Acta Sci. Pol.
Formatio Circumiectus 17 (1) 2018, 175–192
ENVIRONMENTAL PROCESSES

www.formatiocircumiectus.actapol.net/pl/ ISSN 1644-0765 DOI: http://dx.doi.org/10.15576/ASP.FC/2018.17.1.175

ORIGINAL PAPER Accepted: 1.03.2018

# RIP-RAP REVETMENT EXPLOITATION AND DESIGNING PROBLEMS: THE CZARNY DUNAJEC RIVER CASE STUDY

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## ABSTRACT

All issues related to the maintenance of mountain rivers engineering structures, especially to river banks reinforcement, are extremely important to river engineering and flood protection works. The selection of appropriate hydraulic structures depends on many factors. When designing such devices, one should take into account, among other things, the type of soil, the hydrodynamic conditions, the atmospheric phenomena and the chemical condition of the water. Examples of hydraulic structures include weirs, gabions, rip-rap, boulder ramps etc. Efficient operation thereof depends on the careful execution of those structures. In case of the rip-rap revetments, there is a number of guidelines specifying the required physical and mechanical characteristics of the crushed stone used. In the present paper we discusses the methods of river bank protection, and we present the selection of rip-rap by defining technical specifications for the size of the crushed stones, the rip-rap, and the filter bed used in this context. In particular, we focus on the quality of the filter material used for the laying of crushed stones. Filtering material is laid directly underneath the rip-rap, and its faulty selection may often lead to failure of river bank reinforcement structures. For this paper we have analysed three rip-rap revetment structures within the town of Nowy Targ. A number of granulometric measurements and rip-rap sloping gradients were carried out at each station. Two stability conditions, and one permeability condition have been tested.

**Keywords:** rip-rap revetment, mountain river, filter bed

## INTRODUCTION

Issues related to the regulation of rivers and the strengthening of river banks are very important in river engineering. The selection of appropriate reinforcements depends on many factors. When designing the structures, one should take into account, among other things, the type of soil, the hydrodynamic conditions, the atmospheric phenomena and the chemical condition of water. Examples of structures strengthening the riverbed include weirs, gabions, stone rip-rap revetments, boulder ramps and other devices. In connection with the Water Framework Directive in force in the European Union, engineering activities in the scope of hydraulic engineering should be undertaken with the least possible interference versus the natural environment. Hydro-technical structures should meet technical and environmental (ecological) requirements. When regulating rivers, it is recommended that natural building materials be used, such as crushed stone or wood. Effective operation of all types of reinforcements depends on the proper, careful execution

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thereof. In the case of reinforcements of stone rip-rap, there are a number of guidelines regarding the physical and mechanical properties of the stone used and the filter applied. The purpose of the present work is to determine the stability of existing stone rip-raps on the Czarny Dunajec River. The scope of the work included field measurements and the elaboration of the data along with the analysis thereof. Various designs of river brank protection devices have been described, and the specifics of stone rip-raps have been discussed. The methodology included studies of substrate granulation, and stone rip-rap sizes, using the Wolman method, in three places in the town of Nowy Targ. Subsequently, cumulative grain size diagrams and granulometric curves were made on the basis of in situ measurements. Two stability conditions, and one permeability condition have been tested. The operation of the rip-raps for specific hydrodynamic conditions was also assessed, in which the correlation between hydrodynamic conditions and the characteristic diameter of the rip-raps were determined.

## RIVERBANK PROTECTION WITH STONE RIP-RAP REVETMENTS

The purpose of securing the banks of the river channel is stopping or minimizing its lateral erosion, as well as regulating the riverbed. There are many types of structures fulfilling the above-mentioned functions, whereas the selection of the most suitable type is determined by the following factors:

- the type of soil substrate, in which the riverbed is formed,
- water velocity in the riverbed (under various water levels/conditions),
- the frequency and duration of high water,
- changes in the level of groundwater in relation to the level of the water table in the watercourse,
- groundwater feed (inflow) speed, depending on geological conditions,
- atmospheric phenomena,
- the possibility of mechanical damage, and the impact of chemically contaminated waters (Jędryka 2007).

Among the methods of protecting the river banks and regulating the river, weirs, gabions, stone rip-raps, and boulder ramps can be mentioned. Stone rip-rap revetment is used to strengthen the lower and middle slopes of the escarpment or for local protection in places that are particularly exposed to erosion. Rip-raps can be made, with or without fences, on ballast made of gravel, 10–15 cm thick. Complementing the rip-rap construction with the strengthening of wicker cuttings, we obtain the so-called live rip-rap revetment. In places where exudations occur, the slope under the stone rip-rap is additionally secured with geotextile (under the layer of ballast), acting as a reverse filter. The thickness of the stone rip-rap should not be less than 30 cm, and the slope should not be greater than 1 : 2 (Jędryka 2007). The stone for making the rip-rap revetment should not be weathered, and it should be resistant to water, frost, and resistant to chemicals found in water (for example: granite, porphyry, andesite, as well as hard and medium hard sandstone (lapanow.pl).

Recommended physical and mechanical properties of crushed stone:

- compressive strength in dry air condition: at least 20–80 MPa,
- frost resistance in cycles of at least 21–25
- abrasiveness on Böhme grinding wheel: 0.25–05,
- volumetric weight: for igneous and transformed rocks, g = 2.4–3.0 $kN \cdot m^{-3}$; for sedimentary rocks $g$ = 1.9–3.0 $kN \cdot m^{-3}$,
- water absorption capacity: 0.5–12%.

In accordance with the EU Water Framework Directive, technical measures applied to the maintenance of river beds and mountain streams should be “close to nature”, and undertaken in interdisciplinary cooperation with naturalists. And so, with a justified need to secure the banks or bottom of the riverbed, it is recommended that reinforcements be used made of natural building materials such as crushed stone or wood. Such structures can be successively composed of mesh and stone baskets, gabions, or stone rip-raps (see: Fig. 1), caisson structures, or riffle pools with increased roughness (Korpak et al. 2008).

An important element of the stone rip-rap revetment structure, requiring a separate discussion, is the filter. The main function of the filter is to maintain a close contact between the stone rip-rap and the soil, by creating a stable contact surface (Lagasse et al. 2006). In practice, the filter is implemented by using geotextile or aggregate ballast with an appropriate

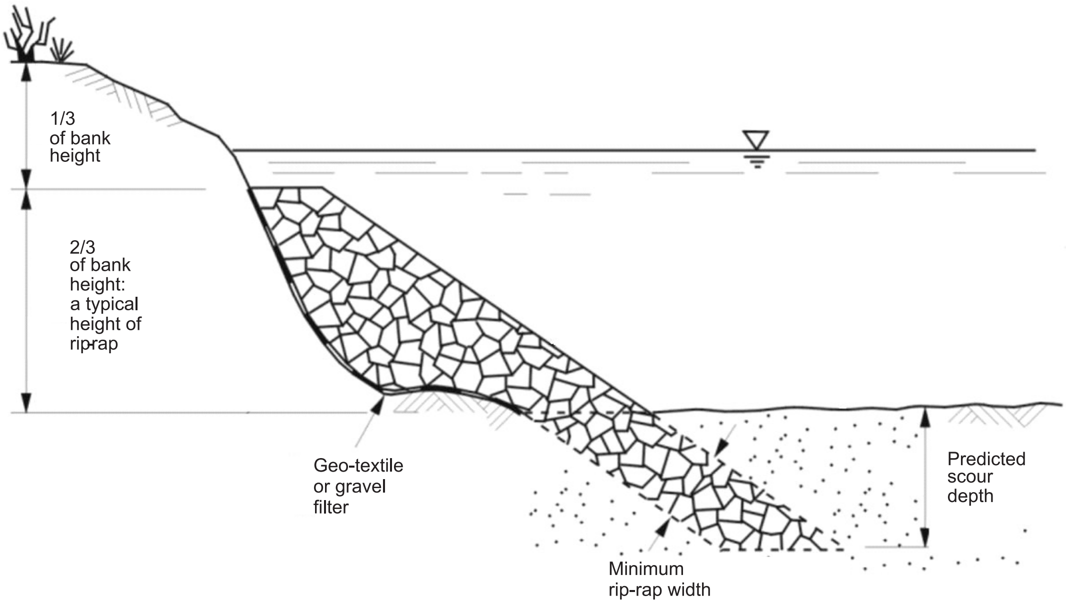


**Fig. 1.** Scheme of the rip-rap structure (acc. to Keller and Fowler 2005)

grain size. In some situations it is recommended that a combined filter be used, containing both a granular layer and a geotextile layer (Lagasse et al. 2006).

The need for the application, and the way of designing the filtration layer is determined by the characteristics of the soil substrate underlying the rip-rap. In cases where the soil consists mainly of relatively large particles (coarse sand and gravel), no filtration layer is required. Careful design, selection and installation of the appropriate material, acting as a filter, plays an important role in the proper functioning of the rip-rap revetment. Figure 2 shows a schematic diagram of three most typical filter systems in a stone rip-rap (Lagasse et al. 2006). The main tasks of the filter include:

- retention of soil particles,
- providing a free-flow zone between the rip-rap and the soil (Lagasse et al. 2006).

In order to maintain proper soil retention, the pores in the filter should be small. At the same time, maintaining a high permeability of the filter requires larger pores with high densities. In order to achieve full functionality of the filter, it is necessary to maintain a balance between retention and permeability. This condition is related to finding the optimal material, both reconciling soil retention and guaranteeing filter permeability. Depending on the internal stability of the soil and the size of the pores in the filter, over time, processes take place that change its structure.

As Molski (2010) emphasizes, the unfavourable impact of filtration on the stability of earthy hydro-technical structures and the soil substrate – including river bank reinforcement structures – may be manifested in the form of quicksands (liquefaction of the ground), suffosion, hydraulic leak or ejection (Philip et al. 1979, Wiłun 1982, Żak et al. 1995, Molski et al. 1997, Pisarczyk 2001, Żak 2003). It should be noted that changes in the soil, caused by filtration, do not occur in only one of the forms mentioned, but are combined and connected to each other to a greater or lesser extent.

And so in succession, to define the aforementioned phenomena, the suffosion as defined by Żbikowski (1962) is a phenomenon consisting in raising small grains of soil, which that fill the skeleton of grains of larger dimensions that remain intact in their previous position. The particles can be moved to a different location or elevated out of the soil substrate. As a result, caverns or channels may be created; the phenomenon then takes on the characteristics of a hydraulic leak. Suffosion is more commonly found in substrates of non-compact, unstable soils that are in contact with a filter of large pores. Large pores sequentially do not

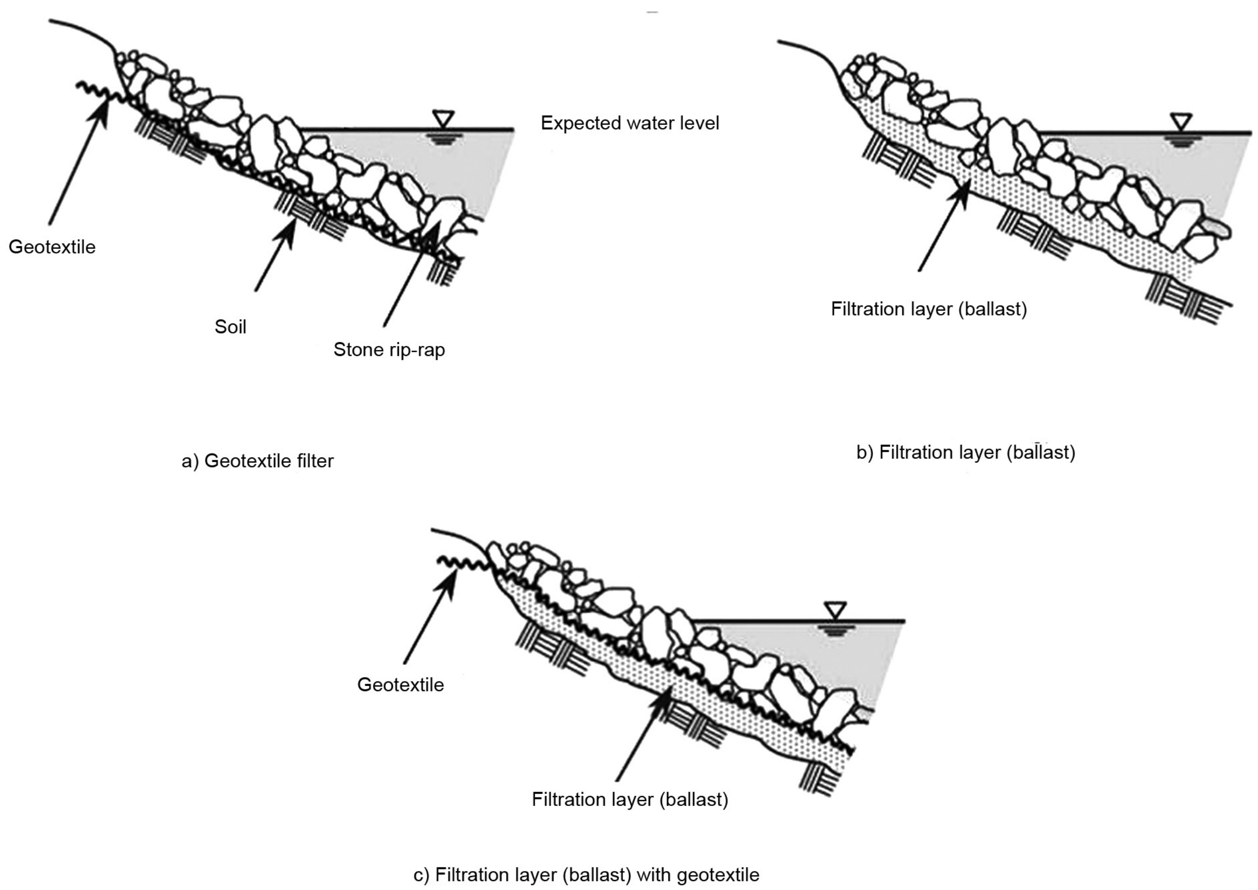


**Fig. 2.** Cross-section of river channel with a rip-rap revetment (Lagasse et al. 2006)

retain small particles, which are removed by leaks and by pressure variability, leaving only large particles. Suffosion increases the erosive potential by weakening the soil structure under the rip-rap revetment (Lagasse et al. 2006). In turn, a hydraulic leak is the formation of a duct (channel) in the soil mass, filled with soil of a disturbed structure, connecting places with higher and lower water pressure in the pores. On the surface, the hydraulic leak is visible in the form of outflows of the water-soil mixture. Hydraulic leak arises when the water pressure in the soil reaches a value equal to the weight of the layers of soil above it. In this case, the effective stress decreases down to zero. The phenomenon of leaking usually occurs in less compact soils with permeable soils underneath them. Further, the ejection of the soil, consisting in shifting all grains of a certain volume of soil – often together with the reinforcement elements which weigh down on them – such as filters or drains. The displaced mass usually increases its volume and, consequently, also its porosity. The phenomenon of ejection occurs both in the vertical direction (upwards), and horizontally in the substrate of water-impoundment structures. Sometimes, the ejection also occurs downwards. The last of the listed phenomena are the quicksands. The latter occur when the soil loses the characteristics of a solid, and it turns into a liquid state - this phenomenon applies to fine-grained soils and silty sands.

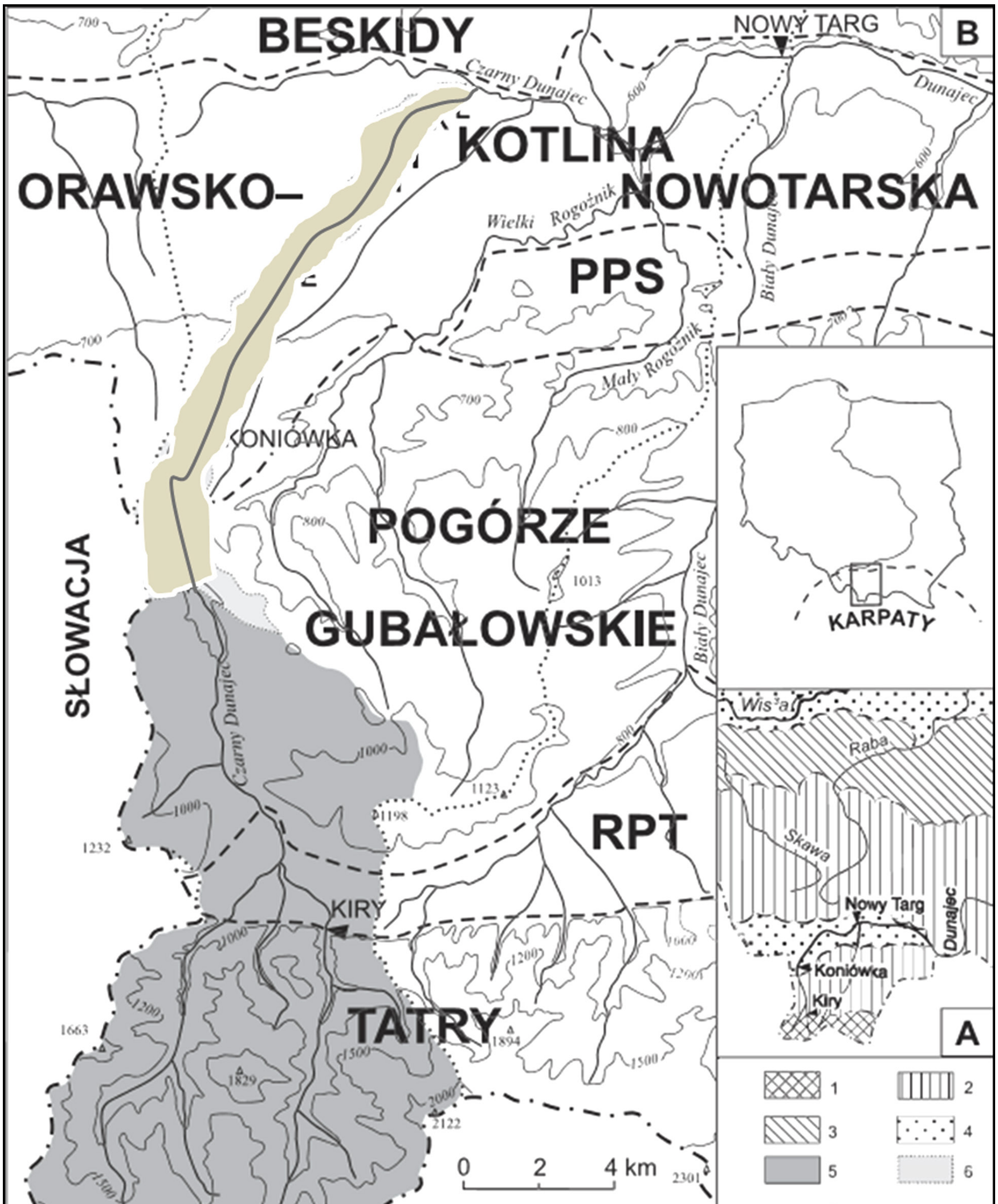


**Fig. 3.** Location of the Czarny Dunajec River against the back ground of physiogeographic regions of southern Poland (A), and drainage network and physiography of the Czarny Dunajec River catchment, with detailed setting of the studied area (B): 1 – high mountains; 2 – mountains of intermediate and low height; 3 – foothills; 4 – intramontane and submontane depressions; 5 – the Czarny Dunajec River catchment up to the beginning of the studied section; 6 – catchment area increment along the studied section; 7 – boundary of the Czarny Dunajec River catchment; 8 – boundaries of physiogeographic units; 9 – studied section; 10 – flow-gauging stations; PKB – Pieniny Klippen Belt; STT – Sub-Tatran Trough (Wyżga et. al. 2008)

## MATERIAL AND METHODS

### Description of the catchment under investigation

The Czarny Dunajec River catchment (see: Fig. 3) is characterized by a very diverse geological structure. The area is built of crystalline rocks, carbonate rocks, Podhale flysch and fluvioglacial formations. The Czarny Dunajec River drainage basin covers several regions: Western Tatras, Rów Podtatrzański, Gubałowskie Range, Kotlina Orawsko-Nowotarska, and Działy Orawskie (Korpak et al. 2008).

Czarny Dunajec is a river located in the south of Poland, in the Małopolska province. It is considered the initial section of the Dunajec River, which is the right tributary of the Vistula (Wisła) River. The surface of the Czarny Dunajec catchment is 456 km², and its length is 48 km. The source of the Czarny Dunajec River is deemed to be the Wyżni Chochołowski Potok, which springs under the Wołowiec mount in the Western Tatras at an altitude of about 1500 metres a.s.l. (Korpak et al. 2008). Granite and quartzite bed load is predominant in the Czarny Dunajec riverbed. In the initial section – up to Chochołów – the percentage of granitoids increases; further, it continues to decrease all the way down to Nowy Targ. The maximum freshets on the Czarny Dunajec are associated with continuous and violent summer rains occurring from June to August. The largest flow occurred in 1934, at 870 $m^3 \cdot s^{-1}$, whereas the minimum flow was recorded in 1964, at 0.85 $m^3 \cdot s^{-1}$ (Korpak et al. 2008). Intensive exploitation of the bed load was carried out in the Czarny Dunajec riverbed. This exploitative activity manifested itself after the Second World War, and it intensified particularly in the 1970s, here as in other river beds of the Carpathian watercourses. The exploitation took place both in an organized manner, with the help of mechanical equipment; and in an unorganized and more dispersed way. Thus, gravel and boulder material was removed from the surface of the gravel bars, or in fact, all material found in the river bed was taken out. In connection with the exploitation of the bed load, the protective armouring of the bed was being destroyed, and dredging occurred in the exploited section. These changes were reflected in increased headward erosion of the bottom of the channel in the higher sections (Korpak et al. 2008).

### Studied stone rip-raps

Stone rip-raps were examined in three locations in Nowy Targ (see: Fig. 5, 6, 7). The points examined are located in the following places (see: Fig. 8):

- below the bridge at Kowaniec,
- below the footbridge near the Hala Lodowa,
- below the bridge on Krakowska street.

The height of rip-rap revetments ranged from 0.8 m in places with the smallest sloping angle, to 1.6 m. The sloping angle of rip-raps ranged from 22° to 45°. No filter was found in the rip-rap revetments. The diam-

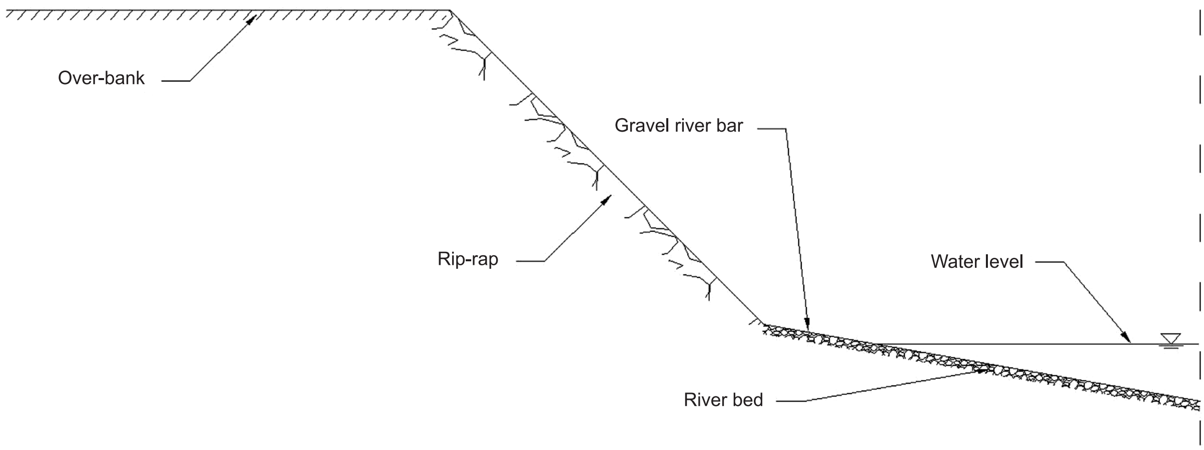


**Fig. 4.** Diagram of the river bank structure with stone rip-rap in Nowy Targ on the Czarny Dunajec River

**Fig. 5.** Stone rip-rap in the first studied point (Nowy Targ on the Czarny Dunajec River)

**Fig. 6.** Stone rip-rap in the second studied point (Nowy Targ on the Czarny Dunajec River)

**Fig. 7.** Stone rip-rap in the third studied point (Nowy Targ on the Czarny Dunajec River)

eter of the stones in the rip-rap remained in the range between 0.24 m and 1.43 m.

The general scheme of the stone rip-rap revetment structure in Nowy Targ is illustrated in Figure 4.

The width of the Czarny Dunajec river bed in Nowy Targ is between 15–25 m. Above the rip-rap, there is a floodplain terrace (over-bank), densely covered with vegetation. Above the terraces, levees run parallel to the river. The height of the floodplain above the bottom of the river bed measures from 1 to 3 m.

## Research methodology

The study covered the Czarny Dunajec river bed, which is a tributary of the Dunajec River. The methodology was based on the appointment of several research stands (see: Fig. 8), each with stone rip-rap and gravel bar below. A number of granulometric measurements according to the Wolman method (1954) were carried out on each of the stands. 100 boulders were measured in the rip-rap, and 100 stones of the bed load, at each of the test points. Taking into account the diameters, the allocation of subsequent samples to the appropriate size classes was determined. Then, granulometric curves were performed. Based on the latter, the conditions of stability and permeability of the rip-rap were examined. The next step was to calculate the characteristic diameters of the rip-rap, and to analyse them. The characteristic diameter of crushed stones in the rip-rap – assuming that the flow in the river bed changes in a gradual and uniform manner – was calculated according to project guidelines for the state of Connecticut in the USA (Drainage Manual Chapter 7 of 2000):

$$D_{50} = \frac{0.00594 \cdot V_a^3}{d_{avg}^{0.5} \cdot K_1^{1.5}}$$

where:

$D_{50}$ – characteristic diameter, m,

$V_a^3$ – mean velocity of water flow, m/s,

$d_{avg}$ – average depth of the flow, m,

$K_1$ – correction factor, calculated from the following formula:

$$K_1 = \left[1 - \left(\frac{\sin^2 \theta}{\sin^2 \Phi}\right)\right]^{0.5}$$

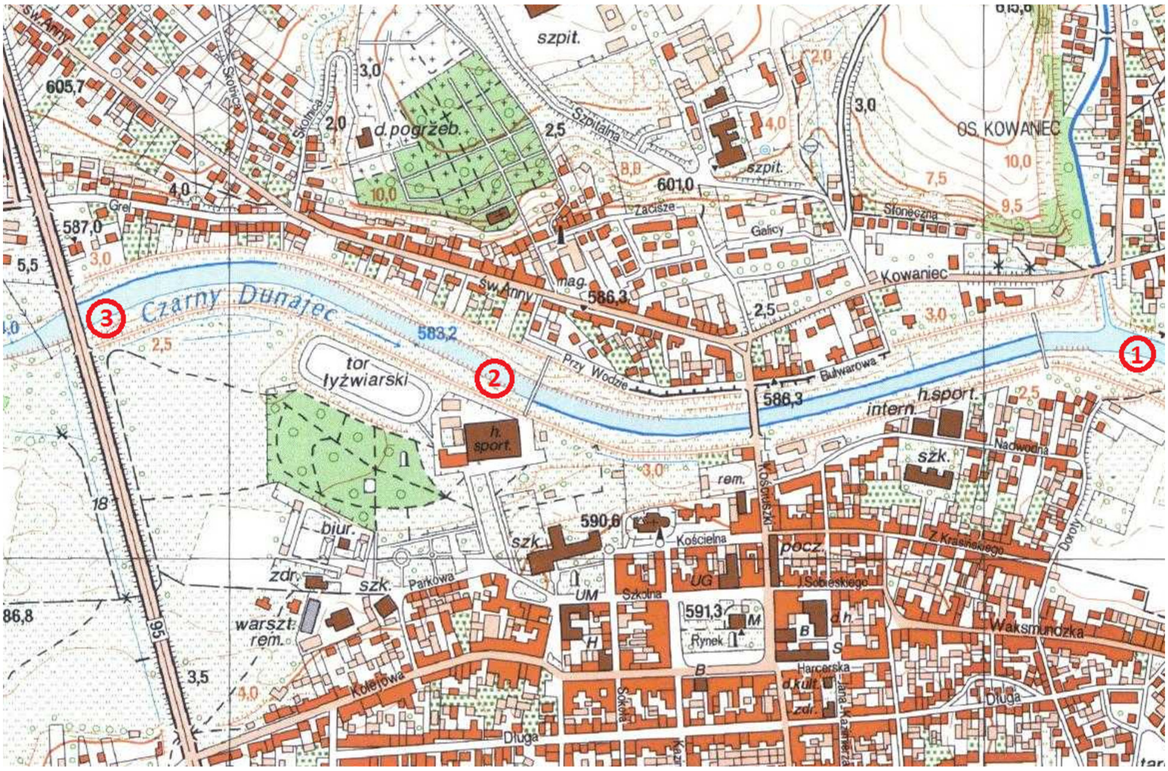


**Fig. 8.** Fragment of the map of Nowy Targ, with the points where the samples were taken (geoportal.gov.pl)

where:

θ – (theta) angle of rip-rap placement,

Φ – (phi) angle of the natural formation of the rip--rap.

The average depth and flow velocity used in the above equation are measured in the main river channel. The main channel is defined as the area between the river banks (see: Fig. 9).

In order to protect the river banks against erosion, it may be necessary to additionally use a filter in the stone rip-rap. Such filter prevents leaching of finely-grained material from the gaps in the stone rip-rap layer. Under normal conditions, the filter is only necessary if the material underlying the rip-ray layer is very loose (for instance, homogeneous sand, silt) or when an extremely high safety factor is required. The demand for the filter can also be checked against the conditions of stability and permeability. Diameter values for the conditions are taken from the granulometric curves (Keller and Fowler 2005).

Stability condition:

$$\frac{D_{15}\,(\text{rip-rap})}{D_{85}\,(\text{river-bank material})} \leq 5$$

and

$$\frac{D_{50}\,(\text{rip-rap})}{D_{50}\,(\text{river-bank material})} \leq 25$$

Permeability condition:

$$\frac{D_{15}\,(\text{rip-rap})}{D_{15}\,(\text{river-bank material})} \leq 5$$

$D$ – grain diameter taken from the granulometric curves.

In cases where the correlation of the grain diameter of the rip-rap versus the river bank material does not

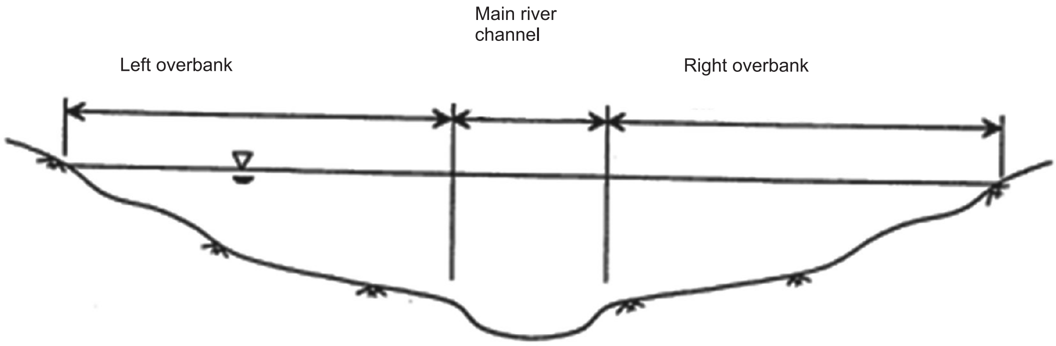


**Fig. 9.** A cross-section showing the main river channel (after: Drainage Manual Chapter 7, 2000)

meet the condition, a filter needs to be applied (Keller and Fowler 2005).

## RESEARCH RESULTS AND DISCUSSION

In this sub-section, we present granulometric curves of the samples from the river bank material on the gravel bars, and stones in the rip-rap revetments, in the three examined points (see: Fig. 8). The diameters of the river bank material in the first study point ranged from 0.01 m to 0.105 m, in the second point, from 0.017 to 0.081 m, and in the third point, from 0.001 to 0.127 m. The diameters of the stones in the rip-rap revetments, in the first point were in the range between 0.24 m and 1.3 m, in the second point, between 0.22÷1.4 m, and in the third point, between 0.25÷1.43 m.

In the first examined point, coarse (thick) gravel predominated in the river bank material, whereas medium stones were the smallest fraction (see: Table 1). The proportion of coarse gravel fraction was 57% (see: Fig. 10). The stone rip-rap revetment was dominated by average boulders, whereas the size class of very large stones was the least numerous (see: Table 2). Medium fraction boulder constituted 68% (see: Fig. 12).

**Table 1.** Data collected at point 1 for the gravel bar (Kowaniec – Nowy Targ, Czarny Dunajec)

| | Gravel bar 1 | | | | | |
|---|---|---|---|---|---|---|
| | Number of grains | Size class | Size range | Mid-range size | % | Cumulative % |
| | | | | 0 | 0 | 0 |
| | 4 | Medium-sized gravel | 8–16 | 12 | 4% | 4% |
| | 57 | Coarse gravel | 16–32 | 24 | 57% | 61% |
| | 34 | Very coarse gravel | 32–64 | 48 | 34% | 95% |
| | 3 | Small stones | 64–90 | 77 | 3% | 98% |
| | 2 | Medium-sized stones | 90–128 | 109 | 2% | 100% |
| Total | 100 | | | | | |

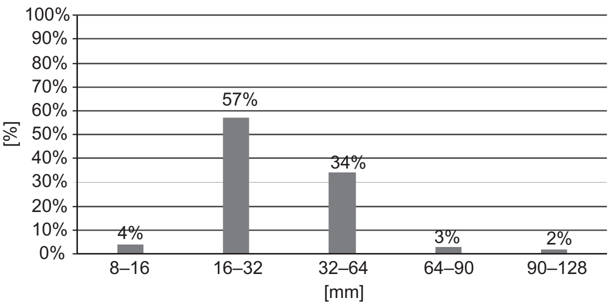


**Fig. 10.** Grain size analysis for the gravel bar (Kowaniec – Nowy Targ, the Czarny Dunajec River)

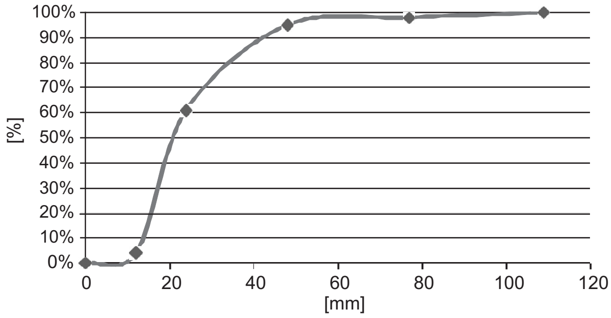


**Fig. 11.** Grain-size curve for the gravel bar (Kowaniec – Nowy Targ, the Czarny Dunajec River)

**Table 2.** Data collected at point 1 for the rip-rap revetment (Kowaniec – Nowy Targ, the Czarny Dunajec River)

| | Rip-rap revetment 1 | | | | | |
|---|---|---|---|---|---|---|
| | Number of grains | Size class | Size range | Mid-range size | % | Cumulative % |
| | | | | 0 | 0 | 0 |
| | 1 | Very large stone | 180–256 | 218 | 1% | 1% |
| | 24 | Small boulder | 256–512 | 384 | 24% | 25% |
| | 68 | Medium-sized boulder | 512–1024 | 768 | 68% | 93% |
| | 7 | Large boulder | 1024–2048 | 1536 | 7% | 100% |
| Total | 100 | | | | | |

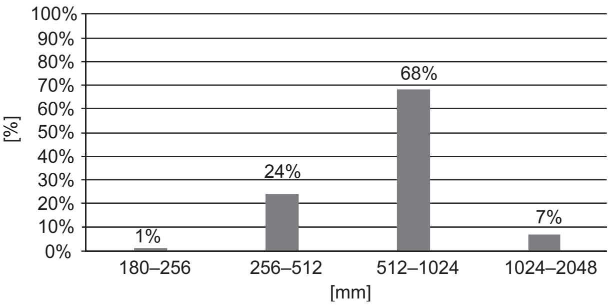


**Fig. 12.** Grain size analysis for the rip-rap (Kowaniec – Nowy Targ, the Czarny Dunajec River)

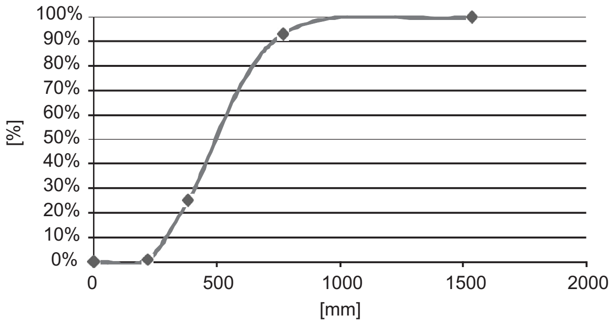


**Fig. 13.** Grain-size curve for the rip-rap (Kowaniec – Nowy Targ, the Czarny Dunajec River)

In the second study point, very coarse gravel predominated in the coastal material, and small stones were the least numerous (see: Table 3). The fraction of very coarse gravel amounted to 67% (see: Fig. 14). The stone rip-rap revetment was dominated by the mid-sized boulder, whereas very large stones were the least numerous size class (see: Table 4). The average boulder fraction amounted to 57% (see: Fig. 16).

**Table 3.** Data collected at point 2 for the gravel bar (Hala Lodowa – Nowy Targ, the Czarny Dunajec River)

| | Gravel bar 2 | | | | | |
|---|---|---|---|---|---|---|
| | Number of grains | Size class | Size range | Mid-range size | % | Cumulative % |
| | | | | 0 | 0 | 0 |
| | 21 | Coarse gravel | 16–32 | 24 | 21% | 21% |
| | 67 | Very coarse gravel | 32–64 | 48 | 67% | 88% |
| | 12 | Small stones | 64–90 | 77 | 12% | 100% |
| Total | 100 | | | | | |

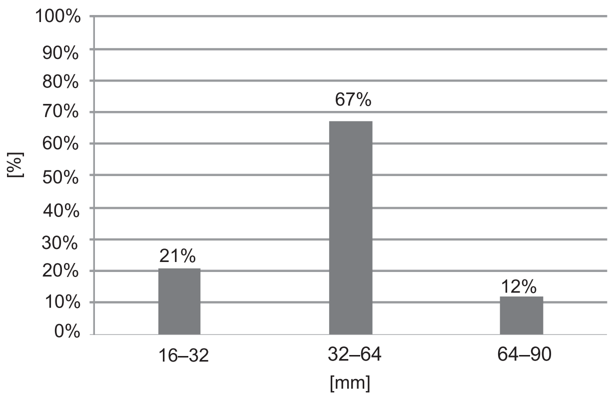


**Fig. 14.** Grain size analysis for the gravel bar (Hala Lodowa – Nowy Targ, the Czarny Dunajec River)

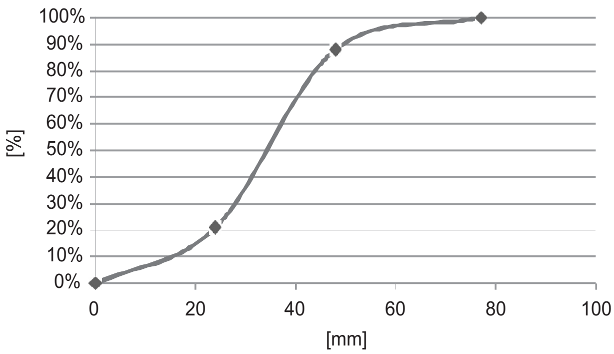


**Fig. 15.** Grain-size curve for the gravel bar (Hala Lodowa – Nowy Targ, the Czarny Dunajec River)

**Table 4.** Data collected at point 2 for the rip-rap revetment (Hala Lodowa – Nowy Targ, the Czarny Dunajec River)

| | Rip-rap revetment 2 | | | | | |
|---|---|---|---|---|---|---|
| | Number of grains | Size class | Size range | Mid-range size | % | Cumulative % |
| | | | | 0 | 0 | 0 |
| | 3 | Very large stone | 180–256 | 218 | 3% | 3% |
| | 25 | Small boulder | 256–512 | 384 | 25% | 28% |
| | 57 | Medium-sized boulder | 512–1024 | 768 | 57% | 85% |
| | 15 | Large boulder | 1024–2048 | 1536 | 15% | 100% |
| Total | 100 | | | | | |

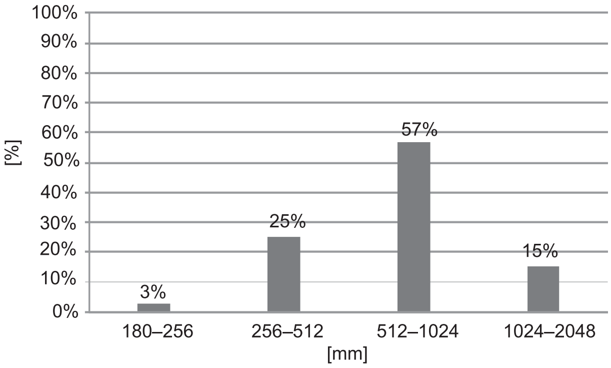


**Fig. 16.** Grain size analysis for the rip-rap (Hala Lodowa – Nowy Targ, the Czarny Dunajec River)

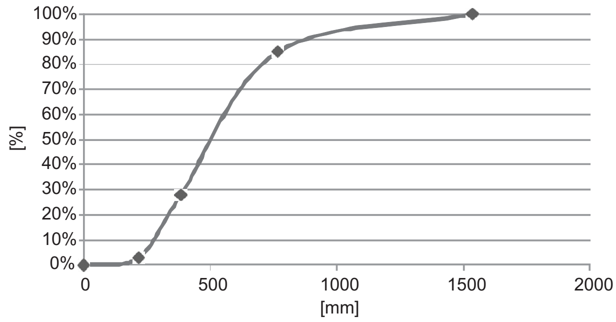


**Fig. 17.** Grain-size curve for the rip-rap (Hala Lodowa – Nowy Targ, the Czarny Dunajec River)

In the third examined point, in the river bank material, very thick gravel predominated, and medium gravel was the least numerous (see: Table 5). The share of the fraction of very coarse gravel amounted to 60% (see: Fig. 18). In the rip-rap revetment, mid-sized boulders were dominant, while the size class of very large stones was the least numerous (see: Table 6). The mid-sized boulder fraction amounted to 58% (see: Fig. 20).

**Table 5.** Data collected at point 3 for the gravel bar (Krakowska – Nowy Targ, the Czarny Dunajec River)

| | Gravel bar 3 | | | | | |
|---|---|---|---|---|---|---|
| | Number of grains | Size class | Size range | Mid-range size | % | Number of grains |
| | | | | 0 | 0 | 0 |
| | 2 | Mid-sized gravel | 8–16 | 12 | 2% | 2% |
| | 20 | Coarse gravel | 16–32 | 24 | 20% | 22% |
| | 60 | Very coarse gravel | 32–64 | 48 | 60% | 82% |
| | 14 | Small stones | 64–90 | 77 | 14% | 96% |
| | 4 | Mid-sized stones | 90–128 | 109 | 4% | 100% |
| Total | 100 | | | | | |

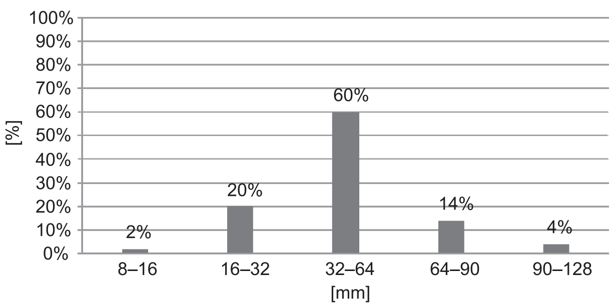


**Fig. 18.** Grain size analysis for the gravel bar (Krakowska – Nowy Targ, the Czarny Dunajec River)

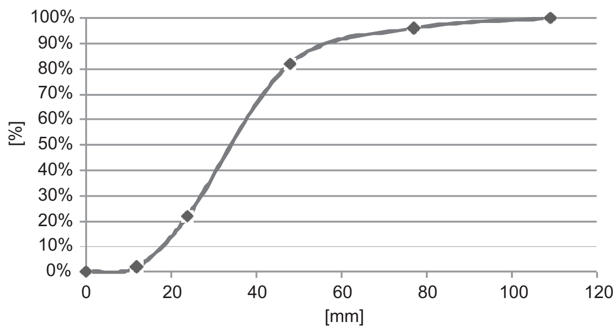


**Fig. 19.** Grain-size curve for the gravel bar (Krakowska – Nowy Targ, the Czarny Dunajec River)

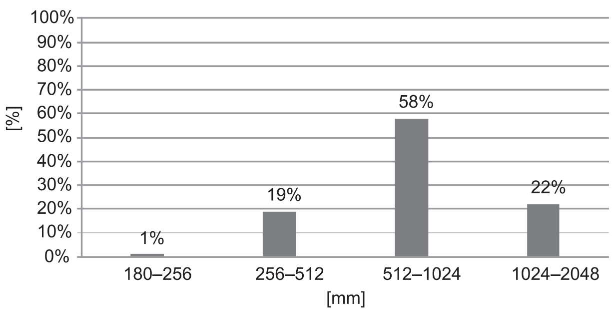


**Fig. 20.** Grain size analysis for the rip-rap (Krakowska – Nowy Targ, the Czarny Dunajec River)

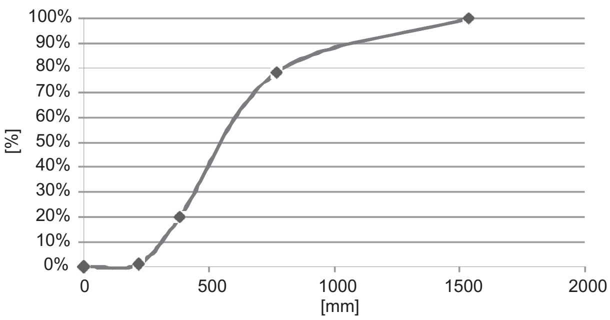


**Fig. 21.** Grain-size curve for the rip-rap (Krakowska – Nowy Targ, the Czarny Dunajec River)

**Table 6.** Data collected at point 3 for the rip-rap revetment (Krakowska – Nowy Targ, the Czarny Dunajec River)

| | Rip-rap revetment 3 | | | | | |
|---|---|---|---|---|---|---|
| | Number of grains | Size class | Size range | Mid-range size | % | Cumulative % |
| | | | | 0 | 0 | 0 |
| | 1 | Very large stone | 180–256 | 218 | 1% | 1% |
| | 19 | Small boulder | 256–512 | 384 | 19% | 20% |
| | 58 | Medium-sized boulder | 512–1024 | 768 | 58% | 78% |
| | 22 | Large boulder | 1024–2048 | 1536 | 22% | 100% |
| Total | 100 | | | | | |

The granulometric curves we have developed were subsequently used to check the conditions of stability and permeability (see: Fig. 11, 13, 15, 17, 19, 21).

- Stability condition 1

$$\frac{D_{15}\,(\text{rip-rap})}{D_{85}\,(\text{river-bank material})} \leq 5$$

$$\frac{330}{39} = 8.46 > 5$$

$$\frac{310}{46} = 6.74 > 5$$

$$\frac{350}{46} = 7.61 > 5$$

Calculation of the first stability condition produced the results presented in Table 7.

**Table 7.** Presentation of calculation results for the first condition of stability, for the three studied points

| No. | $D_{15}$ (rip-rap) mm | $D_{85}$ (bed load) mm | $D_{15}/D_{85} \leq 5$ |
|---|---|---|---|
| 1 | 330 | 39 | 8,46 |
| 2 | 310 | 46 | 6,74 |
| 3 | 350 | 46 | 7,61 |

- Stability condition 2

$$\frac{D_{50}\text{ (rip-rap)}}{D_{50}\text{ (river-bank material)}} \leq 25$$

$$\frac{500}{22} = 22.73 < 25$$

$$\frac{510}{34} = 15 < 25$$

$$\frac{550}{35} = 15.71 < 25$$

Calculation of the second stability condition produced the results presented in Table 8.

**Table 8.** Presentation of calculation results for the second condition of stability, for the three studied points

| No. | $D_{50}$ (rip-rap) mm | $D_{50}$ (bed load) mm | $D_{50}/D_{50} \leq 25$ |
|---|---|---|---|
| 1 | 500 | 22 | 22,73 |
| 2 | 510 | 34 | 15,00 |
| 3 | 550 | 35 | 15,71 |

- Permeability condition

$$\frac{D_{15}\text{ (rip-rap)}}{D_{15}\text{ (river-bank material)}} \leq 5$$

$$\frac{330}{17} = 19.41 > 5$$

$$\frac{310}{21} = 14.76 > 5$$

$$\frac{350}{21} = 16.67 > 5$$

Calculation of the permeability condition produced the results presented in Table 9.

**Table 9.** Presentation of calculation results for the condition of permeability, for the three studied points

| No. | $D_{15}$ (rip-rap) mm | $D_{15}$ (bed load) mm | $D_{15}/D_{15} \leq 5$ |
|---|---|---|---|
| 1 | 330 | 17 | 19,41 |
| 2 | 310 | 21 | 14,76 |
| 3 | 350 | 21 | 16,67 |

The first condition of stability and the permeability condition have been exceeded. Only the second condition of stability was met, and confirmed for each tested point (see: Table 10):

1. $D_{50}$: currently is 22 mm – should be 20 or more.
2. $D_{50}$: currently is 34 mm – should be 20.4 or more.
3. $D_{50}$: currently is 35 mm – should be 22 or more.

The first condition of stability was exceeded by 1.74÷3.46. For the condition to be met, the stones in the bed load should be correspondingly larger (see: Table 10):

1. $D_{85}$: currently is 39 mm – should be 66 mm or more.
2. $D_{85}$: currently is 46 mm – should be 62 mm or more.
3. $D_{85}$: currently is 46 mm – should be 70 mm or more.

The permeability condition was not met for any of the points examined. What is more, it significantly exceeds the designated range (9.76÷14.41) (see: Table 10):

1. $D_{15}$: currently is 17 mm – should be 66 mm or more.
2. $D_{15}$: currently is 21 mm – should be 62 mm or more.
3. $D_{15}$: currently is 21 mm – should be 70 mm or more.

At each of the studied points, the angle of the slope of the rip-rap revetment was measured at six places, at equal intervals along the entire length, and on this basis, the average angles of inclination were calculated. The angles remained in the range of 31÷40° (see: Table 11).

Taking into account the average inclination angle of the rip-rap revetment at individual points, we are able to calculate the characteristic diameters of the stone rip-rap for theoretical average flow velocities and average filling depth (see: Table 12).

**Table 10.** Required gravel diameters for meeting particular conditions

| No. | $D_{85}$ (bed load) minimum diameter mm | $D_{50}$ (bed load) minimum diameter mm | $D_{15}$ (bed load) minimum diameter mm |
|---|---|---|---|
| 1 | 66 ≤ | 20 ≤ | 66 ≤ |
| 2 | 62 ≤ | 20.4 ≤ | 62 ≤ |
| 3 | 70 ≤ | 22 ≤ | 70 ≤ |

**Table 11.** Inclination angles for rip-rap in particular points (θ)

| No. | N1-θ, ° | N2-θ, ° | N3-θ, ° |
|---|---|---|---|
| 1 | 40 | 35 | 31 |
| 2 | 42 | 37 | 32 |
| 3 | 35 | 37 | 38 |
| 4 | 37 | 33 | 30 |
| 5 | 45 | 38 | 31 |
| 6 | 43 | 32 | 22 |
| Average angle θ | 40 | 35 | 31 |

**Table 12.** Rip-rap characteristic diameters depending on discharge

| No. | $V_a$ m · s$^{-1}$ | $d_{avg}$ m | θ, ° | Φ, ° | $K_1$ | $D_{50}$ |
|---|---|---|---|---|---|---|
| 1 | 0.3 | 0.1 | 40 | 44 | 0.3792 | 0.002 |
| | 0.6 | 0.5 | | | | 0.008 |
| | 0.9 | 0.7 | | | | 0.022 |
| | 1.2 | 1 | | | | 0.044 |
| | 1.5 | 1.2 | | | | 0.078 |
| | 2 | 1.4 | | | | 0.172 |
| | 2.5 | 1.5 | | | | 0.325 |
| | 3 | 1.6 | | | | 0.543 |
| | 3.5 | 1.7 | | | | 0.837 |
| | 4 | 1.8 | | | | 1.214 |
| | 4.5 | 1.9 | | | | 1.682 |
| | 5 | 2 | | | | 2.249 |
| | 5.5 | 2.1 | | | | 2.921 |
| | 6 | 2.2 | | | | 3.705 |
| | 6.5 | 2.3 | | | | 4.607 |
| | 7 | 2.4 | | | | 5.633 |
| | 7.5 | 2.5 | | | | 6.788 |
| | 8 | 2.6 | | | | 8.078 |
| 2 | 0.3 | 0.1 | 35 | 44 | 0,5641 | 0.001 |
| | 0.6 | 0.5 | | | | 0.004 |
| | 0.9 | 0.7 | | | | 0.012 |
| | 1.2 | 1 | | | | 0.024 |
| | 1.5 | 1.2 | | | | 0.043 |
| | 2 | 1.4 | | | | 0.095 |
| | 2.5 | 1.5 | | | | 0.179 |
| | 3 | 1.6 | | | | 0.299 |
| | 3.5 | 1.7 | | | | 0.461 |
| | 4 | 1.8 | | | | 0.669 |
| | 4.5 | 1.9 | | | | 0.927 |
| | 5 | 2 | | | | 1.239 |
| | 5.5 | 2.1 | | | | 1.610 |
| | 6 | 2.2 | | | | 2.042 |
| | 6.5 | 2.3 | | | | 2.539 |
| | 7 | 2.4 | | | | 3.104 |
| | 7.5 | 2.5 | | | | 3.741 |
| | 8 | 2.6 | | | | 4.452 |
| 3 | 0.3 | 0.1 | 31 | 44 | 0.6710 | 0.001 |
| | 0.6 | 0.5 | | | | 0.003 |
| | 0.9 | 0.7 | | | | 0.009 |
| | 1.2 | 1 | | | | 0.019 |
| | 1.5 | 1.2 | | | | 0.033 |
| | 2 | 1.4 | | | | 0.073 |
| | 2.5 | 1.5 | | | | 0.138 |
| | 3 | 1.6 | | | | 0.231 |
| | 3.5 | 1.7 | | | | 0.355 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 1.8 | | | | 0.515 |
| | 4.5 | 1.9 | | | | 0.714 |
| | 5 | 2 | | | | 0.955 |
| | 5.5 | 2.1 | | | | 1.241 |
| 3 | 6 | 2.2 | 31 | 44 | 0.6710 | 1.574 |
| | 6.5 | 2.3 | | | | 1.957 |
| | 7 | 2.4 | | | | 2.393 |
| | 7.5 | 2.5 | | | | 2.883 |
| | 8 | 2.6 | | | | 3.431 |

From the results, it can be concluded that the higher the flow velocity and the filling depth, the larger the equivalent diameter for the rip-rap revetment. Based on the data in individual points, it can be concluded that the rip-rap has been selected for a specific speed flow and filling level:

1. $D_{50}$: 500 mm – $V = 3$ m · s$^{-1}$; $d = 1.6$ m
2. $D_{50}$: 510 mm – $V = 4$ m · s$^{-1}$; $d = 1.8$ m
3. $D_{50}$: 550 mm – $V = 4$ m · s$^{-1}$; $d = 1.8$ m

## CONCLUSIONS

1. There is a correlation between the average flow rate, the filling depth, the angle of inclination, and the characteristic diameter of the rip-rap. The higher the average flow velocity, the filling, and the angle, the larger the characteristic diameter of the stones in the rip-rap.
2. Taking into account the diameter of stones in the existing rip-raps, it can be stated that they have been designed for an average flow velocity of 3÷4 m · s$^{-1}$ and for the fill in the range of 1.6÷1.8 m.
3. Having verified the stability and permeability conditions for the stone rip-rap, it can be concluded that it would be necessary to use filter ballast or geotextile that have not been previously introduced into the field structure.
4. Lack of filter may cause insufficient protection of the river bank against dilution (suffosion), which usually results in loss of stability of the revetment, and increased erosion (displacement of the rip-rap).
5. The stone rip-rap was designed for medium flow speed, assuming a maximum of v = 4 m · s$^{-1}$. Higher maximum flow velocity may contribute to the tearing off of the rip-rap.

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## AWARIE NARZUTU KAMIENNEGO NA RZEKACH GÓRSKICH (NA PRZYKŁADZIE ZABEZPIECZENIA BRZEGU NA RZECE CZARNY DUNAJEC)

### ABSTRAKT

Zagadnienia związane z utrzymaniem rzek i umocnieniem ich brzegów są bardzo istotne w inżynierii rzecznej. Dobór odpowiednich zabezpieczeń uzależniony jest od wielu czynników. Przy projektowaniu należy brać pod uwagę między innymi rodzaj gruntu, warunki hydrodynamiczne, zjawiska atmosferyczne i chemiczny stan wód. Przykładowymi konstrukcjami umacniającymi koryto cieku są ostrogi, opaski, gabiony, a także narzuty kamienne z kamienia łamanego. Efektywne działanie wszelkiego rodzaju umocnień zależy od ich prawidłowego wykonania. W przypadku narzutów kamiennych istnieje szereg wytycznych dotyczących wymaganych właściwości fizycznych i mechanicznych kamienia łamanego. W pracy omówiono sposoby zabezpieczeń brzegów rzeki, przedstawiając czynniki determinujące wybór narzutu kamiennego przez określenie specyfikacji technicznej dotyczącej wielkości kamienia łamanego, narzutu oraz stosowanego filtra przy narzucie kamiennym. W sposób szczególny zajęto się jakością materiału filtra użytego do ułożenia kamienia łamanego. Materiał filtra jest usypywany bezpośrednio pod narzutem kamiennym i jego niewłaściwy dobór często prowadzi do awarii ubezpieczenia brzegowego. Analizie zostały poddane trzy narzuty kamienne na terenie Nowego Targu. Na każdym stanowisku zostało przeprowadzone szereg pomiarów granulometrycznych oraz kątów usypania narzutu. Sprawdzono dwa warunki stabilności oraz warunek przepuszczalności.

**Słowa kluczowe:** narzut kamienny, rzeka górska, podsypka filtracyjna