Earth Surf. Dynam. Discuss., doi:10.5194/esurf-2016-1, 2016
Manuscript under review for journal Earth Surf. Dynam.
Published: 20 January 2016

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

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Abstract. Armor breakup and reformation was studied in a laboratory experiment using a trimodal mixture composed of sand and gravel. The armor was formed in the initial stage of the experiment under conditions without sediment supply. Higher flow conditions led to the breakup of the mobile armor and the reformation of a new coarser armor. The breakup initially induced a 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 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 slope adjustment such that the new steady state is 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 shear stress values capable of 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 is supplied from upstream. The over-representation of the coarse grains at the bed surface then serves to increase their transport capacity. 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 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 (e.g., Parker and Klingeman, 1982; Jain, 1990). 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 armored surfaces can be both stable and persisting during floods or broken during a flood and reform during the waning phase. Andrews and Erman (1986) were the first to present a field case on the persistence of an armor layer during a flood. Wilcock and DeTemple (2005) predicted the persistence of armor layers during high flow using their surface-based transport model. Clayton and Pitlick (2008) described a gravel bed river with a persistent armored surface. The sediment supply, composed of all grain sizes, provided the replacement for the entrained particles. Conversely, 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 armor did not persist at high flow conditions and reformed at smaller floods. The experiments by Klaassen (1988) provided detailed measurements of armor breakup after a flood wave under bedform-dominated conditions. The armor breakup resulted from the turbulence created in the trough zones of the migrating bedforms. A finer armor reformed at lower flow conditions after the decrease 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 and its stability was tested under a stepwise increase of the discharge. The armor breakup corresponded to the entrainment of the coarse particles, as observed by the authors, and 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 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 the presence of bedload sheets. The supply of finer material can lead to a higher mobility of the coarse sediment and so 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 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 persistence or breakup of an armor layer remain open to discussion. The temporal changes of the bed surface texture during floods is difficult to measure 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 paper is to provide detailed measurements of spatial and temporal changes of the bed surface texture under controlled laboratory conditions to examine the stability of an armor layer under high flow conditions and a limited sediment supply. The temporal changes of the bed surface texture was measured during flow using the technique presented by Orrú et al. (submitted 2015).

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. 1). 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 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 $\mathrm{m^3 s^{-1}}$ 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 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 to enable measurements of the grain size distribution (GSD) of the bed surface using the image analysis technique of Orrú et al. (submitted 2015). The fine fraction was left with its natural color, the medium fraction was painted yellow green and the coarse fraction was painted medium turquoise.

The initial bed was installed with an imposed stepwise fining pattern. The upstream reach was composed of the trimodal mixture (trimodal reach) and the downstream reach was composed of sand (sand reach). The trimodal reach of experiment was characterized by 10 patches of a length of 0.40 m. The length of the most upstream patch was equal to 0.88 m. 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. (submitted 2015).

2.2 Measurements

The water discharge and the longitudinal profiles of the bed and water surface elevations were measured in the same way as presented by Orrú et al. (submitted 2015). The water surface elevation at the downstream end of the flume (at x = 10.62 m) was continuously measured using a pitot tube connected to a linear position sensor. The linear position sensor was connected to the pitot tube by a hose and positioned beside 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 placed on a scale that measured 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. (submitted 2015) (Fig. 3). The equipment used to take the images of the bed surface was here improved (Fig. 4). The design and material of the floating part of the measurement equipment were optimized to reduce its submersion. The bottom of the upstream V-shaped part of the floating device was designed with a certain inclination to obtain a lift force from the flow. The floating device was made 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. (submitted 2015). A new set of polygons was defined using target images created for the color combination used in these experiments.

2.3 Formation of the initial armor

In this section we briefly describe the experiment T1 conducted to create the initial armor tested in experiment T2. Under the imposed supply limited conditions 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 limited amount of sand was available at the bed surface. In the remaining part of experiment T1 when the coarser fractions were less or no longer mobile (i.e., partial transport) the prevalent mechanisms were the winnowing together with the kinematic sieving of the sand.

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. 10) (Orrú et al., submitted 2015). The difference in bed elevation between the trimodal and sand reach in T1 resulted in a streamwise increase in the water surface elevation. This is due to a Bernoulli effect (e.g., Douglas et al., 2005). The trimodal reach of 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. The final stage of the bed of experiment T1 was characterized by an abrupt transition in bed surface texture between the trimodal and sand reach (Fig. 5), which was accompanied by a large step in bed elevation (see later in Fig. 10). The upstream section of the trimodal reach was governed by an imbricated structure (Fig. 6). The armor was considered fully developed after 16 h when no relevant changes of the bed surface texture were observed and the transport rate reached approximately zero.

3 Breakup and reformation of the armor layer

At the beginning of the armor breakup experiment, Experiment T2, the flow velocity was increased by increasing the water discharge and lowering the downstream water level (Fig. 1) to achieve fully mobile transport conditions over the trimodal and sand reach.

3.1 Bed surface texture

Armor breakup and reformation covered a very short period. After the increase of the water discharge the armor started to breakup in several sections of the trimodal reach. Figure 7 shows a section of the trimodal reach where a 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. 7a). Subsequently, the sand entrainment enhanced the gravel mobility extending the breakup and exposing the subsurface over a wider section (Fig. 7b). The measurements of the texture of the bed surface show a fining of the bed between 1 and 4.5 meters (Fig. 8 and Fig. 9). Yet the fining was even stronger than we measured. The measurement taken after 7 minutes (point 3 of Fig. 8) corresponds to the bed state of Figure 7c, and the bed surface was finer at the moment of the breakup shown in Figure 7b (point 2 of Fig. 8) after about 4 minutes.

The breakup and bed surface fining was quickly followed by the formation of a mobile armor coarser than the initial one (point 4 of Fig. 8 and Fig. 9). The coarse sediment supplied from upstream enabled the formation of a new armor and the presence of gravel particles in the substrate aided the armor reformation. After the armor reformation a very limited amount of sand was present at the bed surface (Fig. 8). The fact that the reformed armor was slightly coarser than the initial one resulted in a slight downstream coarsening in the gravel reach.

3.2 Bed elevation

The breakup of the armored surface led to local degradation. The total amount of degradation 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. 6). This enhanced bed stability and consequently some sections of the armor did not breakup. We observed a lateral variation in degradation that is not evident in our measurements (Fig. 10) 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. 7a,b). The breakup led to a fast degradation which was arrested by the reformation of the mobile armor (Fig. 10). The degradation was not uniform in streamwise direction (Figure 10). 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 sand reach (Fig. 10). The progradation ceased at the end of the experiment.

The approach towards an equilibrium state characterized by zero sediment supply was also observed in the sediment transport rate at the front position (Figure 11). We determined the local sediment transport rate at the front q_{front} (Fig. 11) from the migration speed of the front as proposed by Bagnold (1941) in the simple-wave relation:

$$c = \frac{q_{front}}{c_b \Delta} \tag{1}$$

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

The sediment transport rate at the front shows a sudden increase due to the occurrence of the armor breakup (Fig. 11), which was followed by a gradual decrease. The increase in the sediment transport rate coincides with the entrainment of the substrate material and the decrease with the reformation of the mobile armor.

4 Discussion

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). A temporal fining of the bed surface characterized the moment of the breakup and it was followed by a coarsening that led to the reformation of an armor 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 field case the increased degree of armoring was caused by partial transport conditions. In our experiment the coarser armor formed under continued high 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 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 coarser than the initial one are: (a) the supply from upstream being mostly gravel, (b) the sand supplied from upstream not being trapped and (c) the higher flow rate not allowing for the sand to remain between the gravel particles.

Here and in the studies by Vericat et al. (2006) and Wang and Liu (2009) the increase of 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 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.

5 Conclusions

A flume experiment was conducted to investigate the stability of an armor under conditions with a limited sediment supply. The armor was formed under base flow conditions. The armor locally broke up after an increase of the flow rate and rapidly reformed under continued peak flow conditions. The breakup was characterized by a temporal fining of the bed surface due to the exposure of finer substrate sediment and local degradation. After the armor breakup, an armor quickly reformed that was coarser than the initial one. 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 increase of the local sediment transport rate identified the moment of the armor breakup and it was followed by a gradual decrease corresponding to the armor reformation. The breakup of the armor surface enabled the bed slope to adjust to a situation closer to normal flow conditions.

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

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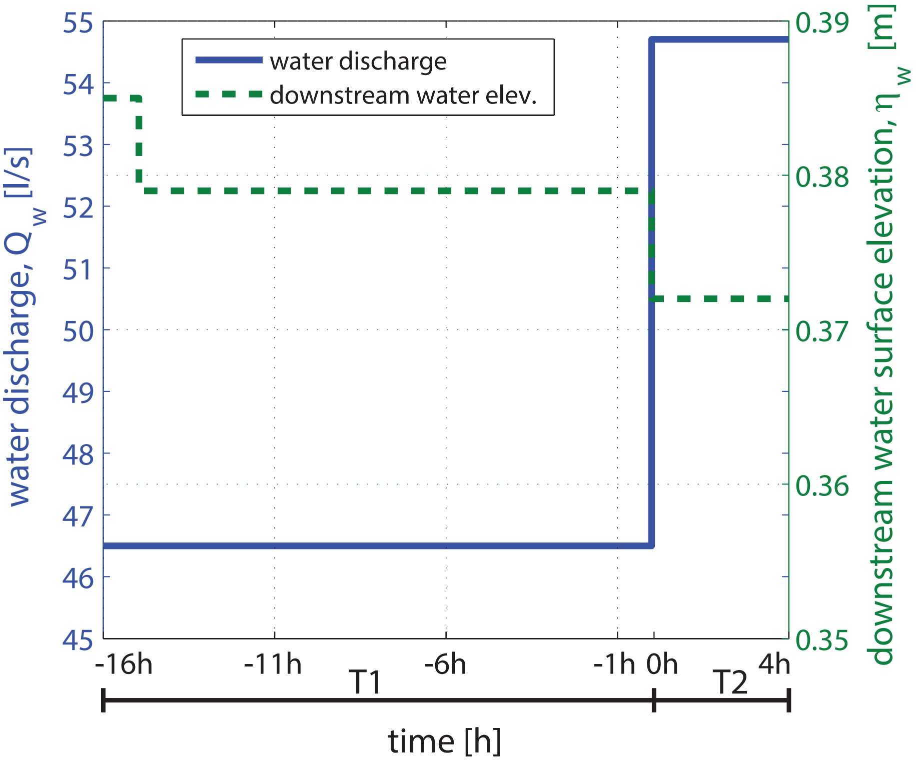

Figure 1. Water discharge, Q_w, and base level, η_w, imposed in the laboratory experiments T1 and T2.

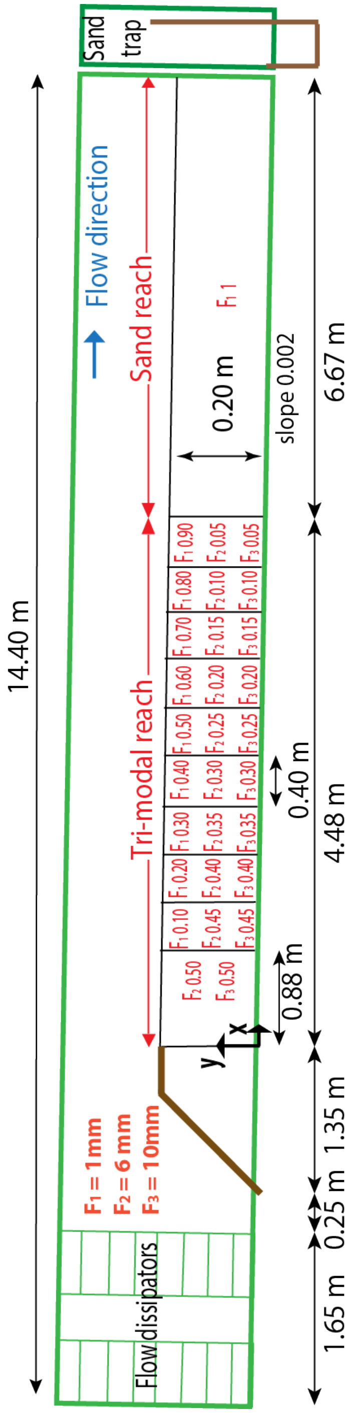

Figure 2. Flume set up and bed initial conditions for experiment T1.

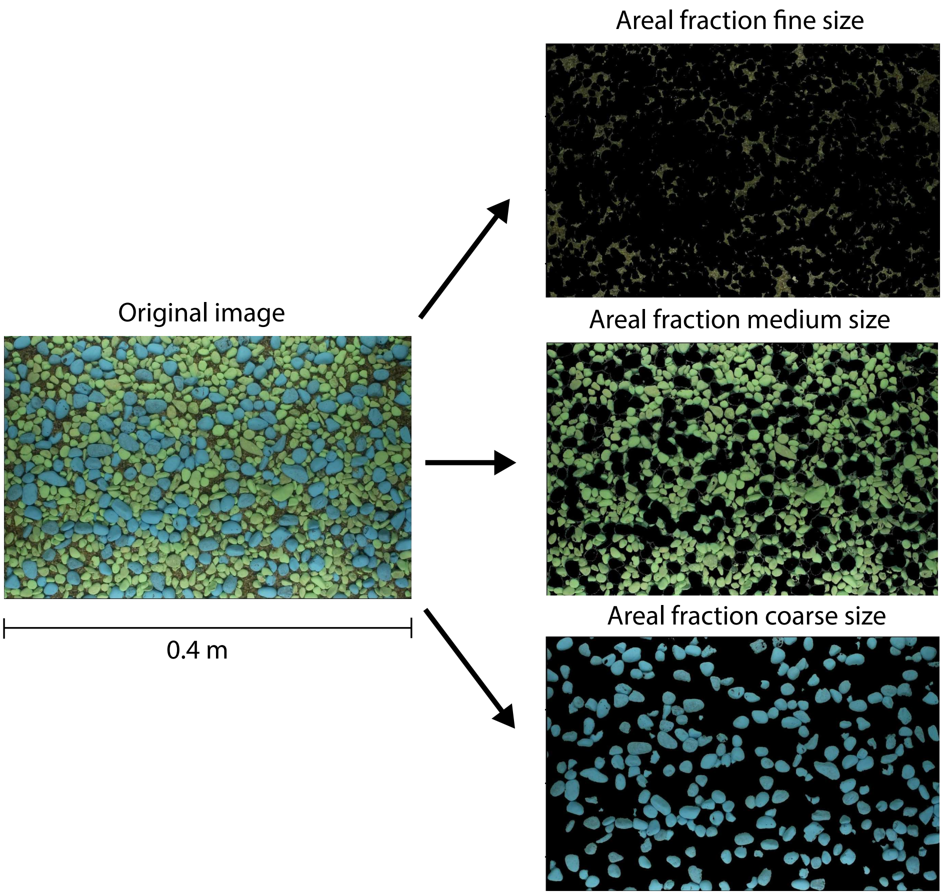

Figure 3. Example of color segmentation for an image of the bed surface used to determine the grain size distribution of the bed surface.

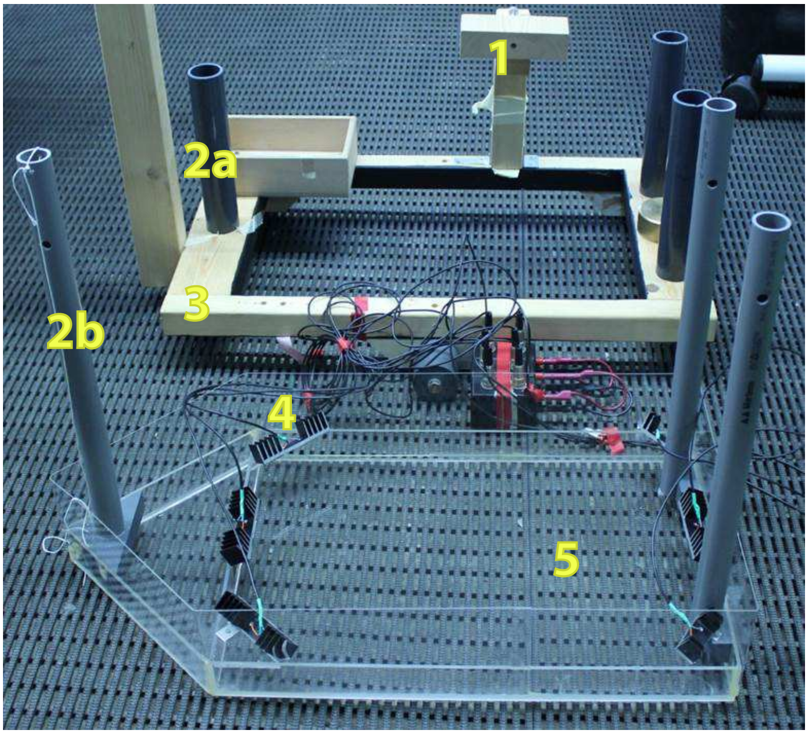

Figure 4. New floating part of the equipment to measure the grain size distribution of the bed surface during the laboratory experiment. The bottom and the walls of the floating part are now made of thin Plexiglas® plates and higher sheets are attached around the walls as a protection from possible water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

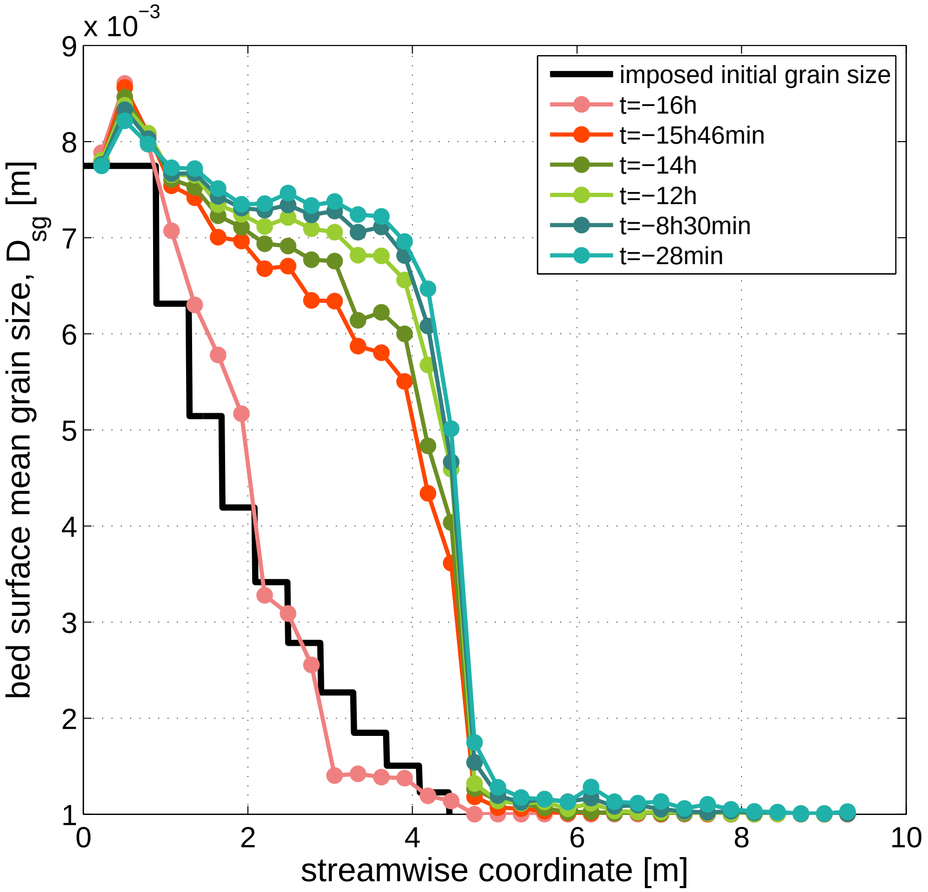

Figure 5. Imposed and measured geometric mean grain size of the bed surface sediment at various times for experiment T1.

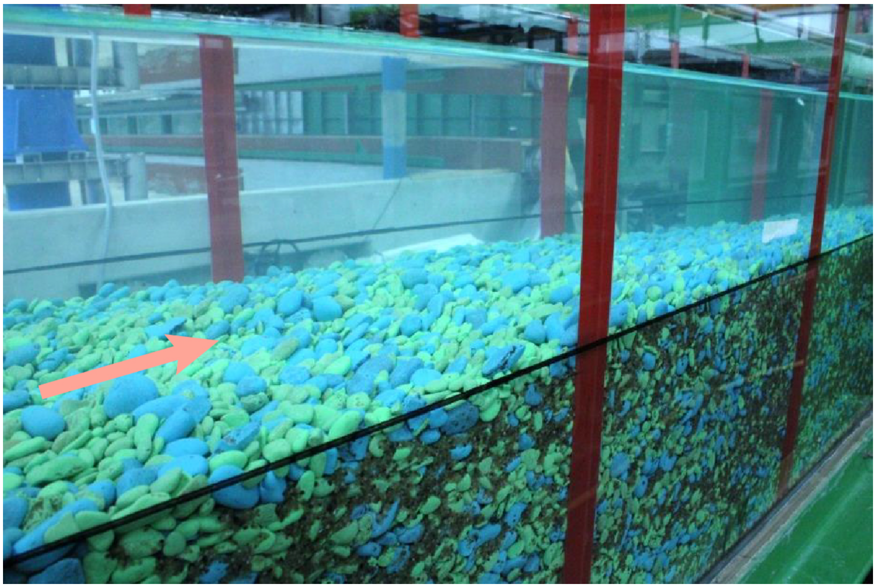

Figure 6. Imbrication of the bed surface at the end of experiment T1. Flow is from left to right.

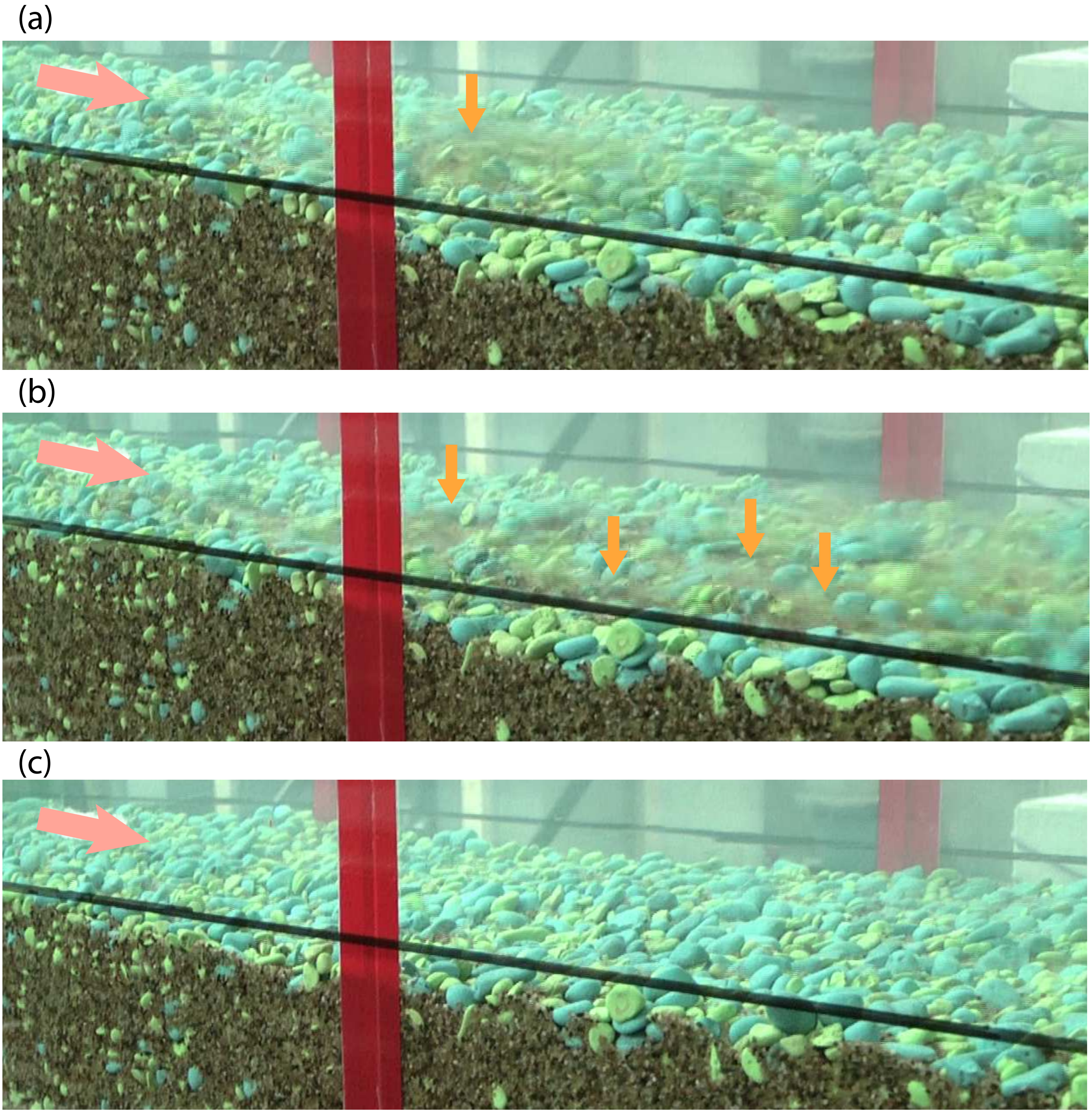

Figure 7. Armor breakup and reformation between compartment 6 and 7: (a) initial local breakup, (b) widening of the breakup and exposure of the finer substrate, (c) initial reformation of the mobile armor. Flow is from left to right.

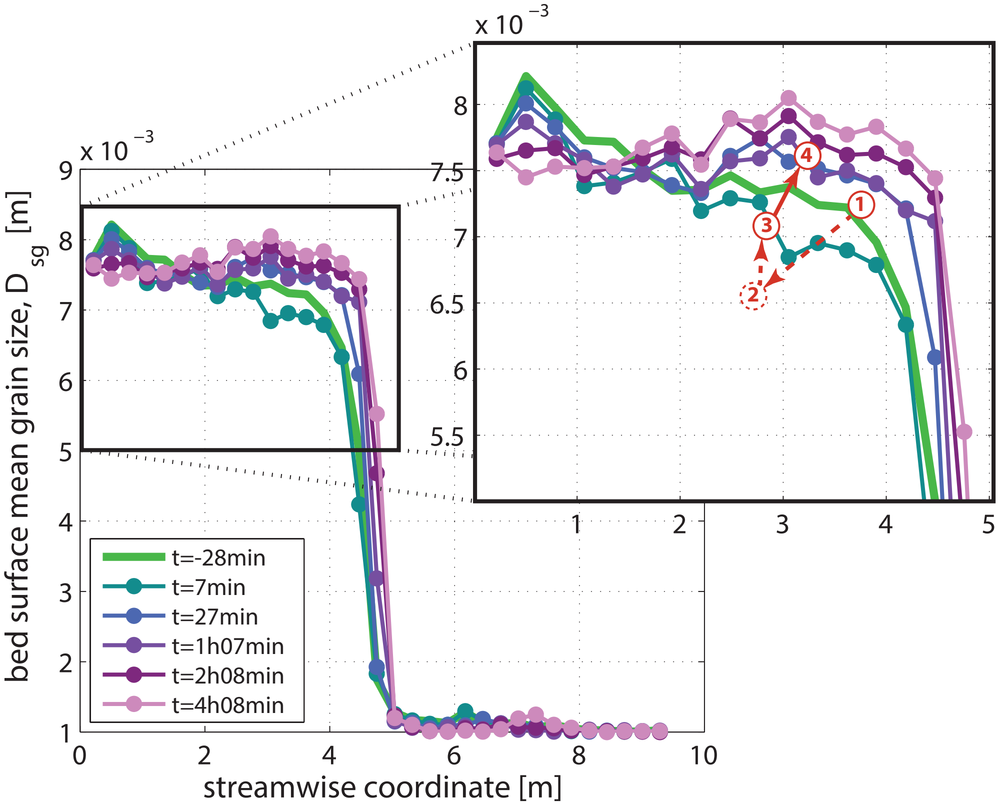

Figure 8. Measured geometric mean grain size of the bed surface sediment at various times for experiment T2. Point 1 to 4 in the zoomed window show the temporal change of the bed surface where point 2 indicates a hypothetical (not measured, see Fig. 7b) finer surface at the moment of the breakup. Please note that point 3 corresponds to the bed surface shown in Fig. 7c right after the reformation of the armor.

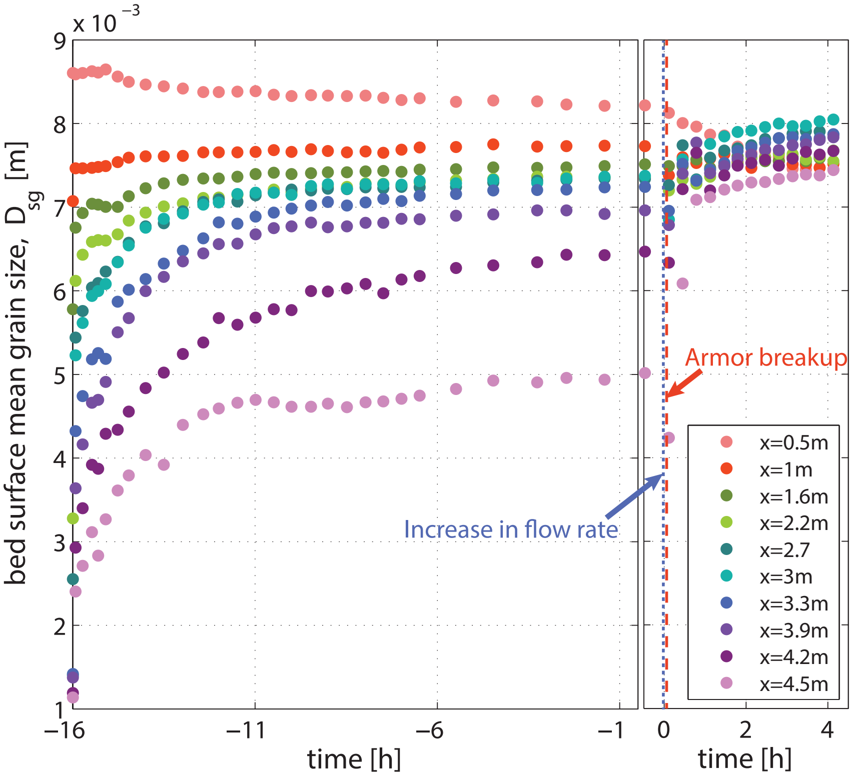

Figure 9. Measured change of the geometric mean grain size of the bed surface sediment at various locations in experiment T1 and T2. The blue dashed line indicates the moment of the increase in flow rate (t=0 h) and the red dashed line indicates the moment of armor breakup (t=4 min).

Earth Surf. Dynam. Discuss., doi:10.5194/esurf-2016-1, 2016
Manuscript under review for journal Earth Surf. Dynam.
Published: 20 January 2016

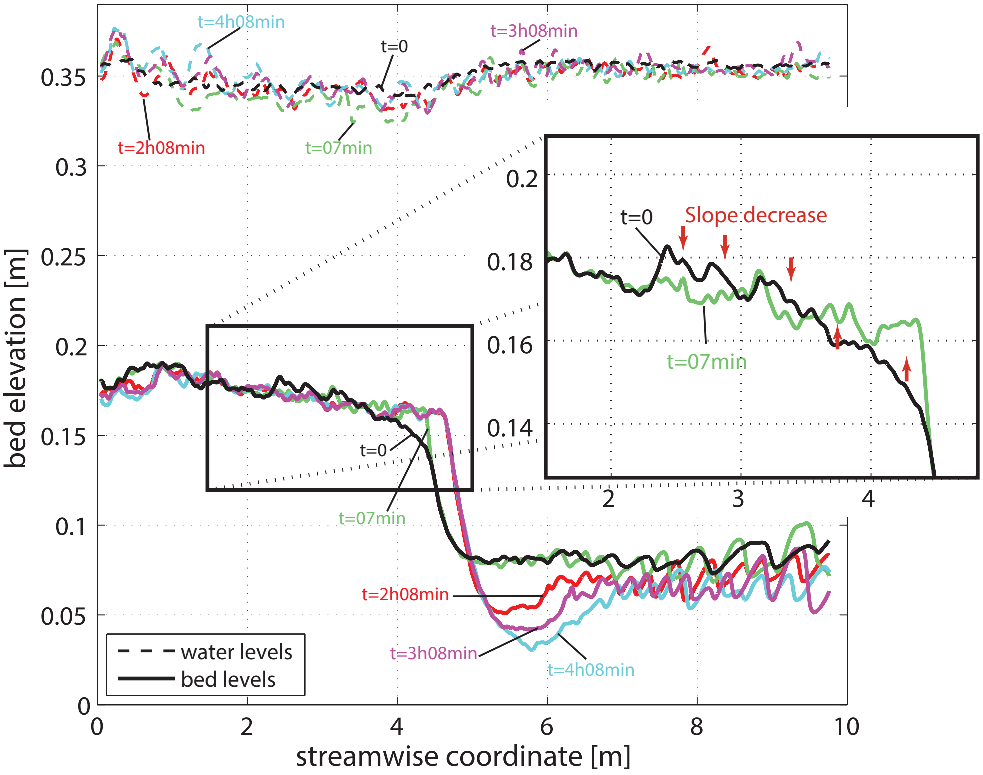

Figure 10. Measured water surface and bed elevation profiles of experiment T2 at t=0 h , after 07min, 2h08min, 3h08min and after 4h08min. The zoomed window shows the degradation occurring during the armor breakup. Flow is from left to right. The profiles were smoothed by a Gaussian filter.

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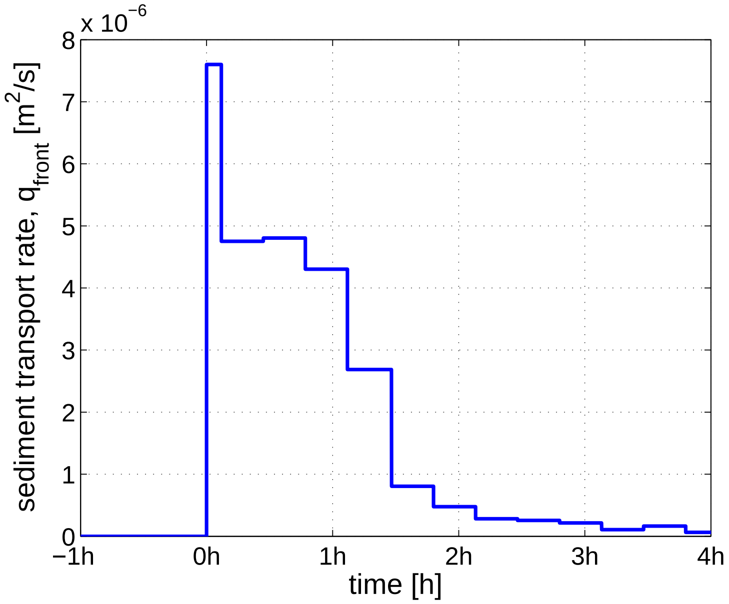

Figure 11. Local sediment transport rate computed from the migration of the front between the trimodal reach and the sand reach using Eq. (1).