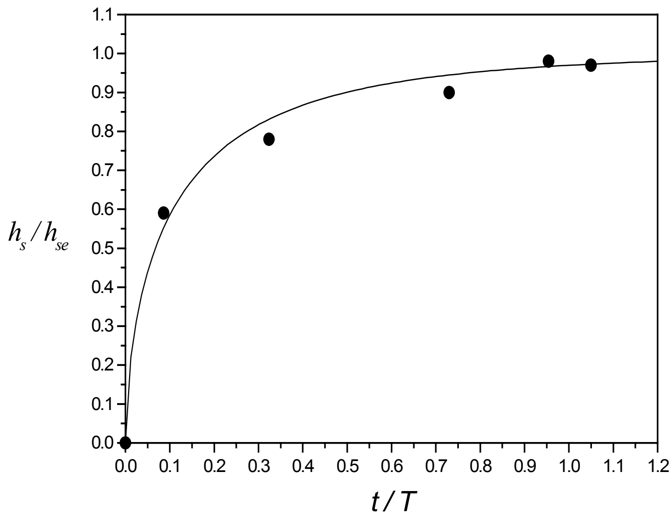

Fig. 10. Temporal variation of the scour depth (h_{se}=14.7 m, T = 500 days)

The diagram in Fig. 10 shows that the scour rate is very variable, and that after a short period of intensive changes, in this case about 2 months long, the process is slowed down. In this particular example, the average scour rate in the initial period was 0.15 m/day.

An estimated quantity of about 2×10^5 m^3 was eroded from this locality in the first year, with an average initial scour rate of about 3800 m^3/day. Observing increased riverbed instabilities on a 40 km long river reach downstream from the city of Novi Sad, it is assumed that such situation is predominantly caused by the eroded material.

Conclusions

Large alluvial rivers strongly react to any artificially imposed flow obstruction, adapting its bed morphology to new conditions. For a river as large as the Danube river (average monthly flow rate 2940 m^3/s), it appears reasonable to expect under the average hydraulic conditions, a period of 1-2 years for the riverbed to stabilize, and to reach its new dynamic equilibrium.

The field investigations confirmed that the evolution of the scour depth may be defined by an exponential function, such as the one given by expression (1). This function also reflects the rate of the scour process.

References

[1] Breusers, H.N.C., "Time scale of two-dimensional local scour", 12th Congress, IAHR, Fort Collins, 1967.

[2] Breusers, H.N.C., Raudkivi, A.J., *Scouring*, Hydraulic Structures Design Manual, IAHR, Balkema, Rotterdam, 1991.

[3] Gaudio, R., Marion, A., Bovolin, V., "Morphological effects of bed sills in degrading rivers", Journal of Hydr. Res., IAHR, Vol.38, No. 2, 2000.

[4] Group of authors, "Hydraulic and morphologic consequences of destruction of bridges at city of Novi Sad", Federal Agency for development and maintenance of inland waterways, Belgrade, 2000 (in Serbian).

[5] Group of authors "Study of influence of destroyed bridges in Novi Sad on flood conditions and river ice evacuation", Institute of Water Resources Development "Jaroslav Cerni", Belgrade, 1999 (in Serbian).

[6] Hassan, N.M.K., Narayanan, R., "Local scour downstream of an apron", Journal of Hydr.Engrg., ASCE, 111 (11), 1985.

[7] Hoffmans, G.J.C.M., Varheij, H.J., *Scour manual*, Balkema, Rotterdam, 1997.

[8] Melville, B.W., Raudkivi, A.J., "Flow characteristics in local scour at bridge piers", Journal of Hydr. Res, Vol.15, No.4, 1977.

[9] Mohamed, M.S., McCorquodale, J.A., "Short-term local scour", Journal of Hydr. Res., IAHR, Vol.30, No.5, 1992.

[10] Mosselman, E., Verheij, H.J., Discussion, Journal of Hydr. Res., Vol.38, 2000, No. 4.

[11] Uyumaz, A., "Scour downstream of vertical gate", Journal of Hydr. Engrg., ASCE, 114(7), 1988.

[12] Wang, Z.Y., "Experimental study on scour rate and riverbed inertia", Journal of Hydr. Res., Vol. 37, No. 1, 1999.