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GRADE CONTROL STRUCTURE INFLUENCES ON STEEP SLOPE STREAM DYNAMICS: BED LEVEL FLUCTUATIONS AND SEDIMENT TRANSPORT VARIATIONS

Influences des barrages de correction torrentielle sur la dynamique des torrents : respirations du lit et variabilité du transport solide

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ABSTRACT

Various kind of structures are used in torrent related hazards mitigation. For instance, transversal structures as check dams and ground sills are often used as grade control structures. They are generally thought to induce decreases in slopes and thus to limit bed load transport. Small scale flume experiments were undertaken to study the effects of these structures on the dynamic equilibrium of steep slope streams, i.e. bed level fluctuations and variations in bed load transport. Bed slope and outlet sediment transport were carefully measured during 30h-experiments. Three different setups were tested: a reference test without grade control structure and two tests with one and three grade control structures. Experiment showed that, in partial transport and constant fluid and solid feeding conditions, grain size sorting induces high perturbations and thus fluctuations of bed state and sediment transport. We observed that the reach-scale-median-slope did not decrease when grade control structures were added. An explanation of the difference between this result and field observations reported in the literature is proposed. In addition, to a smaller time scale, by segmenting the flume length grade control structures induce changes in bed storage and release dynamics: outlet sediment pulses still occur but with higher frequencies and littler volumes.

KEY WORDS

Check dams, ground sills, bedload sheets, armor breaking, sediment pulses, small scale flume tests

RESUME

Différents types d'aménagements sont utilisées pour la protection contre les risques torrentiels. Les ouvrages transversaux tels que les barrages et seuils de correction torrentielle sont souvent utilisés comme ouvrage de contrôle de la pente des cours d'eau. Il est généralement considéré qu'il induisent diminution des pentes et du transport solide. Une campagne de modélisation physique a été réalisée afin d'étudier l'effet des seuils et barrages sur l'équilibre dynamique des torrents, c'est-à-dire sur les respirations du lit et les variations du transport solide par charriage. La pente du lit et le débit solide à la sortie du canal ont été soigneusement mesurées pendant des expériences de plus de 30-h. Trois différentes configurations ont été testées : un test de référence sans ouvrage et deux tests avec ouvrages : un puis trois barrages. Il a été observé que la pente médiane des tronçons ne diminuait pas en présence de barrages. Une explication aux différences observées entre nos résultats et des observations de terrain rapportées dans la littérature est proposée. Par ailleurs, à une échelle de temps plus courte, la segmentation du canal induite par les barrages et seuils engendre des changements dans la dynamique de stockage et déstockage : les pulsations solides au débouché du canal se produisent toujours mais à une fréquence plus importante et avec des volumes plus faibles.

MOTS-CLEFS

Barrage de correction torrentielle, seuils de correction torrentielle, nappe de charriage, dépavage, pulsations solides, modélisation physique en canal

1.INTRODUCTION

Urbanized areas and facilities have increased a great deal during the last decades in European and Japanese mountains, especially on fans and in valleys. Torrent related hazard mitigation has been developed and theorized for more than a century [e.g. Thiéry, 1891]. Grade control structures are included in various technics (plantations, bank protections, dykes, sediment traps, etc.). Substantial research has been carried out on design criteria definition and a large literature exists on subject like toe scouring, civil engineering design and equilibrium slope. However, it is not yet clear how these structures affect sediment transport at different time scale (from instantaneous to long term). To study this point, small scale flume tests were undertaken. We present here some preliminary results.

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2.EXPERIMENTAL SETUP

A 4.8-m-long, 0.107-m-wide, 0.4-m-deep and 12%-steep tilting flume was used. The sediment mixture consisted in natural poorly sorted sediments (diameter from 0.8 to 20 mm) with a median and a mean grain sizes of respectively 3.1 and 5.6 mm. Water and sediment discharges were set constant at respectively 0.55 l/s and 44 g/s. The bed slopes S_i and the outlet solid discharge Qs were measured each 3 to 4 minutes (i represent the rank of the reach from upstream to downstream as illustrated on Figure 1). Three different setups were tested: a reference test (Ref test) without grade control structure and two tests with one and three grade control structures (respectively denoted "1GCS Test" and "3GCS Test").

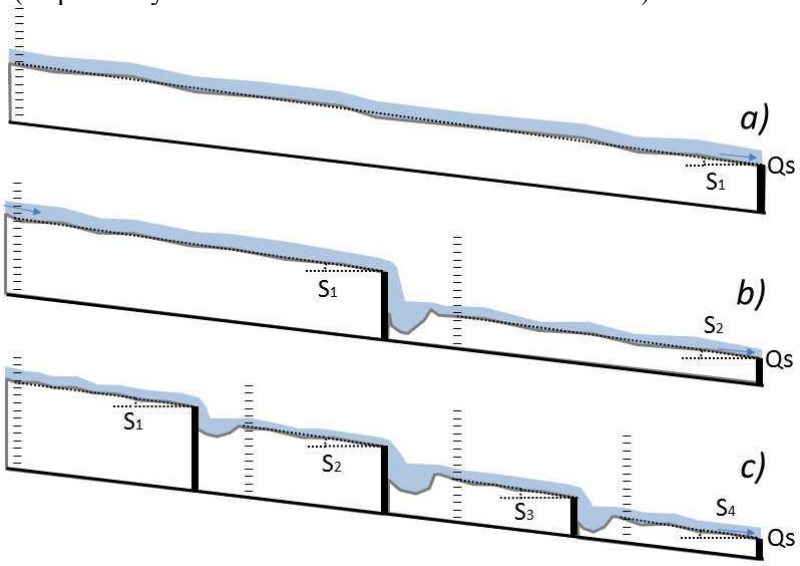


Figure 1. Sketches of the different setup: a) Ref Test; b) 1GCS Test; c) 3 GCS Test.

3.RESULTS

Bed aspect and grain size sorting

The flow induced partial transport following the definition of Wilcock and McArdell [1997]. In such conditions, strong grain size sorting occurs as observed during other flume tests, e.g. [Recking, 2006, Bacchi, 2011]. The bed aspect fluctuates between two extreme states showed by Figure 2: (i) paved aggrading bed with coarse sediments and (ii) eroding bed releasing bedload sheets of fine sediments. These two extreme states and the transition phase were observed on all flume-parts and sometime concerned the entire flume length.

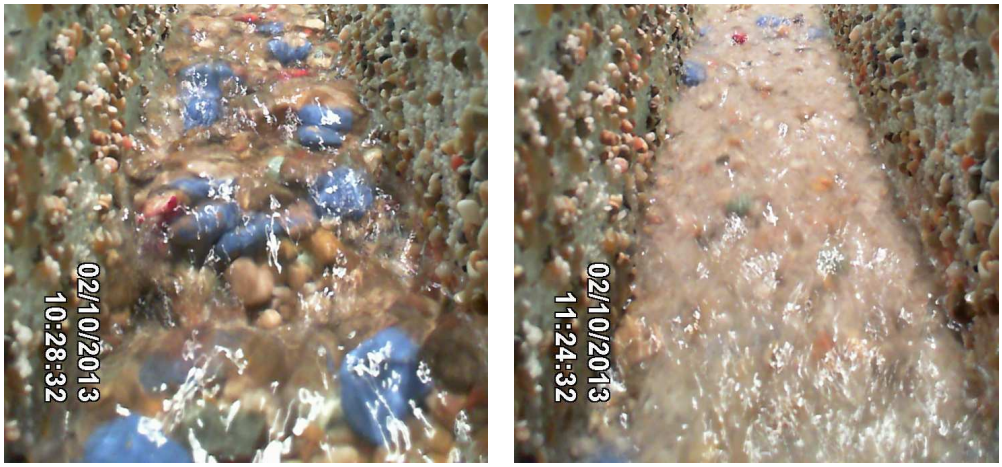


Figure 2. Illustration of two extreme bed aspect : coarse paved and fine bed load sheet

Sediment transport

Bed state (coarse, smooth, transitory) influences flow depth and velocity. This feedback is generally represented by friction laws, as for instance the Manning-Strickler formula. Otherwise, bed load sediment transport is often considered to depend on adimensional shear stress, i.e. to sediment density and diameter and to slope and flow depth or hydraulic radius. Thus, through flow depth, sediment transport depends on bed state. This feedback was observed in field by Yu et al. [2012] and in flume by Recking et al. [2008].

Consistent with this assumption, a correlation between the bed state and sediment transport was observed during the experiments: the rougher the bed, the lower the transport rate and the smoother the bed, the more efficient the transport rate. During the bed pavement and armor breaking events, outlet solid discharges represented respectively about 1 % and more than 300 % of the feeding rate. Bed load discharge showed cycle of weak transport followed by intense bed load pulses.

Bed fluctuations

The mass conservation principle imposes a correlation between bed load transport changes and bed level fluctuations, i.e. the flume temporary stores and releases sediments through aggradations and erosions. These fluctuations in the flume-bed-level induced changes in the reach mean bed slope as illustrated in Figure 1. Reach mean bed slopes varied with time in the range showed in Table 2.

Table 2: Reach mean slope of the different reaches

Run name	REF Test	1GCS Test		3GCS Test			
Reach number from upstream to downstream	1	1	2	1	2	3	4
Maximum slope on 30 h : Smax [%]	14.5	14.7	15.7	14.8	17.1	18.5	16.6
Median slope on 30 h : Smed [%]	11.9	12.0	12.0	12.1	12.5	12.1	11.6
Minimum of slope on 30 h : Smin [%]	11.2	10.8	10.0	10.1	9.4	9.0	7.6

Another aspect of our results concerns the time duration of aggradation-erosion cycles. An inverse correlation between frequencies of fluctuations and reach lengths was observed. This result is consistent with Recking [2006] who showed that in a shorter flume, the mean-slope oscillated faster.

4.DISCUSSION

Grain size sorting effects on sediment transport in flume is widely described in previous work [Recking, 2013, Bacchi et al., 2014], thus is not presented in this paper.

Long term influence on equilibrium slope

Grade control structures are often presented to be built in order to induce decreases in slope and in sediment transport [Jaeggi, 1992]. Consistent with this assumption, many field observations described decreases in slope between grade control structures, e.g. [Iroume and Gayoso, 1991, Martìn-Vide and Andreatta, 2006, Conesa-Garcia et al., 2007, Kostadinov et al., 2011].

Nonetheless, in our small scale models, the median slope S_{med} did not systematically show a decrease when grade control structures were added (Table 2). The comparison with field observation is not straightforward because it is complex to determine in which extend the observed streams were at the equilibrium.

Our flume tests are assumed to be in dynamic equilibrium: the feeding conditions did not depend on the presence of grade control structure and runs lasted more than 30 h, i.e. long enough to reach dynamic equilibrium. In the field, conditions are different. The concept of equilibrium, widely used in lowland rivers, is hard to transposed in steep slope streams [Recking et al., 2013]. Thiéry [1891] ever considered that the more active alpine steep slope streams were not at the equilibrium. We assume that it remain true.

We hypothesize that grade control structures do not intrinsically induce a decrease in the slope, as shown by our results. In addition, despite the presence of grade control structures, some streams are aggrading or stable. In these rivers, structures do not induce any decrease in slope and are generally durably or temporary buried by sediments [Chambon et al., 2010, ETRM, 2010]. Such trends tend to occur in streams with excess sediment supply.

The proposition of Jaeggi [1992] remain true but the shortcut could be detailed as follow: Many very active streams were in disequilibrium and released large amounts of sediments on urbanized fans and valleys. Grade control structures were built to prevent incision, stabilize streambeds and curtail sediment transport. They caught up a height that would be incised in their absence, locally dissipate energy and create fixed point in the streambed. They thus allow milder slopes to settle without generating large backward erosions, i.e. they accelerated milder equilibrium slopes to settle. Grade control structures generate decreases in slope when they are built in stream in disequilibrium, i.e. showing degrading and incision trends. Such structures are generally built in this specific kind of stream, thus decreases in slope between grade control structures are observed most of the time.

Short term influence on erosion volume

At smaller time scales, in the reference test, the erosion events sometimes occurred on the entire flume length. Adding grade control structures shorten the reaches length and thus the maximum erosion event length. Even if the envelop of slope was a little bit wider with grade control structures, the volume of each erosion event decreased. This result is consistent with previous equivalent tests [Bacchi, 2011].

This explain the changes in frequencies of cycles: the continuous outlet sediment discharge can be integrated in time on each cycle of aggradation – erosion, i.e. the total flux can be discretized in a sum of erosion volumes. In our experiment, the solid feeding flux was set constant in all experiments. If each erosion volumes or sediment pulses are smaller, the mass conservation imposes that the frequencies of cycles increases, sediment pulses are more frequent but littler.

5. CONCLUSIONS

Small scale flume tests on grade control structures were undertaken in constant feeding condition. No systematic decreasing trends in slope were observed when structures were added, and an explanation is proposed for the apparent contradiction with field observations. On another hand, short term fluctuations in the bed state tend to substantially increase in frequency: a flume equipped with structures tends to release littler but more frequent bed load pulses. As proposed by Poncet [1995], we conclude from these experiments that check dams participate efficiently in hazard mitigation because "*they release in retail what torrents would too abruptly delivered wholesale*". Further research on hydrology influences has to be undertaken to confirm the accuracy of our results, especially to study effects of high floods inducing equal mobility and of variation of water and sediment supplies.

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