Full Length Research Paper

Slope of siltation of Dam No.7 in the Vidovačka Reka

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Slope of siltation is the slope of the upper surface of the deposited material, which can be considered as the equilibrium bed slope in the specific conditions of the torrent channels with the constructed dams. The formation of siltation is a complex process which is influenced by many factors, most significant being: natural bed slope, competent velocity, depth of flow, density of torrential water and sediment particle-size distribution. The assessment, that is, the forecast of the slope of siltation is a major issue in the practice of torrent management, significant in the selection of the site for dam construction and the decisive factor in the computation of the distance between the dams when they are designed in the system. The need for practical solution of this problem resulted in many formulas for the calculation of the slope of siltation. This paper analyses and verifies some of the most frequently applied formulas in practice, on the explicit example of the siltation of the dam No. 7 in the River Vidovačka. Slightest deviation from the actual, measured values for the slope of siltation is obtained using the Velojić-multiple i Kostadinov calculation formulas, or by regional analytical dependencies. The forecast of the slope of siltation should be carried out by the regional analytical dependences, which should be based on field research on already formed slopes of siltation and should include, in addition to bed slope, an independent variable that characterises the sediment. They would have a regional character with parameters adopted to local conditions.

Key words: Slope of siltation, natural bed slope, sediment particle-size distribution.

INTRODUCTION

Soil erosion is a natural process which cannot be discontinued completely, but can be controlled by erosion control measures and works, that is, its harmful effects can be mitigated. The oldest system applied for centuries is the classical European system based on the construction of transversal structures in torrent channels and the establishment of protective vegetation cover in all parts of the torrential catchment affected by strong erosion.

Construstion of transversal structures in torrent channels aims to mitigate the longitudinal bed slope which leads to the reduction in water velocity, and in this way decreases the destructive power and transport competency of a watercourse. In addition, the storage area is formed behind the construction for the retention of great quantities of sediment.

One of the most significant issues to be solved in the determination of the distance between the dams in the system is the forecast of the newly formed slope of sediment deposited behind the dam, known as the “slope of siltation” in torrent and erosion control theory and practice.

The formation of siltation is a complex process which is influenced by many factors, most significant being: natural bed slope, competent velocity, depth of flow, density of torrential water, sediment particle-size distribution and many others.

The assessment, that is the forecast of the slope of siltation, is a major issue in the practice of torrent management. It is significant in the selection of the site...
Figure 1. Research area.

for dam construction and it is the decisive factor in the computation of the distance between the dams when they are designed in the system. The need for practical solution of this problem resulted in many formulas for the calculation of the slope of siltation. This paper analyses some of them which are most frequently applied in practice, on the example of the siltation of the dam No.7 in the River Vidovačka.

MATERIALS AND METHODS

The research included River Vidovačka in the Trgoviški Timok catchment area, located in the eastern part of Serbia (Figure 1). The River Vidovačka is left component of the River Trgoviške, the right tributary of River Trgoviški Timok. It is formed from two components: right component Garnovice and left component Crna reka. Downstream to the River Lokvanjske, the right component of the River Trgoviška, receives only two tributaries: Rajića creek on the right and Mačak on the left. It springs at elevation of 740 m. The catchment terrain configuration is hilly with slope inclination from 30 to 40%, occupying the area of 8.41 km². The length of the main stem is 5 km, and the average bed slope is 8.1%.

Parent rock in the lower part of the catchment consists of limestones, in the central part - conglomerates and sandstones, and in the upper part - gabbros (Krstić et al., 1976).

Soil type widespread in the catchment area is eutric cambisol (Antonović et al., 1974; Tanasijević and Antonić, 1972-1976).

Plant cover consists of the forests of oak, beech and black locust, and Austrian pine plantations, pastures, meadows and farmlands.

Studies are performed at the dam No.7 in the receiving stream of the River Vidovačka, height 2.2 m, 592 m upstream of the composition with Lokvanjska River.

Data on the longitudinal profile and natural bed slope before the dam erection was acquired by the analysis of the collected technical documents (Petrović, 1967).

The longitudinal profile of the siltation was constructed, and the average slope of siltation and other hydraulic parameters were calculated based on the geodetic surveying data. They were necessary for the computation of the slope of siltation by different formulas.

To determine the particle-size distribution, sediment samples were taken from the siltation behind the dam, from the area of 1.0 m² (1.0 × 1.0), to the depth of the largest grain (Kostadinov,
The samples were sieved and measured to form the particle-size distribution curve which supplied the data on characteristic sediment diameters applied in different formulas.

The slope of siltation was calculated by the formulas which are most commonly applied in practice:

i) formulas based on Thiery’s equation for critical water velocity: Thiery (a), Pimpirev (Kostadinov, 1996).

ii) formulas based on Valentini’s equation: Valentini, Jaggy, Valtyni (Kostadinov, 1996).

iii) formulas for calculations of slope of siltation based on marginal water velocity for bedload detachment and deposition: Chezy, Šamov, Velikanov, Strikler, Thiery (b) (Kostadinov, 1996).

iv) formulas for calculations of slope of siltation based on critical tangential stress for bedload detachment: Krey, Lane, Mirzazage, Shields (Kostadinov, 1996) and

v) regional analytic dependency formulas: Biočev-a, Kostadinov-a i Velojić-a (simple and multifactorial correlation) (Kostadinov, 1996).

By the application of the above formulas, taking into account the measured and calculated parameters, we calculated the slope of siltation of the dam No. 7 in River Vidovačka according to each formula, by which we obtained the relevant parameters for their comparison.

The quantity of the retained sediment was calculated by the Kitin’s formula (Kostadinov, 1987):

\[ W = \frac{m \times h_k^2}{2 \times (I_t - I_z)} \]

where:

- m - average slope of siltation width (m)
- \( h_k \) - effective height of the dam (m)
- \( I_t \) - natural bed slope in decimal form
- \( I_z \) - slope of siltation in decimal form.

RESULTS

The longitudinal profile of the slope of siltation behind the dam No. 7 in the Vidovacka River was defined based on the available technical documents and the geodetic surveying data (Figure 2). It was concluded that the siltation was formed upstream of the dam with average slope \( I_z = 2.69\% \) and natural channel slope on the study stretch accounting for \( I_t = 3.38\% \). The slope of siltation length was 312.0 m and the quantity of the retained bedload behind the dam was \( W = 4.910 \text{ m}^3 \).

Based on the sediment particle-size analysis the particle-size distribution curves are made (Figure 3) showing the values of characteristic diameter (Table 1).

The value of the coefficient of uniformity after Allen-Hazen – \( u \) is

\[ U = \frac{d_{60}}{d_{10}} = 20.00 \]

Such that the sample, that is the sediment particle sizes...
Figure 3. Sediment particle-size distribution curve.

Table 1. Characteristic sediment diameters $d$ (mm).

<table>
<thead>
<tr>
<th>$d_6$</th>
<th>$d_{10}$</th>
<th>$d_{25}$</th>
<th>$d_{50}$</th>
<th>$d_{75}$</th>
<th>$d_{90}$</th>
<th>$d_{95}$</th>
<th>$d_{97.5}$</th>
<th>$d_{max}$</th>
<th>$d_{sr}$</th>
<th>$d_{e}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>1.6</td>
<td>6.5</td>
<td>9.0</td>
<td>22.0</td>
<td>32.0</td>
<td>70.0</td>
<td>82.0</td>
<td>90.0</td>
<td>93.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

are defined as non-uniform (Popović and Kostadinov, 1987) and the dominant grain size was coarse gravel ($d_{sr} = d_{50} = 22.00$ mm) (Todorović, 1991).

The following hydraulic parameters of flow were obtained based on field and laboratory investigations:

i) Cross sectional area ($F$) = 19.36 m$^2$
ii) Wetted perimeter ($O$) = 17.00 m
iii) Hydraulic radius ($R$) = 1.14 m
iv) Mean depth of flow ($h$) = 1.70 m
v) Mean water velocity ($V_{sr}$) = 2.87 m s$^{-1}$
vi) Manning’s roughness coefficient ($n$) = 0.07
vii) Manning’s coefficient of velocity ($C$) = 14.60
viii) Coefficient of flow torrentiality ($K$) = 0.80
ix) Mean channel roughness ($\Delta_{sr}$) = 6.0 cm
x) Density of clean water ($\rho$) = 1.00 t m$^{-3}$
xii) Mean density of torrential water ($\rho_0$) = 1.25 t m$^{-3}$
xiii) Mean density of sediment ($\rho_n$) = 2.65 t m$^{-3}$
xiv) Coefficient of sediment friction ($f$) = 0.75

Based on the measured and calculated parameters, the slope of siltation was computed by each of the cited formulas by different authors. The results of the calculations are presented in Table 2, and also in Figure 4 in the aim of a clearer presentation.

After the construction of the dam No.7 in the River Vidovačka, the siltation formed in the upstream part was characterised by the average slope $I_z = 2.69\%$ which compared to natural bed slope along the stretch $I_t = 3.38\%$, accounted for 71%.
Analysing the obtained results for slope of siltation presented in this paper calculated according the formulas designed by different authors, it can be concluded that only one formula produced the values greater than the measured values (Velojić-multiple), whereas the other formulas produced lower slope of siltation values than the measured ones.

DISCUSSION

In order to control depth erosion and to stabilize the torrential streambed of the Vidovacka River, transversal structures or dams were built.

The construction of these dams made a new bed profile which is different from the previous one both in longitudinal and cross section. It has a reduced fall in the longitudinal section, a widened bed bottom in the cross section. The bedload carried from the slopes of the drainage basin and from the river bed is deposited in the storage area behind the dam and forms an siltation which transforms this naturally steep bed into a graded one. By decreasing the longitudinal fall of the bed and cutting the water velocity, destructive power and transportation capacity of the watercourse are reduced, while the constructed siltation supports the river banks and consolidates the unstable bed.

Furthermore, by constructing a spillover in the main body of the dam in the middle of the torrential stream, the watercourse is directed towards the centre of the river bed and the lateral undermining of the streambanks is prevented.

The constructed technical structures, dams have greatly contributed to the stabilization and consolidation of the Vidobacka River torrential streambed.

In order to intensify the effects of these transversal structures on the processes of depth and lateral erosion in the torrential streambed, it is very important to set them at the right distance so that they do not endanger each other.

The distance between the transversal structures primarily depends on the height of the structures and the natural fall of the streambed, the size of which is already determined and the slope of siltation which has to be determined.

Since determination of the slope of siltation presents a great problem in the process of developing torrent control project documentation and since it is very important in setting the location of the structures and crucial in determining the distance between them, the subject of this study is the analysis of the formulas which are most commonly used in the practice of torrent control for calculating the slope of siltation. The value of the slope of siltation obtained by soil recording of the constructed siltation of dam No. 7 in the Vidovacka River was compared with the values calculated by using the selected formulas.

Eighteen different formulas were used for calculating the values of the slope of siltation and it is interesting to look at the results presented in this paper. Table 2 shows that the values calculated by formula No. 18 (Velojić-multiple) and No. 16 (Kostadinov) are the closest to the measured value.
values of the measured slope of siltation. They are immediately followed by the results of formula No. 1 (Thiery-a), No. 6 (Chezy), No. 9 (Strikler) and No. 15 (Biolčev).

Formulas No. 8 (Velikanov), No. 17 (Velojić simple), No.10 (b-Thiery), No. 7 (Šamov’s) and No. 2 (Pimpirev) gave the results which were by 58 to 76% different from the value of the measured slope of siltation.

The rest of the formulas gave results which significantly deviated from the measured values of the slope of siltation: No. 5 (Valtyni), No. 3 (Valentini), No. 4 (Jaggy), No. 11 (Krey), No. 14 (Shields), No. 12 (Lane) and No. 13 (Mirzazade).

Among five formulas, the results of which are closest to the actual slope of siltation, there are three regional analytical dependencies (Velojić-multiple, Kostadinov and Biolčev), one is based on Thiery’s equation for critical tangential stress for bedload detachment and two calculate the slope of siltation based on marginal water velocity for bedload detachment and deposition (Chezy and Strikler).

All the formulas that are based on Valentini’s equation gave results that significantly deviated from the actual measured values of the slope of siltation, which does not mean that these formulas are not good, but that they are only regionally applicable. Generally speaking, all the formulas in this group were made by testing and field researching the values of the constant in Valentini’s formula for different regions. Thus, the formula after Valtyni is based on the investigations conducted in Czechoslovakia. Unfortunately, similar investigations with the aim of determining the values of the constant that exists in Valentini’s equation have not been conducted in our region, which has had a significant effect on the obtained results.

The formulas that are based on marginal water velocity for bedload detachment and deposition, with the exception of Chezy’s and Strikler’s formulas, as well as the formulas that are based on the critical tangential stress for bedload detachment also gave results with significant deviation from the measured values of the slope of siltation. This means that future research studies related to slope of siltation calculation should deal with accurate determination of the marginal water velocity for bedload detachment and deposition, and the critical tangential stress for bedload detachment in specific states of streambeds and torrential streams.

The regional formulas after Velojić-multiple and Kostadinov gave results with the smallest deviations from the measured values of the slope of siltation.

The analytical dependence after Velojić multiple was defined on the basis of investigating the slope of siltation in the drainage basin of the River Nisava, and the analytical dependence after Kostadinov on the basis of the investigations conducted in in the drainage basin of the River Grdelica and Vranje Valley. Both areas are located in the vicinity of the Vidovačka River drainage basin where our research was conducted.

Application of the formulas of regional analytical dependence gave favourable results because the investigated areas are close to each other, which means that they have similar bedrock and granulometric sediment composition.
Although the Thiery's formula resulted in the minimal deviation, the problem in the application of Thiery's formula in practice is the fact that it is relatively difficult to provide the exact values of all elements necessary for the calculation by this formula.

The fact that the slope of siltation calculation by multiple correlations (Veljčić-multiple) produced a much better result than the simple correlation by the same author implies that a relatively accurate forecast of the slope of siltation can be calculated by the introduction of another element in the regional dependence formulas, primarily the sediment particle-size distribution.

The limitation factor for the application of the formulas of regional analytic dependencies is their regional character, which makes it necessary to perform field research on the already accreted siltations, which would produce several formulas of analytic dependence, but adapted to local conditions. Thus formed formulas of analytic dependence would have the regional character, but they would enable a considerably more accurate calculation of the slope of siltation during the design.

Conclusions

After the construction of the dam No. 7 in River Vidovačka, the formed siltation was 312 m long with average slope, I = 2.69%.

The sediment in the siltation was not uniform (U = 20.00) and the dominant grain size was coarse gravel (d_50 = 22.00 mm).

The analysis of the results calculated by eighteen formulas by different authors show that the resulting values were mainly lower than the values of the slope of siltation measured in the field.

The closest result to the measured slope of siltation was calculated using the Veljčić-multiple and Kostadinov formulas, using the formulas of analytical dependencies.

The calculated results show that the particle size distribution and bed slope have the crucial impact on the magnitude of the slope of siltation.

Therefore, the formulas of the regional analytical dependencies are more acceptable for practical purposes. The limiting factor is that they have a regional character, so it is necessary to intensify the field investigations on the already formed siltations, which would result in several formulas of analytic dependence, but with the parameters adapted to local conditions.

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REFERENCES

Petrović J (1967). Main project for Torrent control of Trgoviška river. Bureau for Projects in Forestry, Belgrade.