Wave-induced ripples development in mixed clay-sand substrates

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ABSTRACT: A large-scale flume experiment was conducted in the Total Environment Simulator, University of Hull. Run 01 was a control experiment with pure sand bed, and clay fraction increased gradually from 4.2% in Run 03 to 7.4% in Run 06. The experimental results demonstrate the significant influence of the amount of cohesive materials in the substrate on ripples evolution under regular surface waves. Most importantly, the cohesive clay added into sand bed dramatically slowed down the rate of bed erosion. Consequently, with the addition of a larger cohesive fraction, the equilibrium time of each run increased exponentially. The paper discusses the slower ripple growth rates with higher cohesive factions, via an influence on critical shear, but highlights that the equilibrium size of ripples is found to be independent of increasing substrate clay fraction. The suspended particles mass (SPM) concentration indicates that clay particles were efficiency suspended and winnowed by wave action.

1. GENERAL INSTRUCTIONS

Wave-induced ripple size is related with the sediment characteristics including sediment particles size and flow properties, such as maximum near-bed orbital velocity (Nielson, 1981; van Rijn, 1993; Nelson et al., 2013 ;). Previous studies, however, focused on the dynamics of bedforms only composed of well-sorted sand. This restrictive sediment type is far from being a realistic representation of natural sediment size distributions, particularly in European coastal and estuarine environments, where mixed sediments with and without fine cohesive components are common (Flemming, 2002). In particular cohesive mixed sediments (mud-sand) influence bedform characteristics (Bass et al., 2011, 2013) and, in turn, the near-bed boundary conditions for turbulence and sediment transport within dynamic models. Bass et al. (2013) highlighted that cohesive clay particles added into sand bed slowed the rate of current ripples development. Particularly, ripples dimensions decrease with increase clay content under unidirectional flow (Bass et al., 2013). Therefore, the present paper concentrates on the influence of cohesive clay on the ripples development under regular wave conditions. The aims can be concluded as following: (1) identifying the relationship between the rate of wave ripple development and initial bed clay fraction; (2) determining the equilibrium height and length of the wave ripples as a function of initial bed clay fraction.

2. METHODS

The main experimental parameters see table 1. 7 bedform elevation profiles (BEPs) were recorded by the acoustic bed scanner URS for each scanning time. These raw data of BEPs were processed by the method based on bedform tracking tool (BTT) that is a numerical code in Matlab (Van der Mark, 2008; Van der Mark, 2009). Van der Mark *et al*. (2008) method was used to determine the locations of wave ripple crests and troughs in a measured bed elevation profile and then to determine the geometric properties of individual bedforms. The equilibrium conditions could be established by the Bass *et al.* (2013) method, where the ripples development by the following equations:

$$\frac{Lt-L_0}{Le-L_0} = 1-(0.1)^{\frac{t-t_f}{T_L-t_f}} \quad (1)$$

$$\frac{Ht}{He} = 1-(0.1)^{\frac{t-t_f}{T_H-t_f}} \quad (2)$$

where Lt and Ht are wave ripples length and height derive from BTT at time t after experiment start, t_f is the delay time of wave ripples appearance, Le and He denote equilibrium wave ripple length and height, L_0 is the wave ripple length of the first appearance of wave ripple, and T_L and T_H are the equilibrium time for length and height. A non-linear fit using the Curve Fitting Tool in Matlab was used to find the best solution for Equations 1 and 2, therefore obtaining Le, He, L_0, T_L and T_H. In present study, T_L and T_H are defined as 90% of wave ripples get equilibrium.

Table 1. Experimental parameters

Run	Duration (min)	f_0 (%)	Salinity (‰)	U_m (m/s)	d_o (m)	H_s (m)
1	290	0	17.8	0.32	0.26	0.16
2*	270	0	19.5	-	-	-
3	300	4.2	19.2	0.33	0.26	0.22
4	250	6.2	17.2	0.31	0.25	0.22
5	510	7.2	20.4	0.30	0.23	0.24
6	630	7.4	19.1	0.30	0.23	0.21

f_0 = initial clay fraction
U_m= maximum near-bed orbital velocity
d_o= maximum near-bed orbital diameter
H_s =significant wave height
*Run 02 was conducted under irregular wave conditions and is not discussed in present paper.

3. RESULTS

3.1 Ripples development

The typical 2D wave ripples were developed during each runs. The ripples evolution of Run 06 with the highest clay fraction is an example. At t=30 min, most of the bed still remained flat, but a nucleus of wave ripples had formed at the edge below the URS transverse. The nucleus expanded towards centre of scanning section by growth of existing ripples and by addition of new ripples, until the ripples occupied most of the bed after 2 hours of experiment start (Fig. 1).

3.2 Equilibrium state

Equilibrium time of ripple length increased exponentially with increasing clay fraction from 66 min of Run 03 to 346 min of Run 04 (fig. 2). Similarly, the equilibrium time of ripple height experienced a sharp increase from 31 min of Run 03 to 120 min of Run 06 (Fig. 2). But the increase rate was relatively slower than that of equilibrium length, which indicates ripple length needs more time to get equilibrium. The equilibrium wave height and length appeared to be independent of initial bed clay fraction for the applied experimental conditions as shown in Figure 2. Equilibrium length remained level from Run 01 to Run 04 and slightly increased to 150 mm of Run 06. Equilibrium height basically kept around 20 mm for all the runs.

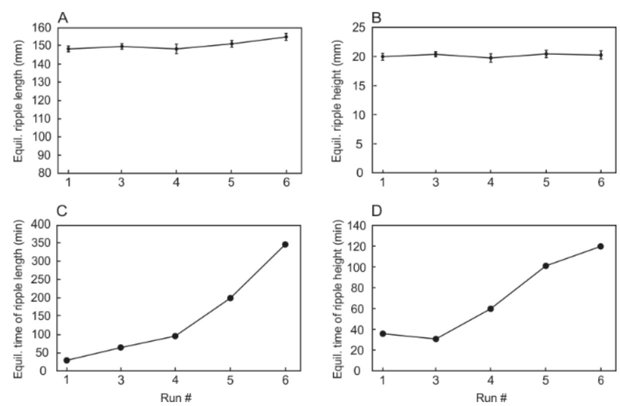

Fig. 2. Equilibrium time and equilibrium ripple length and height against initial bed clay fraction.

4. DISSCUSION

The results of the present experiments above suggest that the cohesive clay reduce wave ripples development rate. The scanning section were covered by 2D wave ripples at beginning of Run 01. In Run 03, all of 7 probes of URS scanned wave ripples at t=15 min. The expanding rate of wave ripples decreased dramatically in subsequent experiments, with first time of whole bed width covered by ripples reaching to 70 min of Run 04, and to 120 min of Run 05 and 06. Besides that, the equilibrium time for both ripple length and height increased exponentially with clay increasing from Run 01 to 06 (Fig. 2). Therefore, the wave ripple growth progressively declined with clay fraction increasing of each run. Mitchener and Torfs (1996) found that the erosion rate under wave condition of pure sand bed was an order of magnitude higher than the 20% and 40% sand bed. Panagiotopoulos et al. (1997) highlighted that bed erosion rate decreases when the clay fraction is higher than 11% under oscillatory flow condition. Therefore, the increase clay fraction of experiments plays a significant role on decreasing bed erosion rate, as a result wave ripple growth rate decreased dramatically from Run 01 to Run 06. Particularly, this paper highlights that the bed erosion rate decreases with a relatively small increase in bed fraction (4.2% to 7.4%), which further narrows down clay content with the influence on the bed erosion rate under wave conditions based on previous studies of Mitchener and Torfs (1996), and Panagiotopoulos et al. (1997).

Visual observation of clean flow water transforming to turbid fluid during experiments indicates that clay particles were suspended from the pores in between sand grains. Grain size analysis reveals that there are pure sand layer at the top of sediment cores collected from ripples crests. This may be explained by the high winnowing efficiency that the waves highly pump amount of clay particles from crests. The waves winnowed clay from the ripple troughs as well, but with a lower winnowing efficiency compare with that of crests because lack of 100% sand layer at top cores. The reason for a relatively lower winnowing efficiency from ripples troughs is possibly higher protection from near-bed oscillatory flow at ripple troughs. The experiments of Bass et al. (2013) also showed current ripples crest comprising clean sand. But the wave winnowing efficiency was presumably higher than that of current, because the pure sand crest only dominated in the highest clay content (18%) experiments of study of Bass et al. (2013).

5. CONCLUSIONS

1. Relatively small increase of clay fraction from 4.2% to 7.4% in present experiments stabilised the flume bed and dramatically slowed down the bed erosion rate.

2. Both equilibrium time of wave ripples length and height exponentially increased with clay content increase.

3. Equilibrium dimensions of wave ripples were independent with clay fraction.

4. Highly efficient winnowing of clay particles from bed presumably contributed to constancy of equilibrium wave ripple length and height.

6. ACKNOWLEDGMENT

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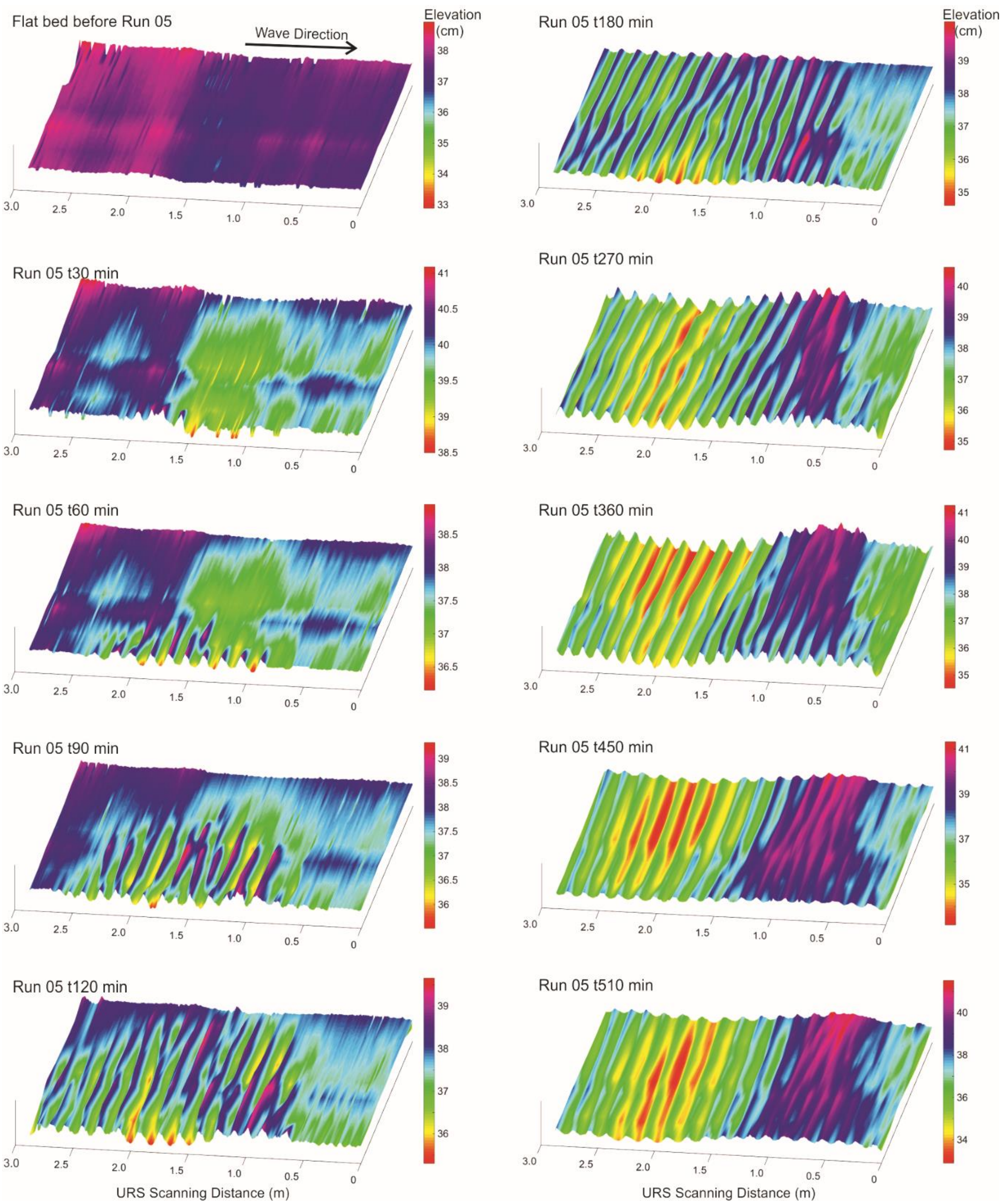

Fig. 1. 3D image of wave ripples evolution of Run 05 with initial clay fraction of 7.2%.