Response to the Reviewers' comments

Armor breakup and reformation in a degradational laboratory experiment

C. Orrú, A. Blom, W.S.J. Uijttewaal

Anonymous Referee #1

SUMMARY

This paper examines how the texture of a mixed sand-gravel channel bed responds to changes in flow discharge. It is qualitatively interesting to see the formation of static armor during high flow followed by breakup of this armor and reformation of a coarser mobile armor during subsequent high flow. Furthermore, application of new techniques for repeated longitudinal profiles of grain size and bed elevation offers new quantitative insight into armoring processes. While some of the observations are interesting, I think they are insufficient to merit publication. Though it was very long (20 h), only one experiment was run. Therefore, it is impossible to determine the reproducibility of these results or the dependence of the armor formation and breakup processes on the specific initial bed configuration, pattern of flow changes, and trimodal bed texture. Additional experiments to vary at least one of the experimental variables (e.g., magnitude of low and high flow) would provide much more insight into the controlling factors of bed armoring. Furthermore, the manuscript is poorly organized and needs to be fundamentally restructured. The abstract and conclusion are nearly identical and do not establish the motivation and implications for this work. The introduction is very disorganized and does not follow a logical progression in presenting information about past work. For example, the opening sentence of the paragraph at line 18 on page 1 seems unrelated to the remaining content in the paragraph. Some information in the methods (section 2) really belongs in the results (section 3); e.g., section 2.3. In the results, there are several assertions made without proper explanation. For example, on page 4, line 14- 15, an "imbricated structure" is mentioned, but there is never any discussion of when the imbrication developed or what morphological features suggest this interpretation. Related to this, there are several interpretations in the results (section 3), which really belong in the discussion (section 4); e.g., section 3.2, lines 9-10. Finally, all figures should be mentioned in the manuscript (currently Fig. 2 is missing), and the figure numbering should correspond to the order of mention (currently Fig. 10 is mentioned before Fig. 6).

Given these concerns, I therefore recommend rejection for this manuscript. I encourage the authors to run additional experiments, then more clearly present their results for future publication of this work. Further minor comments are listed below.

We thank Reviewer #1 for his/her comments. We have revised the Abstract, Introduction, Discussion and Conclusion sections. Section 2.3 has been moved to the Results section. We have added more information on the imbricated structure. Section 3.2 (lines 9-10) has been moved to the Discussion. Figure 1 has now been mentioned.

MINOR COMMENTS

1) In the abstract, the phrasing, "trimodal mixture composed of sand and gravel," implies that there are three components, but only two are mentioned here. It would be better just to list the three sizes (1, 6, and 10 mm) here.

We have specified the mixture and the grain sizes in the abstract (Page 1, Lines 1-2).

2) Page 3, line 13-17. Why do you impose a stepwise fining pattern in the initial bed? How does this reveal the dynamics of static and mobile armor formation better than a uniformly graded bed? Please explain in the manuscript. Also, the description of patch lengths is confusing. You should refer here to Fig. 2, which is never mentioned in the text.

We have clarified the choice of the initial stepwise fining pattern in the Introduction (Page 2-3, Lines 35, 1-3). We have provided more information on the compartments more precisely and now refer to Figure 1 (Page 3, Lines 25-29).

3) Section 2.2 on grain size techniques is insufficient to understand these techniques. Unless you have a strong reason to delve into the details, I suggest summarizing this to one or two lines then referring to Orru et al (submitted 2015) for further information. I also suggest removing Figures 3 and 4 for this reason.

We have revised this part of the text and added information on the image analysis technique and the equipment applied to take images of the bed surface (Page 4, Lines 15-28).

4) In describing the armor breakup and reformation, it is very difficult to see these bed changes from image to image in Figure 7. Could you apply some kind of image differencing technique to make the changes more apparent? The quantitative information in Figs. 8 and 9 is much more useful. Finally, unless you can justify them with more quantitative information, I would suggest removing the assertions on page 4, line 27-29, about textural changes between grain size analyses.

The images in Figure 8 are snapshots from a video. The sand in transport in the parts indicated by the arrows makes part of the images (a) and (b) a bit blurry. The fact that image (c) indicates that there was no more transport of sand and the armor has reformed.

5) The methods used for characterizing the bedload transport rate from the front propagation are confusing (page 5 and Fig. 11). Where is the front being measured, in terms of the streamwise coordinate? Is there really no observed transport here prior to the step increase in discharge (as indicated in Fig. 11), or are you just assuming this?

The front progadation is measured at the crest. Before the increase in discharge, sediment was transported over the front (Figure 12 b) but this did not lead to front progradation.

6) At page 5, line 26, it is not clear whether the mentioned bed load transport rate is referring to the propagating front bed load transport or some other measurement. It is curious that a bed load trap is mentioned on page 2, lines 32-33, but then never again mentioned in the paper.

Thank you. We have now included information about the sediment transport measured at the downstream end of the flume (Figure 12, Page 6-7, Lines 32-34, 1-13). We have analysed these results in more detail.

7) Finally, I am a bit concerned that no mention of the shear stress or Shields parameter is made here, despite the fact that this is usually considered an important variable in studies of the evolution of mixed sediment surfaces and armoring (e.g., Wilcock and Crowe, 2003).

Thank you. We have now added an analysis of the Shields stress (Figure 11, Page 6 Lines 23-31).

Anonymous Referee #2

GENERAL COMMENT

This paper presents the results of an armor breakup experiment, under condition of low sediment supply and changing hydraulics. The topic is of interest because armor is present and controls the morphodynamics in many rivers, and because the physics of armoring is complex and still largely misunderstood. Flume experiment is a good way to approach the processes involved. Before reviewing the paper, I had a look to the online discussion. I agree with referee 1 that the paper suffers from a series of drawbacks and can largely be improved. However I will not be as severe as he was, and I consider that it is a nice experiment which results deserve to be presented to the community, after major revision of the paper.

Major comments

My main comments concern the experimental set-up. When reading the paper the first time, I wondered if I missed something when I discovered the experimental set-up: why do you need a gravel sand transition for studying the armor breakup and reformation? This is an enigma. You could have done the same experiment without the sandy part of the flume? Or maybe this was motivated by a particular reason, but it is not explained in the paper. Actually your experiment is far to be out of interest, but what you studied seems more to be a gravel sand transition. This is a situation present in many rivers, which physics is also poorly understood. With your experiment you could describe precisely how the coexistence of armor and sand patches behave during flood: starvation and erosion of the sandy place, replacement by the gravel wave, impact of reduced slope in the propagation of the gravel wave and armor reformation. Such experiment allows very well documented measurements, and we would expect a very fine analysis of the hydraulics. What were the hydraulics conditions: flow depth, velocity, energy slope, Fr, Shear stress, Shields stress? Was there any side wall effects, and if yes can you propose a correction? The results you present in the paper are essentially descriptive. With the hydraulics, you could propose a much convincing quantitative analysis of your results, with a focus on what happens in the sand gravel transition zone. It would be very interesting. To conclude on this comment: either you justify the need of a sandy section for studying the armor breakup and reformation, of you reconsider the paper objective (which also means to reconsider the literature review). I also found a bit frustrating the description of the grain size measurement technique.

We thank Reviewer #2 for his/her suggestions. We have clarified the choice of the initial stepwise fining pattern in the Introduction and we have included the argumentation about the similarities with a gravel-sand transition in the current manuscript (Page 3, Lines 4-11).

SPECIFIC COMMENTS

8) P3 L3: how did you choose the flow conditions?

Flow conditions were chosen such that we obtained the desired sediment mobility, partial transport conditions in order to create the armor in Experiment T1, which was based also on the previous experiment presented in the WRR manuscript, and fully mobile conditions in Experiment T2. In addition, a certain minimum flow depth is required to not significantly affect the flow when using the floating device (Figure 4) to measure the grain size distribution of the bed surface during the experiment.

9) P3 L15: I don't really understand what you mean by patches. Did you consider different grain size in each patch or did you use a trimodal mixture everywhere?

We meant compartments of the initial bed characterized by a different grain size distribution. The compartments were filled with different volumetric fraction contents of the 3 grain size fractions. The sand content increased in streamwise direction in steps of 10 percent for each compartment. We have specified the characteristics of the compartments more precisely (Page 3, Lines 28-29).

10) P3 L16: I suppose that the energy slope was very different than the bed slope?

Figure 1 shows a comparison between the bed slope and the energy slope during Experiments T1 and T2. The large peak in the bed slope indicates the front of the trimodal reach. One can distinguish the migration of the front. In the initial part of Experiment T1 the bed and energy slope were comparable and later they started to differ due to the bed degradation mainly over the sand reach and the presence of the backwater curve. During Experiment T2 the bed and energy slope were comparable only in the upstream trimodal reach where conditions were closer to normal flow.

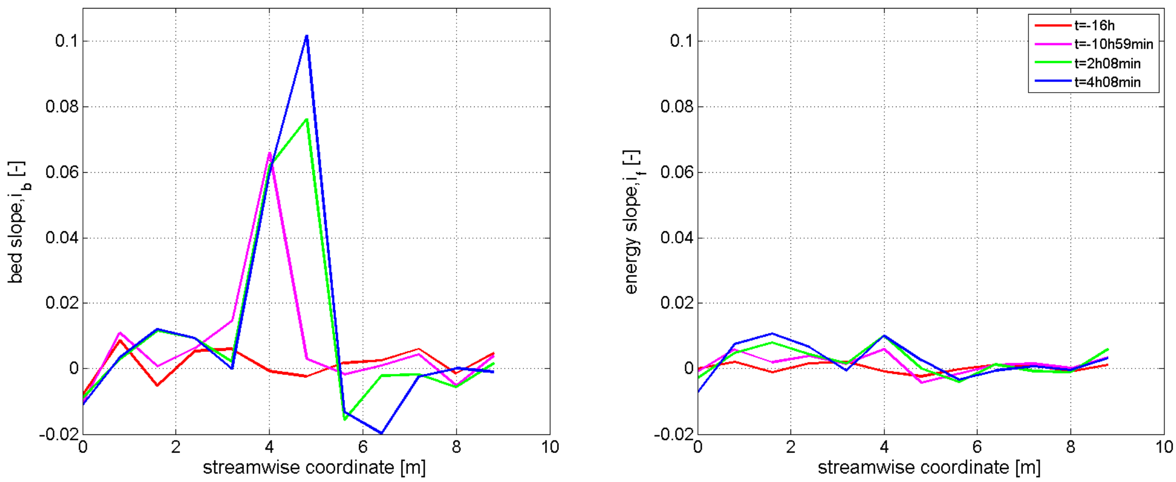

Figure 1 Comparison of bed slope and energy slope during the Experiments T1 and T2.

11) P3 L19: could explain with a few lines? P3 L25-38: this part is very frustrating. A very nice equipment is presented in Fig4 but you don't really explain what it is. The method is not explained. What are these polygons?

We have added some explanation on the measurements of water discharge and bed and water surface elevations (Page 4, Lines 7-11). We have added information on the image analysis technique and the equipment used to take images of the bed surface (Page 4, Lines 15-28). We removed the information on the polygons and now refer to the WRR manuscript.

12) P4 L8-16: this aspect is particularly interesting. I don't know many papers describing in detail this situation.

Thank you. We have treated this aspect in more detail in the WRR manuscript, and we have more clearly stressed it in the current manuscript.

13) P4 L20-25 The armor breakup seems to concern the center of the flume? An evaluation of side wall effects would be interesting here.

The armor breakup seemed to occur randomly in streamwise and lateral direction. It did not concern only the center of the flume. As mentioned in the Discussion section one of the hypotheses is that besides the increase in flow rate, irregularities, randomly distributed over the bed surface, seemed to initiate the breakup due to turbulence.

14) P5 L5-15: you should use the hydraulics (shear stress) to analyze these changes. Did you observe any regressive erosion at the gravel sand transition?

We now present an analysis of the hydraulic conditions (Figure 11, Page 6, Lines 23-31). We did not observe regressive erosion during the experiment.

15) P5 L16-28 This is an interesting result which deserves more comments.

We revised this part and we have added more information (Page 6-7, Lines 32-34, 1-13).

Anonymous Referee #3

GENERAL COMMENT

This paper describes a laboratory experiment where armor was built on an initial condition, then broken up and reformed. The paper describes an interesting experiment, but felt incomplete in that the methods are included elsewhere in a submitted paper (not accessible as far as I know), the discussion and conclusion were very brief and does not quite relate the results to an implication in the real world, which I would hope for. The paper would benefit in clarity with some reorganization - it took me multiple reads to understand certain sections. Some sections I still do not understand. I offer some suggestions for making the paper easier to understand. I recommend a major revision and addition of more detail and information before publication of this paper.

SPECIFIC COMMENTS

16) Abstract I would like to see mentioned in the abstract something about the initial bed condition. It is spatially varying and that is important information.

We now mention the initial bed condition in the abstract (Page 1, Lines 2-4).

17) I don't know exactly what is meant by "closer to normal flow conditions".

We have added information about normal flow conditions in the text (Page 6, Lines 15-22).

18) Section 2 experimental setup It would make much more sense to me to move paragraph 2, beginning "An initial experiment" to the end of the section after describing the sediment mixture and initial bed.

We have moved this paragraph to the end of the section (Page 3- 4, Lines 31-33, 1-5).

19) It would be useful to mention in the text that experiment T1 goes from -16 to 0 hours and T2 goes from 0 to 4.

We have now specified the time intervals in the text (Page 4, Lines 2-5).

20) In Figure1 it is not clear where "downstream" is in "downstream water surface elevation." Do you mean "sand reach"?

The water surface elevation was measured at the downstream end of the flume (x = 10.62 m). We have added this information to the caption of Figure 2.

21) Section 2.2 measurements
I'm having a hard time saying it is okay to review and accept this paper before seeing and evaluating (Orru, submitted 2015) is available to view and evaluate. I know this is a difficult situation if that review is taking longer than expected, but I cannot evaluate the methodology that is the basis for all of the results. The description here should be more complete, instead of assuming one can read Orru, submitted 2015.

We have now clarified and added information on the image analysis technique and the equipment used to take pictures of the bed surface (Page 4, Lines 15-28). We provide the pdf of the manuscript that is currently under review with WRR to the reviewers.

22) Section 2.3 Because the bed is spatially varying, it is important to say where things happened. Where did the armor form? Say it in the text, and label the armor section in Figure 5, even if you think it is obvious.

We have mentioned where the armor formed in the text (Page 5, Lines 3) and now indicate the zone in Figure 5.

23) Last sentence of 2.3 "Armor was considered fully developed after 16 h" (note that this is "0 hr" in this paper's figures, etc.).

Thank you, we have added this information (Page 5, Lines 17).

24) The described bed step is curious to me. Does this have any relevance to nature or "mess up" any of the interpretation of the lab results.

We have clarified the formation on the step in bed elevation in the text (Page 5, Lines 5-14).

25) Section 3 "increasing the water discharge" - please state increased from what to what, even though it is in the figure, it is good to put it in the text. ("increase by 25%" or something like that) Give the reader an idea of how much it was increased.

We have added this information (Page 5, Lines 21-22).

26) Section 3.1's first paragraph very hard to follow. "Yet the fining was even stronger than we measured" - Why? Suggest rephrasing this paragraph and asking around if it makes sense to colleagues.

We have clarified this paragraph (Page 5, Lines 25-33).

27) Figure 8 - the points vary in streamwise coordinate in the figure (there is spread in the x-axis)- are they supposed to represent one point in the streamwise coordinate? I was a bit confused by this.

Thank you, we revised Figure 9.

28) Section 3.2 It is not clear to me how does figure 10 show lateral variation in degradation?

Figure 6 and our measurements do not show lateral variation in degradation, yet this was only observed by the author. We have now avoided referring to Figure 6 to avoid confusion.

29) Not much is reported about the sediment transport captured in the sediment trap?

We have now included information about the sediment transport measured at the downstream end of the flume (Figure 12, Page 6-7, Lines 32-33, 1-13).

30) Section 4 discussion
Some of these sentences could be rearranged for better understanding. I don't know what is the field case in "in the field case"?

We have specified the reference (Page 8, Lines 13-14).

31) In general the discussion seems short and confusing, and could be improved by providing implications for natural streams. Yes, comparisons to other studies were given, but not really related back to nature. By adding more content and having a better narrative, the discussion could be really improved.

We have revised the Discussion section and we have discussed implications of the current study to rivers (Page 7, Lines 15-22).

32) The conclusions section is similarly hard to follow. There should make some mention of the initial bed condition and what was "base flow". Is there an implication to the last sentence?

We have revised the Conclusions section mentioning the initial bed conditions and the implication of the adjustment of the bed and the approach to normal flow conditions (Page 9, Lines 7-9). Base flow corresponds to conditions of a low water discharge.

Armor breakup and reformation in a degradational laboratory experiment~~: detailed measurements of spatial and temporal changes of the bed surface texture.~~

Clara Orrú[1], Astrid Blom[1], and Wim S. J. Uijttewaal[1]

[1]Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA, Delft, The Netherlands.

Correspondence to: C. Orrú (C.Orru@tudelft.nl)

Abstract. Armor breakup and reformation was studied in a laboratory experiment using a trimodal mixture composed of ~~sand~~ a 1 mm sand fraction and two gravel fractions (6 and ~~gravel. The armor was formed in the initial stage of the experiment~~ 10 mm). The initial bed was characterized by a stepwise downstream fining pattern (trimodal reach) and a downstream sand reach, and the experiment was conducted under conditions without sediment supply. ~~Higher flow~~ In the initial stage of the experiment an armor formed over the trimodal reach. The formation of the armor under partial transport conditions led to ~~the breakup of the mobile armor and the reformation of~~ an abrupt spatial transition in the bed slope and in the mean grain size of the bed surface, as such showing similar results to a previous laboratory experiment conducted with a bimodal mixture. The focus of the current analysis is to study the mechanisms of armor breakup. After an increase in flow rate the armor broke up and a new coarser armor quickly formed. The breakup initially induced a bed surface fining due to the exposure of the finer substrate, which was accompanied by a sudden increase of the ~~local~~ sediment transport rate, followed by the formation of an armor that was coarser than the initial one. The reformation of the armor was ~~due to~~ enabled by the supply of coarse material from the upstream degrading reach and the presence of gravel in the original substrate sediment. ~~Provided that the gravel supply from upstream suffices for armor reformation, armor breakup enables~~ Here armor breakup and reformation enabled slope adjustment such that the new steady state ~~is~~ was closer to normal flow conditions.

1 Introduction

The formation of an armor ~~layer~~ has two different origins (e.g., Parker and Klingeman, 1982; Jain, 1990). A static armor is created when there is a lack of sediment supply and ~~the flow is characterized by small~~ limited shear stress values ~~capable of~~ enable entraining only the finer grains present at the bed surface. A mobile armor forms ~~to enable the coarse sediment to be transported downstream when coarse sediment~~ when a sediment mixture governed by a range in grain sizes is supplied from upstream. The over-representation of the coarse grains at the bed surface then serves to increase their transport ~~capacity~~rate. The coarsening of the bed surface of a static armor is mainly caused by the winnowing or ~~the~~ washing out of fines from the bed (e.g., Parker and Klingeman, 1982; Dietrich et al., 1989). For a mobile armor the coarsening is mainly ~~due~~ related to kinematic sorting or the infiltration of fines into the bed (e.g., Parker and Klingeman, 1982; Mao et al., 2011).

The presence of an armor layer can reduce bed elevation changes as it prevents the underlying finer sediment from being entrained by the flow Armoring processes have been mainly investigated under controlled laboratory conditions. Many authors focused on the characteristics of the bed structure during armoring studying the bed arrangement and the stability of cluster particles (e.g., Church et al., 1998; Hassan and Church, 2000; Piedra et al., 2012; Heays et al., 2014). The stability of a gravel bed can be increased by the presence of cluster particles (e.g., Church et al., 1998; Hassan and Church, 2000; Piedra et al., 2012; Heays et al., 2014). The armoring process is influenced by the nature of the sediment supply (e.g.,)ParkerKlingeman1982, Jain1990Dietrich1989, Sklaretal2009. Little is The experiments by Dietrich et al. (1989) showed that a decrease of the sediment supply rate corresponds to a more efficient armor development. Also the grain size distribution of the bed material and, in particular, the increase of sand content plays a role in the armoring process by reducing vertical sorting (Marion and Fraccarollo, 1997) or by reducing surface roughness and facilitating the rearrangement of the bed particles (Curran and Waters, 2014). Another aspect is the influence of different flow rates on the development of the armor (Hassan et al., 2006; Guney et al., 2013). Hassan et al. (2006) indicated a general increase of the armoring degree with an increase of the flow rate. They also showed that temporally varying flows leads to stronger armoring than steady flows.

Still little is known on the evolution of armor layers during high flow conditions (Vericat et al., 2006; Yager et al., 2015). The available studies demonstrate that behavior of an armor under peak flow (Vericat et al., 2006; Yager et al., 2015). Studies have demonstrated that during peak flow armored surfaces can be both stable and persisting during floods or broken during a flood stable and persist or broken and reform during the waning phase of the flood event. Andrews and Erman (1986) were the first to present a field case on the persistence of an armor layer during a flood. armor persistence during peak flow. Using their surface-based transport model Wilcock and DeTemple (2005) predicted the persistence of armor layers during high flow using their surface-based transport modelan armor of a certain grain size distribution using transport rates measured in the field. Clayton and Pitlick (2008) described a gravel bed river reach of the Colorado River with a persistent armored surfacearmor. The sediment supply, composed of all grain sizes, provided the replacement for the supplied from upstream provided the sediment for the replacement of the entrained particles. Conversely, Grains from a persistent armor can exchange grains with the transported load (Wilcock and DeTemple, 2005). Despite these examples of armor persistence, there are also examples in which the armor does not persist during peak flow. Vericat et al. (2006) described armor breakup and reformation in a large river regulated by a dam. The Vericat et al. (2006) field measurements showed that Their field measurements illustrated that the armor did not persist at high flow conditions under peak flow and reformed at smaller floods.The flow values.

Various causes of armor breakup have been distinguished. The laboratory experiments by Klaassen (1988) provided detailed measurements of armor breakup after a flood wave under bedform-dominated conditions. The armor breakup resulted Here armor breakup appeared to result from the turbulence created in the trough zones of the migrating bed-forms. A finer armor reformed at lower flow conditions after the decrease in the waning phase of the flood wave. Wang and Liu (2009) conducted a laboratory experiment studying armor breakup under a shortage of sediment supply. The armor was created at low flow conditions under base flow and its stability was tested under a stepwise increase of the discharge. The armor breakup corresponded to the entrainment Armor breakup was due to an increased mobility of the coarse particles , as observed by the authors, and and led to a sudden increase of the bed load transport. Persistence of the armor layer can be due to replacement of entrained particles by sediment supplied from upstream (Clayton and Pitlick, 2008). Such a persistent armor remains while exchanging grains with the sediment transport (Wilcock and DeTemple, 2005). The stability of a gravel bed can be increased due to particle arrangement such as the presence of cluster particles (e.g., Church et al., 1998; Hassan and Church, 2000; Piedra et al., 2012; Heays et al., 2014). Causes of armor Other causes of armor breakup are the increase of the water discharge due to floods (Vericat et al., 2006; Wang and Liu, 2009; Spiller et al., 2012), as well as turbulence (Klaassen, 1988), sediment supply from upstream , or and the presence of bedload sheets. The supply of finer material can lead to a higher an increased mobility of the coarse sediment and so can therefore mobilize the armor (Sklar et al., 2009; Venditti et al., 2010a, b; Spiller et al., 2012). The presence of bedload sheets can reduce the stability of the armor armor stability by reducing the bed roughness and increasing the flow velocity (Iseya and Ikeda, 1987; Kuhnle and Southard, 1988; Recking et al., 2009; Bacchi et al., 2014). The conditions that characterize The conditions and parameters that determine the persistence or breakup of an armor layer remain open to discussion. The are still unclear. One of the problem is the fact that it is difficult to measure temporal changes of the bed surface texture during floods is difficult to measure peak flow in the field (Wilcock and DeTemple, 2005).Only in the field case by Vericat et al. (2006) measurements were conducted also during a flooding period.

The objective of the present this paper is to provide study the mechanisms of armor breakup and their consequences by providing detailed measurements of spatial and temporal changes of the bed surface texture under controlled laboratory conditionsto . The changes of the bed surface texture were measured during flow using the technique developed by Orrú et al. (2014, 2016). We examine the stability of an armor layer under high flow conditions and under peak flow under a limited sediment supply. The temporal changes of the bed surface texture was measured during flow using the technique experimental set-up was characterized by an initial streamwise fining pattern, following a previous laboratory study on armor formation in which a reach characterized by an initially gradual fining pattern under a limited sediment supply rate and partial transport conditions, developed into a more abrupt spatial transition in grain size and slope (Orrú et al., 2016).

The results presented by Orrú et al. (2016) . suggest a similarity with a gravel-sand transition (e.g., Yatsu, 1955; Shaw and Kellerhals, 1982; Parker, 1991a, b; Frings, 2011; Venditti et al., 2015), yet the mechanisms prevailing in the experiment were likely not comparable to the ones governing natural gravel-sand transitions. Relevant mechanisms in the development of a gravel-sand transition are the progradation of a gravel wedge (Paola et al., 1992; Seal et al., 1997), basin subsidence (Paola, 1988; Parker and Cui, 1998), base level change (Pickup and Warner, 1984; Sambrook Smith and Ferguson, 1995), and suspended load (Venditti and Church, 2014; Venditti et al., 2015), which do not play a role in the Orrú et al. (2016) experiment as well as in the current laboratory experiment. Nevertheless, the current experiments may provide insight in the co-existence of an armor and a sand patch during peak flow.

2 Experimental set-up

2.1 Experimental settings

The experiment was carried out at the Water Laboratory of the Faculty of Civil Engineering and Geosciences of Delft University of Technology. The experiment was conducted in a tilting flume that was 14 m long, 0.40 m wide, and 0.45 m high. The upstream water supply was controlled by a water pump and the downstream water level was set by a tailgate located at the downstream end of the flume. No sediment was supplied from upstream. At the downstream end of the flume the transported sediment was collected in a sediment trap.

An initial experiment (T1) was conducted to create an armor under low flow conditions. The flow conditions were increased in experiment T2 in order to test the stability of the armor layer (Fig. 2). The flow regime was subcritical in both experiments. During the initial experiment the water discharge was equal to 0.0465 . The downstream water surface elevation was adjusted during the first flow hours and maintained constant for the remainder of the experiment. The total duration of the initial experiment was 16 hours. At the beginning of experiment T2 the water discharge was set equal to 0.0547 and the downstream water surface elevation was decreased through lowering the tailgate. Water discharge and water surface elevation were maintained constant for the remainder of the experiment that lasted 4 hours.We used a trimodal sediment mixture which that was composed of a fine sand fraction ($D_{50,1}$ =1 mm) and two gravel fractions, a medium fraction ($D_{50,2}$ =6 mm) and a coarse fraction ($D_{50,3}$ =10 mm). The sediment fractions were painted in a different color different colors to enable measurements of the grain size distribution (GSD) of the bed surface using the image analysis technique of Orrú et al. (2016). The fine fraction was left with its natural color, the medium fraction was painted yellow green, and the coarse fraction was painted medium turquoise.

As mentioned above the experimental set-up was similar to the one by Orrú et al. (2016). Here we use a trimodal mixture rather than a bimodal one. The initial bed was installed with an imposed stepwise fining pattern. The upstream reach was composed of the trimodal mixture (the trimodal reach) and the downstream reach was composed of sand (the sand reach). The trimodal reach of experiment was characterized by 10 patches of compartments characterized by a length of 0.40 m . The (Fig. 1), and the length of the most upstream patch was equal to compartment was 0.88 m. The Each compartment was characterized by a different initial volumetric fraction content of the 3 fractions (Fig. 1). The sand content increased in streamwise direction in steps of 10 percent for each compartment. The bed slope was set equal to 0.0022. For further details about the characteristics of the bed and the method used to install it we refer the reader to Orrú et al. (2016). We refer to Orrú et al. (2016) for details regarding the method to install the initial bed.

An initial experiment (T1) was conducted to create an armor under base flow conditions. The flow conditions were increased in Experiment T2 to assess the stability of the armor under peak flow (Fig. 2). The flow regime was subcritical in both experiments. During the initial experiment the water discharge was equal to 0.0465 $\mathrm{m^3 s^{-1}}$. The downstream water surface elevation was adjusted during the first few flow hours and maintained constant for the remainder of the experiment. The total duration of Experiment T1 was 16 hours, and the time interval of experiment T1 is from -16 h to 0 h. At the beginning of Experiment T2 the water discharge was set equal to 0.0547 $\mathrm{m^3 s^{-1}}$ and the downstream water surface elevation was decreased through lowering the tailgate. For the remainder of the experiment water discharge and water surface elevation were maintained constant (Fig. 2). Experiment T2 lasted 4 hours, and the time interval of Experiment T2 is from 0 h to 4 h.

2.2 Measurements

The water discharge ~~and the~~ was constantly measured at the input water pipe using a flow meter that measured the travel time of an acoustic signal. Two laser instruments mounted on a carriage were used to measure longitudinal profiles of the bed and water surface elevations ~~were measured in the same way as presented by Orrú et al. (2016). The water surface elevation at~~ at the center of the flume approximately every 20 minutes. The laser instrument used to measure bed elevation was placed in a watertight eye-shaped box that was slightly submerged to avoid reflections of the signal on the water surface. At the downstream end of the flume (at x = 10.62 m) the water surface elevation was continuously measured using a pitot tube~~connected to a linear position sensor. The~~ . A linear position sensor was connected to the pitot tube by a hose and positioned ~~beside~~ besides the flume. The transported sediment was caught in a sediment trap at the downstream end of the flume. The sediment was pumped to a small tank which was placed on a scale ~~that measured~~ for measuring the submerged sediment mass.

The grain size distribution of the bed surface was measured during flow over the entire observation section (≈10 m). The measurements were taken using the image analysis technique developed by ~~Orrú et al. (2016)~~ Orrú et al. (2014, 2016), which is based on color segmentation, i.e. the division of the pixels of an image into color groups (Fig. 3). To this end each grain size fraction was painted in a different color. The equipment used to take the images of the bed surface was ~~here improved~~ composed of a carriage that enabled moving the equipment along the flume and a floating device (Fig. 4). ~~The~~ A camera was connected to the carriage. The floating device, which was slightly submerged, was connected to the carriage using PVC pipes. The lower pipes had a smaller diameter than the upper ones to allow for vertical motion of the floating device and automatic adjustment of the level of the floating device to spatial changes in the water surface elevation. The design and material of the floating part of the measurement equipment were ~~optimized to~~ here optimized compared to the one presented by Orrú et al. (2016) to reduce its submersion. ~~The~~ For this purpose the bottom of the upstream V-shaped part of the floating device was designed with a ~~certain~~ small inclination to obtain a lift force from the flow. The floating device was made out of thin transparent Plexiglas®. ~~Before processing the images of the bed surface we determined the polygons, to be used in the algorithm by Orrú et al. (2016). A new set of polygons was defined using target images created for the color combination used in these experiments.~~Six small LED lights were mounted on the frame of the floating device to illuminate the bed surface. The images of the bed surface were processed using a Matlab algorithm that provided the areal fraction content of a surface covered by a certain color (i.e., grain size). The areal fraction contents resulting from image analysis were converted into volumetric fractions applying the conversion model of Parker (1991a, b).

2.3 ~~Formation of the initial armor~~

3 Formation of the initial armor (Experiment T1)

In this section we briefly describe ~~the experiment~~ Experiment T1 conducted to create the ~~initial armor tested in experiment T2. Under~~ armor under the imposed supply limited conditions. Over the trimodal reach the ~~grain size selective processes occurring over the trimodal reach led to the formation of an armor (Fig. 5). The~~ initially high rate of sand entrainment combined with the slightly mobile gravel fractions quickly resulted in a coarse ~~and closed bed structure.A very~~ bed surface (Fig. 5). A limited amount of sand was available at the bed surface. In the remaining part of ~~experiment~~ Experiment T1 ~~when~~ the coarser fractions were less or no longer mobile (~~i.e., partial transport)~~ partial transport conditions) due to the formation of an armored bed structure that enhanced particle stability. The prevailing mechanisms were winnowing and the ~~prevalent mechanisms were the winnowing together with the~~ kinematic sieving of ~~the sand.~~ sand. Bed surface coarsening was observed between x = 1 m and x = 4.5 m (Fig. 5). Some randomly arranged irregularities over the armor created gaps between the gravel particles where the finer substrate was exposed.

The armoring occurring over the trimodal reach limited the sediment supplied to the sand reach, which resulted in a strong bed degradation over the sand reach (~~see later in~~ Fig. 6)~~(Orrú et al., 2016). The difference in~~ , as was observed by Orrú et al. (2016). This spatial difference in degradation resulted in a sudden decrease of the bed elevation between the trimodal and ~~sand reach in T1~~ the sand reach. Adjusting to limited sediment supply conditions the bed approached a final state that was characterized by zero sediment transport. For the sand reach, the state of zero sediment transport was governed by a much smaller flow velocity (and so larger flow depth) than for the upstream trimodal reach, which resulted in the observed step in bed elevation. This sudden decrease in bed elevation resulted in a streamwise increase in the water surface elevation~~. This is due to~~ , which is a Bernoulli effect (e.g., Douglas et al., 2005). The trimodal reach of Experiment T1 was characterized by the presence of an M1 backwater curve due to the different bed slopes and so flow depths between the ~~trimodal and sand reach~~two reaches. The final stage of the bed of ~~experiment~~ Experiment T1 was characterized by an abrupt transition in slope and bed surface texture between the ~~trimodal and sand reach~~ two reaches (Fig. 5)~~, which was accompanied by a large step in bed elevation (see later in Fig. 6).~~ .

The upstream section of the trimodal reach was governed by an imbricated structure (Fig. 7). ~~The armor~~ This structure formed in the initial part of the experiment when the gravel fractions were still slightly mobile. The particles quickly found a stable position that enhanced the armor stability. The armor was considered fully developed after 16 flow hours (i.e., at time 0 h) when no relevant changes of the bed surface texture were observed and the sediment transport rate reached approximately zero.

4 Breakup and reformation of the armor layer (Experiment T2)

4.1 Bed surface texture

At the beginning of the armor breakup experiment, Experiment T2, the flow velocity was increased by increasing the water discharge by 18 % and lowering the downstream water level (Fig. 2)~~to achieve fully mobile transport conditions over the trimodal and sand reach.~~

4.2 ~~Bed surface texture~~

. Armor breakup and reformation covered a ~~very~~ short period. After the increase of the ~~water discharge~~ flow velocity the armor started to ~~breakup~~ break up in several sections of the trimodal reach. In the upstream part of the trimodal reach the substrate was coarser due to a limited amount of sand and the bed was highly imbricated (Fig. 7). This imbrication enhanced armor stability and consequently some sections of the armor did not break up. Figure 8 shows a section of the trimodal reach where ~~a~~ some part of the armor was broken. Initially, the dislodgement of a few gravel particles enabled the entrainment of the finer subsurface material over a small section of the bed (Fig. 8a). Subsequently, the sand entrainment ~~enhanced~~ appeared to enhance the gravel mobility~~extending the breakup and~~ , which may have extended the breakup exposing the subsurface over a wider section (Fig. 8b). Blurriness in the images shown in Figures 8a, b indicates the entrainment of sand. The measurements of the ~~texture of the bed surface~~ bed surface texture show a fining of the bed between x = 1 ~~and~~ m and x = 4.5 ~~meters~~ m (Fig. 9~~and Fig.~~ 10). ~~Yet the fining was even stronger than we measured.~~ The measurement taken after 7 ~~minutes~~ min (point 3 ~~of~~ in Fig. 9) corresponds to the bed state of Figure 8c~~, and~~ . As we observed that the bed surface ~~was finer~~ at the moment of the breakup was finer(Fig. 8b), we hypothesize that the bed surface at the moment of the breakup ~~shown in~~ was finer (point 2 in Fig. 9) than the moment of Figure 8~~b (point 2 of~~ c (point 3 in Fig. 9)~~after about 4 minutes~~.
The breakup and bed surface fining ~~was~~ were quickly followed by the formation of a mobile armor that was coarser than the initial one (point 4 of Fig. 9~~and Fig. 10~~). The coarse sediment supplied from upstream enabled the formation of a new armor and the presence of gravel particles in the substrate aided ~~the~~ this armor reformation. After ~~the~~ armor reformation a ~~very~~ limited amount of sand was present at the bed surface (Fig. 9). The fact that the reformed armor was slightly coarser than the initial one resulted in a slight downstream coarsening in the gravel reach.

4.2 Bed elevation

The ~~breakup of the armored surface led to local degradation. The~~ total amount of degradation due to armor breakup depended on the ~~different~~ texture of the substrate material. In the upstream part of the trimodal reach the substrate was coarser ~~with limited amount of sand and the bed was highly imbricated (Fig. 7). This enhanced bed stability and consequently some sections of the armor did not breakup.~~ which limited bed degradation. We observed a lateral variation in degradation characterized by a stronger degradation at one side of the flume that is not evident in our measurements ~~(Fig. 6)~~ since bed profiles were measured only at the center of the flume. ~~As mentioned above, the more sandy substrate in the more downstream section~~

~~facilitated the lengthening of the breakup since the sand entrainment enhanced gravel mobility (Fig. 8a,b).~~ The breakup led to a fast degradation which was arrested by the reformation of the mobile armor (Fig. 6). The degradation was not uniform in streamwise direction~~(Figure 6)~~. Over the reach that suffered from the breakup the slope decreased to adjust to a situation with a shortage of sediment supply. The redistribution of the sediment led initially to aggradation downstream of the breakup area and subsequently to the progradation of the front between the trimodal ~~and~~ reach and the sand reach (Fig. 6). The progradation had ceased at the end of the experiment.

The ~~approach towards an equilibrium state characterized by zero sediment supply was also observed in the~~ decrease of the slope made the bed locally approach normal flow conditions, which indicates a state in which the slope of the water surface is equal to the slope of the channel bed. If boundary conditions of a reach (i.e., upstream water discharge and sediment supply rate, as well as the downstream water surface elevation) are constant for a sufficiently long time, it will reach normal flow conditions (provided that particle abrasion, tributaries, and subsidence or uplift do not play a role). Yet, under conditions of partial transport, in which the coarse fractions of the sediment are immobile, the associated armor can prevent this adaptation of the bed and its approach to normal flow conditions (see Experiment T1 and Orrú et al. (2016)). Here armor breakup enabled adjustment of the bed slope such that the bed slope became closer to the water surface slope and the final bed configuration was closer to normal flow.

During Experiment T1 and T2 the hydraulic conditions not only varied spatially but also temporally (Fig. 11). The adjustment to the limited sediment supply led to a coarsening over the trimodal reach and a larger flow depth over the sand reach (Fig. 11a). Due to the temporal increase of the water discharge and a lowering of the downstream water surface elevation, flow velocities were increased in Experiment T2 relative to Experiment T1. The highest flow velocities were present at the moment of armor breakup (Fig. 11b). Both experiment were characterized by a subcritical flow regime (Fig. 11c). Shields stress values for each sediment fraction were determined accounting for the sidewall correction of Vanoni and Brooks (1957). Highest Shields stress values over the trimodal reach were observed when the armor broke up (Fig. 11d, e, f). Despite the high Shields stress values observed over the entire trimodal reach, the breakup was local and not uniform over the reach. Reformation of the mobile armor was associated with a decrease of the Shields stress (Fig. 11d, e, f).

Figure 12 shows the local sediment transport rate computed from the migration of the front between the trimodal reach and the sand reach (Fig. 12a), as well as the sediment transport rate ~~at the front position (Figure 12). We determined the local sediment transport rate at the front q_{front}~~ measured at the downstream end of the flume (Fig. 12~~) from the~~ b). We determined the local sediment transport rate at the position of the front, q_{front}, from the streamwise migration speed of the front as proposed by Bagnold (1941) ~~in~~ using the simple-wave relation:

$$c = \frac{q_{front}}{c_b \Delta} \quad (1)$$

where c denotes the migration speed of the prograding front in streamwise direction (here determined at the crest), $c_b = 1 - p$, p being the bed porosity (we assume $p = 0.4$) and Δ denotes the height of the prograding front.

The sediment ~~transport rate~~ load at the front was composed of the 3 grain size fractions, whereas the sediment load at the downstream end of the flume was composed of mainly the sand fraction. The transport rates at the front ~~shows a sudden~~

~~increase due to the occurrence of the armor breakup~~ and downstream end of the flume are of the same order of magnitude (Fig. 12). At both locations the sediment transport rate shows a (sudden) increase, which was followed by a gradual decrease. The ~~increase~~ peak in the sediment transport rate ~~coincides with the~~ at the downstream end of the flume shows a time lag. Also the decrease in the sediment transport rate was slower than at the front. The sediment transport rate at the front increased as a result of the armor breakup. This increase at the front coincided with the rapid entrainment of the substrate material and the decrease ~~with the~~ of the sediment transport rate corresponded to the reformation of the mobile armor. Yet, the sediment transport rate at the downstream end seemed to be less affected by the breakup and seemed to respond to primarily the increased flow rate.

5 Discussion

Our experiment indicates that armor breakup and reformation can be a fast process and that the resulting changes in bed elevation may be limited. Information on the time scales of armor breakup and reformation and the order of magnitude of resulting bed elevation changes may be relevant to flood risk and navigation studies over armored reaches, for instance in the upstream part of the IJssel branch of the Dutch Rhine. The dislodgement of armor particles may expose and release fine sediment from the substrate and such sudden supply of fine sediment may result in local aggradation in the downstream reach that creates problems to navigation. The stability of an armor is also of interest to the design of granular filters aimed at protecting structures from scour and in the operation of dams, for instance in the design of flushing flows undertaken to release sediment from a reservoir.

It is still difficult to predict armor breakup. This is due to (a) the possible randomness associated with the position of the breakup, and (b) the fact that its mechanisms are not sufficiently clear. Here and in the studies by Vericat et al. (2006) and Wang and Liu (2009) the increase of the flow discharge led to an increase in the sediment mobility, which caused the armor to break up. The results of our experiment showed an almost uniform increase of the Shields stress over the trimodal reach, however the breakup was local and its position seemed to be random. Let us consider causes additional to an increased sediment mobility that may have played role in the breakup process in our experiment. Sediment supplied from upstream may induce breakup by destabilizing the armor (Spiller et al., 2012). Such mobilization has been encountered when finer material is supplied to the armor surface (Sklar et al., 2009; Venditti et al., 2010a, b; Spiller et al., 2012). By filling the gaps of the coarse surface the fine sediment reduces the bed friction, which increases the flow velocity. A similar process occurs when bed friction is reduced due to the transport of finer material in bedload sheets (Iseya and Ikeda, 1987; Kuhnle and Southard, 1988; Recking et al., 2009; Bacchi et al., 2014). These potential causes can be ruled out in our experiment because the material supplied from the upstream slightly degrading section was mainly coarse. We expect that the destabilization of the armor may also be ascribed to the impact of transported particles onto the gravel particles that are at rest. Klaassen (1988) attributed the destabilization of the armor in his experiments to turbulence originated by migrating bedforms. In our plane bed experiment additional turbulence may have been created by irregularities at the armor surface. Turbulence and the resulting pressure fluctuations due to these irregularities may have caused or increased entrainment of sand from the sandy substrate in the more downstream part of the trimodal reach, which may have enhanced gravel mobility and facilitated the lengthening of the breakup.

The moment of the breakup was characterized by an increase of the bed load transport rate, which was also observed in the laboratory experiments of Klaassen (1988) and Wang and Liu (2009). The increase in the sediment transport rate was rapid and sudden and corresponded to the mobility of the armor particles and the entrainment of the finer substrate material. A temporal fining of the bed surface characterized the moment of the breakup and it was followed by a coarsening ~~that led~~ due to the reformation of an armor that was coarser than the initial one. Similar results were presented by Vericat et al. (2006), however in their case armor reformation occurred only under base flow. In ~~the~~ their field case the increased degree of armoring was caused by partial transport conditions. In our experiment the ~~coarser armor formed under continued high~~ armor reformed under continued peak flow conditions. The coarser upstream section acted as a source of sediment for the finer downstream reach. This supply provided the replacement for the ~~material entrained , likely causing the~~ entrained material, likely resulting in a quick reformation of the armor. The gravel present in the original substrate may have aided armor reformation. Possible causes of the ~~formation of an armor~~ fact that the reformed armor was coarser than the initial one are: (a) the supply from upstream being mostly gravel, (b) the sand supplied from upstream not being trapped in the zone of the broken up armor, and (c) the higher flow rate not allowing for the sand to deposit and remain between the gravel particles.

~~Here and in the studies by Vericat et al. (2006) and Wang and Liu (2009) the increase of~~ Similar to the experiment of Orrú et al. (2016), Experiment T1 showed the development of a reach characterized by a gradual fining pattern and uniform slope into an abrupt transition in bed surface grain size and slope as encountered in natural gravel-sand transitions (e.g., Yatsu, 1955; Shaw and Kellerhals, 1982; Parker, 1991a, b; Frings, 2011; Venditti et al., 2015). Here Experiment T2 provides new insights in the ~~flow discharge caused the armor breakup. Other causes have been found in other studies. Sediment supplied from upstream may induce the breakup by destabilizing the armor (Spiller et al., 2012). This mobilization has been encountered when finer material is added to the armor surface (Sklar et al., 2009; Venditti et al., 2010a, b; Spiller et al., 2012). The fine sediment reduces the mean grain size of the bed surface and by filling the gaps of the coarser surface reduces the bed friction that increases the flow velocity. A similar process occurs when bed friction is reduced due to the transport of finer material in bedload sheets (Iseya and Ikeda, 1987; Kuhnle and Southard, 1988; Recking et al., 2009; Bacchi et al., 2014). These potential causes can be ruled out in our case because the material supplied from the upstream slightly degrading section was coarse. The destabilization of the armor might be ascribed to the impact of transported particles onto the gravel particles that were at rest. The turbulence created at the bed surface might be another potential cause. Klaassen (1988) attributed the destabilization of~~ co-existence of an armor and a sand reach during peak flow such as: the starvation and degradation of the ~~armor in his experiments to additional turbulence originated by migrating bedforms. In our plane bed conditions additional turbulence might be created by the presence of irregularities in the armor surface~~sand reach, progradation of the gravel front, impact of a reduced slope on the progradation of the gravel front and armor reformation.

6 Conclusions

A flume experiment was conducted to investigate the stability of an armor under conditions with a limited sediment supply. The armor was formed formed over a bed initially characterized by a gradual fining pattern under base flow conditions. The armor locally broke up after an increase of the flow rate and rapidly reformed under continued peak flow conditions. Despite the fact that the Shields stress almost uniformly increased over the trimodal reach, the breakup was local and not uniform over the reach. Besides the increased flow rate multiple factors may have contributed to the armor breakup such as the impact of coarse sediment supplied from upstream and turbulence created due to irregularities of the armored surface.

The breakup was characterized by a temporal fining of the bed surface due to local degradation and the exposure of finer substrate sedimentand local degradation. After the armor breakup, an armorquickly reformed that . Despite the limited sediment supply conditions after the armor breakup a new armor, which was coarser than the initial one, quickly formed. Coarse sediment supplied by the upstream degrading reach aided by the gravel in the substrate sediment provided the sediment required for the armor to reform. A sudden , which was aided by the gravel in the substrate sediment. Armor breakup coincided with a sudden and local increase of the local sediment transport rate identified the moment of the armor breakup and it due to the entrainment of the finer substrate material. This was followed by a gradual decreasecorresponding , which corresponded to the armor reformation. The breakup of the armor surface enabled the bed slope to adjust to a situation led to a decrease of the Shields stress and the local bed slope.

Partial transport conditions can prevent the adjustment of the bed and the approach to normal flow conditions (i.e., the equilibrium state was characterized by a backwater). Here armor breakup enabled the adjustment of the bed slope such that the final bed configuration was closer to normal flowconditions., i.e., the bed slope was closer to the water surface slope.

Acknowledgements. The authors especially thank the technicians of the Water Laboratory of Delft University of Technology for their assistance during the experiments.

References

Andrews, E. D. and Erman, D. C.: Persistence in the size distribution of surficial bed material during an extreme snowmelt flood, Water Resources Research, 22, 191–197, doi:10.1029/WR022i002p00191, 1986.

Bacchi, V., Recking, A., Eckert, N., Frey, P., Piton, G., and Naaim, M.: The effects of kinetic sorting on sediment mobility on steep slopes, Earth Surface Processes and Landforms, 39, 1075–1086, doi:10.1002/esp.3564, 2014.

Bagnold, R. A.: The physics of blown sand and desert dunes, Methuen, New York, 1941.

Church, M., Hassan, M. A., and Wolcott, J. F.: Stabilizing self-organized structures in gravel-bed stream channels: Field and experimental observations, Water Resources Research, 34, 3169–3179, doi:10.1029/98WR00484, 1998.

Clayton, J. A. and Pitlick, J.: Persistence of the surface texture of a gravel-bed river during a large flood, Earth Surface Processes and Landforms, 33, 661–673, doi:10.1002/esp.1567, 2008.

Curran, J. and Waters, K. A.: The importance of bed sediment sand content for the structure of a static armor layer in a gravel bed river, Journal of Geophysical Research: Earth Surface, 119, 1484–1497, doi:10.1002/2014JF003143, 2014.

Dietrich, W., Kirchner, J., Ikeda, H., and Iseya, F.: Sediment supply and the development of the coarse surface layer in gravel-bedded rivers, Nature, 340, 215–217, http://www.scopus.com/inward/record.url?eid=2-s2.0-0024484846&partnerID=40&md5=8c9321613ca19a84e3557d3dd4262c54, 1989.

Douglas, J., Gasiorek, J., Swaffield, J., and Jack, L.: Fluid Mechanics. Fifth edition, 2005.

Frings, R. M.: Sedimentary characteristics of the gravel–sand transition in the River Rhine, Journal of Sedimentary Research, 81, 52–63, 2011.

Guney, M., Bombar, G., and Aksoy, A.: Experimental Study of the Coarse Surface Development Effect on the Bimodal Bed-Load Transport under Unsteady Flow Conditions, Journal of Hydraulic Engineering, 139, 12–21, doi:10.1061/(ASCE)HY.1943-7900.0000640, 2013.

Hassan, M. A. and Church, M.: Experiments on surface structure and partial sediment transport on a gravel bed, Water Resources Research, 36, 1885–1895, doi:10.1029/2000WR900055, 2000.

Hassan, M. A., Egozi, R., and Parker, G.: Experiments on the effect of hydrograph characteristics on vertical grain sorting in gravel bed rivers, Water Resources Research, 42, W09 408, doi:10.1029/2005WR004707, 2006.

Heays, K. G., Friedrich, H., and Melville, B. W.: Laboratory study of gravel-bed cluster formation and disintegration, Water Resources Research, 50, 2227–2241, doi:10.1002/2013WR014208, 2014.

Iseya, F. and Ikeda, H.: Pulsations in Bedload Transport Rates Induced by a Longitudinal Sediment Sorting: A Flume Study Using Sand and Gravel Mixtures, Geografiska Annaler. Series A, Physical Geography, 69, 15–27, http://www.jstor.org/stable/521363, 1987.

Jain, S.: Armor or Pavement, Journal of Hydraulic Engineering, 116, 436–440, doi:10.1061/(ASCE)0733-9429(1990)116:3(436), 1990.

Klaassen, G. J.: Armoured river beds during flood, Tech. Rep. 394, Delft Hydraulics, Emmeloord, The Netherlands, 1988.

Kuhnle, R. A. and Southard, J. B.: Bed load transport fluctuations in a gravel bed laboratory channel, Water Resources Research, 24, 247–260, doi:10.1029/WR024i002p00247, 1988.

Mao, L., Cooper, J. R., and Frostick, L. E.: Grain size and topographical differences between static and mobile armour layers, Earth Surface Processes and Landforms, 36, 1321–1334, doi:10.1002/esp.2156, 2011.

Marion, A. and Fraccarollo, L.: Experimental investigation of mobile armoring development, Water Resources Research, 33, 1447–1453, doi:10.1029/97WR00705, 1997.

Orrú, C., Chavarrías, V., Uijttewaal, W. S. J., and Blom, A.: Image analysis for measuring the size stratification in sand-gravel laboratory experiments, Earth Surface Dynamics, 2, 217–232, doi:10.5194/esurf-2-217-2014, http://www.earth-surf-dynam.net/2/217/2014/, 2014.

Orrú, C., Blom, A., Chavarrías, V., Ferrara, V., and Stecca, G.: A new technique for measuring the bed surface grain size distribution during flow and application to a degradational sand-gravel laboratory experiment, Water Resources Research, 2016.

Paola, C.: Subsidence and gravel transport in alluvial basins, in: New perspectives in basin analysis, pp. 231–243, Springer, 1988.

Paola, C., Parker, G., Seal, R., Sinha, S. K., Southard, J. B., and Wilcock, P. R.: Downstream Fining by Selective Deposition in a Laboratory Flume, Science, 258, 1757–1760, doi:10.1126/science.258.5089.1757, http://www.sciencemag.org/content/258/5089/1757.abstract, 1992.

Parker, G.: Selective Sorting and Abrasion of River Gravel. I: Theory, Journal of Hydraulic Engineering, 117, 131–147, doi:10.1061/(ASCE)0733-9429(1991)117:2(131), 1991a.

Parker, G.: Selective Sorting and Abrasion of River Gravel. II: Applications, Journal of Hydraulic Engineering, 117, 150–171, doi:10.1061/(ASCE)0733-9429(1991)117:2(150), 1991b.

Parker, G. and Cui, Y.: The arrested gravel front: stable gravel-sand transitions in rivers Part 1: Simplified analytical solution, Journal of Hydraulic Research, 36, 75–100, doi:10.1080/00221689809498379, http://www.tandfonline.com/doi/abs/10.1080/00221689809498379, 1998.

Parker, G. and Klingeman, P.: On why gravel bed streams are paved, Water Resources Research, 18, 1409–1423, doi:10.1029/WR018i005p01409, 1982.

Pickup, G. and Warner, R.: Geomorphology of tropical rivers II. Channel adjustment to sediment load and discharge in the Fly and lower Purari, Papua New Guinea, Catena Supplement, 5, 18–41, 1984.

Piedra, M. M., Haynes, H., and Hoey, T. B.: The spatial distribution of coarse surface grains and the stability of gravel river beds, Sedimentology, 59, 1014–1029, doi:10.1111/j.1365-3091.2011.01290.x, 2012.

Recking, A., Frey, P., Paquier, A., and Belleudy, P.: An experimental investigation of mechanisms involved in bed load sheet production and migration, Journal of Geophysical Research: Earth Surface, 114, F03 010, doi:10.1029/2008JF000990, 2009.

Sambrook Smith, G. H. and Ferguson, R. I.: The gravel-sand transition along river channels, Journal of Sedimentary Research, 65, 423–430, 1995.

Seal, R., Paola, C., Parker, G., Southard, J., and Wilcock, P. R.: Experiments on Downstream Fining of Gravel I: Narrow-Channel Runs, Journal of Hydraulic Engineering, 123, 874–884, doi:10.1061/(ASCE)0733-9429(1997)123:10(874), 1997.

Shaw, J. and Kellerhals, R.: The Composition of Recent Alluvial Gravels in Alberta River Beds, Bulletin (Alberta Research Council), Alberta Geological Survey and Alberta Research Council, http://books.google.nl/books?id=ByPNSgAACAAJ, 1982.

Sklar, L. S., Fadde, J., Venditti, J. G., Nelson, P., Wydzga, M. A., Cui, Y., and Dietrich, W. E.: Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams, Water Resources Research, 45, W08 439, doi:10.1029/2008WR007346, 2009.

Spiller, S., Rüther, N., Koll, K., and Koll, K.: Bed load movement over a fully developed armor layer–A tracer experiment, in: River Flow 2012, pp. 465–471, CRC Press, doi:10.1201/b13250-72, 2012.

Vanoni, V. and Brooks, N.: Laboratory Studies of the Roughness and Suspended Load of Alluvial Streams, MRD Sediment Series, California Institute of Technology Sedimentation Laboratory, https://books.google.nl/books?id=sccBYAAACAAJ, 1957.

Venditti, J. G. and Church, M.: Morphology and controls on the position of a gravel-sand transition: Fraser River, British Columbia, Journal of Geophysical Research: Earth Surface, 119, 1959–1976, doi:10.1002/2014JF003147, 2014.

Venditti, J. G., Dietrich, W. E., Nelson, P. A., Wydzga, M. A., Fadde, J., and Sklar, L. S.: Mobilization of coarse surface layers in gravel-bedded rivers by finer gravel bed load, Water Resources Research, 46, W07 506, doi:10.1029/2009WR008329, 2010a.

Venditti, J. G., Dietrich, W. E., Nelson, P. A., Wydzga, M. A., Fadde, J., and Sklar, L. S.: Effect of sediment pulse grain size on sediment transport rates and bed mobility in gravel bed rivers, Journal of Geophysical Research: Earth Surface, 115, F03 039, doi:10.1029/2009JF001418, 2010b.

Venditti, J. G., Domarad, N., Church, M., and Rennie, C. D.: The gravel-sand transition: Sediment dynamics in a diffuse extension, Journal of Geophysical Research: Earth Surface, 120, 943–963, doi:10.1002/2014JF003328, http://dx.doi.org/10.1002/2014JF003328, 2015.

Vericat, D., Batalla, R. J., and Garcia, C.: Breakup and reestablishment of the armour layer in a large gravel-bed river below dams: The lower Ebro, Geomorphology, 76, 122–136, doi:10.1016/j.geomorph.2005.10.005, http://www.sciencedirect.com/science/article/pii/S0169555X05003399, 2006.

Wang, T. and Liu, X.: The Breakup of Armor Layer in a Gravel-Bed Stream with No Sediment Supply, in: Advances in Water Resources and Hydraulic Engineering, pp. 919–923, Springer Berlin Heidelberg, doi:10.1007/978-3-540-89465-0_161, 2009.

Wilcock, P. R. and DeTemple, B. T.: Persistence of armor layers in gravel-bed streams, Geophysical Research Letters, 32, L08 402, doi:10.1029/2004GL021772, 2005.

Yager, E., Kenworthy, M., and Monsalve, A.: Taking the river inside: Fundamental advances from laboratory experiments in measuring and understanding bedload transport processes, Geomorphology, 244, 21–32, doi:http://dx.doi.org/10.1016/j.geomorph.2015.04.002, http://www.sciencedirect.com/science/article/pii/S0169555X15001993, laboratory Experiments in Geomorphology 46th Annual Binghamton Geomorphology Symposium 18-20 September 2015, 2015.

Yatsu, E.: On the longitudinal profile of the graded river, Eos, Transactions American Geophysical Union, 36, 655–663, doi:10.1029/TR036i004p00655, 1955.

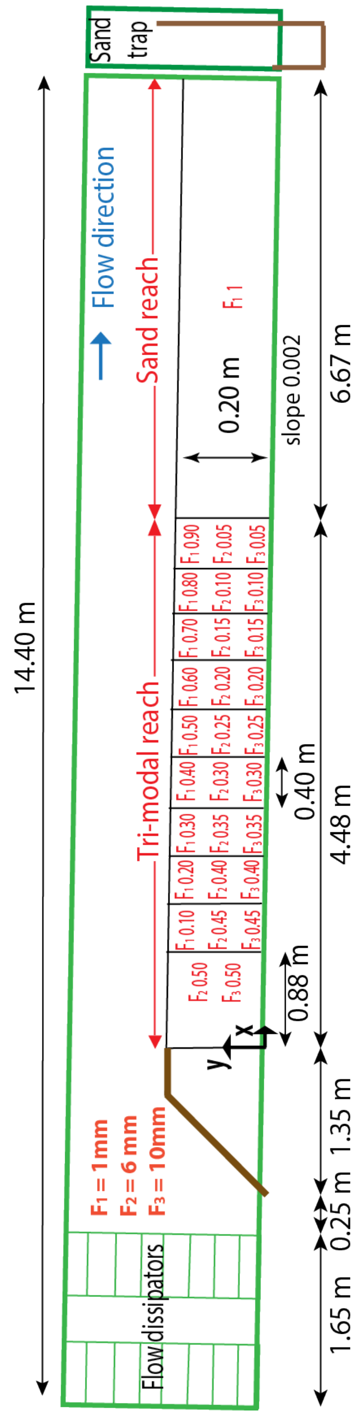

Figure 1. Flume set up and initial bed for Experiment T1. The red numbers indicate the volumetric gravel fraction content in each compartment.

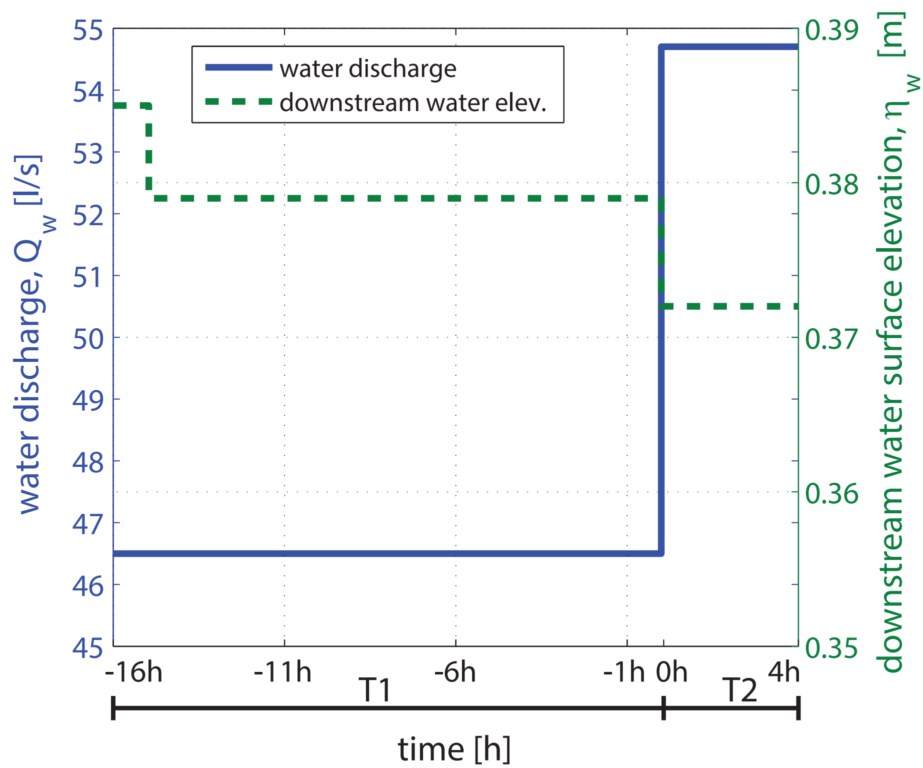

Figure 2. Water discharge, Q_w, and base level (i.e., water surface elevation at the downstream end), η_w, imposed in ~~the laboratory experiments~~ Experiments T1 and T2. The water surface elevation was measured at x = 10.62 m.

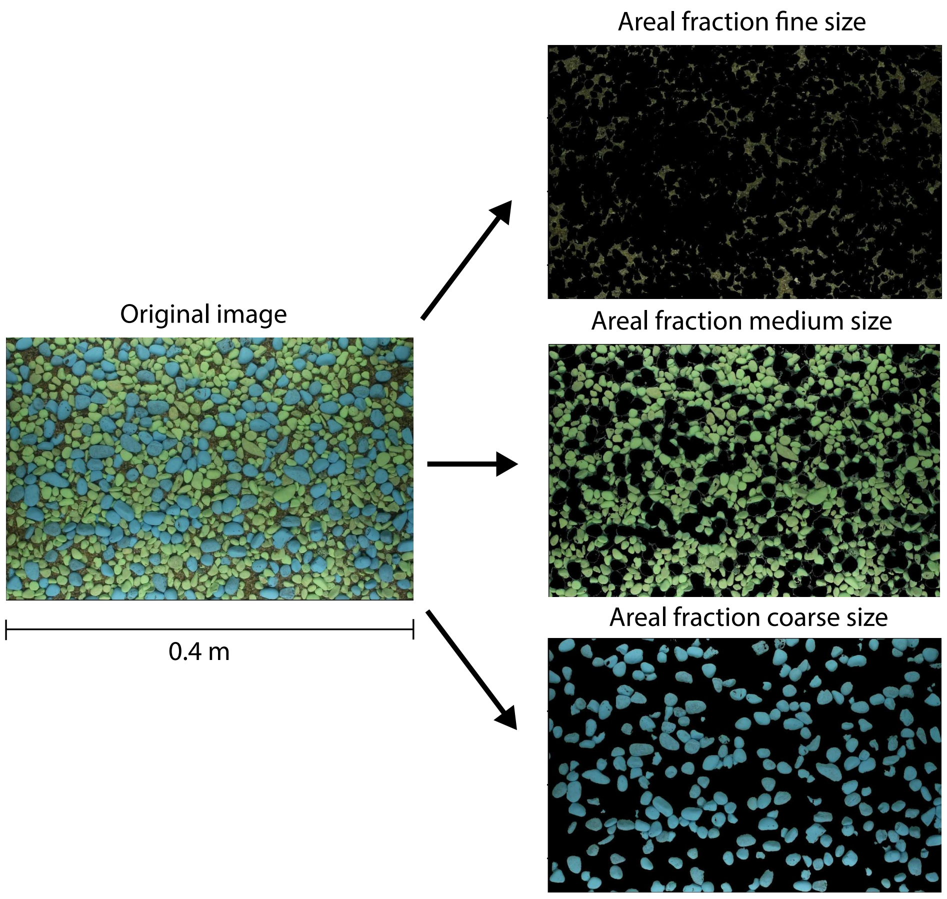

Figure 3. Example of color segmentation for an image of the bed surface ~~used~~ applied to determine the grain size distribution of the bed surface.

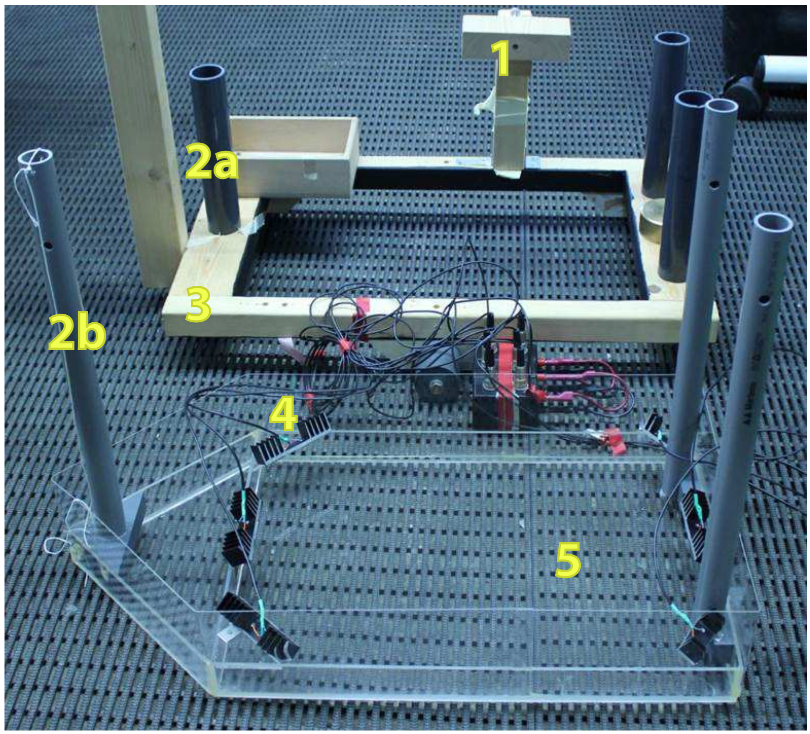

Figure 4. ~~New floating~~ Floating part of the equipment ~~to measure~~ for measuring the grain size distribution of the bed surface during the laboratory ~~experiment~~experiments. ~~The~~ Here the bottom and the walls of the floating part are ~~now~~ made of thin Plexiglas® plates and higher Plexiglas® sheets are attached ~~around~~ along the walls ~~as a protection from possible~~ to avoid water overflow. The numbers indicate: (1) position of the camera, (2a) upper pipe, (2b) lower pipe, (3) carriage, (4) ~~led~~ LED light attached to the cooling plate, and (5) floating part.

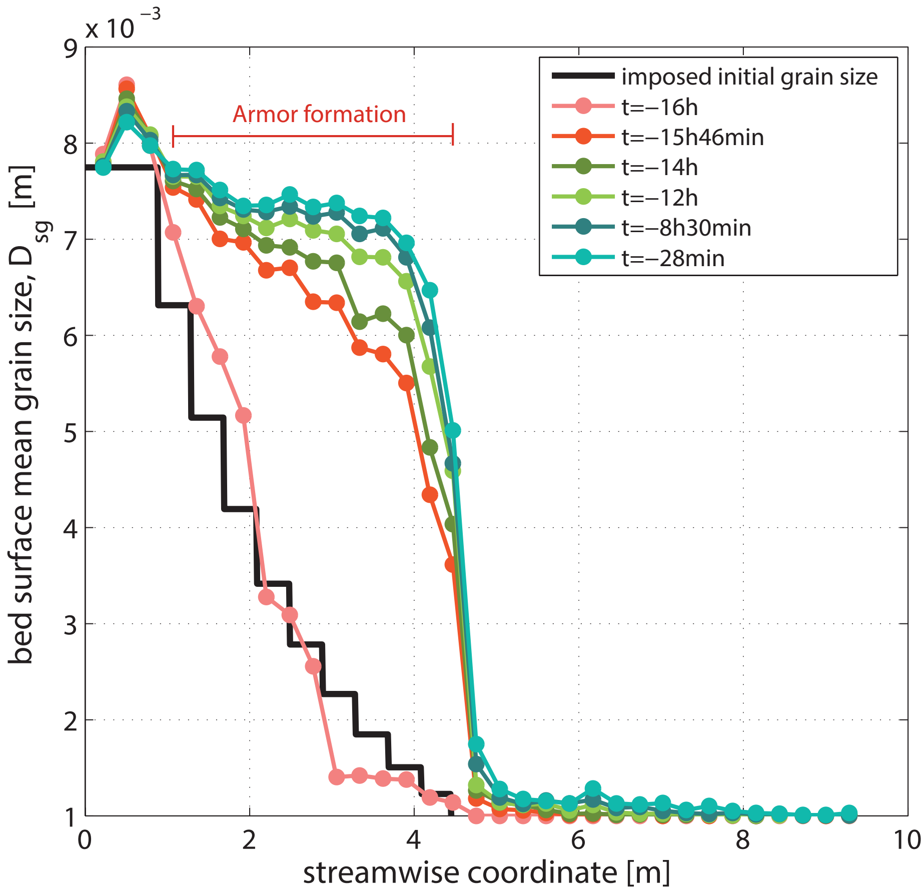

Figure 5. Imposed and measured geometric mean grain size of the bed surface sediment at various times for ~~experiment~~ Experiment T1.

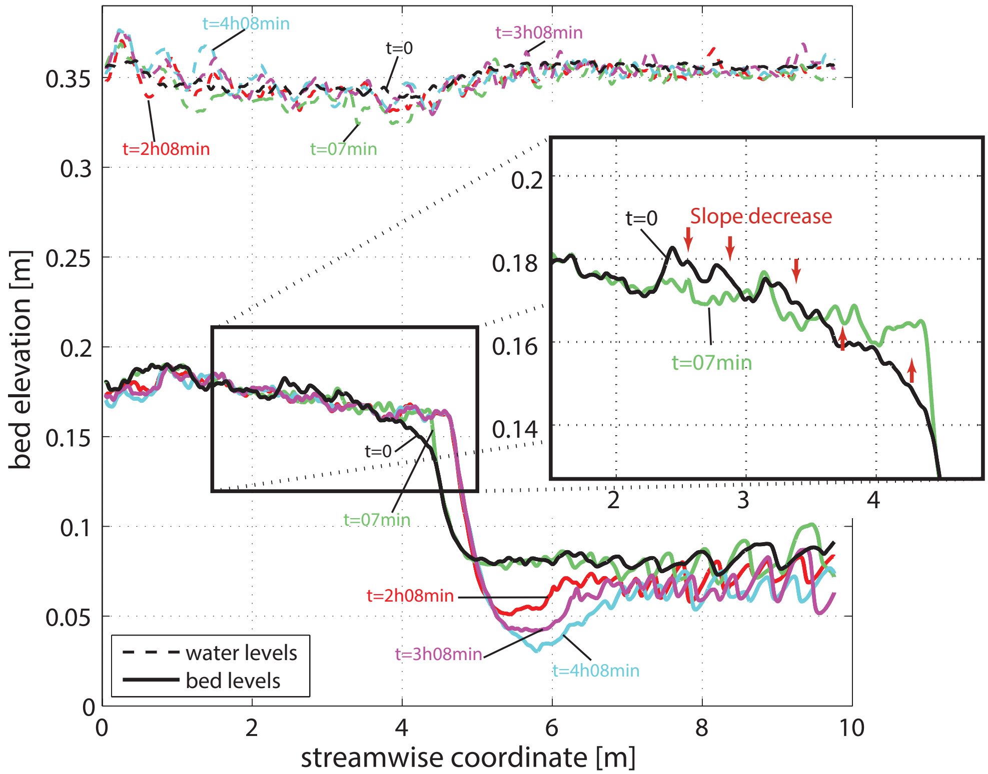

Figure 6. Measured water surface and bed elevation profiles of Experiment T2 at t=0h, 07min, 2h08min, 3h08min, and 4h08min. The zoomed window shows the degradation occurring during the armor breakup. Flow is from left to right. The profiles were smoothed using a Gaussian filter.

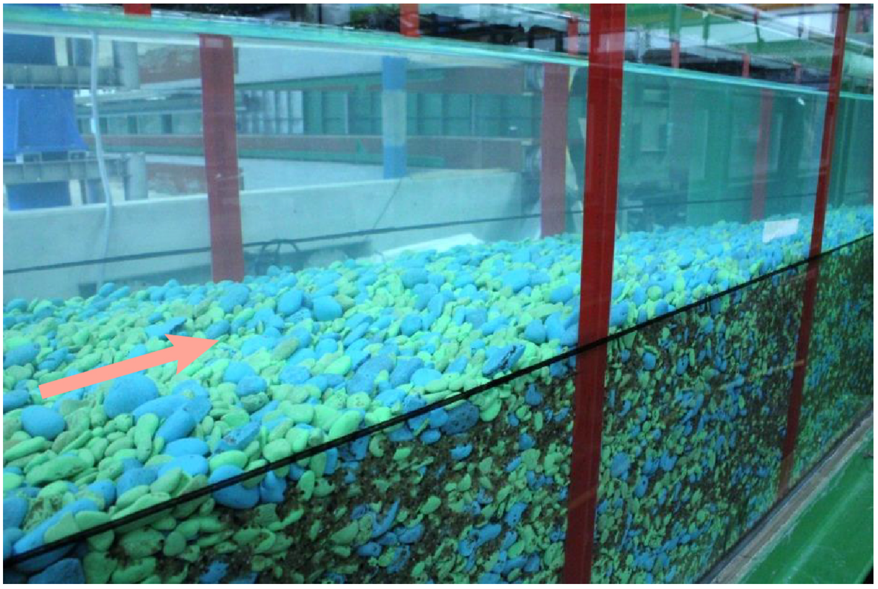

Figure 7. Imbrication of the bed surface sediment at the end of ~~experiment~~ Experiment T1. Flow is from left to right.

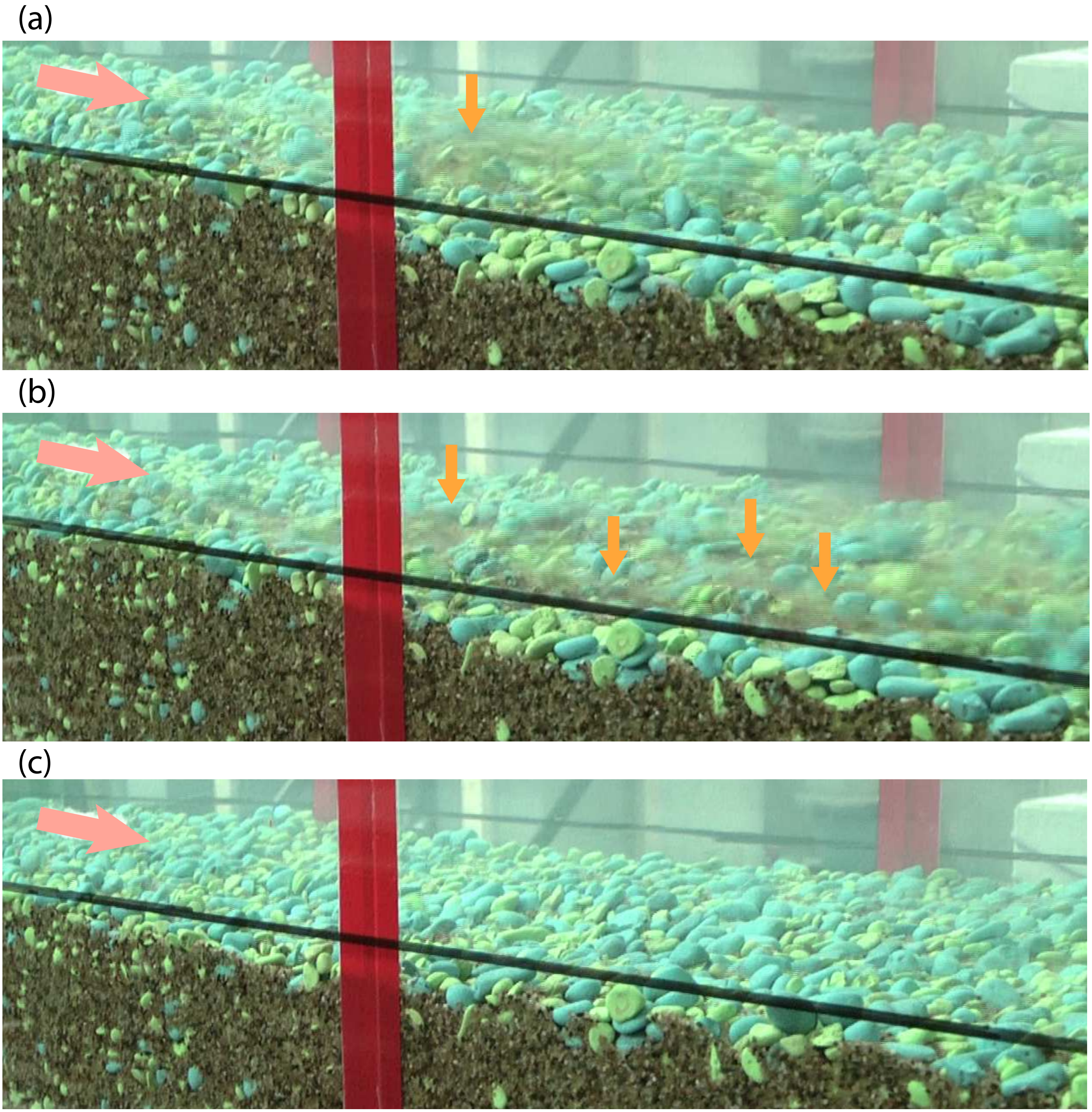

Figure 8. Armor breakup and reformation between ~~compartment~~ Compartments 6 and 7: (a) initial local breakup, (b) widening of the breakup and exposure of the finer substrate, (c) ~~initial~~ reformation of the mobile armor. Flow is from left to right. Blurriness in images (a) and (b) indicates the entrainment of sand (orange arrows).

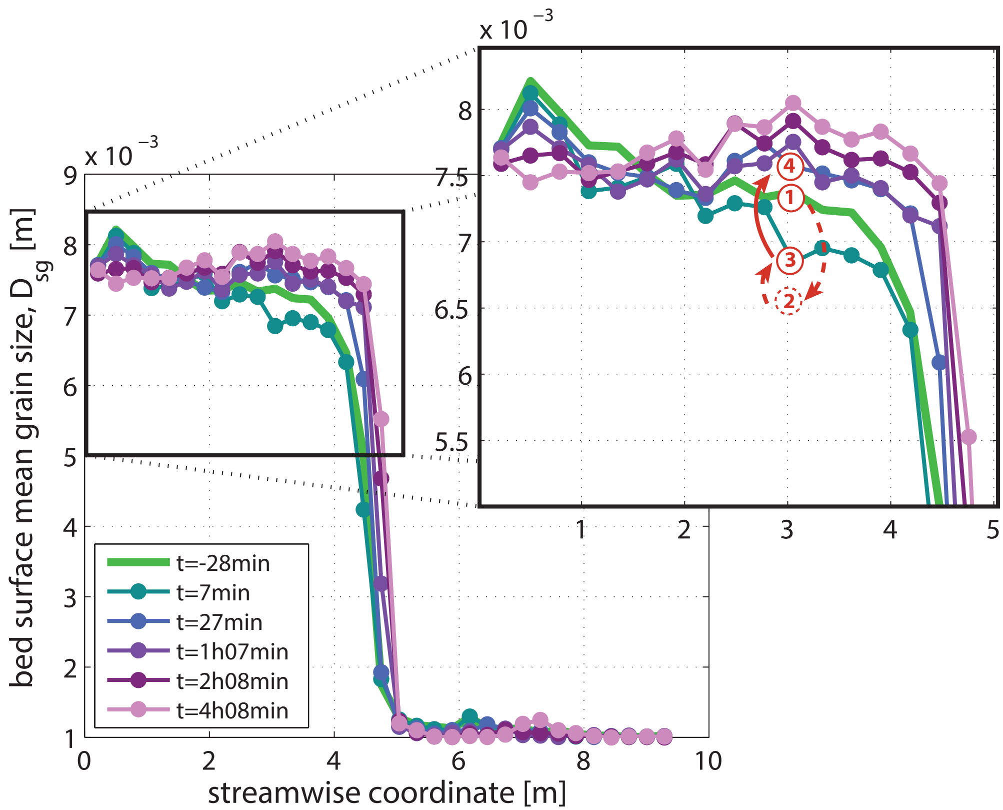

Figure 9. Measured geometric mean grain size of the bed surface sediment at various times for ~~experiment~~ Experiment T2. Point 1 to 4 in the zoomed window show the temporal change of the bed surface~~where point~~. Point 2 indicates a hypothetical (i.e., not measured, see Fig. 8b) finer surface at the moment of the breakup~~. Please note that~~; point 3 corresponds to the coarser bed surface shown in Fig. 8c right after the reformation of the armor.

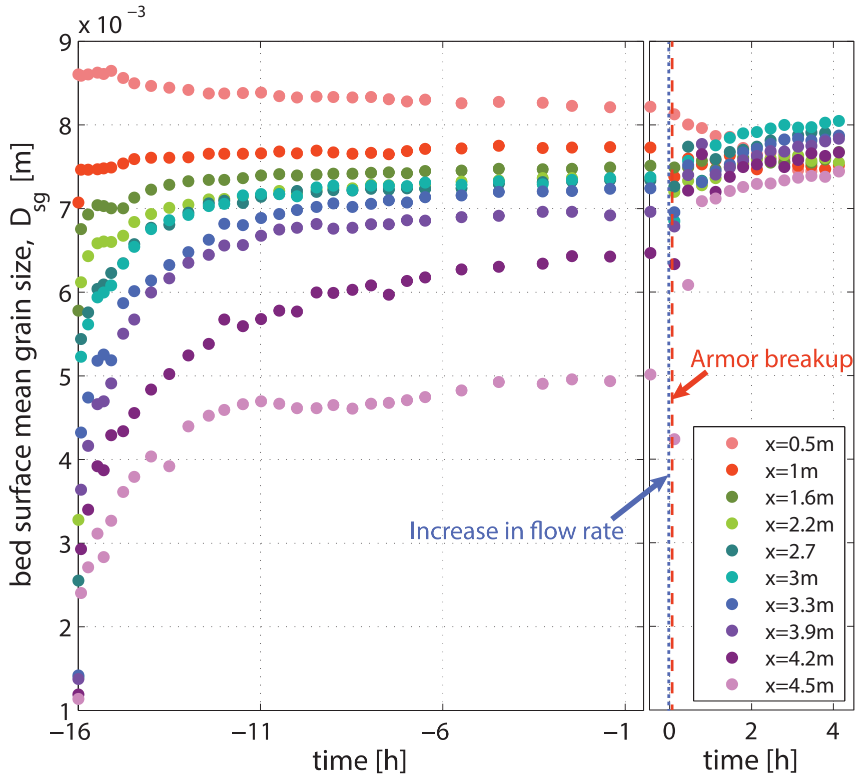

Figure 10. Measured change of the geometric mean grain size of the bed surface sediment at various locations in ~~experiment~~ Experiments T1 and T2. The blue ~~dashed~~ dotted line indicates the moment of the increase in flow rate (t=0 h) and the red dashed line indicates the moment of armor breakup (t=4 min).

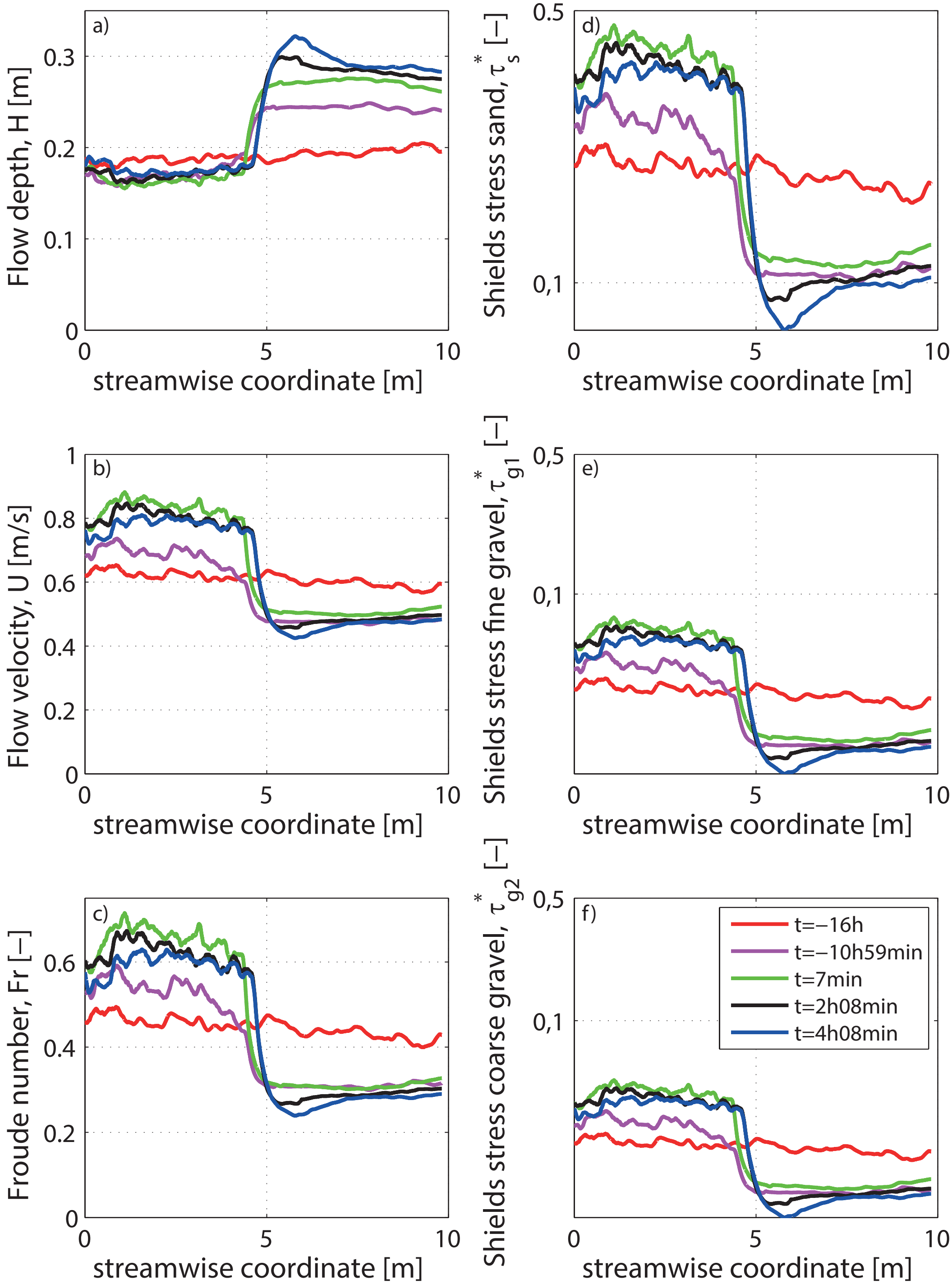

Figure 11. ~~Measured water surface and bed elevation profiles~~ Hydraulic conditions of experiment T1 and T2~~at t=0~~: (a) flow depth, ~~after 07~~(b) flow velocity, ~~208~~(c) Froude number, ~~308and after 408. The zoomed window shows~~ (d) Shields stress for the ~~degradation occurring during~~ sand fraction (logarithmic scale), (e) Shields stress for the ~~armor breakup~~fine gravel fraction (logarithmic scale), (f) Shields stress for the coarse gravel fraction (logarithmic scale). ~~Flow is from left to right.~~ The ~~profiles~~ Shields stress values were ~~smoothed by~~ determined accounting for a ~~Gaussian filter~~sidewall correction due to Vanoni and Brooks (1957).

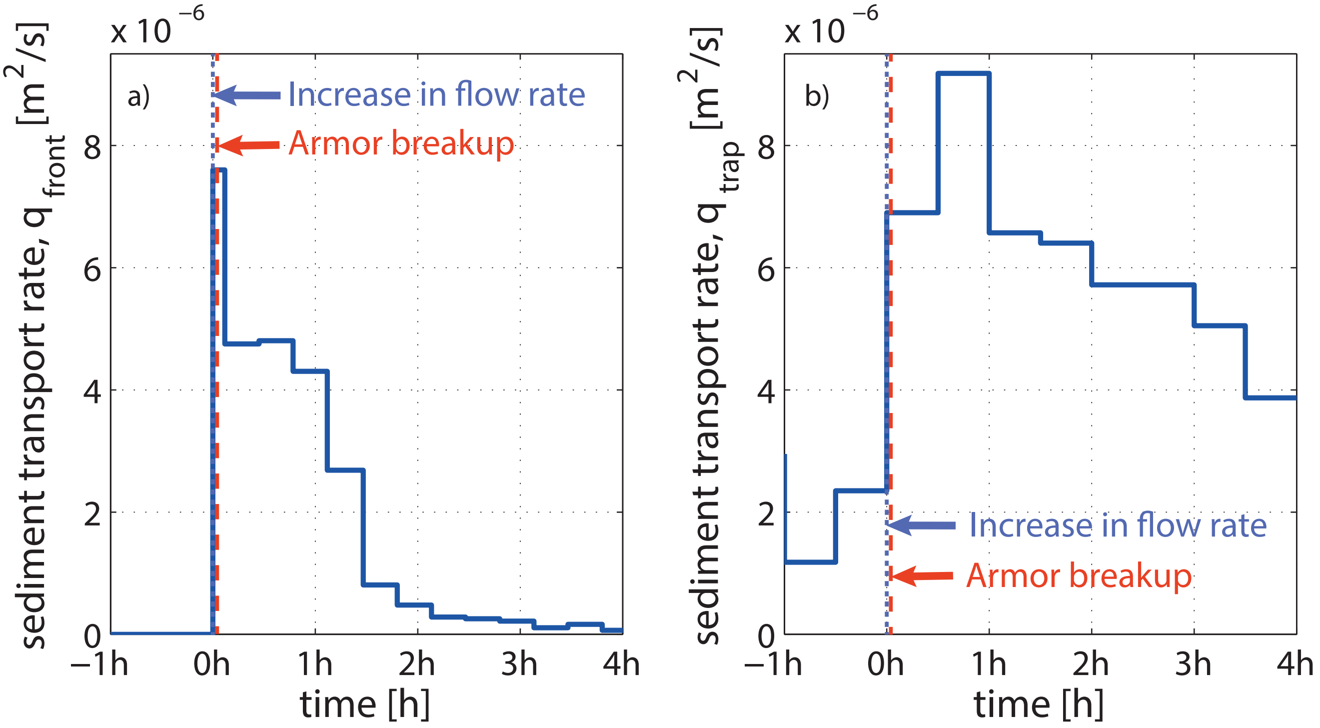

Figure 12. ~~Local~~ Measured sediment transport rate (a) computed from the migration of the front between the trimodal reach and the sand reach using Eq. (1), (b) at the downstream end of the flume. Horizontal line intervals indicate time-averaged values.