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Experimental Study on the deposition behavior of turbidity currents

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Abstract: *In this work, the turbidity current containing kaolin particles was studied two dimensionally in a channel experimentally. Velocity and concentration profiles were obtained by ADV (Acoustic Doppler Velocimeter). These experiments were performed for studying the deposition behavior of the current. The effect of parameters, such as inlet Froude number, inlet opening height of the sluice gate, and the bed slope were studied. To investigate the deposition behavior, the flux of suspended sediments was evaluated. For evaluation of this parameter, it was necessary to separate the suspended sediments region from the above shear layer and near the bed depositional district. Method of determination of these areas was discussed. Results showed that these parameters pose important effects on the structure and deposition behavior of the turbidity current.*

Keywords*: Turbidity current, Inlet Froude number, suspended sediments' flux, Deposition.*

INTRODUCTION

Many geophysical currents occur on the Earth's surface are driven by gravity (Kneller et al. 1999). Gravity or Density currents are of great important among these currents and are often seen in nature in vast scales. Density currents are created as a result of existence of gravitational force and its effect on the density difference between the current and the ambient fluid. Temperature difference, suspended sediments and dissolved chemical materials are agents of density difference. Fig.1 shows a typical density current on a sloping bed schematically. There are many examples of density currents in nature. Thunderstorm outflows, heated surface plumes, or cold or warm water inflows are the other examples of density currents (Alavian, 1986 & Dallimore et al., 2001). The important applications of these currents are in various fields, such as: protection of sea faring vessels, atmospheric pollution, entomology and pest control, gas compression technology, meteorology and weather forecasting, cleaning of oil spills, control of sedimentation in the reservoirs, etc (Hormozi et al., 2006). Turbidity currents are often the governing process in reservoir sedimentation by transporting fine materials over long distances through the impoundment to the vicinity of the dam. Appropriate measures for sediment release through bottom outlets may reduce sedimentation in the reservoir. Operation and rules for reservoir control require the knowledge of turbidity currents to open the bottom gates at the right moment to maximize sediment release while minimizing water loss (De Cesare et al. 2001). So, deposition

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and erosion are of important features of turbidity current which can affect the environment. These problems have encouraged researchers to study the deposition or erosion behavior of the turbidity currents. Garcia (1993) observed that the flow regime changes from supercritical to subcritical through an internal hydraulic jump. In his experimental setup, the bed slope was 0.08 for the supercritical portion and horizontal for the subcritical portion. Silica particles (with a density of 2.65 g/cm^3 and a geometric mean of particles 0.004 and 0.009 mm, respectively) were used as the agents of deposition. Deposition's quantity in the two portions of the channel (sloping and horizontal portions) did not show any major variation. He also used glass beads (with a density of 2.50 g/cm^3 and a geometric mean of particles 0.030 and 0.065 mm, respectively) which are larger in size than silica particles to make the turbidity current. In this case, their results showed that deposition begins at the inlet of the supercritical region and decays exponentially with the distance traveled. Yu et al. (2000) designed their experimental setup in a way to be able to study the effect of plunge phenomenon on the deposition behavior. Their laboratory experiments were conducted to produce both quasi-homogeneous flow and a turbidity current region divided by a plunge section. Silica powder (a noncohesive sediment) and kaolin (a cohesive sediment) were used as the suspended material with a specific gravity of 2.66 and 2.65, respectively. The median particle diameter was 0.05 and 0.0068 mm, respectively. Their results showed that the deposition rate of noncohesive coarse particles exponentially decays along the path for both quasi-homogeneous flow and stratified turbidity current. Most of the coarser particles were deposited in the quasi-homogeneous flow region or within a small distance downstream of the plunge section. Deposition in the turbidity current is primarily governed by fine cohesive particles for the studied cases. The deposition rate of fine cohesive particles increases along the flow direction in both a quasi-homogeneous flow and turbidity current. After the plunge section, however, the increase in the deposition rate slows down with distance (Yu et al., 2000).

This paper is focused on the experimental investigation of the deposition behavior of turbidity currents and the effects of the inlet conditions. Results have shown that the bed slope and inlet parameters such as Froude number and the sluice gate's opening height have a strong effect on the current's structure. The velocity profiles which are the most important characteristic of these flows are measured by Acoustic Doppler Velocimeter. Kaolin was used as suspended materials with D50~12 micron.

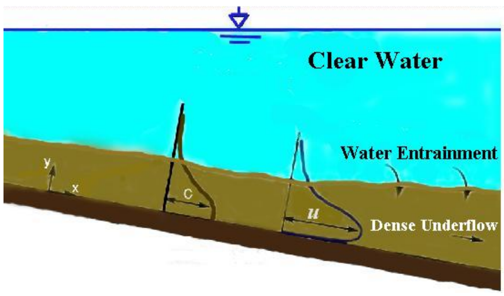


Fig 1. A typical density current on a sloping bed

EXPERIMENTAL SETUP

A channel with an adjustable slope (which changes between 0% and 3.5%) was used for doing experiments. The length of channel was 12m, the width was 0.2 m and the depth was 0.6 m. A gate was installed in the channels entrance to keep the turbidity current separated from the fresh water (to avoid mixing between the current and clear water before the beginning of the experiments). The inlet gate's height was changeable between 4 and 7 cm. Furthermore, the inlet gate's width was set to 0.2 m to keep the entrance turbidity current away from lateral growth.

Thus, the investigation would be two-dimensional. A stainless steel cylindrical supply tank with 2 m^3 volume was placed upstream which contained the turbidity current's mixture. The supply tank was installed at an elevation of 2.5 m from the ground; and a supply pipe fed the dense water from the reservoir into the accumulator. A gate valve controlled the feed rate and the feed rate was fixed at a desired rate. Thus, the current would be in a quasi-steady condition. Kaolin with a specific gravity of 2.65 was used to make a turbidity current mixture. Kaolin was mixed with water in the supply tank. To avoid the return flow, a 25 cm step was constructed at the end of the channel as Fig. 2 shows. Sixty-four valves were installed at the bottom of the step. The number of the opening valves was dictated by the inlet flow to set the discharge rate a little more than the inflow rate to let the entrained water out of the channel.

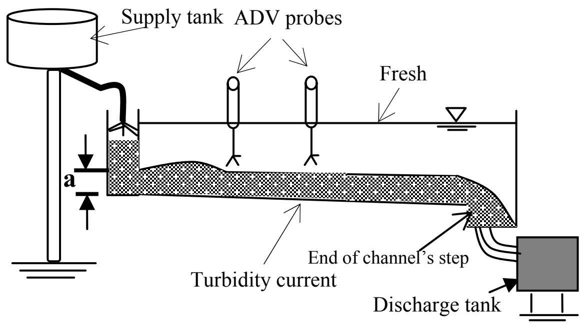


Fig.2. Schematic of experimental setup

To prevent losing fresh water, the

Table 1. Inlet conditions for experiments

Run	*S(%)*	*a(cm)*	*C_0(gr/lit)*	*U_0(cm/s)*	*Fr_{in}*	*T (^0C)*	*Run*	*S(%)*	*a(cm)*	*C_0(gr/lit)*	*U_0(cm/s)*	*Fr_{in}*	*T (^0C)*
1	1	4	1.75	7.39	3.6	19	17	1	7	1.75	4.23	1.55	19
2	1	4	2.5	7.39	3	19	18	1	7	2.5	4.23	1.3	19
3	1	4	6.5	7.39	1.86	19	19	1	7	4.2	4.23	1	19
4	1	5	0.88	5.93	3.6	20	20	1	7	6.5	4.23	0.8	19
5	1	5	1.28	5.93	3	20	21	1	7	8.5	4.23	0.7	19
6	1	5	2.88	5.93	2	20	22	1	7	11.5	4.23	0.6	19
7	1	5	4.8	5.93	1.55	20	23	2	4	1.75	7.39	3.6	19
8	1	5	6.83	5.93	1.3	21	24	2	4	2.5	7.39	3	19
9	1	5	9.55	5.93	1.1	21	25	2	4	6.5	7.39	1.86	19
10	1	6	0.51	4.942	3.6	20	26	2	7	1	4.23	2	19
11	1	6	0.74	4.942	3	20	27	2	7	1.75	4.23	1.55	19
12	1	6	1.66	4.942	2	20	28	2	7	2.5	4.23	1.3	19
13	1	6	2.76	4.942	1.55	20	29	2	7	4.2	4.23	1	19
14	1	6	3.95	4.942	1.3	20	30	2	7	6.5	4.23	0.8	19
15	1	6	6.68	4.942	1	20	31	2	7	8.5	4.23	0.7	19
16	1	7	1	4.23	2	19	32	2	7	11.5	4.23	0.6	19

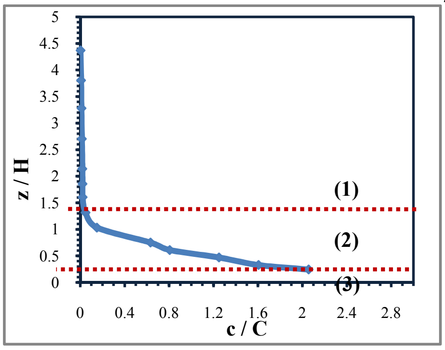
fresh water was replenished at the end of the channel so that the total height of water was kept constant during the experiments. The channel overflow prevents the fresh water from overreplenishing. The velocity profiles were measured by the 10 MHz acoustic Doppler Velocimeter (ADV) made by Nortek Company. Acoustic Doppler anemometry relies on use of pulsed echo sound wherein an ultrasound pulse is emitted along a measuring probe from a transducer and the same transducer received the reflected echo from the surface of small particles suspended within the flow, which are assumed to move with the water velocity. The scattered sound signal is detected by the receivers and used to compute the Doppler shift. Two ADV probes were used for measuring the velocity profiles. The distance between the two probes of this instrument which were placed on a rail conveyor on the channel was 1 m. There is a 5 cm distance between the measured point and ADV probe, and hence it does not disturb the flow at the measurement point. Concentration profiles were also obtained by ADV probes. To obtain these profiles the ABS theory (Nikora and Goring, 2002) were used. This theory is based on the amplitude of the waves scattering from the particles in the flow. ADV probes give the amplitude of the scattering waves in the NDV software (NDV is the software developed by Nortek Company to perform ADV data acquisition and analysis) and the following equation converts these amplitudes to the concentration, $C = P \times 10^{0.0434\,AMP}$ Where P is the calibration parameter which is obtained experimentally. C is the concentration of the current in each point. When the head of the current reached the end wall of the basin and the flow reached a quasi-steady state, measurements in the body of the current with the ADV began. A steady state condition was considered achieved when the measured mean velocities at one point between 2 min were the same. The data acquisition took 35–40 s for each probe's position. The measurement started from the top part of the dense layer and continued into the lower part by lowering the probes into the dense layer until all the desired positions were selected. The total duration of each experiment was about 60 min. These series of experiments were carried out to obtain instantaneous velocities, mean flow properties, and velocity profiles without interfering in the density currents. When the density current reached the end of the channel, it flowed on the ending step and was withdrawn from the channel by some valves to prevent its reflection. The lateral sides of the channel were constructed from glass to permit visual observation of the flow.

Experiments' characteristics are listed in table 1. In this table, S = bed slope, a = inlet gate's height, C_0 = inlet concentration, U_0 = inlet current's velocity, Fr_{in} = inlet Froude number, and T = fresh water's temperature. For all the experiments, the width of the current was equal to the width of the channel (0.2 m). Density currents are turbulent when the Re>2000 (Kneller and Buckee, 2000). To have a turbulent flow, the flow rate was set to its maximum value, so the inlet Reynolds number for all the experiments was greater than 2000 and it had the same value for the experiments ($\mathrm{Re}_{\mathrm{in}}$ = 2965). Inlet Froude number and Reynolds number were calculated as $Fr_{in} = U_0 \big/ \sqrt{g'a\cos\theta}$, $\mathrm{Re}_{in} = U_0 a/\nu$.

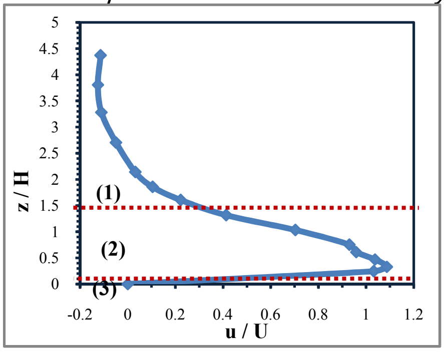
Where, θ is the bed slope, ν inlet current's kinematic viscosity and $g' = (\rho_m - \rho_w)/\rho_w\, g$ reduced gravity acceleration, where ρ_m and ρ_w are the turbidity current and fresh water density, respectively.

DEFINIG THE SUSPENDED SEDIMENTS' AREA

The main aim of this research is studying the depositional behavior of the turbidity current. For this purpose, suspended sediments' flux should be calculated. So, it was necessary to distinguish the region of existence of suspended sediments from other regions properly. Thus, turbidity current from up to down in the normal direction is divided to three regions; 1. shear layer (in which the density irregularity increasingly reduces to zero and the velocity also diminishes to zero). Entrainment of the fresh water into the current occurs in this region. 2. suspended sediment



b) A typical concentration profile



a) A typical velocity profile

Fig. 3. Division of the turbidity current to three zones: (1) Shear layer (2) suspended sediments' zone (3) Depositional area.

zone (or bed load zone), and 3. Depositional area (in which particles are likely to settle down and deposit on the bed). These three zones are shown schematically in Fig. 3.

Shear layer

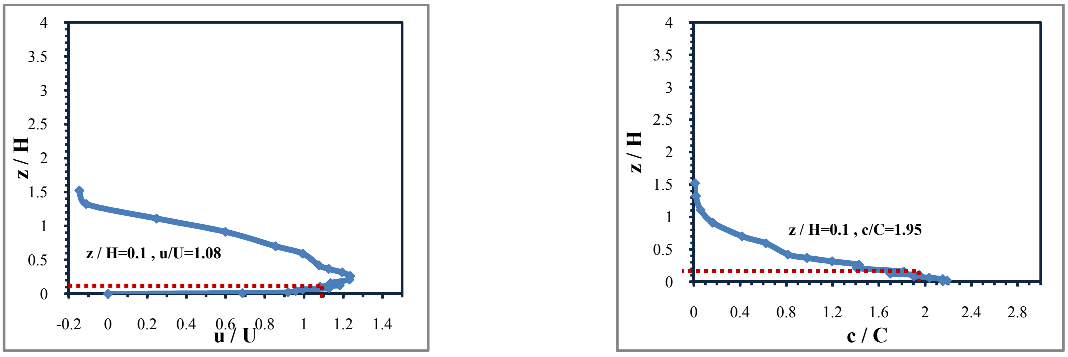
There is a sharp density difference between the main body of the turbidity current and the pure water. Above this sharp density gradient, velocity and density reduce to zero. This layer is known as shear layer (Dallimore et al., 2001). Sediments defuse to this layer and this layer may be included mistakenly in the calculations of the suspended sediments' flux. Therefore, it is necessary to set a criterion to identify the shear layer from the main body of the current. As there is a sharp density gradient between the shear layer and the current, the boundary between these two parts can be realized by naked eye which is known as vision height of the current. As a result, the vision height can be used as the boundary of the shear layer and the current. As, the vision height is not clear all the time so, it is better to use an alternative criterion based on the current's hydraulic properties such as velocity instead of the vision height. For this purpose, there are some norms as alternatives of the vision height (Firoozabadi, et al., 2009, Felix, 2004). In this research $Z_{1/4}$ (the corresponding height of a quarter of the maximum velocity above it) was chosen as the superseding of the vision height in the following calculations.

Depositional area

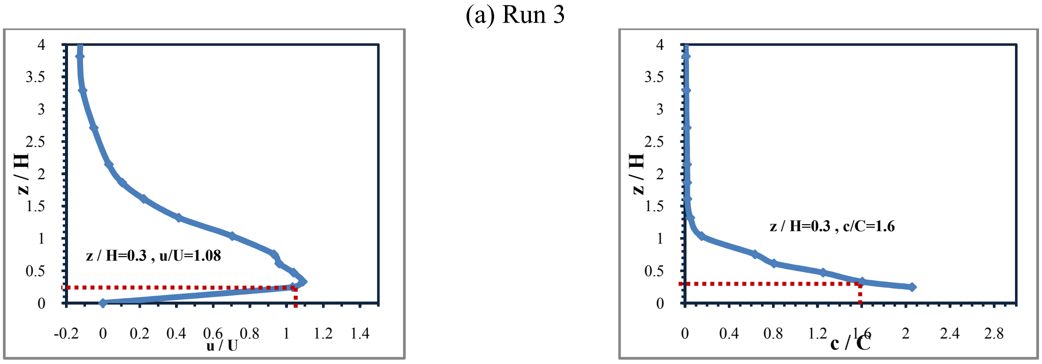
The upper boundary of the suspended sediments' area was determined in the preceding section. The border between shear layer and this area which is determined by $Z_{1/4}$ is the upper boundary. At the moment, deposited sediments should be distinguished from the suspended sediments to prevent from including them in calculation of suspended sediments' flux. The area that deposited sediments exist is called "Depositional area". As particles settle down, they accumulate. As a result, there should be a sudden increase in the density (concentration); so it can be seen in current's density profile. Thus, the border between the depositional area and suspended sediments can be determined by currents density profile. In Fig.4, non-dimensional density and velocity profiles which are non-dimensionalized by their average values have shown. These average values are defined as

$$C = \int_0^\infty c(z)u(z)dz \Big/ \int_0^\infty u(z)dz \text{ , } U = \int_0^\infty u(z)^2 dz \Big/ \int_0^\infty u(z)dz$$

based on Garcia (1993). In this state, it is better to realize the lower boundary of the suspended sediments by the hydraulic of the current, too. For this purpose, the corresponding height of the near bed area's border to its average value z/H, the corresponding concentration of this area's border to its average value c/C and the corresponding velocity of this area's border to its average value are indicated. To determine a general criterion for the near bed area's border, the average and the standard deviation are listed in Table.2. This table shows that the lower boundary of the suspended sediments' area is the place that $u/U = 1.07$ or $z/H = 0.2$.



(a) Run 3



(b) Run 9

Fig 4. Determination of near bed depositional area with the aim of velocity and concentration profiles

Table 2. average and standard deviation of near bed depositional area's criteria

	z/H	u/U	c/C
Average	0.2	1.07	1.97
Variance	0.005	0.008	0.06

TURBIDITY CURRENT'S DEPOSITION BEHAVIOR

Shear layer and the near bed depositional area was introduced in the two preceding sections. Suspended sediments region is located between these two areas. So, the suspended sediments area can now be separated easily. For investigating deposition in turbidity current, suspended sediments flux must be evaluated. Since, at the inlet, all the sediments are suspended, a decrease in the suspended sediments flux in each section corresponds to an increase in deposition in that section; so, the suspended sediments flux is a parameter for studying the deposition behavior of the current. Consequently, it is possible to inspect the current depositional behavior by calculating the suspended sediment flux in each section and comparing it with its value at the inlet. For this purpose, the flux of the mixture should be calculated in each section and with the subtracting of pure water flux from mixture flux; suspended sediment flux would be obtained. $q_m = \int_0^\infty \rho_m u dz$ is the definition of the mixture of the water and sediments. In this equation ρ_m is the density of the mixture. Now, if the pure water flux is subtracted from mixture flux, the suspended sediment flux will be attained. $q_s = q_m - q_w = \int_0^\infty (\rho_m - \rho_w) u dz = (\rho_m - \rho_w) \int_0^\infty u dz$ shows the desired parameter's definition. With calculating the difference between the suspended sediment flux in each section with its value in the inlet, it iss possible to define a parameter for the deposition rate. This expression is $W_s = \frac{q_{s_{in}} - q_s}{q_{s_{in}}}$. It should be noticed that in this equation the integration limit is actually the region of the suspended sediment flux which is located between the shear layer and the near bed depositional area which are determined in the two preceding section. In the following section, results will be discussed.

RESULTS AND DISCUSSION

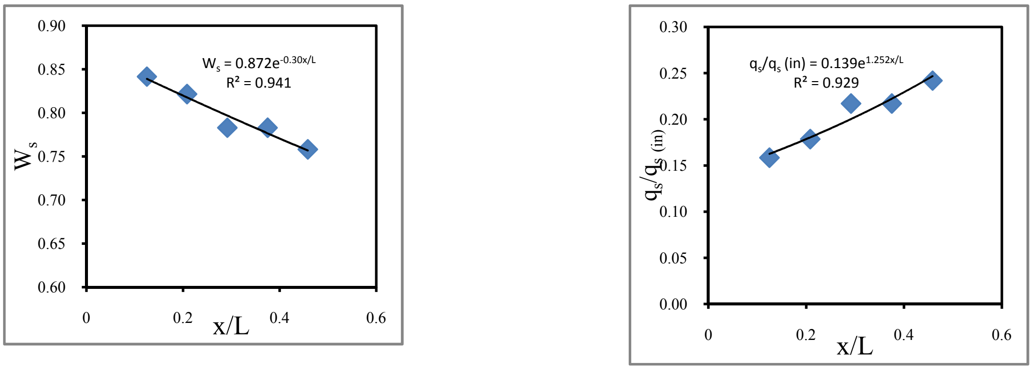
At first, results are considered to investigate the current general behavior in details for slope=1% and the inlet opening height=5cm. Obtained results are shown in Fig.5. Results are illustrated in sections x=1.5, 2.5, 3.5, 4.5, 5.5 m from the inlet. For each certain inlet Froude number, the suspended sediment flux as well as the depositional rate are plotted. In these figures vision height and average velocity (which is obtained by eq.6) in each section are shown. The purpose of plotting of these two later parameters with the formers is inspecting the deposition behavior of the current with the aim of the trend of the average velocity and vision height. In all the figures, the horizontal axis is non-dimensionalized by L (channel's length which is equal to 12m). All the heights and velocities are non-dimensionalized by their inlet amounts. The trend of the deposition rate shows that after the hydraulic jump (which occurs before the x/L=0.125) because of a sudden reduction in the bed shear stress (Garcia, 1993) and a decrease in the current inertia, the ability to suspend and carry the sediments reduces and sediments deposit on the bed. Thus, suspended sediment flux reduces after the hydraulic jump; consequently, deposition rate increases. But, with regard to the channel inclined bed, the current velocity increases gradually and the ability of the current to suspend and carry the sediments increases. Therefore, the deposition rate reduces. Deposition rate decreases exponentially in the channel length. This behavior has been seen in Garcia's (1993) experiments.

The effect of inlet Froude number on the deposition behavior

Deposition rate in the slope=1% and different inlet heights has been shown in Fig.6. This figure shows that in a certain bed slope and certain inlet opening height, the deposition rate decreases when the inlet Froude number increases. The increase in the inlet Froude number is because of the decrease in the inlet concentration. As concentration is the agent of the buoyancy force and the buoyancy force can make the current stable, so, the reduction of the concentration and consequently the buoyancy force builds the interface of the current unstable and the current bears a stronger hydraulic jump. Unstable interface and the stronger hydraulic jump increase the entrainment of the quiescent fluid into dense layer and make the current more turbulent. So, the current can suspend more sediment. As a result, the deposition rate decreases.

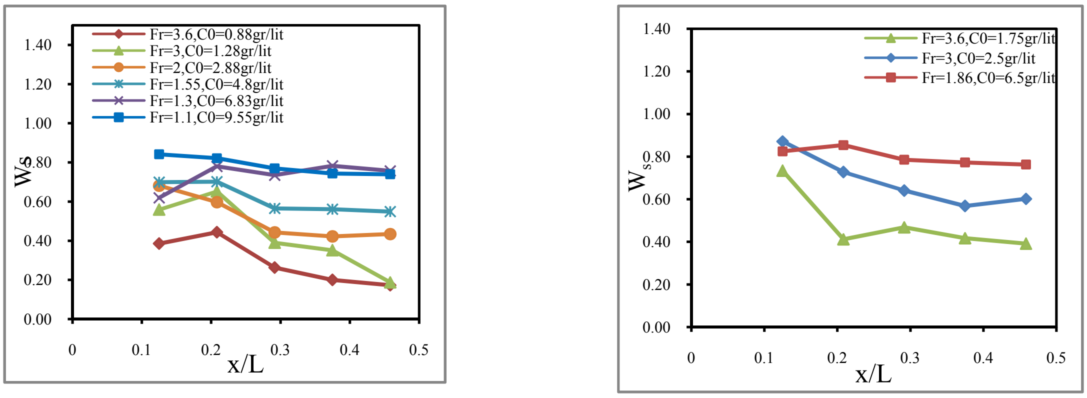
The effect of bed slope on the deposition behavior

To study the effect of the bed slope on the deposition behavior of the current, in some experiments all the inlet conditions were the same. But, the bed slope was changed. Fig.7 shows the effect of the bed slope variation on the deposition rate. Results show that the average velocity of the current increases with increase in the bed-slope, so, current can suspend more sediment and this means that deposition rate will reduce.



Fr=1.1,C_0=9.55gr/lit

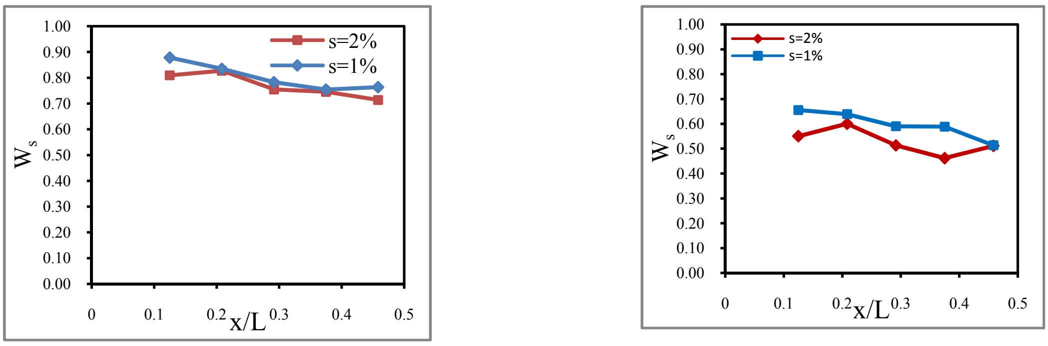
Fig 5. Suspended sediment flux and deposition rate in slope=1% and inlet opening height=5cm



(a) s=1%,a=5cm

(b) s=1%,a=4cm

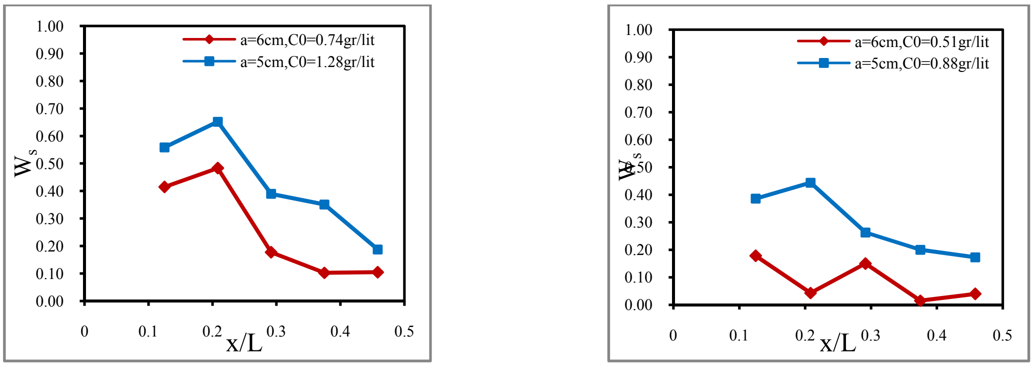
Fig 6. The effect of inlet Froude number on depositional behavior of turbidity current when bed slop=1%



(a) Fr=1.55

(b) Fr=2

Fig 7. The effect of bed slope on the depositional behavior and average velocity of the current



(a) Fr=3 (b) Fr=3.6

Fig 8. The effect of the inlet gate's height on the deposition behavior

The effect of the inlet opening height on the deposition behavior

Change in the inlet opening height causes a change in two governing forces; if inlet opening height changes, either inertia force or buoyancy force will change. These changes would effect on deposition behavior of the current. So, a change in the inlet opening height will bring about changes in the behavior of the current. Experimental results for two different inlet heights are demonstrated in Fig.8. This figure shows that in a constant inlet Froude number, if inlet height increases, deposition rate will decrease. It is obvious that in a constant inlet Froude number, an increase in inlet opening height leads to a reduction in the inlet concentration. Consequently, buoyancy force will decrease as well. Buoyancy force's reduction increases instabilities, turbulences and entrainment in the turbidity current. It means that the current will be able to suspend more sediment. Thus, deposition rate reduces.

CONCLUSIONS

In this paper deposition behavior of the turbidity current was investigated experimentally. The purpose of this work was to study the effect of some inlet parameters such as inlet Froude number, inlet gate's height and also the effect of the bed slope on the deposition behavior of the current. For this purpose, suspended sediment flux was introduced as a criterion for the investigation of the deposition behavior. To calculate this parameter, it was essential to appreciate the suspended sediment area properly. To achieve this goal, turbidity current was divided to three distinct areas: 1. Shear layer (in which the density irregularity increasingly reduces a zero and the velocity also diminishes to zero), 2.Suspended sediment area, and 3. Near the bed depositional area (in which sediments is likely to settle down and deposits on the bed). Shear layer determined the upper boundary of the suspended sediments' area. The border between these two areas was established by $Z_{1/4}$. After that, the near bed depositional area was also determined by means of velocity profiles of the current. Results showed that lower boundary of the suspended sediments' area is the place that $u/U = 1.07$ or $z/H = 0.2$. With the good recognition of the shear layer and the near bed depositional area, the suspended sediments' region would be distinguished easily. In this stage, suspended sediment flux could be calculated in each station and deposition rate would be obtained, consequently. Results showed that, in turbidity currents deposition rate decreases exponentially in the channel length. Furthermore, investigations showed that inlet parameters and bed slope affected the deposition behavior of the current as follows:

- Increase in the inlet Froude number and bed slope will lead to deposition rate's reduction.
- In a constant Froude number, a decrease in the inlet gate's height will result in a increase in the deposition rate.

Nomenclature

b	Channel's width	m	q_w	Pure water flux	lit/min
c	sediment's volume concentration average	gr/lit	Re_{in}	Inlet Reynolds number	-
C_0	Inlet concentration of the current	gr/lit	s	Bed slope (%)	-
$Fr_{d_{in}}$	Inlet densimetric Froude number	-	u	x direction time-averaged point velocity	cm/s
g	Gravity acceleration	m^2/s	U	Turbidity current's average velocity	cm/s
g'	Reduced gravity acceleration	m^2/s	U_0	Inlet current's average velocity	cm/s
a	Inlet gate's height	cm	x	Distance from inlet	Cm
H	Turbidity current's average height	cm	z	Current's height perpendicular to bed	Cm
Q	Inlet current's flux	lit/min	ρ_w	Water density	kg/m^3
q_m	Turbidity current mixture's flux	lit/min	ρ_m	Turbid mixture's density	kg/m^3
q_s	Suspended sediments flux	lit/min	μ	Dynamic viscosity	kg/ms
			θ	Bed slope (in degree)	Degree

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