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Sediment transport and erosion in mountain streams

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Abstract The paper presents first results of laboratory experiments with bed load transport over steep sloped streams with staircase-like structures, the so-called step-pool systems. The initial state of the experiments consisted in the development of armour layers of maximum bed stability at critical discharges. Coloured sediment was added at the beginning of each run to analyse the transport rates of the original bed material and of the feeding material separately. Velocity measurements were carried out by the salt dilution method before, during, and after the procedure of sediment feeding.

INTRODUCTION

During the last century the hydraulic, geological, and morphological processes of mountain streams became more and more important due to densely populated mountain areas. Torrents are characterized by steep slopes, by water depths in the order of the height of the roughness elements, by a wide range of bed material sizes, and by distinct bed structures. Therefore, the relationships and equations for the determination of flow velocity, flow resistance, and bed load transport, developed for gentle sloped streams, are hardly taken into consideration. Based on the laws for low slopes and relatively uniform bed material, investigations were carried out by Rickenmann (1996), Smart & Jäggi (1983), and Bathurst (1985), for example, to determine the behaviour of streams with steep slopes and wide sieve curves. However, the typical staircase-like structures of mountain streams were, most of the time, not considered.

In a first step, experiments were carried out in the Theodor-Rehbock Laboratory of the University of Karlsruhe (Rosport, 1997) to investigate the development of step-pool systems and their influence on bed resistance in the case of clear water flow. The relationship between bed topography, bed load transport, flow resistance, and bed instability are investigated in a second step based on the results of the aforementioned experiments.

The present study describes our first results of the experiments with bed load transport over staircase-like structures. Painted river bed material is added to the flow to investigate the stability of torrents with sediment transport. Due to its colour the feeding material can be analysed separately.

EXPERIMENTS

The experiments were carried out in a 6.8 m long and 20 cm wide tilting flume with a maximum slope of 9.7%. The measuring section at a length of 2.4 m was located 2.5 m downstream of the intake. Three pairs of electrodes were installed within this section to determine the mean flow velocity *u* by the salt dilution method. Thus, the velocity *u* characterizes the mean flow field along the entire measuring section. A vertical plate was fixed at the end of the flume to avoid gliding of the movable bed material. The eroded material was collected in a sediment basket downstream of the fixed steel plate. The content of the basket was analysed at given time intervals to obtain a data set of grain composition and transport rates of the original as well as the feeding material. Furthermore, details of the flume and its equipment are presented by Rosport (1997).

Samples of bed material from the Lainbach torrent in the Alps near Benediktbeuren were collected and analysed by Ergenzinger (1992). The material was scaled by a factor of 1:8 for the flume experiments with the characteristic diameters of d_{16} = 2.3 mm, d_{50} = 10.9 mm, d_{84} = 24.9 mm, d_{90} = 30.2 mm, and $d_{\max}$ = 64 mm. The standard deviation σ of the test material was calculated at $(d_{84}/d_{16})^{0.5}$ = 3.29 mm. The feeding material of the red colour consists of the grain fraction from 5 to 8 mm being equal to the d_{32} of the bed material.

The initial state of each experiment consisted in the development of an armour layer of maximum bed stability. This armour layer was obtained by the stepwise increase of the flow discharge until the "critical discharge" was reached, known from the experiments that were carried out by Rosport (1997 (see Fig. 1)).

According to Fig. 1 a low discharge was adjusted and kept constant until the sediment transport rate dropped to zero. Increasing the flow discharge in small steps, the critical discharge was determined accurately. The critical discharge is defined as the flow rate one step before the complete destruction of the armour layer.

As mentioned above, the present experiments began with the initial state of an armour layer of maximum bed stability at the critical discharge. Simultaneously, the mean velocity along the entire measuring section was determined. The feeding of the painted material began about one minute later. The research programme consisted of four different experiments that were repeated in order to check the reproduction of the results. In each run, a standardized duration time of t = 60 min was chosen for

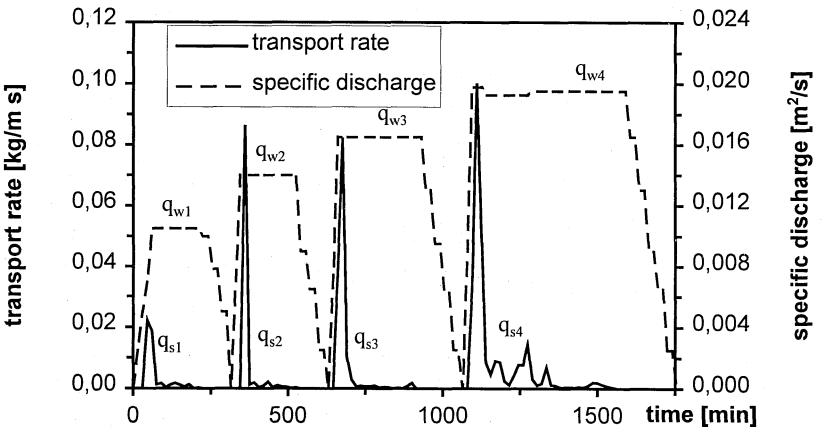

Fig. 1 Procedure to determine the initial state of critical discharge (Rosport, 1997).

sediment feeding. The differences in the experiments are caused by the two different slopes of 7.0% and 9.7% and the amount of feeding material. An amount of 0.5 kg min^{-1} and 1.0 kg min^{-1} was applied. The main characteristics of the four experiments (V1 to V4) are summarized in Table 1. During each run, the basket with the eroded material was removed every 5 min, and the mean velocity was measured every 15 min. The removal of transport material from the basket was not completed with the period of sediment feeding but continued until the end of the experiments. The experiments were completed if less than 200 g bed material were eroded during 60 min, i.e. if the transport rate was less than 0.02 kg m^{-1}·min^{-1}. At the same time, the mean velocity was measured.

Table 1 Characteristic data of the four experiments.

	Slope (%)	Discharge (l s^{-1})	Water depth (cm)	Feeding quantity (kg min^{-1})
V1	9.7	3.20	3.2	1.0
V2	9.7	3.20	3.2	0.5
V3	7.0	5.35	4.3	1.0
V4	7.0	5.35	4.3	0.5

RESULTS

Mean flow velocity

The velocity data of all runs are plotted in Fig. 2 *vs* research time. The continuous and dotted lines represent the mean value of all runs at a certain time, whereas the dots, the squares, the rhombs, and the triangles mark one value each run. First, Fig. 2 shows that the single values deviate remarkably from each other and also from the mean value. The deviations can be explained by differences in the bed topography between two different runs and by changes in the transport rate. During each run, the flow rate was constant, but the transport rate fluctuated, with the effect that the mean velocity fluctuated, too.

Second, at critical conditions Fig. 2 shows that the mean velocities are higher in the experiments with the lower slope of I = 7.0% than those at a slope of 9.7%.

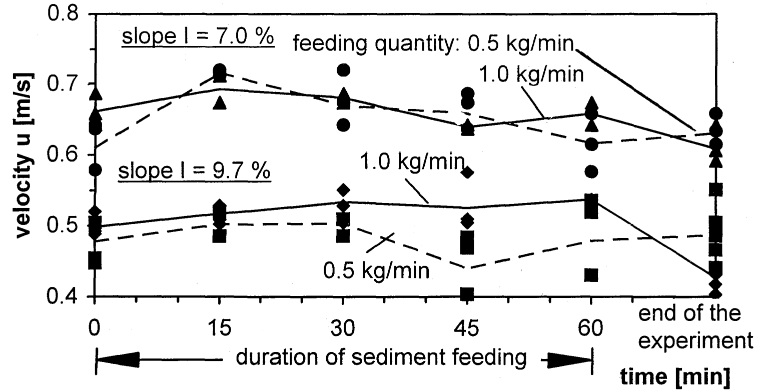

Fig. 2 Mean flow velocity *vs* research time.

This is due to the fact that the critical discharge is higher in the lower slope case than in the case with higher slopes (see also Table 1). Theoretical considerations, concerning the incipient motion of bed material with gentle slopes (see e.g. Shields, 1936; Meyer-Peter & Müller, 1949; Günter, 1971; Dittrich *et al.*, 1996), show the same results. In that case, the balance of forces acting on a particle in the river bed is given in a simplified manner in equation (1):

$$\tau = \rho \cdot g \cdot h \cdot I = \tau_c = c \cdot (\rho_s - \rho) \cdot g \cdot d_c \qquad (1)$$

where τ and τ_c are the shear stresses of flow attack and bed resistance at critical conditions, respectively, ρ is the density of water, and ρ_s is the density of the bed material, h is the water depth, and I is the bottom slope, c is a constant, g is the acceleration due to gravity, and d_c is a characteristic diameter of the bed material.

According to equation (1), the critical shear stress τ_c mainly depends on the characteristic diameter d_c and τ is a function of h and I. If the bottom slope decreases, but the bed material and thus, the resistance remain fixed, the water depth has to increase in order to obtain critical conditions. An increase in flow depth is only possible by an increase in flow rate and a subsequent increase in the mean velocity. The latter case can be explained by typical water depth/discharge relationship.

Furthermore, Fig. 2 shows that the mean velocity in the course of sediment feeding was higher than in the course of clear water flow. The latter was caused by a decrease in roughness of the bed surface during the feeding as observed visually. Mean velocities have been established at each completed run. They distinctly depend on the amount of feeding material. The mean velocity at the beginning and at the end of each run was almost the same when 0.5 kg material was added to the flow per minute. However, the velocity was considerably lower at the end of each run than at the beginning, when 1.0 kg min^{-1} was added. In the first case, the bed roughness was almost the same at the beginning and at the end of each run, whereas in the second case, the roughness at the end of the experiments increased due to the sediment feeding. In the near future, the change in roughness will be determined by the data obtained by a laser displacement meter.

Bed load transport

The total amount of transported material (TTM) as well as the amount of the red painted feeding material transported through the flume (TFM) and the feeding rate in kilograms per minute and unit width of the experiments V1 to V4 are plotted in Figs 3(a)–(d). As the processes of bed load transport are reproducible, the results of one run of each experiment are shown in the figures only.

A comparison of Figs 3(a) and (b) as well as Figs 3(c) and (d) shows that the arrival time of transported material in the basket depends on the feeding rate, but not on the flume slope. After a short delay of 10 min, in the case of 1.0 kg min^{-1} sediment feeding, and of 15 min, in the case of 0.5 kg min^{-1}, the transport rates increase rapidly.

During the time of sediment feeding the transport rates fluctuated remarkably. These fluctuations are mainly caused by the irregular transport of the feeding

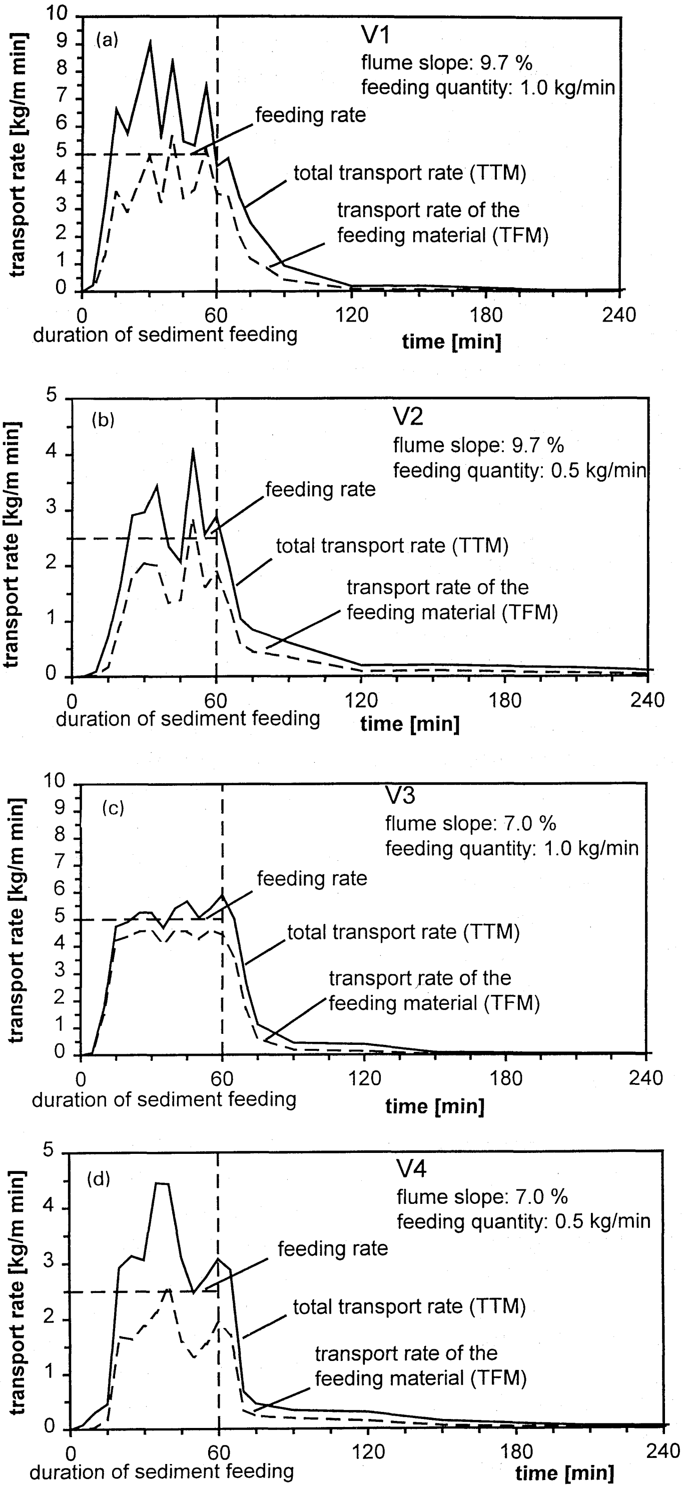

Fig. 3 Transport rates of (a) experiment V1, (b) experiment V2, (c) experiment V3 and (d) experiment V4.

material (TFM). The transport rates of the TFM are predominantly smaller than the feeding rates. Consequently, less feeding material is transported through the flume than material added at the intake independent of the slope and the feeding rate. However, the total transport rate (TTM) was frequently much higher than the feeding rate. According to the TTM, two cases can be distinguished. In the case of runs V1 and V4, the total transport rate is always higher than the feeding rate, whereas in the case of runs V2 and V3 the transport rate is sometimes lower than the rate of the feeding material. In the latter case, less sediment is transported than added in short time intervals.

In experiment V1 the slope of the flume was 9.7% and the amount of feeding material was 1.0 kg min^{-1}, and in experiment V4 a slope of 7.0% was established and an amount of 0.5 kg min^{-1} was added. It is assumed that the transport capacity of the flow was obtained in the two experiments, whereas in run V2 the amount of transported material was lower and in the run V3 higher than the transport capacity of the flow. A slope of 9.7% was established in run V2 and of 7.0% in run V3. The amount of feeding material was 0.5 kg min^{-1} in run V2 and 1.0 kg min^{-1} in run V3. In the case of run V2 it is presumed that the interstices of the bed surface were filled with feeding material. For this reason, a time-dependent increase in bed stability was caused. Due to the sediment feeding, this stable armour layer was destroyed and resulted in a subsequent increase in the transport rate (see Fig. 3(b)). Contrary to run

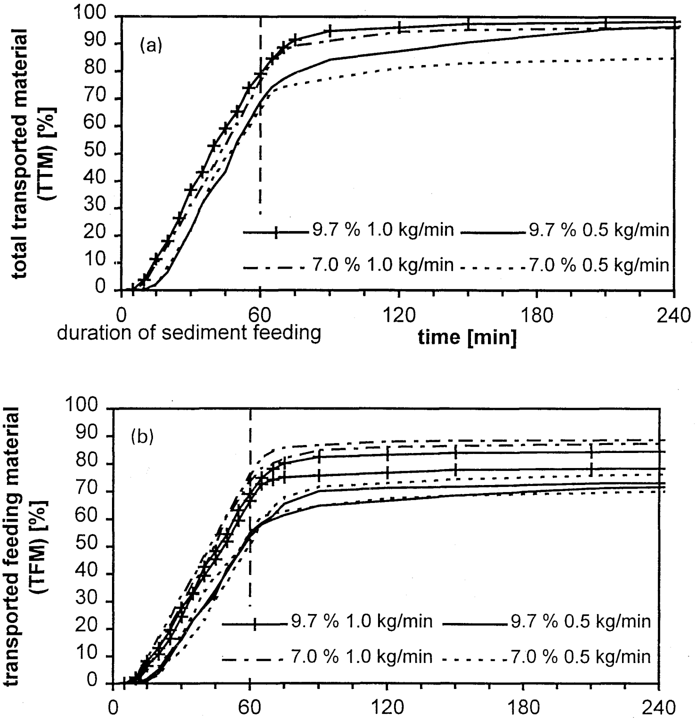

Fig. 4 Percentage of (a) the total eroded sediment and (b) the transported feeding material.

V2 in run V3, more material was added to the flow than could be transported. That resulted in a local and time-dependent settlement of feeding material. The settled material yielded local increases of water depths and shear stresses. Due to these increased flow forces, the bed material was remobilized and transported downstream again. This process is indicated in Fig. 3(c) by a wavy distribution of transport rate *vs* research time.

In Fig. 4(a), the total amount of eroded material in percentage (bed material and feeding material) is plotted as a function of research time. Figure 4(a) shows that 60–80% of the TTM are already eroded during the period of sediment feeding. It is known from an additional analysis that 45–85% of the TTM consist of the feeding material. The percentage of the red painted material (TFM) increases with increasing feeding rate.

The TTM mainly depends on the amount of feeding material, i.e. the higher the feeding rate the higher the TTM. The TTM also depends slightly on the slope. Figure 4(a) shows that the TTM increases with increasing slope.

In Fig. 4(b), the amount of TFM is plotted as a function of research time. During the sediment feeding 50 up to 75% of the total feeding quantity were already transported through the flume. Figure 4(b) shows that the amount of TFM depends on the feeding rate as well, i.e. the higher the feeding rate the higher the amount of TFM. A slope dependency of the TFM is only given in the case of 1.0 kg min^{-1} feeding material. In that case, more material is transported through the flume with a slope of 7.0% than with a slope of 9.7%. However, no distinct slope dependency exists in the case of 0.5 kg min^{-1} sediment feeding. Furthermore, it should be mentioned that only 10–25% of the feeding material remained embedded in the bed surface.

SUMMARY

Analysis of velocity data and transport rates are presented in this paper. They were obtained in laboratory experiments with bed load transport over armoured surfaces in steep streams.

The results of the velocity measurements showed that the mean flow velocities increase while the sediment was added. The mean velocities depend on both the flume slope and the quantity of feeding material.

The analysis of the total transport rates showed high dependence on the feeding rate but only slight dependence on the slope. Both the total transported material (TTM) and the transported feeding material (TFM) increase with increasing feeding quantity and with increasing flume slope. During the sediment feeding more than 60% of the total amount of transported material were eroded, and more than half the sediment consisted of red painted feeding material. Furthermore, less than 25% of the feeding material remained embedded in the bed surface. In conclusion, the bed surface was not destroyed due to the feeding material, but the material was transported over the armour layer. More results will be presented at the Conference in Vienna.

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