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PHYSICAL EXPERIMENTS TO DETERMINE THE STABILITY OF STEP-POOL SYSTEMS IN MOUNTAIN TORRENTS

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ABSTRACT

Laboratory experiments have been conducted to test the stability of self-formed step-pool systems if the initial condition is natural bed material fully-mixed with much larger blocks. Four different measurement series were tested, with various block sizes, block fractions within the bed material and bed slopes. Each series consisted of six different runs starting with constant discharges representing smaller flood events, followed by extreme floods involving particular flow and sediment hydrographs. The resulting longitudinal bed profiles indicate that an optimal block diameter can lead to a stable bed for slopes up to 0.08. For extreme flood events (HQ_{300}) the bed degrades gradually. With slopes up to 0.15 the channel bed degrades beyond acceptable conditions already during HQ_{100}. A comparison with existing approaches to determine the bed stability reveals that the formulas do not lead to satisfactory results for small channel width-to-block diameter ratios.

Keywords: Flood protection, laboratory experiment, sediment transport, step-pool system

1. INTRODUCTION

The village Betelried in the Bernese Alps, Switzerland, has a flood safety problem. The village is located on the alluvial fan of the mountain torrent Betelriedgraben. Flood events with a return period of 30 years (HQ_{30}) lead to an overtopping of the channel banks and the neighboring houses and infrastructure are affected by flooding and overbank sedimentation. To reduce the potential risk mitigation measures are planned. Channel bed stabilization in the upper reaches and a new sediment trap located on the fan apex should reduce the sediment amount reaching the village. To reduce the flood risk it is additionally planned to relocate the channel bed on the alluvial fan to an area with less dense housing.

Hard engineering structures to stabilize the new channel sections are unfavorable from an economical and landscape conservation point of view. To achieve sufficient bed stability the channel bed should be stabilized by adding large blocks leading to either self-formed or man-made step-pool systems. The present study focuses on the evolution, stability and feasibility of self-formed step-pool systems with regard to their application in river training techniques. An overview of the research progress in the field of steep open channels is given in Church and Zimmermann (2007). For the application of self-formed step-pool structures the following questions emerge. Under what circumstances do step-pool sequences form? What determines their geometry, and how can their stability be assessed?

Numerous studies indicate that the step height is controlled by the grain size of the step forming blocks (Judd 1963, McDonald and Day 1978, Whittaker and Jaeggi 1982, Allen 1983, Wohl *et al.* 1997, Lee 1998, Chin 1999, Chartrand and Whiting 2000). In the ongoing debate on the controls on step length two general concepts have emerged. The first group of concepts supposes that step-pool geometry is controlled by the flow field. The most prominent theory of step formation was proposed by Whittaker and Jaeggi (1982), who suggest that the step formation is initiated by large blocks that are deposited under the crest of an antidune. Theories proposing that the step geometry is governed by standing waves (e.g. Allen 1983, McDonald and Day 1978, Judd 1963) i.e. the flow field, should lead to regular step-pool spacing. The second group suggests that the step location is determined by the location of key stones that initiate the formation of steps (Zimmermann and Church 2001). Zimmermann (2009) showed that the ratio W/d_{84} of channel width W to a characteristic grain size d_{84} largely impacts the formation and stability of step-pool sequences.

Abrahams *et al.* (1995) introduced the concept of maximum flow resistance. Based on flume experiments with regularly-spaced check dams they supposed that the step-pool geometry adjusts itself to provide the maximum flow resistance. According to their theory the steepness factor $c = \frac{H/L}{S}$, where H is step height, L step spacing and S channel slope, lies within the range 1 < c < 2. These results were confirmed by field measurements (e.g. Lenzi 2001, Comiti 2003).

Bed roughness and stability in steep open channels has to be assessed on different scales. The following scales apply:

- Reach-scale (10^2-10^3 W): Its development is influenced by pivot points. Rotational erosion is the primary stabilization mechanism so that stability is described via the channel slope.

- Macro-scale (~10^1 W): It is characterized by successions of steep and gently inclined sections – riffles and pools. In wider channels these vertical oscillations are typically associated with horizontal oscillations i.e. different bed-forms (Leopold and Wolman 1957).
- Meso-scale (~10^0 W): In steep open channels this scale is typically associated with large roughness elements organized into step-pool sequences.
- Micro-scale (10^{-1}-10^{-2} W): This scale refers to the grain size distribution and its roughness is typically defined by a characteristic grain diameter.

Steep open channels exhibit a large relative roughness d/h, where d is a characteristic roughness length and h the flow depth, as the roughness elements are of the same order of magnitude as the flow depth even for high discharges. The general concept to use bed-shear stress to determine flow resistance was developed for uniform flow on gentle slopes. The standard Manning, Chézy or Darcy-Weisbach friction laws relating flow velocity v to hydraulic radius R_h, channel slope S and a friction factor do not fully apply for steep open channels with large relative roughness d/h. Attempts were made to adjust traditional approaches to steep channels with rough beds (Bathurst 1978, Lee and Ferguson 2002, Smart *et al.* 2002, Wilcox and Wohl 2006). The approach of Rickenmann (1990) suggests a dimensionless hydraulic geometry

$$\frac{v}{\sqrt{gl}} = c\left[\left(\frac{q}{\sqrt{gl^3}}\right)^{\alpha} S^{\beta}\right] \qquad (1)$$

Here, q = specific discharge, g = gravity acceleration, l = roughness length, and S = bed slope. This approach differs from traditional resistance laws as slope and discharge (depth) have different exponents α, β, and there is no assumption on the velocity profile or uniform flow. The challenge remains to define an appropriate roughness length for beds with roughness elements of the order of the flow depth. In gravel-bed rivers the roughness length is related to a characteristic grain size, whereas this is more difficult for boulder-bed dominated torrents. Aberle (2000) (see also Aberle and Smart 2003) proposes to use the standard deviation of the roughness heights s as a roughness measure in steep open channels with rough beds. The standard deviation s is obtained by analyzing the detrended longitudinal bed profile (see section 3.2). The flow field and the bed roughness are closely interrelated with bed stability. Aberle (2000) determined from flume experiments with ratios 3.1 < W/d_{max} < 6.2 and bed slopes ranging from 0.089 to 0.14

$$q_c = 0.2(gs^3)^{0.5}(\sin\alpha)^{-1.3} \qquad (2)$$

Here q_c = critical discharge for sediment entrainment and α = channel bed angle. Weichert (2006) found a good agreement of his data and Eq. (2). His experiments covered a wide range of 3.3 < W/d_{max} < 13.2 and initial bed slopes in the range of 0.0 – 0.13. Based on Eq. (2) Weichert (2006) developed a design procedure to assess the use of widely-graded boulder mixtures to stabilize steep channels. The concept is to apply a slope larger than the projected final slope and leaving the bed stabilize itself via rotational erosion and the formation of macro- and meso-scale structures. With this approach the engineering company Flussbau AG SAH designed bed stabilization measures for the Betelriedgraben which were then tested at the Laboratory of Hydraulics, Hydrology and Glaciology of ETH Zurich. In the following sections the experimental procedure and selected result will be presented along with a comparison to existing stability approaches for steep open channels. The findings are summarized in the conclusions.

2. EXPERIMENTAL SETUP

To investigate the evolution and stability of step-pool systems, a 1:20 Froude-scaled model of the Betelried torrent was built. Smooth vertical walls were used to represent the banks. Smooth walls increase the hydraulic stress on the channel bed and decrease the possibility to divert forces acting on a grain into the walls i.e. jamming of grains. Zimmermann (2009) observed that much more stable step-pool systems form in experiments with rough walls compared to smooth walls. However for the practical application a slight underestimation of the bed stability creates a safety margin.

2.1 Flume

The experiments were conducted in a 13.5 m long, 0.6 m wide and 0.6 m high tilting laboratory flume (Fig. 1). Its side-walls were made out of glass and PVC. Wooden casing-boards were used to adjust the flume width between 0.25 m and 0.35 m. Their effect on the flow resistance is negligible due to the high bed roughness and the high ratios of flume width W to flow depth h, so that $R_h \cong h$. Initial bed slopes of 0.08 and 0.15 were tested. As the maximum flume slope was limited to 0.1 the bed material was installed in a wedge-shape, reducing the usable flume length to 5 m for the experiments with 0.15 initial slope. For the practical application of the investigated bed stabilization measures no change in bed slope with hydraulic load was attempted. Therefore the sharp-crested weir at the flume end was adjusted in height to allow for parallel erosion rather than rotational adaptation of the bed around a fixed point.

2.2 Sediment

The sediment used consisted of the base material of the alluvial fan of Betelriedgraben to which coarse cobbles and blocks were added. Two boulder fractions with different maximal grain size diameter d_{max} were used, whereof the largest grain sizes represent boulders of approximately 5 tons. The base material and the boulder fractions were mixed to approximate the coarse fraction of the widely-graded grain size distribution proposed by Weichert (2006) (Table 1). The resulting coarse mixture 1 and fine mixture 2 are shown in Fig. 2. Due to the given fine components of the base material the uniformity $\sigma = (d_{84}/d_{16})^{0.5}$ of mixtures 1 and 2 were about twice as high as for the mixtures of Weichert (2006). The boulders were reproduced with fractured material, while the base material was formed with rounded pebbles. This setup represents circumstances usually found in river training practice.

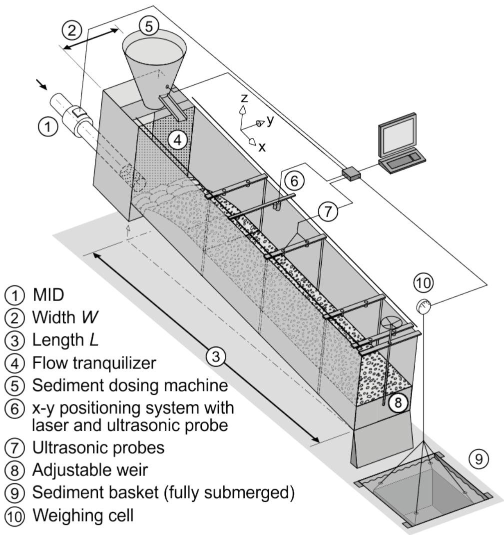

Figure 1. Schematic representation of model flume

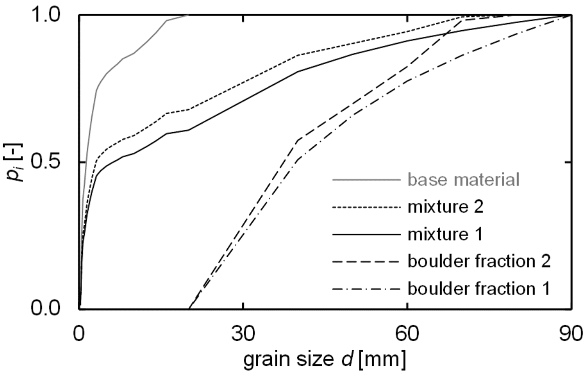

Figure 2. Grain size distribution of mixtures used

Table 1. Grain size characteristics of used model sediment

	d_{16} [mm]	d_{50} [mm]	d_{84} [mm]	d_m [mm]	σ [-]
base material	0.41	1.4	7.4	3.4	4.25
mixture 1	0.53	6.2	45.5	20.9	9.26
mixture 2	0.49	3.0	37.5	16.7	8.73
boulder fraction 1	26.3	39.7	67.4	45.0	1.60
boulder fraction 2	25.6	37.4	61.0	41.4	1.54

2.3 Measurement techniques

The discharge was measured with an electromagnetic flow meter of ±0.1 l/s accuracy. To measure the bed morphology before and after each experiment a laser displacement sensor was used. It was mounted on an *x*-*y* positioning system, with *x* in flow direction and *y* perpendicular to it. This setup allowed for bed scans of 0.02 m × 0.02 m, corresponding to a raster width of 0.22 d_{max} for mixture 1. From the laser scans the longitudinal profiles and the roughness heights were determined. Ultrasonic probes installed at eight fixed locations along the flume were used to measure the water level. To obtain longitudinal water surface profiles, one probe was mounted on the *x*-*y* positioning system. For the hydrograph tests (HQ_{100} and HQ_{300}) sediment was added to the flume using a gravimetric sediment dosing machine. At the flume end a sediment basket collected the outflow. The sediment basket was fully-submerged and continuously weighted by three s-beam load cells. From these measurements resulted the sediment balance and sediment hydrographs.

2.4 Experimental program

Figure 3 illustrates the experimental procedure. Each test series consisted of up to six runs. The first four runs were done with steady flows and no sediment supply. Between each run the bed was scanned with a laser probe (see 2.3). The discharge was held constant until the sediment transported out of the flume was close to zero and visual observation confirmed stable bed conditions. Run durations were typically between 40 – 60 min with the largest bed level changes in the first 15 min. For the last two runs of each series (HQ_{100} and HQ_{300}) the discharge and sediment hydrographs were applied. The input scenarios for the Betelriedgraben torrent were developed by the Flussbau AG SAH and then transformed to model scale. The resulting discharges and sediments feeds are given in Table 2. Table 3 provides an overview of the investigated parameter combinations for the four test series here presented.

Table 2. Scaled discharge and sediment inputs for model test. HQ5 to HQ30 are constant discharges, for hydrographs HQ100 and HQ300 the maximum discharge and sediment feed rate are given

Scenario	HQ_5	HQ_{10}	HQ_{20}	HQ_{30}	HQ_{100}	HQ_{300}
Discharge Q [l/s]	4.5	6.1	7.8	9.5	12.9	16.8
Sediment input [g/s]	-	-	-	-	830	1030

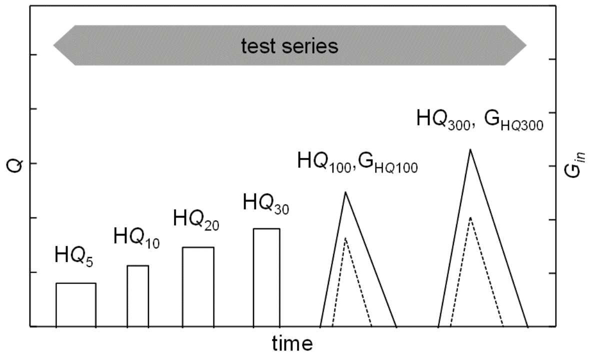

Figure 3. Illustration of experimental procedure. One test series consists out of six separate runs. Between each run the channel bed was scanned with laser probe. Note Q = water discharge and G_{in} = sediment input rate

Table 3. Investigated parameter combinations. A1w uses same parameters as series A1

Test series	Initial slope S [-]	d_m [mm]	d_{max} [mm]	Width W [m]	W/d_{84} [-]	Discharge Q [l/s]
A1	0.08	45.5	90	0.25	5.5	4.5 - 16.8
A1w	0.08	45.5	90	0.25	5.5	4.5 - 12.9
A2	0.08	37.5	80	0.25	6.7	4.5 - 16.8
C1	0.15	45.5	90	0.25	5.5	4.5 - 12.9
C2	0.15	45.5	90	0.35	7.7	4.5 - 12.9

3. DATA ANALYSIS AND RESULTS

3.1 Development of different bed features

From the laser scans longitudinal profiles with a lateral spacing of 0.02 m ($\approx d_{m,mixture1}$) were obtained, resulting in 12 to 17 longitudinal profiles, depending on W. For further analysis these profiles were averaged to obtain a mean longitudinal profile. The evolution of the mean profile is shown in Fig. 5 for the test series A1 and A2. Starting with an initially plane bed, grain fractions with d < 20 mm are washed out and the formation of an armor layer is observed for q = 4.5 l/s (Fig. 4). For discharges up to 9.5 l/s (HQ_{30}) further armoring of the bed takes place, but as the largest fractions are not mobile the average bed level remains unaffected. During the HQ_{100} hydrograph even the largest grains were transported forming step-pool structures. Most of these were broken up again during the HQ_{300} hydrograph thereby generating new step-pool structures. For the finer mixture 2 the average bed slope was lowered to 0.076 during the HQ_{300} hydrograph regardless of the weir height adjustment at the flume end.

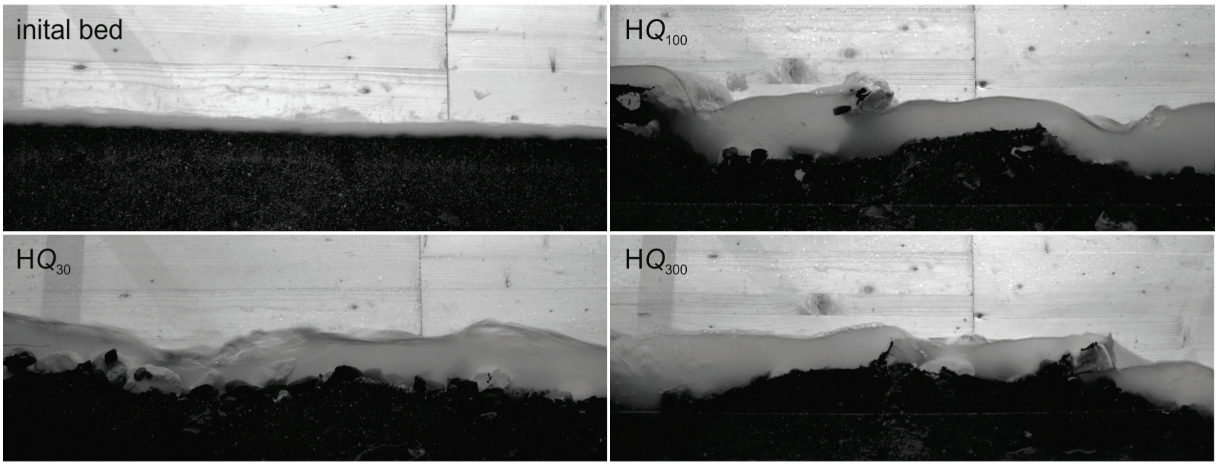

Figure 4. Side view of initial bed, during HQ_{30} event, after HQ_{100} and HQ_{300} peak flows. Flow direction from left to right

For both series C1 and C2 with an initial slope of 0.15 the weir at the flume end could not be lowered sufficiently to inhibit rotational erosion during the HQ_{100} hydrograph. The final slopes were 0.11 for series C1 and 0.10 for C2 (Fig. 6). The evolution of the profiles of test series C2 is characterized by major material loss and a deeper incision of the channel bed as compared with series C1. Due to the higher bed slope the largest grain fractions were already mobilized during the HQ_{30} event. The stream power for a HQ_{30} scenario at S = 0.15 exceeds the stream power of a HQ_{100} scenario at S = 0.08 by almost 40%. This corresponds with the larger channel incision observed during the series C1 and C2. During the HQ_{100} hydrograph the channel bed eroded to the fixed flume bottom, so that no HQ_{300} hydrographs were tested for S = 0.15.

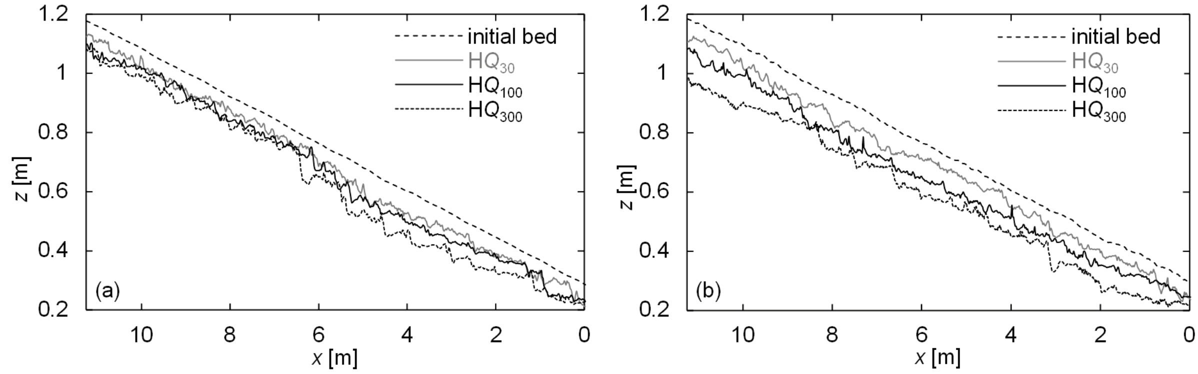

Figure 5. Evolution of longitudinal profile with increasing discharge for test series (a) A1 and (b) A2 with initial bed slope of S = 0.08

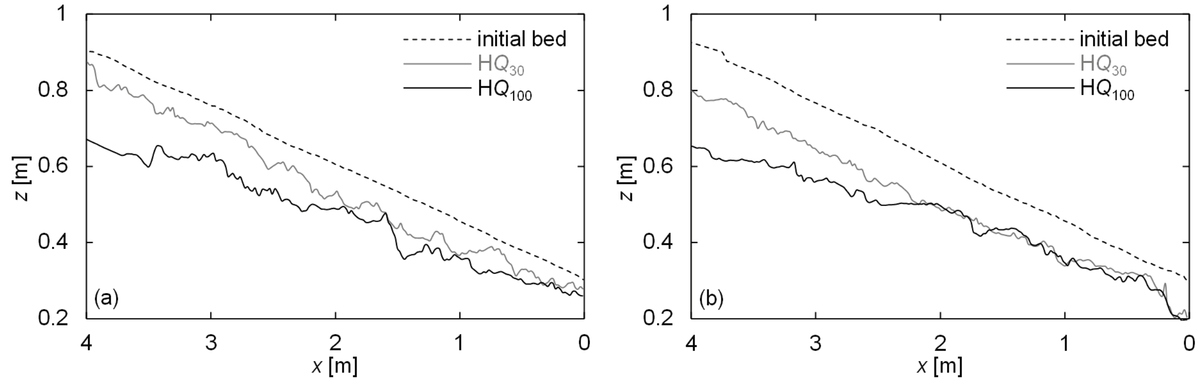

Figure 6. Evolution of longitudinal profile with increasing discharge for test series (a) C1 and (b) C2 with initial bed slope of S = 0.15

After each scenario the average longitudinal profile was examined for step-pool and macro scale riffle-pool structures. Step-pool sequences were identified using the method of Milzow *et al.* (2006) explained in the following. The local slope was determined over a section length of 1 W. From the frequency distribution of the local slopes, 0.2 was determined as threshold for a section to be identified as a step (marked grey in Fig. 8) for the runs with S = 0.08. For the test series with an initial slope of S = 0.15 the threshold was 0.3. This method agrees well with the visual identification. Following Weichert (2006) macro-scale bed features were identified by computing the local slope over a section length of l_s = 4 W. All sections with a minimum length of 0.5 m with a slope higher than the average slope were identified as riffles in contrast to sections with slopes lower than average as pools (Figs. 8 and 9).

Figure 8a shows that steps are primarily found in the steeper riffle section and are irregularly spaced over the flume length. A total of 9 steps were identified from the profile of test series A1. Series A1w with identical parameters showed 11 steps. For the test series A2 with the finer mixture (Fig. 8b) 13 steps were identified in total. The steps in series A2 are more regularly spaced and no step concentrations are observed in the riffle sections. However, the step height is with 1 d_{max} comparably small. Most of the step structures i.e. S > 0.2 consisted of only one to two larger grains. Tightly locked force chains described by Zimmermann (2009), or To *et al.* (2001) are only observed in 4 of the step structures (Fig. 7).

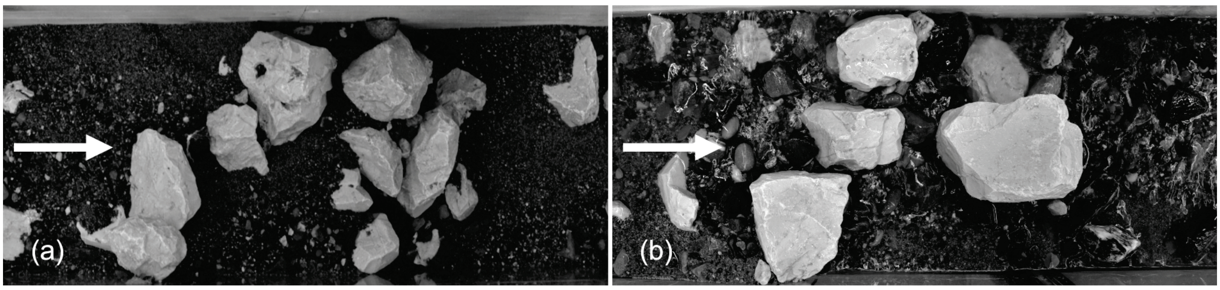

Figure 7. Picture of (a) tightly-interlocked step and (b) loose accumulation of large grains for test series A2 after HQ_{100}.

For the runs with an initial slope of 0.15 a maximum of two macro-scale bed features was observed. Compared to A1 and A2 the undisturbed flume section for test series C1 and C2 is small and thus does not allow for the formation of more macro-scale features. Neglecting the step at the inlet series C1 shows a sequence of 5 regularly spaced step-pool structures (Fig. 9a). The profile of series C2 shows only two steps whereof one applies to grains stuck at the outlet weir as a model effect (Fig. 9b).

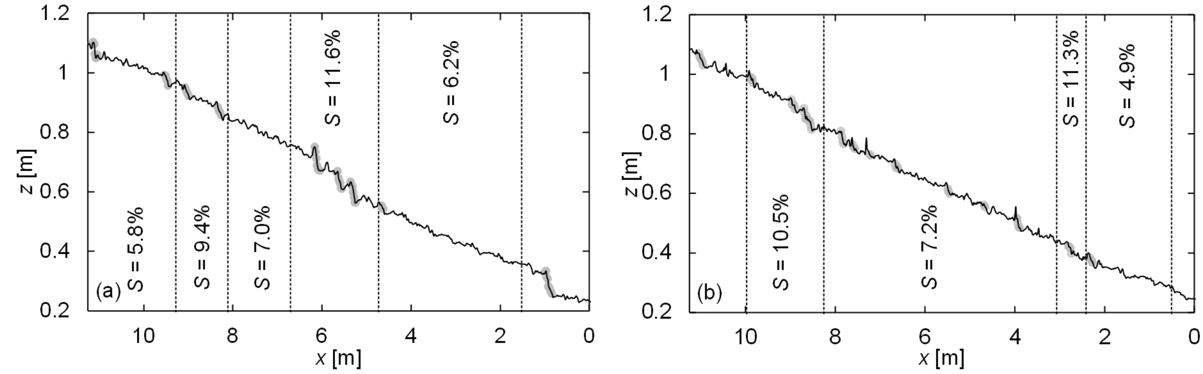

Figure 8. Mean longitudinal profile after HQ_{100} for test series (a) A1 and (b) A2. Step structures in meso-scale in grey. Dashed lines confine sequences of steep (>0.08) and flat (<0.08) slopes i.e. riffle-pool structures in macro scale. Reach-averaged slopes are 0.08 (±0.002)

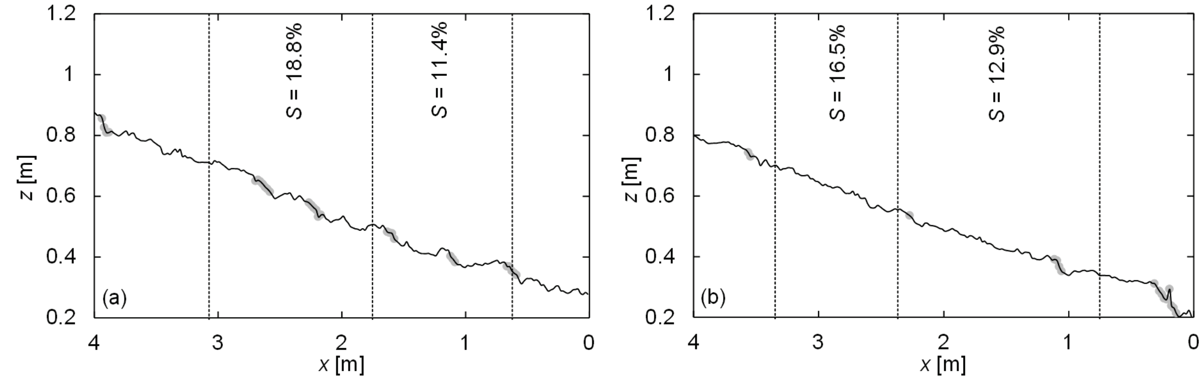

Figure 9. Mean longitudinal profile after HQ_{30} for test series (a) C1 and (b) C2. Step structures in meso-scale in grey. Dashed lines confine sequences of steep (>0.15) and flat (<0.15) slopes i.e. riffle-pool structures in macro scale. Reach-averaged slopes are 0.15 (±0.002)

3.2 Roughness and bed stability

The hydraulic conditions in an open channel are determined by the channel slope and the bed roughness. Thus, the bed stability is directly affected by its roughness. The standard deviation of the roughness heights describes the roughness in steep open channels (Aberle *et al.* 2003). To determine the standard deviation the reach- and macro-scale trends of the longitudinal profile were removed. The reach scale trend i.e. the average bed slope was removed from the profile as illustrated in Fig. 10. Macro scale bed features lead to local trends in the reach scale detrended profile. To obtain the roughness opposed by meso-scale bed features like step-pool sequences, macro-scale trends were also removed. All calculations of the standard deviations were based on the macro-scale detrended profile. As stated by Weichert *et al.* (2009) the length over which the standard deviation is determined affects its value. As Weichert *et al.* (2009) worked in the same flume with a similar setup the standard deviation was likewise calculated over a length of 22 d_{max} (≈2 m for mixture 1). Consequently the standard deviation was taken over a section length of 2 m for each midpoint lying on the longitudinal profile. To obtain the meso-scale roughness the midpoint values were averaged for all profiles.

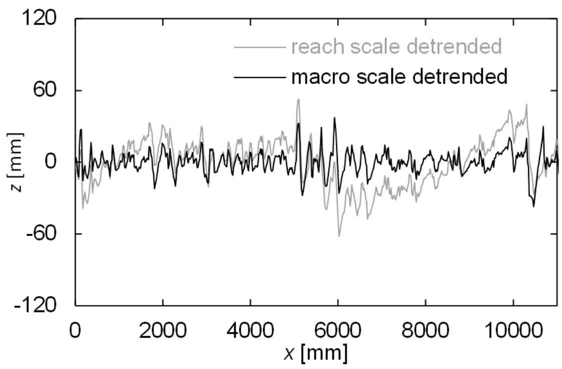

Figure 10. Illustration of data processing: After removal of reach-scale trend profile significant local trends caused by macro-scale bed features are still visible

If a bed experiences a discharge above the critical discharge (condition A in Fig. 11) the channel bed will adapt to the new hydraulic stress. There are two main adaption mechanisms, the channel slope *S* decreases (condition C in Fig. 11), roughness s of the bed increases (condition B in Fig. 11), or a combination of both. In our case by adjusting the weir height no slope degradation was attempted, so that the bed can only restabilize by increasing its roughness. Weichert (2006) showed that both processes contribute equally to restabilization, indicating a major difference to the experiments of Aberle (2000) and Weichert (2006).

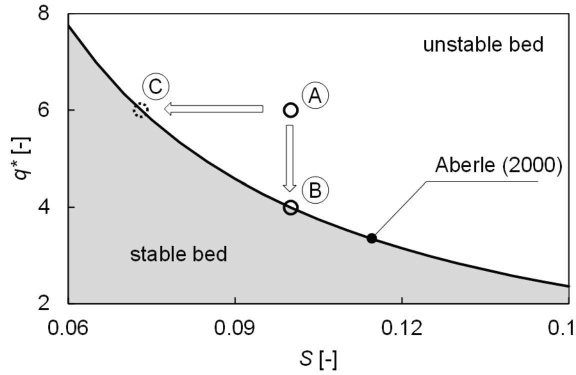

Figure 11. Illustration of different reach-scale stabilization mechanisms (adapted from Weichert 2006)

Figure 12 compares the measured bed forming discharges q_{obs} with the critical discharges from Eq. (2). The values for the experiments with a bed slope of 0.08 (black in Fig. 12) lie within the ±30% range for q_{obs} up to 0.031 m^3/sm. For observed discharges > 0.031 m^3/sm the critical discharge is significantly underestimated. Interestingly, the values for the highest observed discharges are again within ±30%. For the runs with observed discharges above 0.05 m^3/sm sediment input was applied. It was visually observed that the sediment input significantly lowered the bed roughness by filling up scour holes, so that these values cannot directly be compared to Eq. (2) resulting from steady discharge and no sediment input.

Experiments with an initial bed slope of 0.15 (grey in Fig. 12) are slightly above the parameter range S = 0.05 – 0.14 for which Eq. (2) was developed. However, they support the trend that the critical discharge q_{crit} is underestimated by more than 30%. Weichert (2006) reports that he did not observe a decrease in s for discharges $q > q_{crit}$. Interestingly this was observed three times between steady runs from three different test series. Additionally it seems counter intuitive that for the finer mixture sometimes a larger standard deviation of the bed roughness is measured and thus a larger stability is predicted by Eq. (2) than for the coarser mixture with a larger d_{max}.

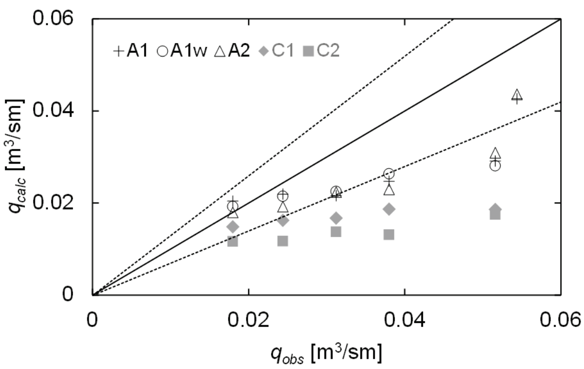

Figure 12. Comparison of measured bed forming discharges and values calculated with Eq. (2). Dotted lines represent ±30% lines

4. DISCUSSION

4.1 Effects of channel width and grain size

The results clearly indicate that the run with the largest W/d_{84} ratio shows the least pronounced step-pool structures and thus the least stable bed. For series C2 the ratio W/d_{84} = 7.7 is above the limit of 6 for which step-pool structures contribute significantly to the bed stability (Zimmermann *et al.* 2010). With W/d_{84} = 6.7 the runs from series A2 are slightly above the limit of 6. Nevertheless step structures are observed (Fig. 8). However the value proposed by Zimmermann *et al.* (2010) applies to steps with tightly interlocked force chains and not loose conglomerates of grains. As described, this is only observed for 4 steps. The trend that smaller W/d_{84} ratios lead to more stable steps is confirmed with the present data. The negative impact of large W/d_{84} ratios appears to have more effect than the positive impact of a smaller specific discharge.

4.2 Assessing bed stability

The concept to use the standard deviation of roughness heights to assess bed stability in steep open channels (Aberle 2000, Weichert 2006) underestimates the stability for the data in Fig. 12. One main difference to previous experiments (Aberle 2000, Weichert 2006) is that rotational erosion around a pivot point was the dominant stabilization mechanism in the reach-scale. However it seems unlikely that meso scale features formed by parallel erosion possess a higher stability than these formed by rotational erosion. A second aspect is that our data were collected at low W/d_{max} ratios (2.8 for series

A1, A1w, C1; 3.3 for series A2 and 3.8 for C2). According to Zimmermann *et al.* (2010) the effect of "jamming" i.e. force chains become more and more important for small relative widths. Therefore it seems that the standard distribution of the roughness heights does not account for the increased stability of the roughness elements especially under small relative widths. The Authors think that the use of the jamming ratio W/d_{84} (Zimmermann 2009) to account for the relative width improves the assessment of bed stability.

Another aspect is that the determination of *s* is sensible to both the sampling interval of the laser probe i.e. the resolution of the longitudinal profile, and the section length used. Differences in the sampling resolution of the longitudinal profile and the standard deviation could lead to systematic errors.

5. CONCLUSIONS

This research deals with self-stabilization processes and the assessment of bed stability in mountain torrents. For the Betelriedgraben investigated it is concluded that for the smaller bed slope of 0.08 the channel bed is stabilized by using sediment mixture 1. Even for extreme floods (HQ_{300}) the bed degrades gradually and the average incision depth of 1.2 m compared with the prestressed bed is acceptable. On the steep slope of S = 0.15 the channel bed degrades beyond what is acceptable in a HQ_{100} event and an increase in channel width is counterproductive for bed stabilization.

The comparison with the existing stability approach reveals that the formulas do not render satisfactory results for small channel width-to-block diameter ratios and conditions where parallel erosion is the dominant reach scale erosion process. It remains unclear why beds with different sediment mixtures and relative widths should have a similar predicted stability (e.g. test series A1 and A2).

For practical applications the use of homogenous mixtures of large grain sizes of up to 1.8 m in nature is not possible. In addition the large material loss caused by the restructuring of steps poses a major problem in reaches with less transport capacity further downstream. The focus of the ongoing research project is to develop a design guideline for nature-oriented man-made step-pool structures. This approach would still use the self-stabilizing mechanisms in mountain torrents but improve its applicability in river training projects.

From a scientific point of view efforts should be made to verify the present findings and expand the concepts discussed for cases with small relative widths, thereby including cases with more realistic boundary conditions i.e. sediment and discharge hydrographs.

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