Flume Experiments of Response of a Delta Profile to Temporary Waxing Discharge: The Case of Silt-Sized Diatomaceous Earth

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Abstract

The delta profile changes corresponding to hydraulic condition, such as flow discharge, sediment supply rates and sediment type. In order to examine silty delta profiles under temporary waxing flows, we conducted experiments in which a silty delta was developed under several patterns of hydrograph. The findings are as follows. (1) When the flow discharge increases, sedimentary process of a delta is determined by increase rates and there occurs aggradation, backstepping, and progradation respectively as the rate becomes large. (2) If the flow was kept at high discharge for a while before waning, the delta prograded forming a steep foreset slope, regardless of increasing rates. (3) In the phase of decrease of flow discharge, under slowly waning flow, the delta developed with backstepping followed by aggradation when the topset was quasi-equilibrium state, but prograded when the condition of the topset was quasi-equilibrium state, while under fast waning flow, a sedimentary process of a delta was always aggradation on the topset regardless of the increase rate of discharge at the previous phase.

It is expected that applying these findings contribute to estimating unsteady hydraulic conditions like floods from geologic records of a silty delta.  

Key words: delta profile, unsteady flows, flume experiments, silty delta

Introduction

A deltaic topography is a feature of not only river mouths but also smaller scale landforms such as lee slopes of unit bars, dunes or washed-out ripples that have long wavelengths relative to wave heights. It is known from experimental studies that the profile (in a vertical section parallel to the flow) of a delta changes according to the flow velocity (Jopling, 1965; Kojima and Yokokawa, 1997), the sediment supply rate (Okazaki et al., 2004), sediment transport modes (Okazaki et al., 2004; Reesink and Bridge, 2007; 2009) and sediment types (Jopling, 1965; Kostic and Parker, 2003). Suzuki and Endo (2010) found a different trend of change in the profile of silty deltas than sandy deltas
by flume experiments, in which the contact between the foreset and the bottomset changes from tangential through angular to again tangential with increase of flow discharge, while sandy deltas do not take tangential at lower flow regime than angular.

Suzuki and Endo (2010) investigating silty deltas conducted experiments only under constant flow discharge. In this study, we focused on the change of a silty delta profiles caused by temporarily increasing flow discharge like a flood. We conducted flume experiments, by varying the rates of increase and decrease in flow discharge and the duration during in which the high flow discharge continued.

**Experiment**

The flume was 1 m long, 15 cm deep, and 2.7 cm wide that was designed to assume 2-D vertical section. Used sediment was silt-sized diatomaceous earth (mean density 2.2 kg/m³, median diameter 37.8 μm, mode diameter 48.8 μm), the settling velocity of which calculated based on Stokes low was $9.9 \times 10^{-2}$ (cm/s) that was equivalent to a quartz particle of 31 μm.

The observation area for a delta was set to be 50 cm downstream away from the supply point of water and sediment, which allows us to take account of the erosion of bed of topset due to increasing flow discharge. In this study, we limited runs to only cases where the bedforms on the topset were bedload sheet (Reesink and Bridge, 2007) through the run.

The sediment supply rate (sediment amount introduced into the flume per unit time) was 3.0 g/min in all runs. Suzuki and Endo (2010) found that newly recognized tangential contact caused by turbidity currents at lower regime than that of angular contact (600 ml/min), in which the lower regime was 200 ml/min and the relatively higher was 600 ml/min. In this study, flow discharge was varied between these values, i.e., 200-600 ml/min in one sequence of temporarily waxing and following waning discharge. The initial topography was formed by flowing water at 200 ml/min for enough time for the delta to be in a stable state. The delta size was determined by the vertical difference between the elevation of the topset face and the bottom of the flume, and the resultant delta size was about 7 cm in height. Three different rates of increasing discharge (+20 ml/min, +80 ml/min, +800 ml/min) were examined; taking 20 min, 5 min and 30 s to increase discharge from 200 to 600 ml/min. After attaining the maximum discharge (600 ml/min), two cases of sustained period, 0 and 20 min, were tested. Besides, two different rates of decreasing discharge (−20 ml/min, −800 ml/min) were conducted, taking 20 min and 30 s from 600 to 200 ml/min. Fig. 1 shows various patterns of hydrograph. Run index numbers used below represent paths in Fig. 1, for example, B3 means that the flow waxes taking 5 minutes, sustains high discharge for 20 minutes and wanes taking 20 minutes.
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Fig. 1. Schematic of experimental hydrographs. Segments A, B and C mean increasing discharge of the rate of +20 ml/min, +80 ml/min, +800 ml/min, respectively. Segments 1, 2 mean decreasing flow discharges at the rate of -20 ml/min and -800 ml/min immediately after waxing, respectively. Segments 3, 4 mean sustained high discharge (600 ml/min) for 20 min and following decreasing flow discharge at the rate of the -20 and -800 ml/min. Run index numbers, for example, A3, represent a path composed of combination of segments.

Results and discussion

Observation

(1) The change of the delta profile depending on the increase rates of flow discharge

At low increase rates of flow discharge (+20 ml/min), the foreset slope gradually became steeper (Fig. 2A). The mechanism was as follows; as the discharge increased, the separated flow became vigorous and suspension load increased, therefore the sediment supply rate onto the foreset decreased. Due to the decrease in sediment supply onto the foreset, the dominant sediment transport mode on the foreset shifted from turbidity currents to grain flow. Thus, the delta became steeper gradually by realizing a metastable state corresponding to the flow discharge at any moment, and the process of delta development was progradation.

At middle increase rates of flow discharge (+80 ml/min), the foreset slope gradually became steeper (Fig. 2B) apparently similar to the case of +20 ml/min, but the process was different. Because transport modes changed from turbidity currents to grain flow in short time and sediment supply rate on the slope decreased quickly, so each surge of grain flow did not arrive to bottomset and its running distance became shorter. The depocenter on the slope shifted to the upper part of the foreset through "backstepping" (Van Wagoner et al., 1990).

At high increase rates of flow discharge (+800 ml/min), the foreset slope became slightly gentle (Fig. 2C). In this case, the topset was eroded quickly due to the high flow velocity caused by the fast-waxing flow, and the eroded sediments flowed down the slope as high concentrated turbidity currents. The turbidity currents were the effective mechanism that transports and settles a large amount of sediment to the lower part of the foreset and the bottomset, which resultingly made the slope gentler. In this case
just after the flow velocity reached to 600 ml/min, the water depth on the topset did not attain to the equilibrium state and was erosive.

(2) The case where the high flow discharge was sustained

While the high flow discharge, 600 ml/min, continued for 20 minutes before the flow waned, the delta prograded having a steep slope similar to the angle of repose because the grain flows ran from the upper part of the foreset, although there was a different appearance between the cases of the faster increasing rates (+80 and +800 ml/min) and the slower (20 ml/min). After the flow discharge waxed at the rates of +80 and +800 ml/min, the superimposed micro-delta with steep slope was generated and migrated on the upper part of the formerly generated gentle foreset of the existing delta. Otherwise, after the flow discharge increased at the rate of +20 ml/min, the foreset became totally steep as noted in the above, and the progradation of the whole foreset slope was observed.

(3) The change of the delta profile depending on decrease rates of flow discharge

The change of the delta profile in the waning flow was different according to the gradient of delta slope, whether steep or gentle before the discharge decreased.

(3a) The case where the delta was gentle before waning (Run C1 and C2)

In the case where the increase rate of the discharge was large (+800 ml/min), the delta slope became gentle, at which point the water depth on the topset did not attain to the equilibrium state; the topset was still erosive. Under such situations, different types of the change of delta profiles were observed according to the decreasing rate of discharge.

At the low decrease rate of flow discharge (-20 ml/min) (Run C1), the topset was erosive in the early stage because the discharge was high for a while. Sediments produced by erosion of the topset were transported as turbidity currents and settled onto all through the foreset with a uniform thickness. In the latter stage of the decrease in discharge, the topset became less erosive, and the transport mode on the foreset
changed to grain flow, while the separated flow was still intensive and a large part of transported sediments got suspended. The depocenter on the foreset shifted to the upper part, and backstepping was observed. In the last stage, the water depth on the topset decreased and achieved to the equilibrium state and turbidity currents again dominated because the amount of sediment directly furnished onto the foreset increased due to a decline of the separated flow. The turbidity current accelerated the sedimentation on the lower part of the delta and the slope became gentle.

At the high decrease rate of flow discharge (-800 ml/min) (Run C2), aggradation occurred on the topset preferentially, because the discharge changed into small in a short time and the topset became nonequilibrium state and depositional, so the foreset became less depositional. After the discharge reached to the minimum (200 ml/min), the topset attained to the equilibrium state and turbidity currents generated on the upper part of the foreset and flowed down on the slope leading to a uniform veneer of deposits. (3b) The case where the delta was steep before waning (Run A1-A4, B1-B4, C3,C4)

After the discharge increased at the low and middle rates (+20 and +80 ml/min) (Run A1, A2, B1, B2) or when the large discharge (600 ml/min) was sustained for a while (20 min) (Run A3, A4, B3, B4, C3, C4), the delta contained a steep part on the upper area of the delta, therefore there was a change point of gradient on the foreset. The water depth on the topset was adjusted to the high discharge (600 ml/min). Under such situations, there was the difference in the sedimentary process around the change point of gradient within the foreset, depending on the decrease rate of discharge.

At the low decrease rate of flow discharge (-20 ml/min), the topset was always quasi-equilibrium state. The foreset gradient changed gradually being in the quasi-equilibrium state, corresponding to the discharge of any time (A1, A3, B1, B3, C3), thus the slope became gentle.

At high decrease rate of flow discharge (-800 ml/min), the topset could not realize the quasi-equilibrium state and became depositional during the fast wane of discharge. After the discharge reached to 200 ml/min, the topset attained to the equilibrium state and transported sediments flowed down as turbidity currents passing the upper steep part to settle on the lower part, creating a gentle slope covering the change point of gradient, i.e., aggradation occurred (Run A2, A4, B2, B4, C4).

The model of the delta profile depend on temporary waxing discharge

Based on the above results, we propose a qualitative model of development of a silty delta under flows of temporarily waxing and following waning (Fig. 3), supposing that under the initial low discharge, the foreset slope of a silty delta is gentler than the angle of repose because of turbidity current. In Fig. 3, the change of delta is expressed as a path in the diagram that is determined by hydrograph. Note that in the phase of decrease of flow discharge, there was hysteresis in the development process. Even if the decrease rate was the same, the path of change of a delta is different according to the previous state. After high rate increase of discharge, the condition of the topset was
nonequilibrium state accompanied by gentle foreset slope, while after slow rate increase or after duration of sustained high discharge, the topset was quasi-equilibrium state accompanied by steep foreset slope, which causes the difference about whether the topset is erosive, depositional or stable and about the effective sediment supply rate on the foreset.

Using this model, hydrograph can be estimate qualitatively from geological strata of silty deltas formed under temporary waxing. Here we consider imaginary strata of silty deltas shown in Fig. 4A. In Fig. 4A(1) shows the strata formed during the change of the delta profile from “a gentle slope with tangential contact” to “a steep slope with angular contact,” and finally it changes gradually into “a gentle slope and tangential contact.” This suggests that at first the flow discharge increased at relatively slow rate to the maximum velocity and the discharge was sustained for a while, and finally the flow discharge decreased at relatively slow rate. Thus, the hydrograph is considered to change through the path like the curve of B(1) in Fig. 4. The delta profile of A(2) in Fig. 4, shows “a gentle slope followed by backstepping” on the upstream side and “gentle
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Fig. 4. (A) Imaginary strata of silty deltas formed under temporarily waxing flows. (B) The hydrographs correspond to the development of silty deltas shown in (A).

slope” on the downstream side. This pattern suggests fast waxing and following slow waning, the hydrograph of which is considered to be like B(2) in Fig. 4. About A(3) in Fig. 4, the strata shows the change from “a gentle slope followed by the backstepping” into “a superimposed micro-delta progradation keeping the steep slope”, and further downstream “aggradations followed by progradation of gentle slope” can be seen. This suggests that the flow discharge increased at middle rate to the maximum velocity and then the discharge was sustained for a while, and at the last stage the flow discharge decreased at relatively fast rate. Thus, the hydrograph is considered to be like the curves B(3) in Fig. 4.

Summary

To propose a model of silty delta profiles due to temporary waxing discharge followed by waning, experiments testing several patterns of hydrograph, up and down between 200 and 600 ml/min were conducted. It was observed that the delta profiles were different according to the rates of increase and decrease in flow discharge and the duration during which the high flow discharge continued. The findings are as follows. (1) When the flow discharge increases, sedimentary process of a delta becomes aggradation at high increase rates of discharge (+800 ml/min), backstepping at middle increase rates (+80 ml/min), and progradation at low increase rates (+20 ml/min). (2) If the flow was kept at high discharge (600 ml/min) for a while (20 minutes) before waning, the delta prograded forming a steep foreset slope, regardless of increasing rates. (3) In the phase of decrease of flow discharge, there was hysteresis in the development process that causes the difference for the same decrease rate, because after high rate increase of discharge the condition of the topset was nonequilibrium state accompanied by gentle foreset slope, but after slow rate increase or after duration of sustained high discharge the topset was quasi-equilibrium state accompanied by steep foreset slope. Under slowly waning flow (-20 ml/min), the delta developed with backstepping followed by aggradation when the topset was quasi-equilibrium state, but prograded when the
condition of the topset was quasi-equilibrium state. Under fast waning flow (−800 ml/min), a sedimentary process of a delta was always aggradation on the topset regardless of the increase rate of discharge at the previous phase.

The results of this study indicate that the hydrograph of nonequilibrium flow can be interpreted from the patterns of sedimentary structures of silty delta. The cases tested in this study can be applied to, for example, geologic records of a silty deltaic topography such as the lee slope of dunes with relatively long wavelength formed by flood in river or tidal current.

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References


