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BED MORPHOLOGY IN STEEP OPEN CHANNELS

STATE-OF-THE-ART AND FIRST RESULTS OF A FLUME STUDY

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ABSTRACT

The present paper outlines first results of a research project currently performed at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of the Swiss Federal Institute of Technology (ETH) in Zurich. The purpose of the research project is to investigate the bed morphology and the stability in steep open channels hazard assessment. A better knowledge of bed morphology and stability is also required for the design of stable and nature-orientated man-made structures. First results concerning bed morphology show that within the typical step-pool geometry the predominant structures are steps that are orientated transverse to the direction of flow. The formation of ring-structures, clusters and oblique or curved steps depend on flume width, slope and discharge. The rising frequency of transversely orientated steps with increasing slope can be attributed to the adaptation towards a more stable structure. The occurrence of macroscale structures similar to alternate bars can be observed for larger channel widths, however, it is shown that they represent an independent bedform type.

Key words: Bed morphology, Torrents, Step-pool, Flume Experiments

INTRODUCTION

Flood events in mountainous regions caused significant damages in recent years. Consequently, there is a rising demand for the quantification of flood risks in mountain streams and torrents. Mobilised and deposited sediment plays a key role within the physical processes responsible for these damages. In this respect, a better understanding of processes determining the stability in steep channels represents an issue of great importance.

The longitudinal stream profiles of mountain streams and torrents are often characterised by alternating sequences of steeper and flatter slopes, commonly addressed as steps and pools. These distinct bed features are very stable under usual flow conditions. Nevertheless, during high-intensity, low frequency flood events there is a potential for breaking up these structures and the intermediate coarse armour layer (Hayward 1980, Grant et al. 1990). The resistance of the underlying material is significantly smaller, such as the erosion of large amounts of sediment is

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likely to occur during bed forming discharges. Bed erosion is usually accompanied by channel degradation, which in turns influences the mobilisation of sediment stored in the hillslopes. The eroded and transported sediment tends to deposit in the downstream reaches of the torrent where channel gradients generally decrease. The deposited material reduces the effective cross-section and inundations are likely (Johnson and Warburton 2002). As the density of population and infrastructures in the downstream part of a torrent is often high, the potential for damage increases (Bezzola et al. 1994).

In order to prevent riverbed degradation constructive solutions such as check dams, block ramps or weirs are often applied. Although these structures proofed their efficiency for riverbed stabilisation they are often negatively assessed in terms of their ecological impact. As the demand for sustainable and ecological river training nowadays becomes more and more important, intensive research is currently going on (Lenzi 2002, Semadeni 2004). Figure 1 shows an example of a nature-orientated man-made structure built in the River Dala in Switzerland in 2000. Findings concerning bed morphology and stability of natural step-pool-systems would be helpful for the development of design criteria for such types of structures.

Fig. 1: Nature-orientated man-mad structures as bed stabilisation of a steep channel (S=8%) during low flow (left) and high flow (right), River Dala, Switzerland

BED MORPHOLOGY

Mountain streams differ from lowland streams in several important respects. Hydraulics of high-gradient streams is strongly influenced by large boulders with sizes in the same order of magnitude as flow depth. These boulders represent large-scale form roughness causing high energy losses. The longitudinal profile of mountain streams and torrents shows a staircase-like structure divided into reaches of alternately steeper and flatter slopes associated with shallower and deeper flow depths respectively. These changes in flow are a fundamental characteristic of almost all rivers (Leopold et al. 1964), but are especially pronounced in steep boulder-bed channels. Grant et al. (1990) noted that for mountain streams successions of steeper and flatter reaches occur at several different scales. At the smallest scale the channel is composed of individual bed particles (microscale). The accumulation of the largest bed elements result into organized bedforms. In high-gradient channels these bedforms are composed of groups of large boulders forming obstacles approximately transverse to the direction of flow. Successive steps are separated by plunge pools, so bedforms in torrents are often characterised by step-pool sequences (mesoscale). In addition steps and pools may be superposed by macroscale bar structures. Considerations at different scales are important because macroscale structures introduce an additional component of flow-resistance (Hey 1988).

Several researchers outlined classification schemes in order to distinguish between characteristic patterns of mesoscale structures (Grant et al. 1990, Schälchli 1991, Montgomery and Buffington 1997). In most cases these morphologies are categorised in dependence on longitudinal slope because channel gradient data might be estimated reasonably.
Table 1 summarises the slope ranges given in literature for the occurrence of the following bed morphologies: riffle-pools, plane beds, rapids, steps and pools and cascades.

Tab. 1: Slope ranges for bed morphologies

	Riffle-Pool	**Plane bed**	**Rapids**	**Step-Pool**	**Cascade**
Montgomery and Buffington (1997)	<0.015	0.015-0.030	----	0.030-0.065	>0.065
Chartrand and Whiting (2000)	0.001-0.015	0.001-0.035	----	0.015-0.134	>0.050
Schälchli (1991)	----	0.015-0.050	0.015-0.070	0.035-0.125	0.090-0.300
Grant et al. (1990)	0.002-0.015	----	0.015-0.035	0.030-0.075	0.045-0400

The slope classes for the morphologies differ significantly depending on the observer. These differences can be attributed to the nonconsistent definitions of the categories and their limitations. Due to the great variability in torrents a consistent definition of morphology types is hardly possible. Consequently the great overlap of the slope classes is not surprising. Additionally the overlap indicates that other factors in addition to stream gradient such as bed rock, riparian vegetation, large woody debris and debris flows may play an important role in determining channel forms (Montgomery and Buffington 1997). Accordingly, before applying the term "steps and pools", it is necessary to state which kind of definition is taken as a basis.
Nevertheless, according to the different influences of bed morphology classes on flow resistance and stability, the classification of present bed features is an important component for the assessment of stability.

Mesoscale structures

As steps are obstacles orientated in most cases transverse to the direction of flow, they are often compared with transverse ribs described in gravel-bed streams (Koster 1978). Unlike the ribs, steps are formed by the accumulation and interlocking of large boulders around a few key particles (Grant et al. 1990, Zimmermann and Church 2001). In forested regions steps may be formed by large woody debris (Heede 1972) or bedrock outcrops in the channel (Hayward 1980).

Step size, orientation and origin determine the type of the step and are largely dependent on channel gradient, boulder size and channel boundary.

Fig. 2: Step-pool system in nature (Campo-Creek, Switzerland, Schälchli 1991) and in the flume (VAW)

Step-pool geometry can be described by a number of morphometric features. Several researches (e.g. Chartrand and Whiting 2000, Zimmermann and Church 2001) focus on statistical analysis of step-pool geometry in order to find correlations between these features. The examination of geometrical attributes is one way to evaluate potential hypothesis for the morphogenesis of steps and pools. A second possibility is the direct observation of the formation processes within a flume experiment. Although the morphometric studies established correlations between several characteristic features the most apparent result of the studies is the large variability. This can be attributed to the wide range of parameters controlling step-pool-formation (Grant et al. 1990). Furthermore, most of the studies are mainly based on reach-averaged values (Grant et al. 1990, Chartrand and Whiting 2000). However, the analysis of the variations of the morphometric features within one reach indicates the random nature of step-pool geometry (Zimmermann and Church 2001).

In contrast to morphometric features the classification of plan form structures is often neglected although it is an important issue concerning the assessment of the basic physical processes. Furthermore, the knowledge of occurring plan form structures can be used for a proper design of nature-orientated man-made structures.

Several authors describe step-orientation as approximately transverse to the direction of flow (Fig. 2). Zimmermann and Church (2001) noted that steps often form diagonally and are rarely parallel. Grant et al. (1990) observed in two mountain streams in the USA that some steps are orientated obliquely (70° to 80°) to flow or form broad “V´s” pointing upstream. Hayward (1980) found that boulder steps are arranged in a straight or curved line across the channel. According to Brayshaw (1984) coarse alluvial channels reveal two frequently occurring bedforms. For the first, particles are entrapped in the train of a protruding particle, forming a stream-lined tail. For the second, particles are arrested to form an imbricated cluster on the upstream side of the particle. The combination of transversely orientated with stream-lined stone lines directly leads to ring or cell structures observed by Church et al. (1998) and Kozlowski and Ergenzinger (1999).

Macroscale structures

In bed load carrying channels the mesoscale structures can be superposed by macroscale bed forms as bars in curves or bar structures alternately located on both banks. Such bar forms are mainly observed and described for gravel-bed streams where riffle-pool sequences (mesoscale) are superposed by alternate bar structures (macroscale). Riffles and pools are spaced more or less regularly at a repeating distance equal to 5 to 7 channel widths. Leopold et al. (1964) found a similarity in spacing of the riffles in both straight and meandering channels and suggested that the mechanisms which create the tendency for meandering are also present in straight channels. The formation of alternate bars is described and analysed by Jäggi (1984), who obtained his results from flume experiments for slopes ranging up to 1.2 %.
Meandering is mainly attributed to lowland rivers, where Froude-numbers are generally small ($Fr < 0.5$). Flume experiments show that the formation of meanders can also be observed for $Fr > 1$ (Zeller 1967). In order to distinguish between the different meander forms the meanders observed at higher Froude-numbers are called "pseudomeanders". As streams and torrents in mountainous regions are often restricted in width, either by topographical constrictions or canalisation the formation of structures similar to alternate bars is not surprising.

In gravel-bed rivers the bed material tends to be somewhat larger on the riffles or gravel bars than in the pools. This is expressed by the fact that boulders can be observed in the gravel bars whereas the adjoining pools may be quite free of any larger components. In contrast to this in steep channels with pseudomeanders large boulders are observed in all parts independent on bar location. This may indicate that pseudomeandering tendencies in boulder-bed rivers are an independent bed form (Rosport 1997).
Rosport (1997) noted that for these types of structures two different threshold values for the stability should be distinguished: The first threshold value determines the formation of steps and pools and is attributed to normal flood events. Larger discharges, associated with extreme flood-events, are responsible for the formation of macroscale structures and are accompanied by a reconstruction of the whole river bed.

Fig. 3: Dry bed of a canalised mountain stream (S= "several percent", h< 0.5m) after a small flood event. Attention should be paid to the periodic location of bank erosion. (left, from Zeller 1967) and in the flume (right, VAW)

According to Leopold et al. (1964) three different main channel forms can be classified: straight, meandering and braided. Following the classification scheme of da Silva (1991) alternate bar structures should be considered additionally. Da Silva presented delineation criteria for the different channel forms in dependence on the main parameters which are channel width, flow depth and mean grain size diameter (Fig. 7). Zarn (1997) analysed data from flume experiments and proposed a modification of the line delineating the transition between alternate bars and straight channels. The modified criterion is shown in Figure 7 by a dashed line.

FLUME EXPERIMENTS

The purpose of the present research project is the study of bed morphology and stability in steep open channels in order to find a new approach concerning the quantification of stability and to obtain useful information for the design of nature-orientated man-made structures.
For this reason flume experiments are performed in a tilting flume at slopes of 5 %, 9 % and 13 %. A wide-graded sediment mixture is used as bed-material. In order to investigate the influence of macroscale structures on bed morphology and stability, experiments are carried out at two different widths.
Because of the importance of bed morphology on physical processes in torrents the sensing of the topography plays an important role and is performed by a laser-system mounted on a positioning system that automatically scans the bed surface in a predetermined regular, dense pattern. This procedure results in a detailed digital elevation model (DEM). With the DEM-data the slope is calculated by linear regression according to Rosport (1997).
Additionally the positioning system is equipped with an ultrasonic device detecting the water surface. During flow conditions, both ultrasonic and laser devices are used to receive information about flow depth and wetted width respectively.
The recognition of bed patterns out of the DEM-data by statistical methods, such as variograms, autoregression curves or spectral analysis, does not provide reasonable results (Aberle 2000). Therefore, step-pool geometry is additionally recorded by visual observation.
Due to the complex flow field, high resolution measurement of local hydraulic parameters would be laborious. Therefore the salt dilution method is applied to obtain spatially averaged hydraulic parameters. A group of four probes arranged in a cross section, is used in order to obtain information about the section-wise repartition of the specific discharge. Furthermore the eroded sediment load is trapped at the flume outflow and photographs are taken of the dry bed surface to obtain remote sensed information about the grain size distribution of the armor layer.

RESULTS

Mesoscale structures

According to the observed step structures in nature, step plan forms have been divided into seven different categories as shown in Fig. 4. Types A to C represent step-structures orientated transverse (A), oblique (B) or curved (C) towards the flow direction. Types D and E are semi- or fully-developed ring structures respectively, whereas type F represents clusters. Type G is a single boulder representing a macroroughness and thus is not a step. However, this type is included in the analysis because the flow field around a large boulder may show a similar appearance as the steps, however to a smaller horizontal extent.

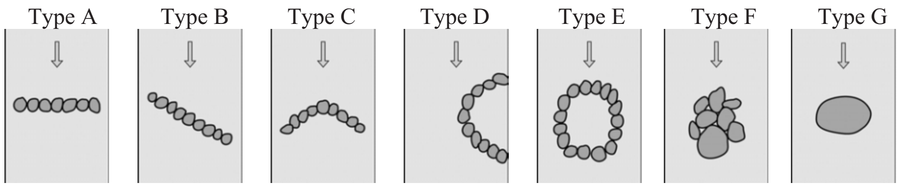

Fig. 4: Classification of plan form steps

The experiments are performed for slopes of 5 %, 9 % and 13 %, for the two flume widths of 0.30 m and 0.60 m and discharges ranging from 2 l/s to 18 l/s. The sediment mixture is filled into the flume with a constant thickness and a plane surface. The bed is then loaded with a discharge allowing for armouring and step-pool formation. After a stable bed developed the visual observation is carried out. Afterwards the discharge is increased and a new sequence of destabilisation and restabilisation of the bed occurs. This procedure results into the visual investigation of 23 torrent beds and 593 classified steps. Each step observed is then attributed to one of the above categories. As the variability within one structure is large it has to be taken into consideration that the classification of the steps is subjective. Nevertheless, some clear tendencies can be seen in the evaluation of Figures 5 and 6.

The predominant plan form of steps is type A independent of slope and flume width. The increase of frequency for step type A with increasing slope, is accompanied by a decrease in occurrence of cluster structures (type F) and large single macroroughnesses (type G). With increasing slope the available amount of energy rises and consequently the flow has the potential to form larger and more pronounced structures.

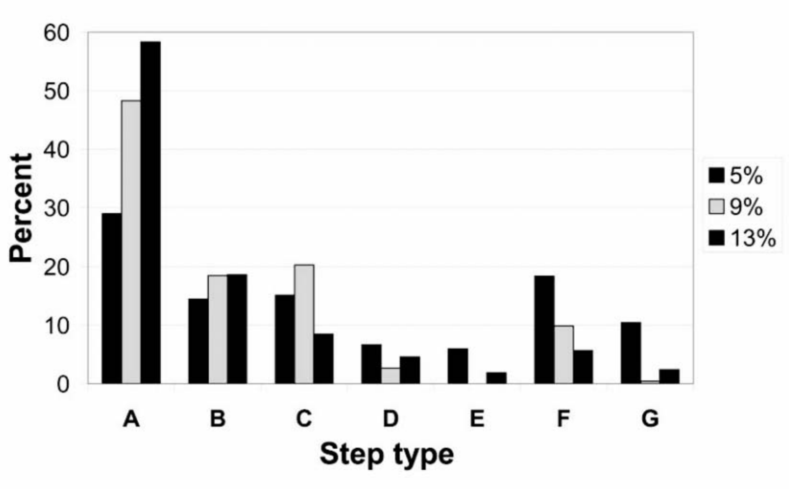

Fig. 5: Frequency distribution of step-forms for different slopes.

Another important result from the visual observation is the evidential occurrence of ring-structures and clusters in boulder-bed rivers normally associated with gravel-bed rivers. These structures are stable structures for given boundary conditions. As a consequence a single step type or a combination of different types can be used to realise nature-orientated man-made structures to stabilise the river bed (Semadeni et al. 2004).

The dependency of step type frequency on channel width is shown in Figure 6. The changes in frequency of types A & C and D & E respectively, show that ring structures and arched steps require more space. Their occurrence is therefore more dominant for large flume widths.

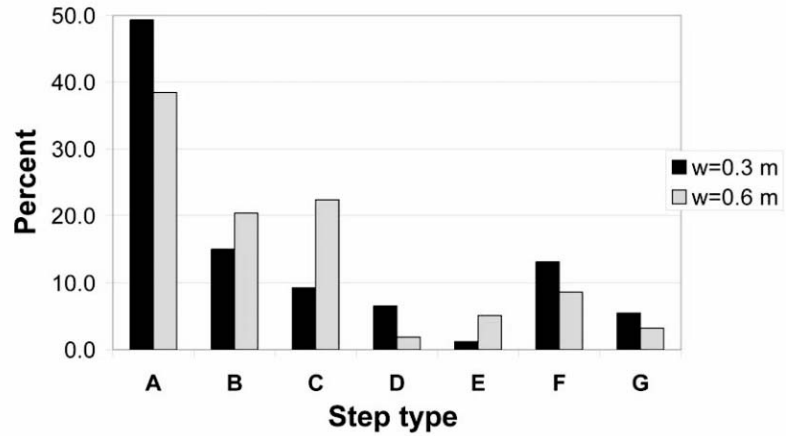

Fig. 6: Frequency distribution of step-forms for different flume widths.

Macroscale structures

The occurrence of macroscale structures is controlled by processes mainly determined by channel width, slope, grain sizes and flow. As within the experiments width, slope and discharge are varied, different macroscale structures could be observed. Table 2 in connection with the diagram proposed by da Silva (1991) and the modification proposed by Zarn (1997) is used to verify if such type of diagram can also be used for steep channels with coarse bed material. The increase in discharge within experiments with same slope and width leads to the data points following the lines depicted in Figure 7 from top left to down right.

Whereas the transition from braided to alternate bars proposed by da Silva (1991) is consistent with the data of the flume experiments, the transition from alternate bars towards a straight channel is well described with the modification made by Zarn (1997). The term “transition” used in Table 2 represents a morphology where last relics of alternate bars could be observed.

Tab. 2: Macroscale structures observed in the flume experiments

S [-]	w [m]	Q [l/s]	Morphology		S [-]	w [m]	Q [l/s]	Morphology
0.05	0.3	8	straight		0.09	0.6	2	braided
0.05	0.3	10	straight		0.09	0.6	6	alternate bars
0.05	0.3	12	straight		0.09	0.6	8	alternate bars
0.05	0.3	13	straight		0.13	0.3	2	alternate bars
0.05	0.3	15	straight		0.13	0.3	3	transition
0.05	0.6	10	alternate bars		0.13	0.3	4	straight
0.05	0.6	14	alternate bars		0.13	0.3	5	straight
0.05	0.6	18	alternate bars		0.13	0.3	6	straight
0.09	0.3	5	transition		0.13	0.6	2	braided / alternate bars
0.09	0.3	6	straight		0.13	0.6	3	alternate bars
0.09	0.3	7	straight		0.13	0.6	4	alternate bars
0.09	0.3	8	straight					

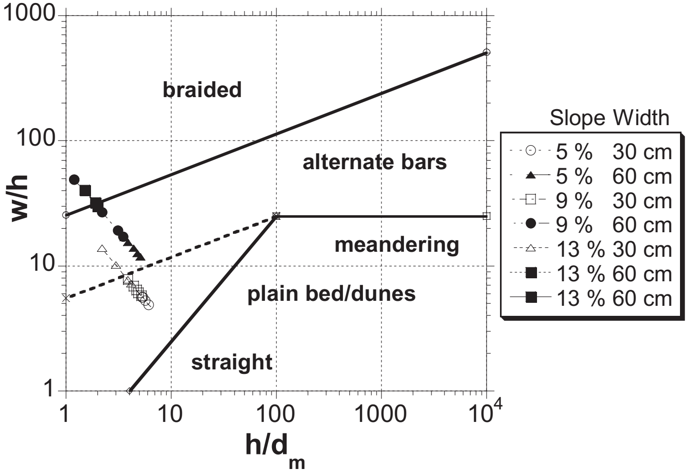

Fig. 7: Classification scheme proposed by da Silva (1991)

Figure 8 shows an example for an alternate bar structure observed in the flume. Whereas alternate bars in gravel-bed rivers are superposed by riffle-pool sequences, the figure shows that in boulder-bed channels step-pool sequences can be observed independent on bar location. Nevertheless, the density of large bed elements in the transition between the bars tends to be somewhat larger than in the pools, as it is typical for riffle-pool sequences.

In contrast to Rosport (1997) the formative processes of both, mesoscale and macroscale structures observed in the flume experiments can be attributed to equal discharges.

However, it has to be distinguished whether the diagram shown in Figure 7 is used on a macroscale base or on both, macroscale and mesoscale. With respect to the macroscale features the modified diagram gives reasonable results. Classifying bedforms in terms of both, macroscale and mesoscale structures, the described pseudomeandering tendencies superposed by step-pool sequences in boulder-bed channels should be treated as an independent bedform.

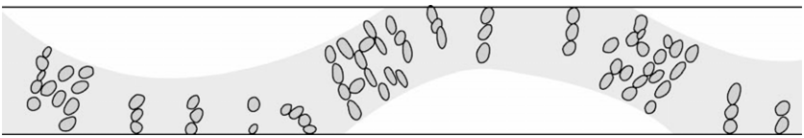

Fig. 8: Pseudomeandering bedform superposed with steps and pools in the flume.

OUTLOOK

The present paper outlines first results of the visual observation of step-pool structures formed in flume experiments. Additional features such as step-length, step-height, type of step support, pool shape, size and orientation of step forming boulders among others are recorded. The evaluation of the complete data set should bring out more detailed results concerning bed morphology. Additionally the presented data of step form will be evaluated by correlating it to both streampower and the actual bed slope obtained from linear regression of the DEM-data.

In a second step the detailed data concerning hydraulics, topography and sedimentology allows for a sectionwise consideration of stability. The photographical analysis allows the determination of the grain size distribution of the armour layer. The DEM-data can be used to carry out a sectionwise consideration of the eroded volumes. With this data, the destabilisation and reconstruction processes of step-pool systems for different slopes and discharges will be evaluated.

In this connection the definition of stability is important. In step-pool-systems the definition of stability is linked to the considered scale. The destabilisation of a single step leads to the rearrangement of the large elements and can either destroy or reinforce the stability of the following steps. The potential to increase stability by rearrangement of the large boulders in combination with different observed failure mechanisms indicate the need for a more sophisticated analysis of stability in step-pool-sequences.

CONCLUSIONS

Flume experiments are performed at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of the Swiss Federal Institute of Technology (ETH) in Zurich to simulate the formation and investigate the characteristics of step-pool geometries.
In accordance with field observations steps orientated transverse to the direction of flow are the predominant bed feature. Additionally the observed frequency of this step type increases for

steeper slopes. This shows not only that the straightly transverse orientated step type is the most stable structure, but is also indicative for the formation processes involved.
Straight step structures can easily form structures, whereas arched steps or ring-structures need more width to develop. Additionally, the entrapment of stones in stream-line direction is less probable than the entrapment of stones by interlocking transverse to the flow direction. These structures just form when This is confirmed by the observation that the height of in stream-line stone lines is determined by just a single stone, whereas type-A-structures are often composed of three or four stones lying on top of each other (Fig. 2).
According to a theory proposed by Abrahams et al. (1995) step-pool geometry adapts towards a maximisation of flow resistance. In terms of the plan form geometry the flow resistance is able to maximise due by forming transverse step structures (type A). This can also be attributed to the difference in step composition described before. The dimension of the structure particularly in all but the flow direction determines the flow resistance. As type A represents a higher and broader structure than any other bedform type, they are the predominant bed feature of step-pool systems following the theory of maximum flow resistance.

The evaluation of macroscale structures indicates that the diagram of da Silva (1991) should be modified according to Zarn (1997) in order to predict the morphology of torrents correctly. The similarity of the pseudomeanders in boulder-bed rivers to the alternating bars of gravel-bed rivers is limited to the macroscale. Considering both macroscale and mesoscale features, steps and pools being superposed by pseudomeanders should therefore be treated as an independent morphological type.

LIST OF SYMBOLS

d_m	Mean grain size [m]	Q	Discharge [m^3/s]
h	Flow depth [m]	S	Slope [-]
w	Flume width [m]		

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