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Criteria of Incipient Re-suspension of Deposition by Density Currents

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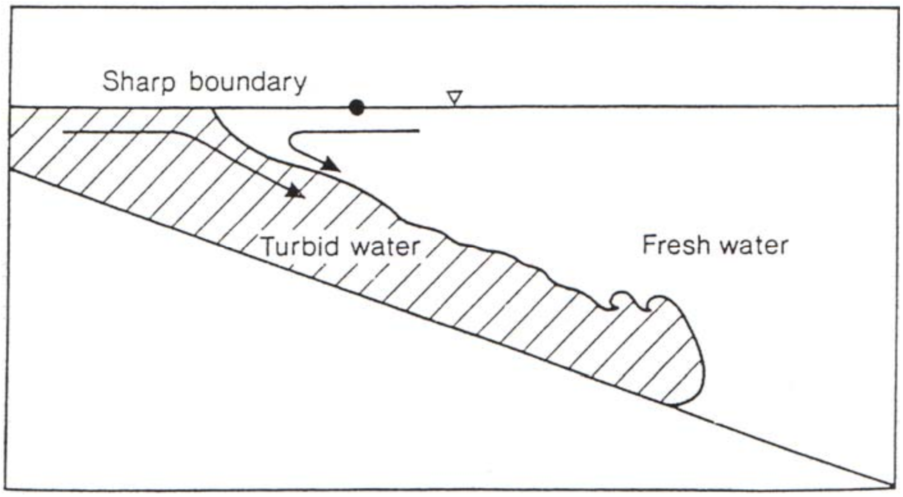
ABSTRACT

During a storm with heavy rainfall within a reservoir watershed, lots sediments, caused from soil erosion and slope sliding, will mix with flood and flow into the reservoir. When the concentration of fine sediments in the flow is sufficient high, density or turbidity currents will occur, which usually dives into deeper water and sustains to migrate on the bed until the currents arrived and stopped by a dam. The turbidity current can cause water muddy and increase the amount of silting substantially on the reservoir. If those silting sediments deposited just for relative short period, they might be easily disturbed or re-suspend by the turbidity current in a next storm event. Thus, disturbance of the silted sediments may be one key reason for aggravating the muddy water in the reservoir. This study investigates the erosion capability of turbidity current by flume experiments and to find out criteria of the incipient scouring and its characteristics. Saline density currents were created in a transparent flume with 2 % slope, and bed of silted fine material was arranged by slow settling of Kaolin-water mixture. Experimental findings are: (1) Development of the silted thickness at the test section needs 2 hours settling to reach a stable condition and be close to the original fixed bed-level as using 42 g/L Kaolin-water mixture. (2) As constant inflow discharges were 31.6 cm^2/s, 94.5 cm^2/s, and 143.6 cm^2/s, minimum concentrations to igniting the incipient erosion were 123 g/L, 30 g/L, and 15 g/L, respectively. (3) The erosion of bed material occurred both at the head and the body of the density current. The former had bigger erosion rate in a short time, but the latter had more accumulative souring depth in our experiments. (4) Some of the re-suspended sediments fell onto the erodible bed, but some were carried further downstream by the currents. The amount of re-suspended sediment obviously decreased to zero as the water-salt interface of rolling body developed stable.

Keywords: turbidity current, density current, erosion, re-suspension, scouring, Kaolin clay.

1. INTRODUCTION

The mechanism of flows of muddy, or turbid, water was first recognized in the study of sediment-laden streams continuing beneath the surface of larger bodies of water. Figure 1 shows a diagram of such a flow of dense turbid water entering a lake or reservoir and starting to flow as a turbidity current beneath the less-dense fresh water. Where a turbid river enters a lake a sharp boundary between clear and muddy water is visible at the surface (Simpson, 1997). In general, sediments in the turbidity current transport and deposited along the bed. The behaviors of the turbidity current was not easily observed and examined in fields, so laboratory experiment had been commonly used. For example, to the process of erosion and deposition, Parker et al.(1987) examined turbidity currents laden with non-cohesive silt (silica flour) moving down a slope the bed of which is covered with similar silt. The currents were free to erode sediment from, and deposit sediment on, the bed. Mohrig and Marr (2003) had set one particular style of turbidity-current generation by laboratory experiments, their evolution from the sudden failure and subsequent down-slope transport of pre-existing continental shelf or slope deposit. Notable observations of the experiments are three mechanisms, which are grain-by-grain erosion of the sediments from the leading edge of the parent flow, detachment of thin layers of shearing material from the head of the parent flow, and turbulent mixing at the head of the parent flow. Further, turbidity currents from continental margins to the deep sea also caused surprisingly little erosion en route, resulted from analysis of material data in fields (Weaver and Thomson, 1993). Nevertheless, in this study, experiments were carried out to understand how density current re-suspend fine sediments on the bed. To simplify various factors affecting the erosion phenomena and easier for observation, saline density currents which do not carry sediment were made as the erosion engine to directly plunge on a long flume.



(from Simpson, 1997)

Figure 1 A Turbidity Current Flowing into a Large Volume of Fresh Water.

2. EXPERIMENTAL PROCEDURES

Experimental Setup

The experimental setup, shown in Figure 2, consisted of a transparent flume, which was 2 % in slope, 40 m in length and 10 cm in width. An adjustable overfall tube was constructed at the downstream of the channel for controlling the water levels. Saline density current supply system was installed at a mixing fluid tank and a constant head tank. To control the discharge of saline current, a discharge control unit was set to command the pump. The test section, in the bed of which silted material were full of the volume of 1.0 cm × 1.0 m ×10.0 cm, was located 8.54 m down stream of the main entry. Those silted materials were made by a grain itself gravity settling, which the procedures were shown in Figure 3. To observe the velocity of the head of the density current, a video typed the arriving time of per meter at lateral location. To focus on the scouring or re-suspending of saline density current to silted material (Kaolin clay), other two video machines were used to type full view of the test section and the depth of scouring, respectively. As the density current arrived the dam and that the scouring didn't continue, one case of experiments was set to end. If the scouring constant occurred and that the current had reached the dam, the switch of the second outflow outlet was opened to emission the current until the scouring phenomenon ceased. After a case of experiments finished, the silted material of the test section was absorbed by a collecting fan for estimating the volume of the silted material loss.

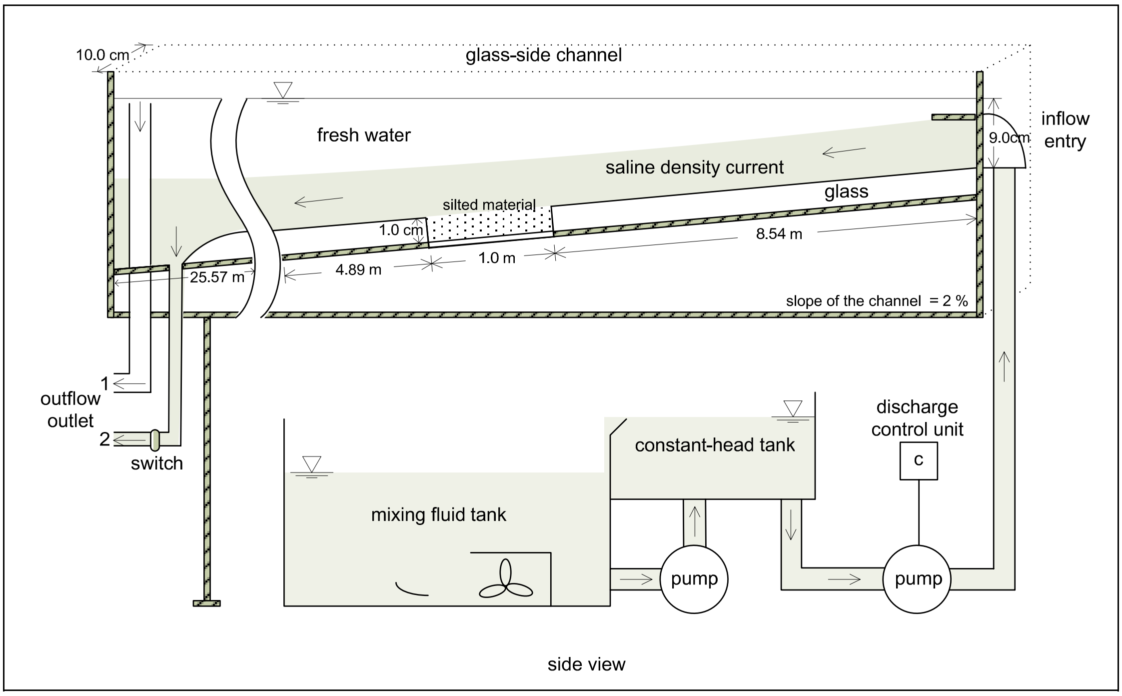


Figure 2 Layout of Experimental Equipment.

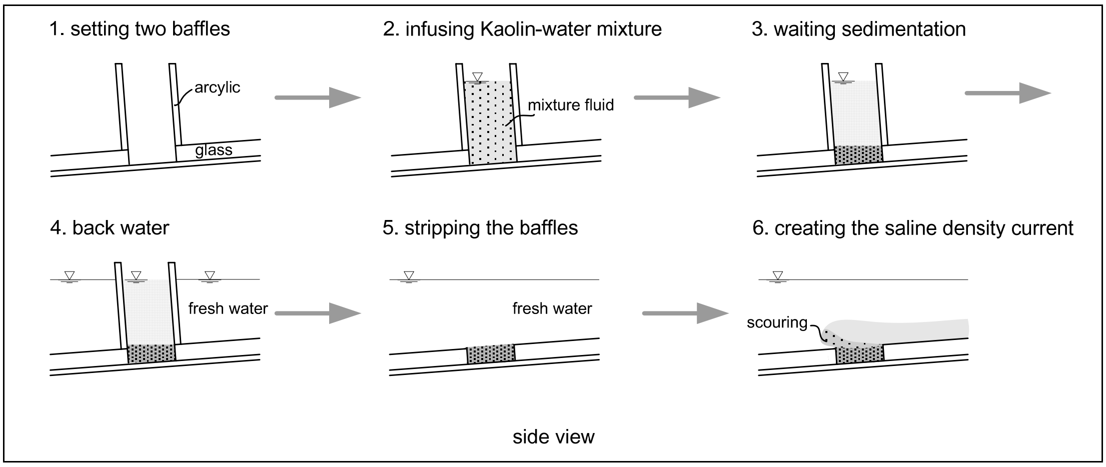


Figure 3 Procedures of Producing Silted Material.

Calibration of Kaolin-Water Mixture

The silted material of the test section was arranged by slow settling of Kaolin-water mixture. For containing the slope of the bed close to longitudinally uniform, the concentration of the mixture must be determined by observing the height of the sedimentation of the mixture, which the volume of mixture were all deployed with 8 liters. As shown in Figure 4, after the settling time cost 60 minutes, all the mixture which were arranged with different concentration(range from 40 g/L to 55 g/L), stayed with gradual variation of the level of the sedimentation, and the height of 42 g/L was close to 10.0 mm(the test section was 10.0 mm in height). To avoid the bed of the test section large change for sedimentation, in the initial set or during the experimental process, the Kaolin-water mixture with 42 g/L was tested several times. Figure 5 shows that there were approximately similar in the trace of the level of sedimentation to the same concentration of the Kaolin-water mixture with 42 g/L, and 120 minutes later, the height of the sedimentation was close to steady, which the difference to height of the test section was about +1.2 mm. Therefore, for each experimental case, the Kaolin-water mixture with 42 g/L were employed in producing the fine bed in the test section, and the settling time was contained two hours at least. In addition, the grain size distribution of the Kaolin clay had shown in Figure 6 by hydrometer analysis test. The main parameter of the grain size were $D_{50} = 0.002$ mm, $\sigma_g = 2.25$, $C_u = 9.18$, respectively. The specific gravity of the Kaolin clay were also test out, $G_s = 2.50$.

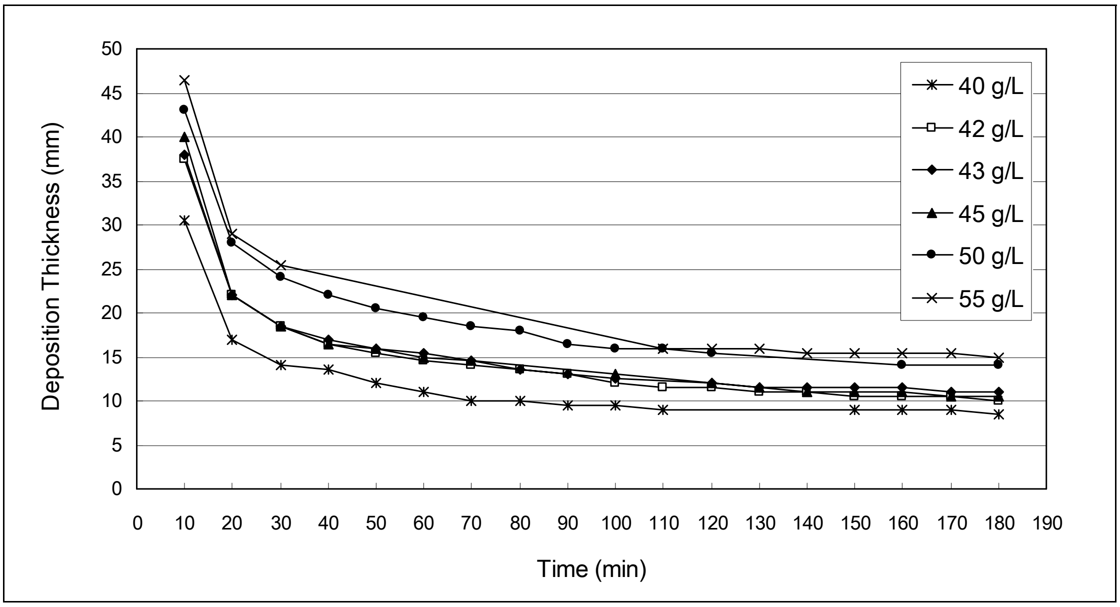


Figure 4 Settling of Kaolin-Water Mixture with Different Initial Concentration.

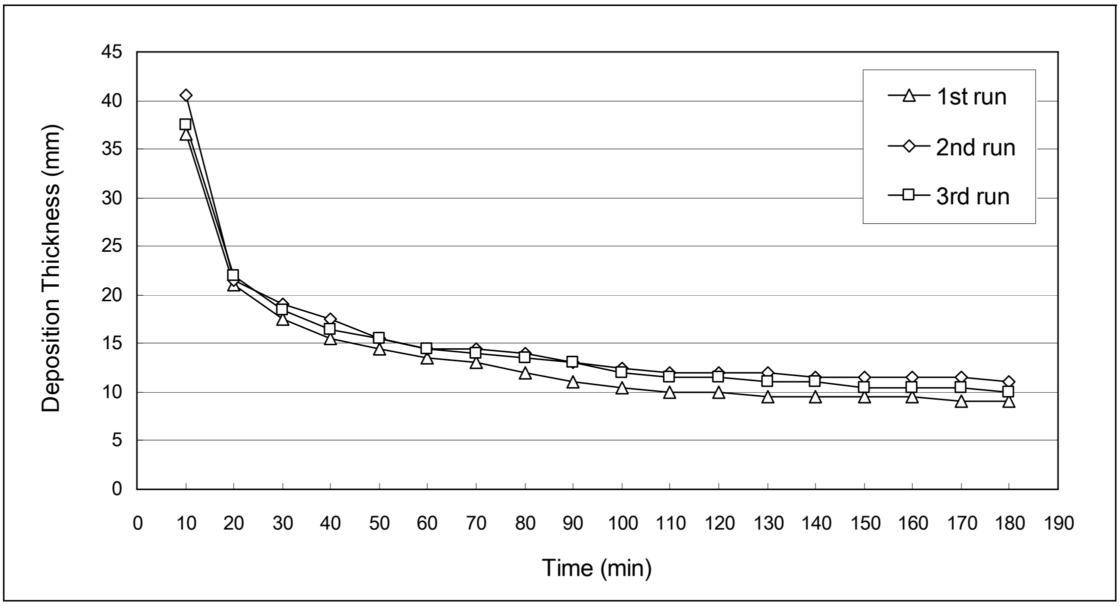


Figure 5 Settling of Kaolin-Water Mixture for 42 g/L as Initial Concentration.

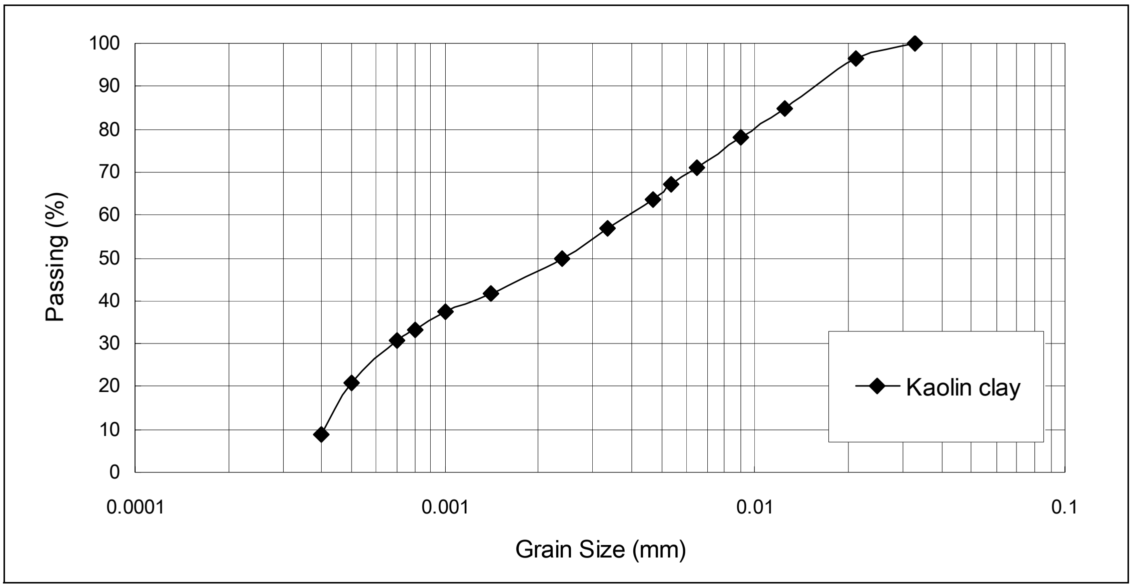


Figure 6 Grain Size Distribution of the Employed Material.

Experimental Conditions

Table 1 lists the experimental conditions of 13 runs. In this table, in each run, experimental time was also limited to 3 hours, included the time of setting the fine bed at the test section. The main control experimental parameters were determined by the supply of the inflow discharge (q_{in}) and the concentration of saline density current (C_s). In addition, the initial water level, controlled by the height of overfall tube, was set 9.0 cm in depth at the inflow entrance of the upstream. The initial concentration of Kaolin clay (C_b) was also calculated roughly, according to variation volume of the deposition at second hours of settling.

Table 1 Experimental Conditions.

runs number	q_{in} (cm^2/s)	C_s (g/L)	C_b (g/L)
TL-1	31.57	80	NA
TL-2	31.57	100	NA
TL-3	31.57	110	NA
TL-4	31.57	123	239
TM-1	94.50	25	344
TM-2	94.50	30	248
TM-3	94.50	60	NA
TM-4	94.50	123	NA
TH-1	143.60	10	305
TH-2	143.60	15	NA
TH-3	143.60	20	NA
TH-4	143.60	50	258
TH-5	143.60	123	240

Note: NA = not available

3. EXPERIMENTAL RESULTS

Incipient Criteria of the Concentration

Figure 7 shows the results of the 13 runs whether the erosion had occurred or not by saline density current, for the silted clay of the test section. In this figure, When the constant inflow discharge were controlled as 31.6 cm^2/s, 94.5 cm^2/s, and 143.6 cm^2/s, the minimum concentration of saline density current which ignited the incipient erosion were 123 g/L, 30 g/L, and 15 g/L, respectively. This indicated that the discharge had increase about 4.5 times from 31.6 cm^2/s to 143.6 cm^2/s, and whereas the igniting had concentration decreased about 8.2 times from 123 g/L to 15 g/L. This also suggested that the discharge had more powerful and sensitivity to effect the threshold for igniting the incipient erosion by the saline density current, of course when the initial concentration of the silted clay were made similar, approximately. In addition, Figure 8 shows three runs results of the head velocity of the density current. Those tree runs were TH-5, TM-4, and TL-4, respectively. All of them had the same concentration of saline density with 123 g/L, but their inflow discharge had the different mounts, which were 143.6 cm^2/s, 94.5 cm^2/s, and 31.6 cm^2/s, respectively. In this figure, for all of them, the trend of the head velocity had a little increase along the distance of the bed. Further, calculating their mean velocity were 24.7 cm/s, 20.8 cm/s, and 16.1 cm/s.

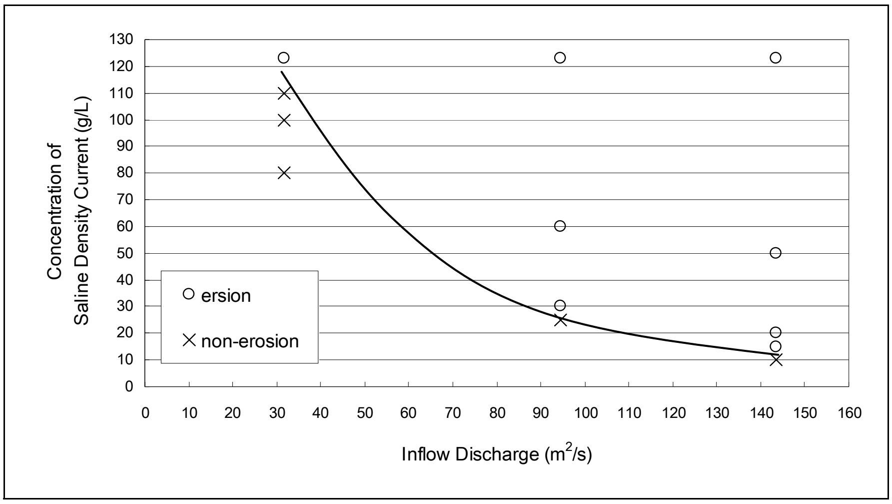


Figure 7 Criteria of the Incipient Erosion by Saline Density Current.

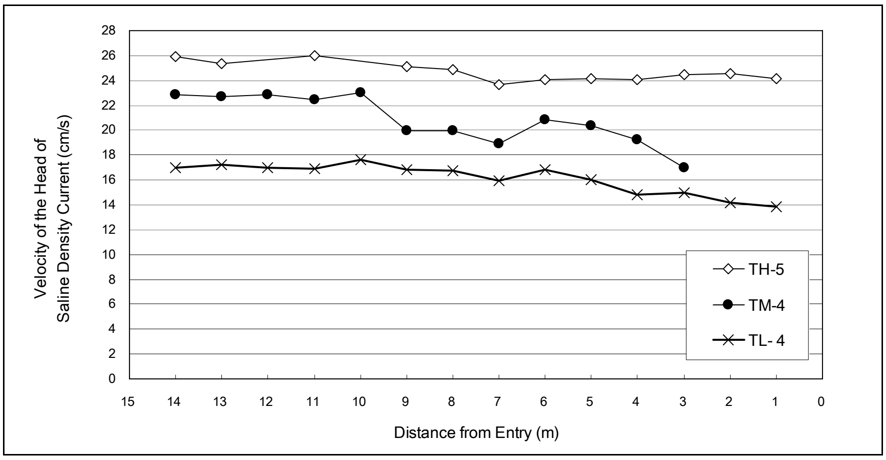
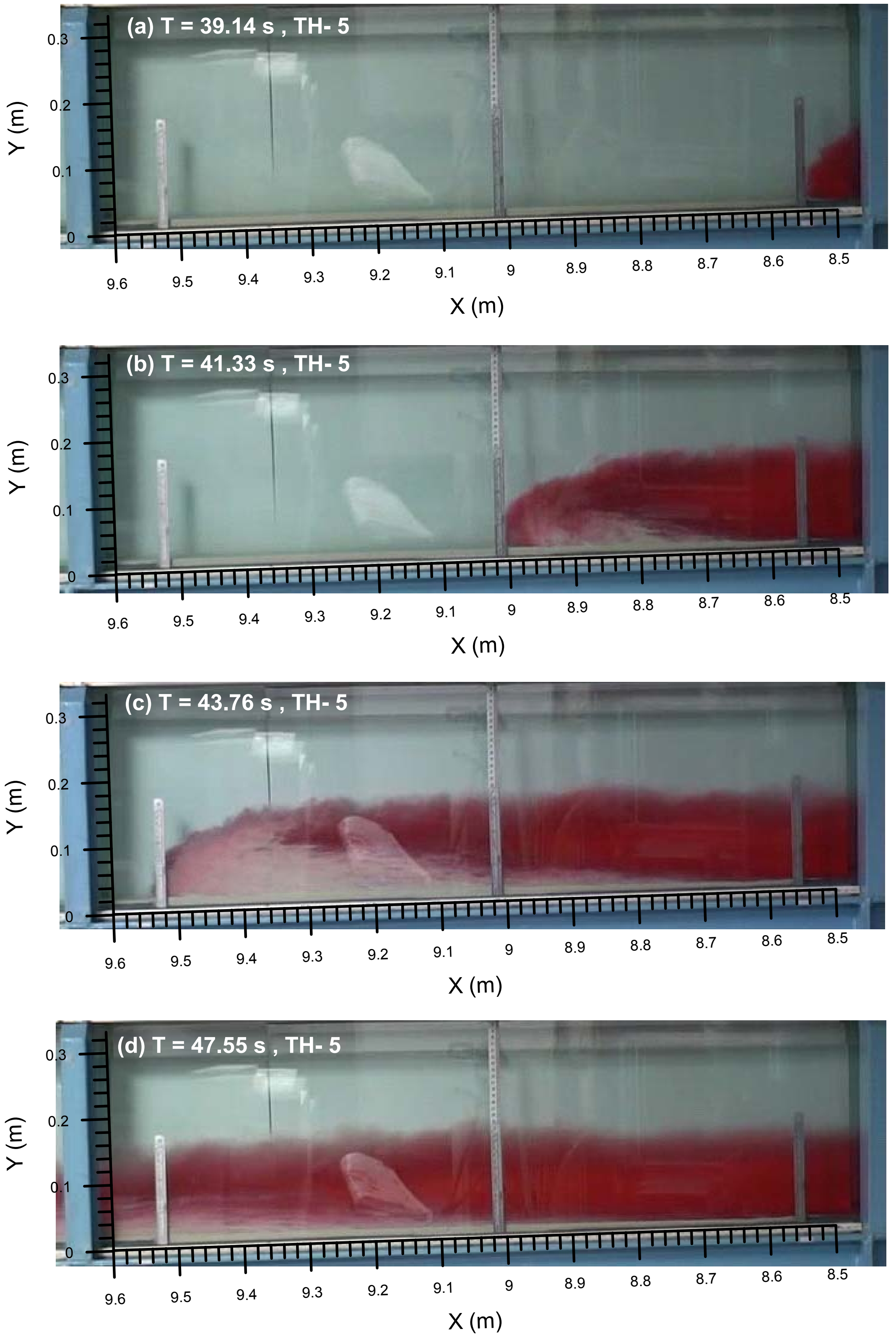


Figure 8 Distribution of the Head Velocity for the Density Current.

Erosion for Silted Clay

Figure 9 presents the process of erosion for Kaolin clay (white color) of the test section by saline density current (read color), which was worked in TH-5 runs. In this figure (b), at experimental time T= 41.33 s, the saline density current had transmitted into the test section (located at X= 9.0 m), and some of Kaolin clay had obviously carried out and mixed with the fluid of the current. This stated that the velocity stress of the current was large enough to scour a partial of surface clay. In the same figure from (b) to (c), more and more clay were carried out and especially full of the head of the saline current, in the duration of scouring along the bed of test section. Some of those re-suspend clays were entrained or left from the bed, and some were mixed or interacted with the bed by fluid turbulence, and others respected itself gravity to settle back to the bed. On the other hand, the erosive property to the structure of the saline current was indicated that the most scouring explicitly occurred on the head bottom. When the scouring of the density current started, they increasingly carried out the white clay along the bed of the test section, as shown in the same figure above. Except the head, there still was weak erosion occurring on the body of the density current. As shown in Figure 9 (c) (d), for focusing on the section from 9 m to 9.54 m, although the head of the density had passed through this section, the fallowing body of the density current still dragged on a few clay. However, the scouring for silted clay had already decreased obviously with more stable of the water-salt interface of the rolling body. In other words, the head of the density current dominated the souring stranger than the body of it.

Figure 10 presents the erosive ratio calculated according to DV cam typing the side of the glass wall at X = 9.0 m. In this figure, to TH-5 run, the erosive ratio of the head were 0.40 mm/s, 0.16 mm/s, 0.24 mm/s in the forward 3 seconds, respectively; the erosive ratio of the body had more vibration from 0 to 0.24 mm/s during the time from 3 to 13 seconds. However, the ratio trend had decayed as like a concave curve. To the silted clay, the head of the density current had the bigger erosive ratio, but its scouring time was very short and rapid, whereas the body scouring time had lasted 10 seconds, which was 3.3 times than the head scouring. To calculate further, the accumulative depth of the erosion was 0.79 mm and 0.191 mm, respectively, for souring on the head and the body. This revealed that the erosive ratio of the head had larger than the body, but for souring time the body had caused larger than the head. For this reason, the body of fallowing the head would be also the key factor in discussing the erosion of the silted clay by density current.



NOTE: T = experimental time

Figure 9 Full view of Test Section in TH-5 run.

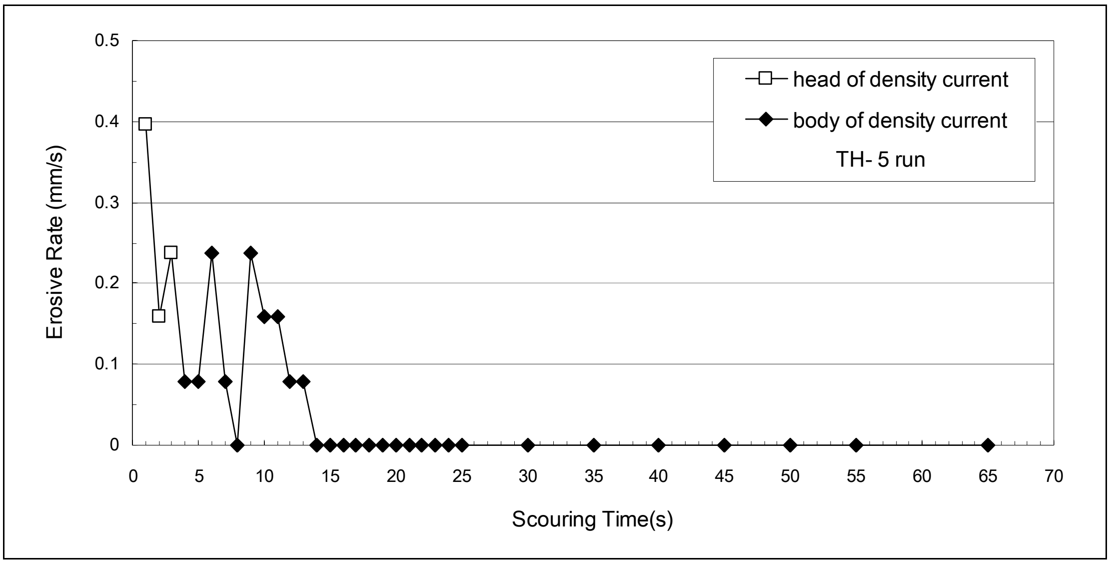


Figure 10 the Variation of Scouring Depth at Flume Wall in TH-5 Run.

4. DISCUSSION AND REMARKES

In this study, experiments were carried out to understand how density current re-suspend fine sediments on the bed. To simplify various factors affecting the erosion phenomena and easier for observation, saline density currents which do not carry sediment were made as the erosion engine to directly plunge on a long flume with 2% in slope. A dig-in section was set of the bed of the flume for silted clays. Further, to focus on the scouring of loose or weakly-bounded clays. On this section, called as test section, initial concentrations of Kaolin-water mixture were considered for slow settling in it during a short time period.

By the experimental set-up, development of the silted thickness revealed that it necessarily takes 2 hours for settling to reach a more stable condition and to closely match the original fixed-bed elevation by using 42 g/L as Kaolin-water mixture. On the other hand, when controlling the inflow discharge to increase about 4.5 times from 31.6 cm^2/s to 143.6 cm^2/s, the criterion for igniting the incipient souring of the silted clay revealed that the concentration of saline density current had changed to decreased about 8.2 times from 123 g/L to 15 g/L. This also suggested that discharge is more powerful and sensitive to influence the re-suspension threshold. In addition, the experimental results showed that erosion phenomenon occurred on both the head and the body of saline density current. The former was more aggressive with bigger erosion rate in a short time, but the latter was gentle but with more accumulative souring depth. During the souring period, some of the re-suspended sediments fell onto the bed, but some travel by the current, and the amount of re-suspended sediment obviously decreased to zero when the water-salt interface of rolling body developed into stable.

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