Hydraulic Review of the Flood Protection Measures in Bardejov

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Abstract. The contribution is dedicated to hydraulic analysis of the flood protection of county town Bardejov in the north-east part of Slovakia where after numerous floods on the Topľa River the flood protection has been constructed just partially in the central residential area of the city (phase I.) Next phases II. and III., which append to phase I. upstream and downstream are currently in a process of evaluation, so the flood protection of the city is far from being complete. The submitted article deals with hydraulic assessment of realized flood protection measures and their impact on proposal of phases II. and III. Authors have solved the given problem using mathematical modelling of open channel flow for steady and unsteady conditions of flood discharge at really measured flood wave in the year 2010 which was very close to the value of $Q_{100}$ water. At the same time, they have proposed flood protection measures on the Topľa River in localities which are not considered and not solved by present realized flood protection. Proposed flood protection measures downstream and upstream of the realized flood protection were proven by mathematical modelling in HEC-RAS software program and they should get under control even the historical flood which appeared in Bardejov City in 2010.

1. Introduction

The Topľa River springs in Čergov mountain chain with total length of 130 km. It is the right-hand tributary of the Ondava River with river basin area of 1506 km². City of Bardejov was affected more times by flood events and the frequency of them rapidly increased since the year 2000. The most destructive flood affected Bardejov in June 2010 and that was the reason for proceeding with the construction of flood protection measures. The proposed flood protection measures of the town Bardejov on the Topľa River are divided on 5 km long reach into three phases between river kilometres (rkm) 101.400 up to 106.493. The first phase, which is located in the central part of the city between bridges Vinbarg and Mokroluh, was realised by construction of flood protection walls (Phase I.) along the river (Figure 1) [1].

Coming from existing flood protection the emphasis of the research team was put on hydraulic analysis of the capacity of the Topľa River reaches which are located downstream and upstream of the realized flood protection. Based on performed analysis using mathematical modelling in HEC-RAS software program possible flood protection measures were proposed in these localities. The illustration of the catastrophic flood in June 2010 is shown in Figure 2 [1].
Figure 1. Illustration of the flood protection phases on the Topľa River in Bardejov

Figure 2. Illustration of the flood event in Bardejov, June 2010

2. Materials and Methods
As already mentioned, the flood protection measures in the middle part of the Topľa River (Phase I.) were realized between two bridges in the total length of 1460 m. They were constructed as concrete vertical walls along both sides of the river reach. The reason for such a solution was – first of all – lack of space. Due to construction of flood protection walls in 2015 (Figure 3) the capacity of the river increased up to level of hundred-year water $Q_{100} = 330 \text{ m}^3 \cdot \text{s}^{-1} + 30 \text{ cm safety margin}$ (the peak of the flood wave in June 2010 was at discharge of $Q = 307 \text{ m}^3 \cdot \text{s}^{-1}$). Additional smaller modifications have been realized, as well, i.e. cross-section profile stabilization, longitudinal slope correction, etc. [1, 2].
Figure 3. Flood protection walls along the Topľa River in Bardejov (photo Šoltész)

In the upstream reach of the river above the realized flood protection (Phase II.) the river bed is created by debris material and is not regulated in any way. The only modification was performed under the highway bridge to extend the river and to increase the capacity of the river (Figure 4).

Figure 4. River bed modification of the Topľa River bed in Bardejov (photo Kupa)
More critical situation is on the reach of the Topľa River under the realized flood protection. The capacity of the river bed is not sufficient, slopes of the river are in desolate state and there are several important buildings in the vicinity of the river endangered as school, kindergarten, shopping center (Figure 2) or new individual family houses.

For the analysis of the water level and discharge regime the mathematical modelling has been introduced using HEC-RAS modelling software [3]. Necessary data about the morphology of the river were obtained by the administrator of the Topľa River – Slovak Water Management Enterprise (SWME). Some cross-sections of the upstream and downstream reaches nevertheless had to be measured additionally. The hydrological data (precipitation, discharge, rating curves) were provided by Slovak Hydro-meteorological Institute (Figure 5 and 6).

**Figure 5.** Daily precipitation amounts in the period of flood in the year 2010

**Figure 3.** Discharge course in the period of flood in the year 2010
3. Results and discussions

The second flood wave illustrated in Figure 6 which was very close to $Q_{100}$ and therefore it was used for calibration. Fortunately, exactly in the section of the realized flood protection is located the gauging station. The flood wave maximum was at the value $Q = 307 \text{ m}^3\text{s}^{-1}$ and the volume of it was approximately 18.1 mil. m$^3$. For mathematical modelling itself the steady and unsteady surface flow calculation was involved using HEC-RAS modelling software [4, 5]. All sections of the analyzed three phases were joint in the model together and calibrated. Example of the model assembly of analyzed reach of the Topľa River is illustrated for the Phase I. section in HEC-RAS software environment in Figure 7.

![Figure 7. Illustration of Phase I. section cross sections with realized flood protection walls](image)

After the calibration process of the model and introduction of input and boundary conditions the first numerical analysis was dedicated to river reach in Phase I., i.e. to verify if the already realized flood protection is sufficient or not. The results (Figure 8) of the modelling have convinced us in positive direction. The water level line is sufficiently lower than the left and right side bank, the only problem appears at the downstream bridge where the cross section fields of the bridge are in pressure mode but not flooded. There is necessary to undertake corrections to increase the capacity of bridge cross section fields. Similar situation on the Topľa River in Bardejov would occur at $Q_{100}$ discharge.

![Figure 8. Longitudinal profile of the Phase I. section - actual state at flood $Q = 307 \text{ m}^3\text{s}^{-1}$](image)
Realized flood protection measures are protecting the middle part (Phase I. section) but it is necessary to finish flood protection measures for the Phase II. and Phase III. sections, as well. Otherwise the situation from June 2010 can repeat (Figure 2). Performed field survey in the Phase II. section has shown that beyond protection dikes there is unused space (somewhere up to 30 m) which could be used for extension of the river bed to ensure the sufficient flood protection at $Q_{100}$ discharge. This possible extension is apparent from Figure 9.

**Figure 9.** Illustration of the actual and proposed cross section of the Topľa River in Phase II. section

4. Conclusions

In Bardejov city were realized after the flood event in June 2010 flood protection measures to certain extent. Presented paper strives on base of hydraulic analysis to review existing flood protection in the middle section of the Topľa River inside of Bardejov city. The analysis has shown that the existing flood protection construction is able to convey in this reach the discharge of $Q_{100}$ value. The problematic spot remains the downstream Vinbarg bridge, and especially the downstream Phase II. section which is the most endangered part of Bardejov city. Results of the analysis before and prognosis of the surface water level regime after proposed flood protection measures on the Topľa River in Bardejov city point out that the necessity of their realizations as soon as possible. The proposed measures were discussed with the SWME administrator and were in full conformity with the planning strategy of water management of the SWME in this region.
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