ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
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INFLUENCE OF THE LENGTH OF RIVER BED SECTION AND THE BOUNDARY CONDITION ON THE ACCURACY OF THE CALCULATED WATER SURFACE LEVEL FOR DESIGNING STRUCTURE IN THE RIVER BED

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Keywords: *boundary condition, design water level, HEC – RAS, hydraulic computation, river bed computational section length*

ABSTRACT

When designing structures in the watercourse, it is necessary to determine the design water levels in the closer or wider object zone. The river flow is a complex phenomenon that depends on the river bed characteristics that vary over time (hydrological, meteorological, geological, psamological, hydraulic, morphological and others). In order to calculate the relevant hydraulic values (water surface level, depth and velocity), it is necessary to prepare adequate basis and create a representative mathematical model. The model reliability is directly affected by the length of computational section and posed boundary conditions. On a short computational section boundary condition has dominant impact on calculated hydraulic values, while on a too long section the cost of basis data preparation get unnecessary increased.

This paper presents hydraulic analysis of the South Morava River in the Grdelica Gorge in Southeastern Serbia, with the aim of the Graovo bridge protection against flood flows. The analyzed river section has expressed river bed characteristics variability with a particularly large narrowing downstream of the bridge. Therefore, it is necessary to set the calculation section and the boundary condition correctly, in order to obtain unbiased results on the model in the area of river bed training works. HEC – RAS software was used for modeling and analysis.

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1. Introduction

River flow represents a complex process that depends on the characteristics of the river course that change over time (hydrological, meteorological, geological, psamological, hydraulic, morphological and other factors). In order to calculate the relevant hydraulic values (water surface level, depth and velocity), it is necessary to prepare adequate data and create a representative mathematical model.

In engineering practice, flow in open channels is observed with regard to the change in the shape of the water surface and the change in flow parameters such as velocity and depth over time. Due to the shape of the water surface, the flow can be divided into uniform and non-uniform. Considering the change of parameters in time, stationary and non-stationary flows with gradual changes and non-stationary flows with sudden changes are distinguished [1].

In this paper stationary flows are analyzed, the quantities that describe them (velocity, water depth, pressures, forces and energy) do not change over time or changes are slow enough that can be negligible.

The development of mathematical simulation models enabled complex calculations covering a large number of uncertainties that were overcome by implementing assumptions into the modeling [2]. The reliability of the hydraulic model is directly affected by the length of the computational section and the setting of boundary conditions [3]:

- On a short computational section, boundary condition has dominant impact on calculated hydraulic values.
- Too long sections increase the cost of data preparation, so calculation section length should be set cost-effectively.
- Boundary condition should be set to have insignificant impact on the calculated water surface levels in bridge cross section in order to get reliable results.

This paper presents a simulation model of the section of the South Morava River in the area of the Graovo bridge in the Grdelica gorge. River bed training works have been designed for the river bed stabilization 110 m downstream and 80 m upstream of the bridge. Hydraulic simulation model was prepared and run using HEC – RAS software version 6.0.

2. Materials and methods

2.1. Study area and input data

Figure 1. The Graovo bridge construction site, Stationary km 1+302,25 [4]

The Graovo Bridge over the South Morava River (Figs. 1 and 2) is located at the entrance to the Grdelica Gorge in Southeast Serbia (Fig. 3). Strategic infrastructure is located on the selected section, primarily the recently built E-75 highway and the international railway corridor towards Athens. Due to the construction of the E-75 highway, significant human interventions were made on the configuration of the terrain, which also had an impact on the river flow. At some sections, there have been significant changes of natural watercourse of the South Morava River. There are sections where river bed was trained by stabilization works, while at some part of the watercourse forced narrowing of the river bed was designed [4].

For the purposes of hydraulic analyses, the natural watercourse bed, the banks, as well as 32 cross profiles were recorded. The position of the analyzed computational section is shown at Fig. 3. Cross sections include the minor watercourse bed and part of the inundations on the left and right banks. Cross profiles with a total length of 1544,29 m were recorded at an average distance of 10 – 20 m. Input data for hydraulic simulation model represents theoretical flood flows which are estimated using gauging data of annual peak flows at hydrological station Grdelica:

- Design flow with probability of occurrence 2% – $Q_{2\%} = 604\ m^3/s$;
- Design flow with probability of occurrence 1% – $Q_{1\%} = 687\ m^3/s$.

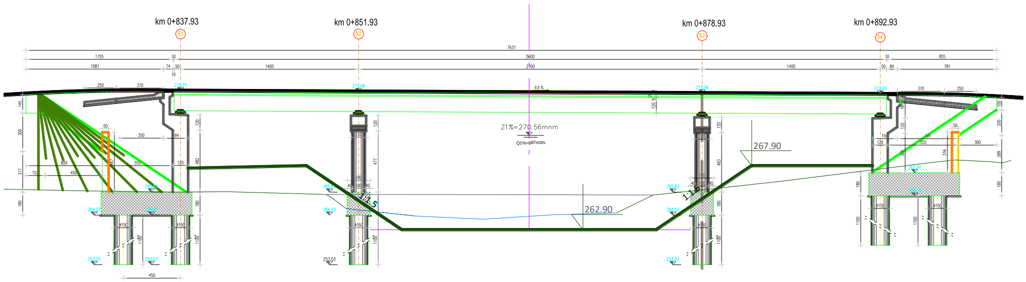

Figure 2. The Graovo bridge cross section, Stationary km 1+302,25 [4]

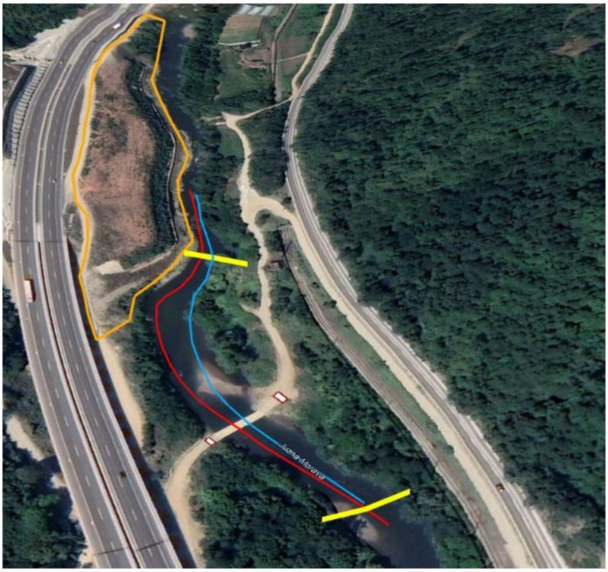

Figure 3. The Graovo bridge on the South Morava River in the Grdelička Gorge [4]

2.2. Hydraulic model

HEC – RAS software is used for modeling and analysis [5]. Water surface levels are computed from one cross section to the next by solving the Energy Equation (1) with an iterative procedure called the Standard Step Method (Fig. 4):

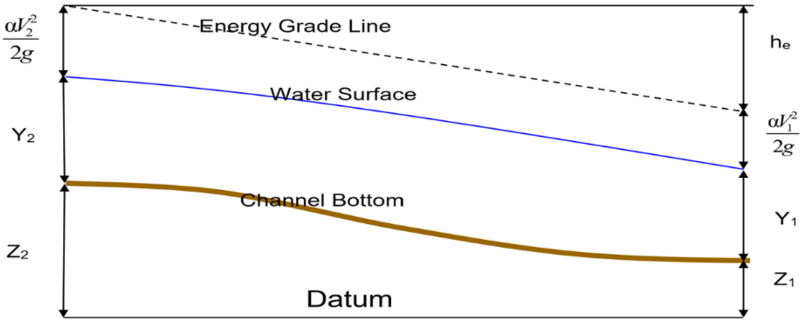

Figure 4. Calculation scheme in HEC – RAS [4]

$$Z_2 + Y_2 + \alpha_2 \frac{\upsilon_2^2}{2g} = Z_1 + Y_1 + \alpha_1 \frac{\upsilon_1^2}{2g} + h_e, \tag{1}$$

where Z_1, Z_2 are elevation of the main channel inverts;

Y_1, Y_2 – water depth at cross sections;

υ_1, υ_2 – average velocities (total discharge/total flow area);

α_1, α_2 – velocity weighting coefficients;

g – gravitational acceleration;

h_e – energy head loss.

To conduct calculation, boundary condition must be set at the downstream end of the computational section if flow is subcritical or at the upstream end if flow is supercritical [5 – 7]. The boundary condition should be set in such a way that objective calculated water surface levels are provided. In presented model, normal depth is selected as downstream boundary.

Many input parameters used for HEC – RAS like normal depth as a downstream boundary condition, has some uncertainty and errors. The important thing is that the position of downstream boundary has to be far enough from downstream of computational section of the river that any errors associated with the method which is applied in order to assume an energy slope for downstream boundary do not impact results [3].

Four different scenarios that have been analyzed are shown in Table 1. The scenarios were created for different positions of the downstream boundary condition and different morphological characteristics of the cross profiles. For Scenarios 1 and 2, the geometry of the natural watercourse is used, and for Scenarios 3 and 4, a new geometry was formed, which is the basis for river training works in order to accept and reduce the water level due to the design flood flows.

Design flood flows $Q_{1\%}$ = 687 m³/s and $Q_{2\%}$ = 604 m³/s impacts have been selected and water surface levels have been calculated.

Table 1. Analyzed scenarios in water surface level computation

Scenario 1 – URSS (Figs. 6 and 7)	Untrained river bed – boundary condition set in the Graovo bridge zone
	(**URSS** – Untrained river bed short section)
Scenario 2 – URLS (Figs. 5 and 7)	Untrained river bed – boundary condition is set at downstream end from the bridge
	(**URLS** – Untrained river bed long section)
Scenario 3 – TRSS (Figs. 6 and 8)	Trained river bed – boundary condition set in the Graovo bridge zone
	(**TRSS** – Trained river bed short section)
Scenario 4 – TRLS (Figs. 5 and 8)	Trained river bed – boundary condition is set at downstream end from the bridge
	(**TRLS** – Trained river bed long section)

Figure 5. The South Morava River through the Grdelička Gorge – the bridge Graovo – boundary condition 1,3 km downstream of the bridge

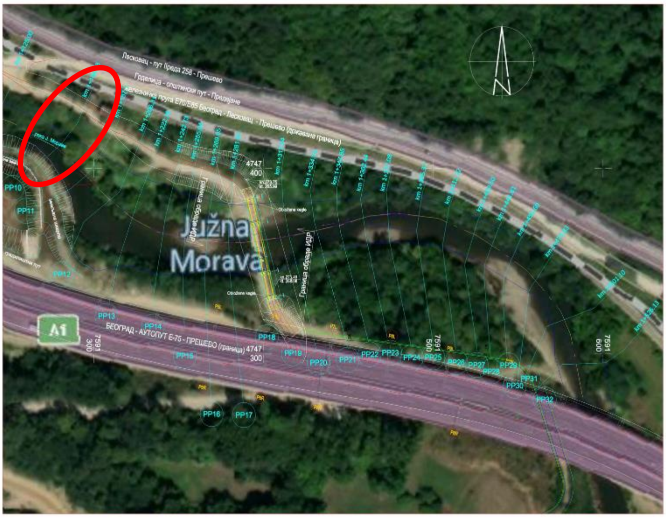

Figure 6. The South Morava River trough the Grdelička Gorge – the bridge Graovo – boundary condition 140 m downstream of the bridge

For Scenario 1 and 3 at the downstream end (cross profile PP1 shown in Fig. 7) normal depth as boundary condition was set, and for subcritical flow regime water surface levels calculated toward the upstream end of calculation section.

For Scenario 2 and 4 on the downstream end (cross section PP11, shown in Fig. 8) normal depth as boundary condition was set, and for subcritical flow regime water surface levels calculated toward the upstream end of calculation section.

There are significant river bed morphology changes (minor river bed contraction and widening) between cross sections PP1 and PP11.

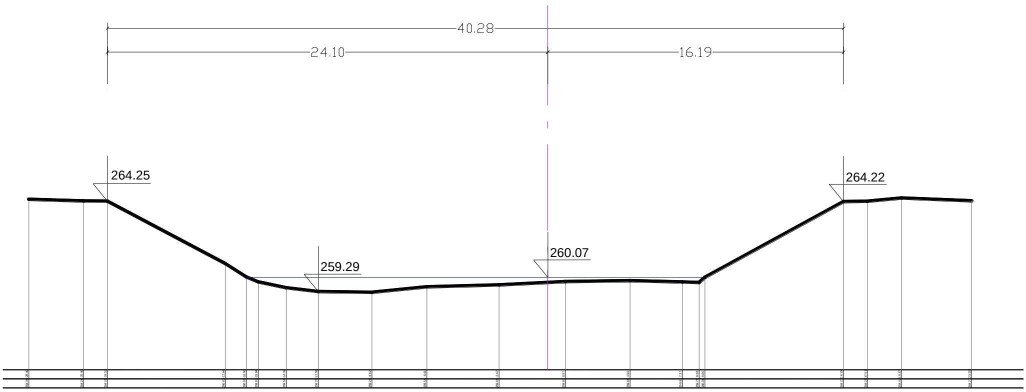

Figure 7. Boundary condition for Scenarios 2 and 4, Cross Section 1, Stationary km 0+000 [4]

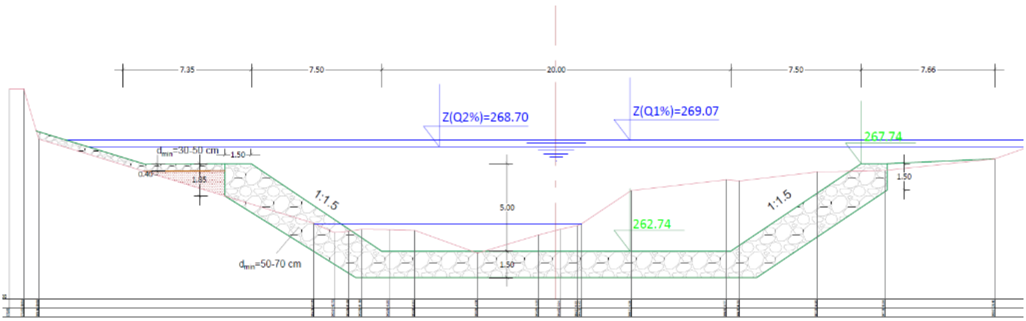

Figure 8. Boundary condition for Scenarios 1 and 3, Cross Section 11, Stationary km 1+187,10 [4]

3. Results

The results of the HEC – RAS simulation model are presented in Figs. 9 and 10 in parallel for Scenarios 2 and 4 and 1 and 3 respectively, and for the design flow with 1 % probability of occurrence ($Q_{1\%}$).

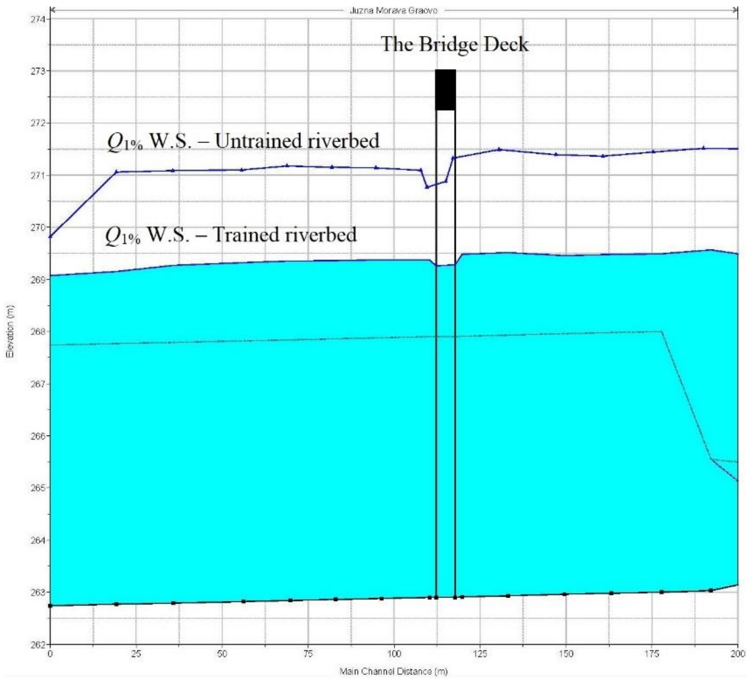

Figure 9. The Long profile near the bridge Graovo, Stationary km 1+304, for Scenario 1 vs. Scenario 3

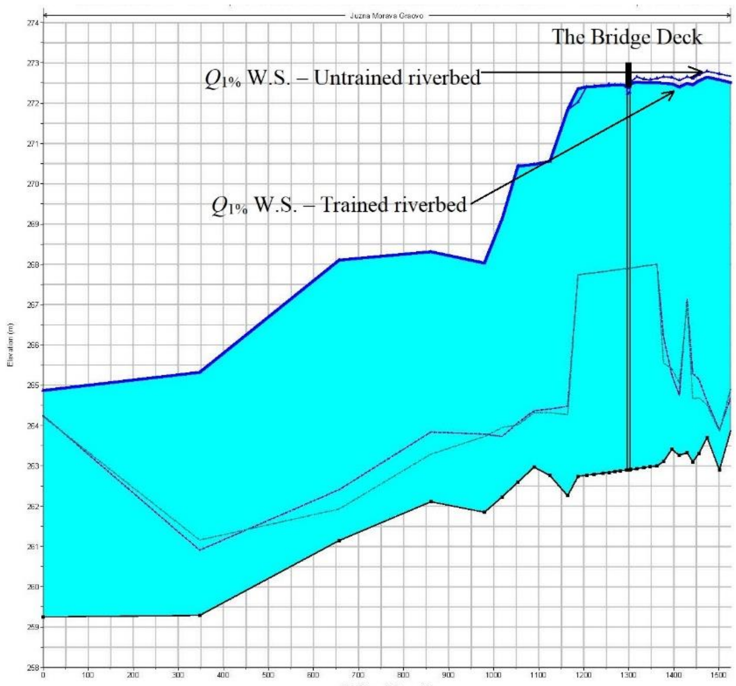

Figure 10. The Long profile near the bridge Graovo for Scenario 2 vs. Scenario 4, Stationary km 0+000

Due to the significant contraction in the river bed from profile PP2 to profile PP11, there is “bottle neck effect”, water lag upstream (Fig. 10). Even though boundary condition “normal depth” set on the PP11 looks very convenient, in both Scenario 1 and 3 (Fig. 9) it could not take into account “bottle neck effect”, so it seems that the bridge has very good hydraulic conductivity, but in reality, the bridge could be submerged by the flood waters.

In Tabs. 2 and 3 numerical results of the hydraulic simulation model are presented.

Table 2. Comparison of WS elevation on the bridge cross sections 18 (downstream) and 19 (upstream) for design flow $Q_{1\%}$

$Q_{1\%}$ = 687 m³/s	Cross Section 18	Δ		Cross Section 19	Δ
	W. S. Elevation	**(m)**		**W. S. Elevation**	**(m)**
SCENARIO 1	271,09	**1,32**	**Graovo Bridge CS**	271,33	**1,08**
SCENARIO 2	272,41			272,41	
SCENARIO 3	269,37	**3,07**		269,48	**3,00**
SCENARIO 4	272,44			272,48	

Table 3. Comparison of WS elevation on the bridge cross sections 18 (downstream) and 19 (upstream) for design flow $Q_{2\%}$

$Q_{2\%}$ = 604 m³/s	Cross Section 18	Δ		Cross Section 19	Δ
	W. S. Elevation	**(m)**		**W. S. Elevation**	**(m)**
SCENARIO 1	270,64	**1,09**	**Graovo Bridge CS**	270,84	**1,03**
SCENARIO 2	271,73			271,87	
SCENARIO 3	268,97	**2,79**		269,07	**2,72**
SCENARIO 4	272,44			272,48	

As it is shown in Table 1, for $Q_{1\%}$ = 687 m^3/s, calculated water surface levels, for untrained river bed differs 1,32 m near the bridge due to the adopted distance of the boundary condition (Scenario 1 and 2). For $Q_{1\%}$ = 687 m^3/s calculated water surface levels, for trained river bed differs 3,07 m near the bridge due to the adopted distance of the boundary condition (Scenario 3 and 4). A similar ratio of calculated water levels is obtained for the design flow $Q_{2\%}$ = 604 m^3/s (Table 2).

By setting the boundary condition like in Scenarios 2 and 4, unbiased results can be obtained.

4. Conclusion

When modeling river flow in the zone of structures in the river bed, it is necessary to pay attention to the section length and to set boundary conditions sufficiently far away from the structure to avoid the dominant impact of the boundary condition on the calculated water surface levels.

Case study, in the area of the Graovo bridge on the South Morava River in the Grdelička Gorge, has shown that calculated water surface levels could significantly vary. It depends on the way of the boundary condition setting due to the significant impact of the river bed shape variation on the downstream section which is not considered if the short section is analyzed (often the case).

In some cases, during the flood, water may overflow the bridge structure due to the practice of applying a short calculation section.

During floods in narrowed sections due to the lowering of the water level compared to the natural regime, there is an increase in velocities and local turbulence, which results in an increase shear stress and erosion potential and increases the risk of landslides, which can significantly threaten the existing infrastructure (bridges, railways and highways).

The results show that there is neither a significant difference in water levels between Scenarios 2 and 4, nor a risk of water overflowing the bridge. Based on such results, the question whether it is necessary to train the river bed by correcting morphology arises.

To get an answer to this question, it is crucial to calculate the possible general erosion and the erosion around the bridge piers.

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