COMPARISON OF BED STABILIZATION METHODS IN TWO EXPERIMENTAL FACILITIES – INFLUENCE OF INHOMOGENITIES

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Abstract

For the design of bed stabilization measures physical models are still an indispensable tool. A straight flume model with vertical walls (mostly a tilting flume) is usually used for almost straight river reaches to keep the costs low. As part of one specific project it was established, that a simplified model in a straight flume resulted in higher bed stability then the real one in a full scale model. For the river Bregenzerach a so called rip rap was tested in a straight flume. This rip rap consisted of coarse stones which were extracted from an artificial bed incision of a flood protection work. The aim of the rip rap is to prevent bed degradation along the 1.3 % steep passage from the unchanged bed upstream to the incised bed downstream. The same bed stabilization measure was also tested in a full scale model, but it has been less stable. The essential differences between the two models were the transition from the rip rap to the river bed upstream and downstream, short groins for ecological and morphological river design and slightly changing bed widths. All inhomogenities of the river led to higher local stresses. This situation has resulted in an earlier movement of the rip rap. Thereby local channels were formed, which finally led to complete destruction of the bed stabilization. In conclusion at least the final implementation proposal for a bed stabilization measure should be tested in a full scale model. For an engineer it is important to be careful in using design equations developed in a straight flume if the real situation is different.

Introduction

Primary aim of the project was to find an economical and ecological method to stabilize an about 400 m long reach of the river Bregenzerach in Mellau (Vorarlberg/Austria). This section has a bed slope of 1.3 %. Upstream and downstream of the rip rap area the river has a mean slope of 1 %. The steeper section of the river should connect the upstream unchanged part with the deepened downstream part without any ramp or sill in an ecological and near-to-nature way. A sketch of the length profile is given in figure 1. Deepening of the river bed was carried out to improve the flood protection for the municipality of Mellau. The results presented here are a side outcome of this study.

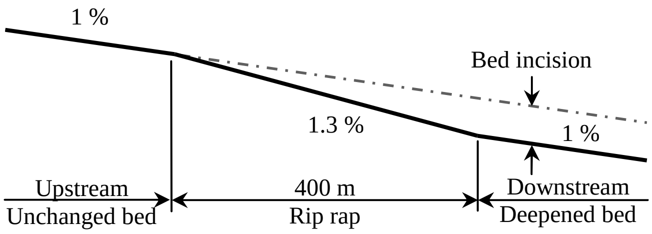

Figure 1: Schematic length profile of the investigated river reach

To find a solution in an efficient way two models were used. At first in a straight flume model the general behavior of the intended bed stabilization was investigated. Second a full scale model was used to look at special problems, e.g. the side input of large amounts of bed load from a torrent as a result of heavy rainfalls. Both models are scaled by 1:40 and the Froude's model law (e.g. Bogardy, 1959) was used. To give the reader the opportunity to compare the results of our experiments with similar problems all values are given in real dimensions mostly. If not it is especially indicated.

Table 1: Hydrology

Return Period	Nature Discharge (m^3/s)	Full Scale Model Discharge (l/s)
MQ	11	1.1
HQ2	110	10.9
HQ5	150	14.8
HQ10	230	22.7
HQ30	320	31.6
HQ100	390	38.5
HQ300	450	44.5

Table 1 shows some statistical discharge values of the river reach concerned. The discharges in the 3rd column were only used for the full scale model. Discharges for the straight flume model, which is just a section model with vertical walls, were derived using the method of equivalent shear stresses. Details of this method are given in the chapter “Straight Flume Model”.

Bed Material

Grain size distributions and mean values of the grain sizes used in the experiments are summarized in figure 2 and table 2. The mean grain diameter d_m and the d_{50} of the rip rap are about 3 times higher than the mean diameter of the original bed material. The mean diameter d_m was calculated according to Meyer-Peter & Mueller, 1948. The d_{30} of the rip rap is about 4 times higher and the d_{90} about 2.6 times higher.

The rip rap material should be extracted from deepening the river bed in the downstream river reach by sieving and separating the coarsest fractions of the original bed material.

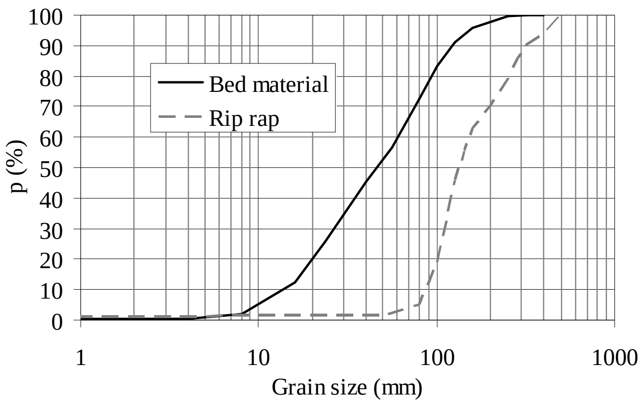

Figure 2: Grain size distributions (original bed material of the river and rip rap)

Table 2: Grain sizes (mean values)

	Bed load	Rip rap
d_{30} (mm)	27	111
d_{50} (mm)	46	135
d_m (mm)	61	180
d_{90} (mm)	122	330

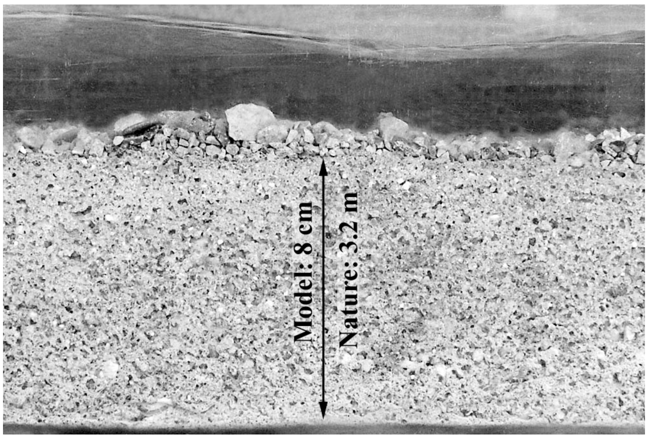

Figure 3: Bed material and rip rap in the flume (side view, flow direction from left to right)

From the rip rap material 689 kg/m² were used in the experiments. This is equal to an on the average 45 cm thick layer (density of rip rap material was 1523 kg/m³ including porosity). In the experiment a 3.2 m layer of the same mixture as the bed load below the rip rap represented the subsurface of the river bed. Figure 3 shows the side view of the flume model with both layers. In the full scale model the top layer has the same thickness (689 kg/m²).

Figure 4 gives an impression of the rip rap just before the experiment in the flume model started. This figure will be used later to compare different steps of the flume experiment and the full scale model.

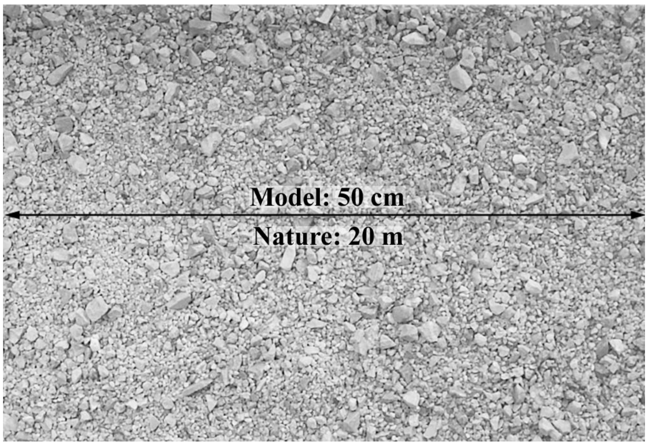

Figure 4: Rip rap in the flume prior to experiment (top view)

Straight Flume Model

For the straight flume model a tilting flume 18 m in length and 0.54 m in width with vertical smooth plexi glass walls was used. This width is sufficient for section models with a water depth up to about 10 cm and it represented 52 % (21.6 m) of the natural mean bed width (41.9 m). The length of the rip rap in the model was 10 m which is equivalent to 400 m in nature.

Because the flume model represented simply a section of the whole river it was not possible to use the same discharges (given in table 1) as in the full scale model. Instead of that the method of equivalent shear stresses was used. First the experiment was started with low discharges were no movement of the rip rap was to expect. From water and bed level measurements water depth were calculated and the roughness of the rip rap derived. To separate the roughness of the river bed from the roughness of the smooth walls a method, described in Gessler, 1990 was used. With this method it is possible to get the shear stress acting on the rip rap solely for every discharge in the flume. An equivalent sand roughness of about 400 mm was obtained, which is about 25 % higher than the d_{90} and about three times higher than the d_{50} (see table 2) of the rip rap. Thus the roughness of the rip rap is dominated by the largest grains. The 25 % higher sand roughness than the d_{90}

can be explained by the edged grains which were used instead of rounded material.

In a 2nd step the relation discharge – shear stress for a mean cross-section of the rip rap area with natural roughness at the banks was calculated (figure 5).

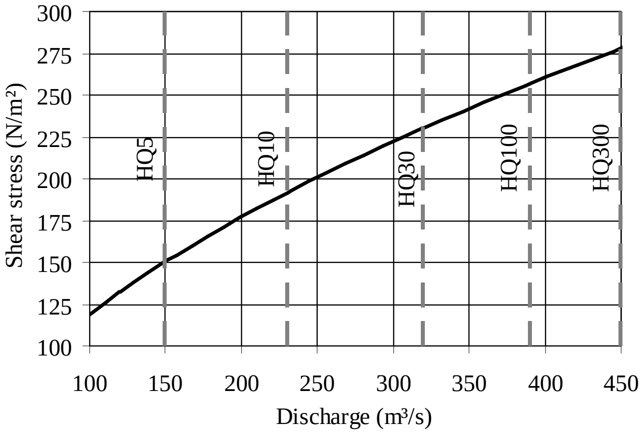

Figure 5: Relation discharge – shear stress for a mean cross section of the rip rap area

Now this relationship could be compared with the shear stresses obtained from the flume. With this it was possible to choose the appropriate discharge in the flume for any required shear stress to simulate natural floods. During the experiment the discharge was increased step by step and the behavior of the rip rap observed. Each discharge in the model was held constant for 120 min at least which is equal to 12.6 hours in nature. Additionally to visual observations water levels were measured for each discharge and bed levels after each discharge.

Bed stability results

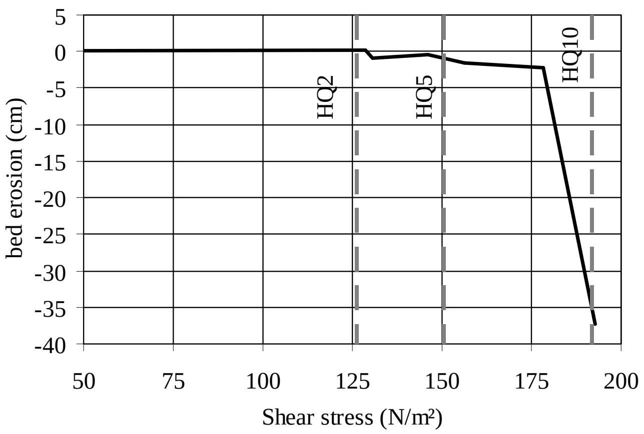

Figure 6: Mean bed erosion with increasing shear stress for a 100 m long section of the rip rap

At a shear stress of 156 N/m² which is equal to a 5-year flood only minor bed erosion (less than 1 cm) were measured. Several stones of the rip rap changed their position but no overall bed load transport could be observed. At shear stresses higher than HQ5 the bed erosion increased slightly.

Figure 6 shows the mean bed erosion for a 100 m long section of the flume. This section was located 100 m downstream of the beginning of the rip rap. At the step from 178 N/m² to 193 N/m² (+8.4 %) large areas of the rip rap began to move and fast erosion of the river bed occurred. This change of the river bed is visualized in figure 7. The upper areas of the pictures in figure 7 are close to the left smooth wall of the flume. Near the wall the rip rap was more stable than in the rest of the flume.

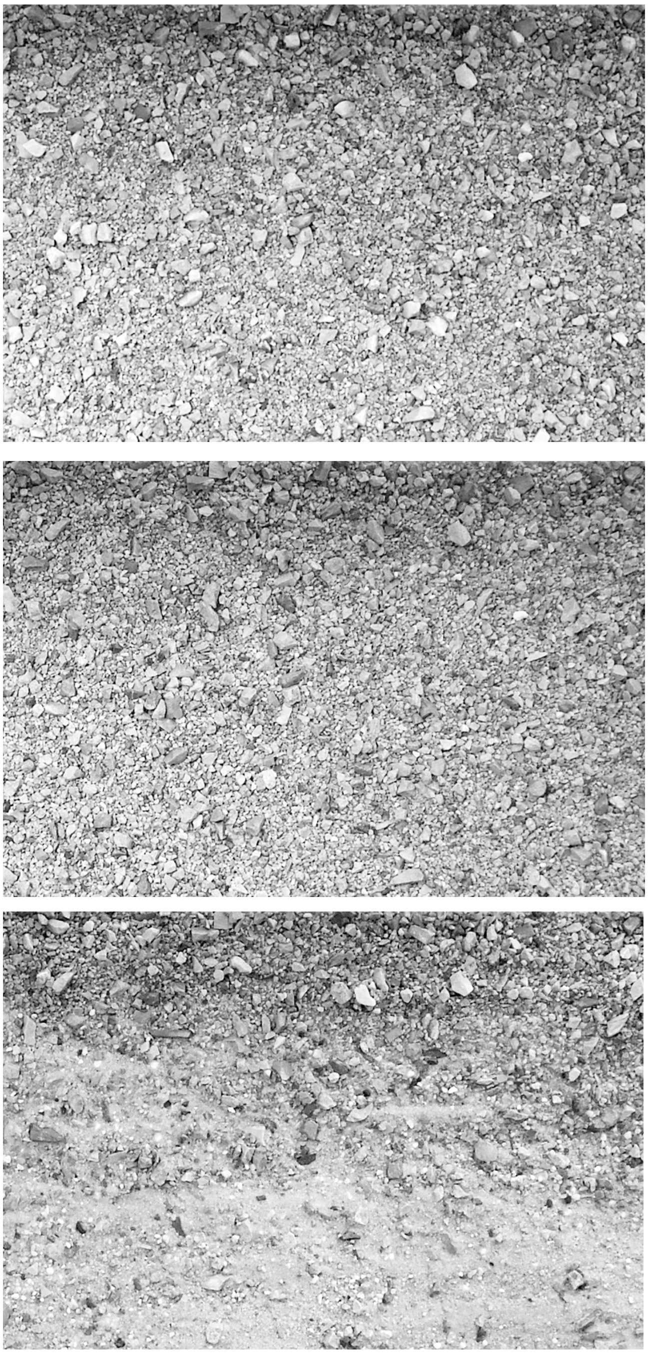

Figure 7: Rip rap in the flume (same 20 m long area as in figure 4) after shear stresses of 156 N/m² (top), 178 N/m² (middle) and 193 N/m² (bottom), flow direction from left to right

The mobility of particles can be characterized by the Shields value $\theta = R_b \cdot J/((s-1) \cdot d)$. R_b is the hydraulic radius of the bed, J the energy slope, s the relative density of bed material to water and d a characteristically grain diameter. For bed load transport usually a critical Shields value θ_{cr} = 0.047 (Meyer-Peter & Mueller, 1948) is used. Movement of single grains can be observed much earlier, starting at θ = 0.01 (Novak & Nalluri, 1984). The ratio of θ/θ_{cr} is shown in figure 8. Erosion of the river bed was observed not until the θ_{cr} of the d_m of the rip rap was exceeded. An armoring process which was characterized by relocation of grains and partial bed load transport stabilized the river bed. The river bed was quite stable till θ/θ_{cr} = 0.7 for the d_{90} and 1.3 for the d_m. A remarkable erosion started at the next investigated discharge, the HQ10 (θ/θ_{cr} = 0.77 for the d_{90} and 1.4 for the d_m). The fast erosion process during this discharge can be explained by the large θ/θ_{cr} (= 4) for the d_m of the sub layer which was exposed to the surface after displacement of the rip rap. Additionally the experiment was carried out without feeding bed load to the river.

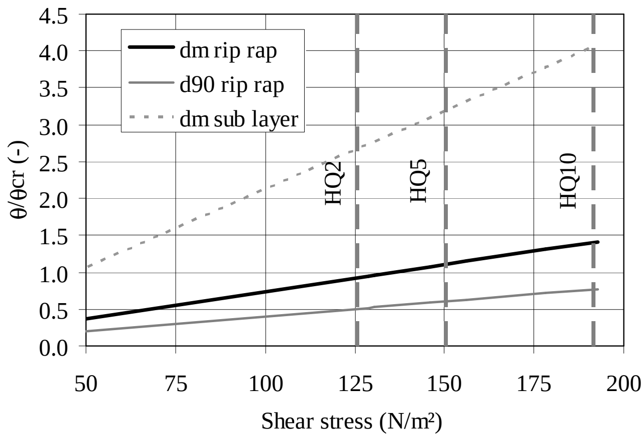

Figure 8: Ratio θ/θ_{cr} with increasing shear stress

At this moment it was clear that the rip rap with the chosen material is stable only up to floods with a return period less than 10. Until a discharge of about 200 m³/s, which is equal to a shear stress of about 178 N/m², the bed erosion can be neglected (figure 6). At higher loads the bed will erode. The deepening of the river bed depends not only on the load but also on the amount of bed load from upstream. In any case it will be necessary to repair the river bed afterwards.

Full Scale Model

The full scale model represented a 900 m long section of the river including banks, groins of different sizes and two small torrents flowing in from the left. The rip rap itself was 400 m long. Upstream and downstream of the rip rap 200 m respectively 300 m long sections of the river were modeled. In the rip rap section the bed width changed slightly (min/max = 0.8). It ranged from 37.2 m to 47.2 m with a mean width of 41.9 m. Figure 9 shows the part of the model with the rip rap area (from cross section width 47.2 m to the last groin on the right) and the inhomogenities (inflows and groins). The size of the groins ranged from about 1 m to 4 m in height and 5 m to 10 m in length. In figure 10 the flow at a small flood downstream of a groin can be seen.

For the rip rap, the sub layer and bed load the same material as in the flume model (described in the chapter "Bed Material") was used.

Figure 10: Flow at 44 m³/s in the area of the second groin from left in figure 9

The experiment was carried out similar to that in the flume model. The discharge was raised step by step and water levels as well as bed levels were measured at each step. The duration of each discharge step was the same as in the flume. Bed load was fed at the upstream end of the model by a conveyer belt for all discharges $\geq$ 90 m³/s. Both inflows, shown in figure 9, were dry during the experiment.

Bed stability results

Until a discharge of 90 m³/s only minor erosion at the

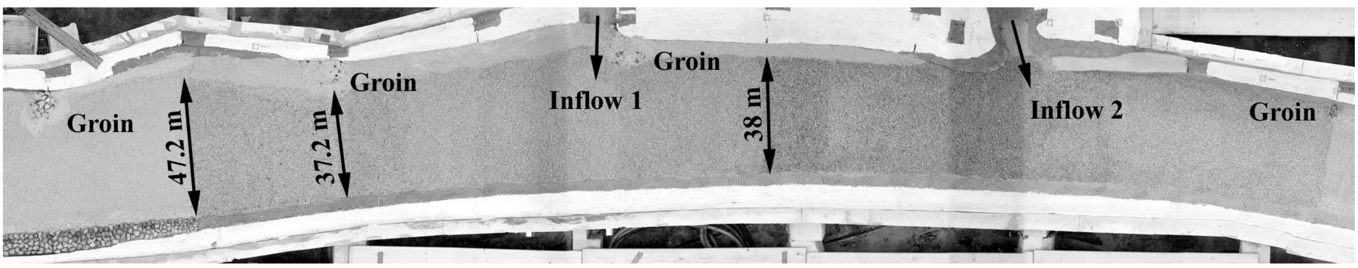

Figure 9: Model area with rip rap and inhomogenities (flow direction from left to right)

groins were observed. The overall stability was as good as expected from the flume experiment. But during the next step (110 m³/s – HQ2) the process changed. The rip rap was much less stable than in the flume and the bed began to erode (compare figure 6 and figure 11). Trenches were formed in the bed. One of these trenches can be seen in figure 12. The cross section in figure 12 is just downstream of the inflow 1. This trench was situated at the right bank and started at the upstream origin of the rip rap. It had a length of about 200 m. Further downstream this trench faded and a new trench developed near the left bank. After rising the discharge to the next step (150 m³/s – HQ5) the discharge concentrated on these trenches. Starting from these small trenches a widening process was observed which led to a wider but less deep channel (figure 12).

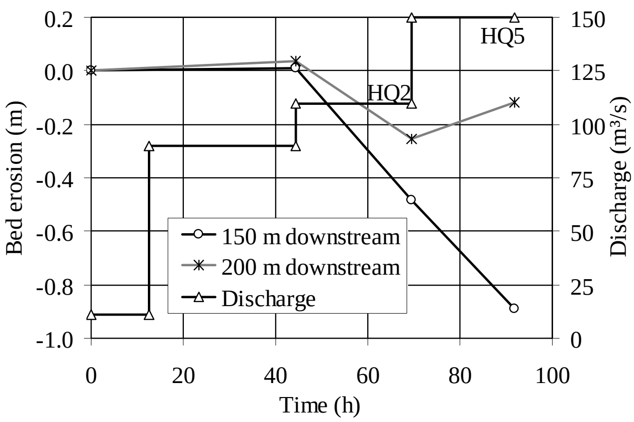

Figure 11: Mean bed erosion in 2 cross sections (150 and 200 m downstream of the origin of the rip rap)

Due to the large amount of bed load input from erosion in the upstream area of the rip rap the bed didn't erode but even raised in some cross sections downstream (see the 200 m downstream cross section in figure 11).

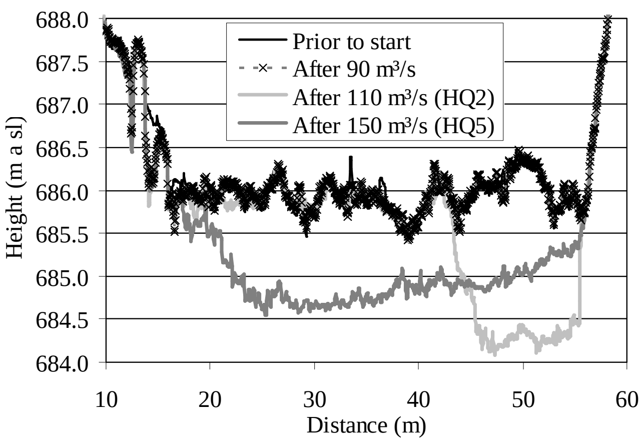

Figure 12: Erosion in cross section 150 m downstream of the origin of the rip rap

In figure 13 an about 100 m long section of the rip rap area which corresponds to the cross sections in figure 11 and 12 is shown at 3 stages. First stage is the situation after 90 m³/s. The river bed has not yet eroded. In the left half of the river, near the inflow bed load from upstream is visible. In the 2nd stage after 110 m³/s more bed load from upstream was transported over large parts of the rip rap without significant erosion on it. Near the right bank a trench was eroded (see also figure 12) and the boulders of the footing of the bank protection work are visible. In the 3rd stage after 150 m³/s the river bed is a mixture of gravel from the sub layer and eroded rip rap material from upstream. The trench at the right bank is filled up partly (see also figure 12) and the footing of the bank protection work is covered with bed load from upstream again.

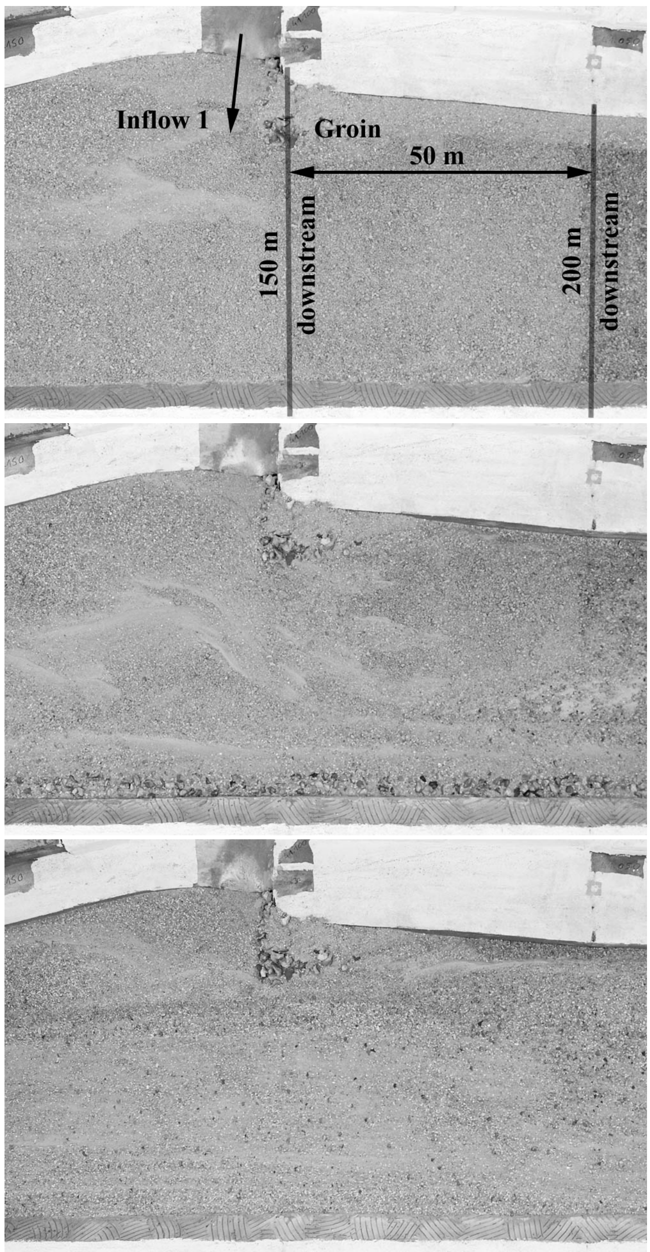

Figure 13: Rip rap after a discharge of 90 m³/s (top), 110 m³/s (middle) and 150 m³/s (bottom), flow direction from left to right

Conclusions

Both experiments, the straight flume model with vertical walls and the full scale model, show different results, despite the fact that the same scale and the same bed material were used. The essential differences between the two models were the transition from the rip rap to the river bed downstream, a slight change of bed widths and short groins for ecological improvement. In the full scale model the rip rap eroded much earlier then in the flume. In the flume the bed was quite stable till 200 m³/s discharge and was complete destructed at 230 m³/s (HQ10). In contrast in the full scale model the rip rap was only quite stable till 90 m³/s. At 110 m³/s (HQ2) large parts of the bed were eroded and at 150 m³/s (HQ5) completely destructed. Destructed means that the rip rap was no longer able to fulfill its main task to stabilize the upstream river reach of the Bregenzerach.

Expressed in terms of mean bed shear stresses the rip rap of the river bed was quite stable (grain sizes $d_m = 180$ mm, $d_{90} = 330$ mm) with only minor erosion till 178 N/m² in the flume and just 112 N/m² in the full model (63 % or less than 2/3). Nearly the entire river bed was destructed at 193 N/m² in the straight flume and 150 N/m² in the full model (78 % or about 3/4). The non-dimensional Shields values, calculated with $\theta_{cr} = 0.047$ and $d_m = 180$ mm are summarized in table 3.

Table 3: Non-dimensional Shields values θ/θ_{cr} (with $\theta_{cr} = 0.047$ and $d_m = 180$ mm)

Mean shear stress (N/m²)	θ/θ_{cr}	behavior of the rip rap
112	0.8	full model: quite stable
150	1.1	full model: destructed
178	1.3	flume: quite stable
193	1.4	flume: destructed

First the rip rap was not only eroded near the groins at the left bank as expected but also on the other side near the right bank. A trench was formed and endangered the bank protection work on the right side. The only explanation for this process is that all the inhomogenities of the river led to an increased turbulence which was transported over the whole river bed. This process resulted in a higher shear stress and as a consequence earlier movement of the riprap in some parts of the bed. Thereby local channels were formed. Finally this channeling process destructed the bed stabilization completely. Similar results were found during experiments for the so called granulometric bed improvement for the river Danube east of Vienna at a slope of only 0.04 % and much lower shear stresses (Hengl et al, 2011). A second attempt to explain the observations is that the river bed is narrowed by the groins not only by their length but a little bit more. This will lead to a higher load on the reduced bed width. But in this case the highest load must occur at the narrowing downstream of the groins and the erosion has to start in this areas and not near the other bank of the river as was observed here. To analyze this process more in detail additional experiments are necessary were the turbulence is measured first without and second with inhomogenities.

To define the necessary size of bed stabilization measures physical models are still an indispensable tool. The final implementation proposal for a bed stabilization measure should be tested in a full scale model if homogeneities are present. At least and if possible inhomogenities should be included also in straight flume models. For an engineer it is important to be careful in using design equations developed in a straight flume without homogeneities if the real situation is different.

Acknowledgment

As mentioned above the results presented here are a side outcome of a larger experimental study. Both models were financed by the Austrian Federal Water Management Authority at the province Vorarlberg.

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