THE STABILITY OF ALTERNATIVE GRAVEL MOUNTS WITH STACKED BOULDERS DURING MAJOR FLOOD STAGES INSIDE CHANNELIZED RIVERS

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1. INTRODUCTION

The introduction of alternative arrowhead-shaped gravel mounts inside channelized rivers creates a meandering flow, thus increasing the flow heterogeneity. Under medium-sized flood stages, refuge able areas are observed behind each gravel mount where small aquatic animal might find refuge from the force of the flood discharge (Beretta Piccoli et al. 2022). Results have also highlighted that under larger flood stages the stability of the gravel mounts may not be guaranteed. For this reason, an improvement design with the introduction of stacked boulders is here proposed.

2. INSTALLATION METHOD

The gravel mounts were constructed above flat gravel bed of thickness h_{bed}=4 cm using homogeneous gravel with averaged diameter d_{50}=1.65 cm. Multilayered gravel bed was proven to be more stable in Beretta Piccoli et al., 2022. Like the experiment conducted with the original gravel mounts' design, seven mounts were installed on alternative sides of the experimental channel every 0.8 m along the physical model using the same gravel as the bed. Each mount has triangular shape with linearly decreasing height from the channel's side wall to the mount's toe, upstream width of 0.3 m and downstream width 0.35 m. The mounts' transverse length was reduced to 0.5 m (from 0.6 m in the original design), while the height was kept 4.35 cm, as it was found to be the optimal shape in Beretta Piccoli et al. 2021. Differently to the original design, the outline of each gravel mount was reinforced by two layers of boulders placed like fallen dominoes in downstream direction. The larger rocks (D_{50}=6.28 cm) were placed inside the gravel bed trying to maintain the linearly reducing height of the mounts' profile. The downstream layer had a general angle of 20°-30° from the horizontal, while second layer was placed on top of it with slightly steeper angle. Two more layers of stacked boulders were placed at the sides of the channel along the entire model's length. Beretta Piccoli et al. 2022, proved that such morphology generates flat water surface in these regions. The rocks were placed facing downstream, but the angles were increased to 50°-60°. The height of the external layer was 8.35 cm equal to the gravel mounts' peaks, while for the internal layer was slightly lower. The physical model is shown in Photo 1. The channel slope was set to I=1/100 while Q=0.155 m^3/s is the largest discharge measurable inside the experimental channel. A metal bar was installed at the model's downstream end to improve its stability. Bed and water elevations were measured using a point gauge with 0.1 cm resolution. For the flow velocity an electrical-magnetic current meter was used with 0.05 s frequency, 30 s sampling time and sensitivity ±0.5 cm/s.

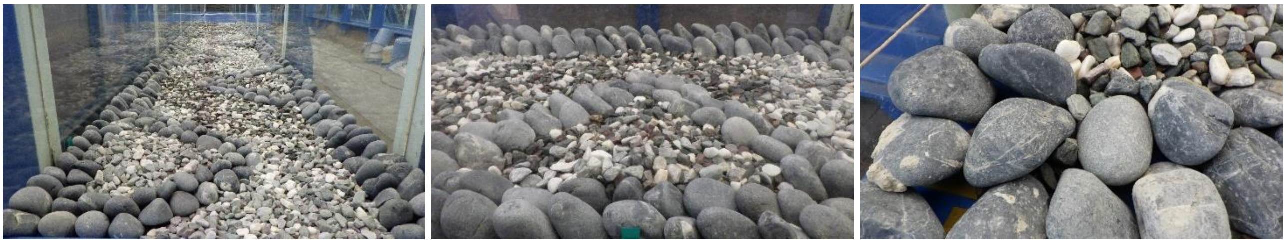

Photo 1 Left (a): Improved gravel mounts' model viewed from downstream. Centre (b): a gravel mounts shown from the left side wall. Right (c): closer look at the stacked boulders around the gravel mounts (viewed from downstream).

The Froude Number [-] is calculated as follows:

$$Fr = \frac{v_{ave}}{\sqrt{g \cdot h_{ave}}} = \frac{Q}{B \cdot h_{ave} \cdot \sqrt{g \cdot h_{ave}}} \quad (1)$$

The average flow velocity v_{ave} is obtained from the discharge Q=0.155 m^3/s divided by the multiplication of the channel width B=0.8 m with the average flow depth h_{ave} [m]. This parameter is calculated from the difference between the average water elevation z_{ave} minus the bed thickness h_{bed}=4 cm. The gravitational constant g is equal to 9.81 m/s^2.

Assuming a model scale S=10, hydraulic quantities are evaluated based on Froude's similarity. Under this principle, the physical model would represent a 54 m long section of an 8 m wide river with steepness 1/100. The friction on the gravel mounts' surface is shown with the average friction coefficient f [-] calculated as follows:

$$f = 4 \cdot I \cdot R_{hy} \cdot \frac{2 \cdot g \cdot (h_{ave} \cdot B)^2}{Q^2} \xRightarrow{R_{hy} \approx h_{ave}} f = 8 \cdot g \cdot I \cdot \frac{h_{ave}^3 \cdot B^2}{Q^2} \quad (2), (3)$$

In this paper, the hydraulic radius R_{hy} [m] is assumed to be equal to the average water depth h_{ave}. Because the channel's side walls are made of glass, the roughness is completely different from the gravel surfaces occurring in rivers.

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The characteristic grain size D84 [m] is important to estimate the height of the roughness layer above gravel bed and to understand what flow resistance is generated by the gravel mounts at the studied hydraulic conditions. The formulas of Rickenmann and Recking (2011) for rivers with gravel bed are used here:

$$\sqrt{\frac{8}{f}} = 6.838 \cdot \left(\frac{h_{ave}}{D84}\right)^{0.153} \quad (4)$$

$$U^{**} = 3.2 \cdot q^{**^{0.395}}, \text{ where } U^{**} = \frac{Q}{(h_{ave} \cdot B) \cdot \sqrt{g \cdot I \cdot D84}} \text{ and } q^{**} = \frac{Q}{B \cdot \sqrt{g \cdot I \cdot D84^3}} \quad (5), (6), (7)$$

The boundaries of Eq. (4) are $5.07 < h_{ave}/D84 < 18900$, while Eq. (5) is valid for $q^{**} > 100$:

3. EXPERIMENTAL RESULTS

After four days of measurements under $Q=0.155$ m^3/s, a total of 21 grains have been transported downstream of the model installation. Some local movement and grain shaking has been observed, but only the top of the gravel mounts appear to have been modified by the discharge. No movement nor shaking of stacked boulders has been observed for the entirety of the experiment. The average water depth is $h_{ave}=17$ cm and the Froude number is Fr=0.9. As shown in Figure 1, the construction of stacked boulders at the side of the channel successfully flattens the water surface there. Small waves are still observed around the central part of channel above each gravel mounts.

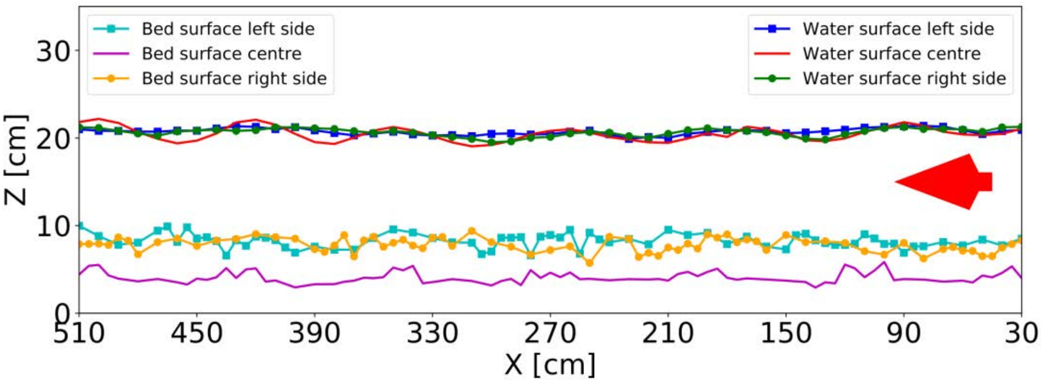

Figure 1 Gravel bed and water surfaces along the left side, the centre and the right side of the channel. The flow direction is given by the red arrow. Coordinate X=0 cm is the upstream end of the physical model (axes not in scale).

In prototype scale, the average water surface becomes $h_{ave}=1.7$ m and the discharge $Q=49$ m^3/s. As shown in Table 1, the average friction coefficient is f=0.10, while from Eq. (4) the characteristic grain size D84=0.32 is found ($h_{ave}/D84=5.31$). The iteration of Eq. (5), Eq. (6) and Eq. (7) with one another confirms the obtained results with $U^{**}=20.3$ and $q^{**}=108$. The roughness layer almost matches the height 0.435 m of the gravel mounts in prototype, successfully confirming a significant disruption of the flow field above the gravel bed. Also, the observed partial erosion on the top of each mount (i.e. above the roughness layer) described in the previous paragraph, appears to match the mathematical results.

Table.1 Hydraulic parameters in prototype scale: the average water depth h_{ave}, the discharge Q, the channel slope I, the average friction coefficient f and the characteristic gravel size D84.

h_{ave} [m]	Q [m^3/s]	I [-]	f [-]	D84 [m]
1.70	49	0.01	0.10	0.32

4. CONCLUSIONS

The long-term stability of the improved gravel mounts' design was successfully confirmed under major flood stages. Flat water surface at the side of the channel is achieved thanks to the construction of stacked boulders at same coordinates. Significant flow disruption above the gravel bed is confirmed by the formulas of Rieckenmann and Riecking (2011), with the roughness layer almost matching the height of the gravel mounts. The ecological improvements can now be studied under smaller discharges and the results compared to what observed around the original gravel mounts' design.

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