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Turbidity Currents Head Motion over Artificially Roughened Beds

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Abstract: Density currents are flow of one fluid within another of a different density. Turbidity currents can be generated when the density difference is caused by suspended sediments. Turbidity currents are major agents of sediment transport in reservoirs. They are characterized by a well-defined head that is followed by a layer known as the body of the current. In this paper, the effect of artificial roughness on head motion is investigated experimentally. A total number of 36 experiments were performed using three rough beds as well as a smooth bed. The roughness elements were in cylindrical shape. The influence of head concentration, head height and bed slope on head velocity were studied using dimensionless analysis. It was found that all rough beds decrease normalized head velocity in comparison with the smooth bed. However, the effective height of the roughness elements that are higher than a critical value is reduced due to a new phenomenon which is called "Head Rise" by the authors. Dimensionless head height increases as the height of roughness elements rises. The dimensionless head velocity is almost independent of slope for smooth and rough beds. An equation is presented in order to predict the head velocity moving over rough beds.

Key words: Turbidity currents · Head · Head rise · Rough bed · Cylindrical roughness

INTRODUCTION

Density currents are generated when fluid of one density is released into fluid of a different density. Density currents are produced where gravity acts upon a density difference between one fluid and another and thus such currents also bear the name of gravity currents [1]. The density difference can be caused by suspended materials, temperature gradients, dissolved contents or a combination of them. In case of turbidity currents, the major driving force is gained from suspended sediments. Density currents are mainly horizontal flows and can be even generated by a minor density difference of a few percent [2]. These currents occur in both natural and man-made situations and attracted researchers of various disciplines. In estuaries, turbidity or salt water intrusions can travel long distances upstream along rivers. Large-scale atmospheric movements, thunderstorms outflows, sea-breeze fronts and snow avalanches are natural examples of such currents [3]. Common industrial examples of density currents are oil spillage in oceans, waste water discharge in rivers and propagation of toxic gases in mines. Turbidity currents are dominant mechanism in reservoir sedimentation and can unload or even resuspend bed materials during passage [4]. Turbidity currents increase reservoir dead volume via sedimentary deposition, adversely affects water intake structures and facilitates sediments entrance into the dam power plants [5]. In order to tackle sedimentation problems and improve reservoir operations, a better understanding of turbidity currents is required.

In dam reservoirs, turbidity currents are mostly underflows which consist of three main parts, namely plunge point, body and head. The head is the leading edge of turbidity currents which is deeper than the following flow and has a raised noise at its foremost point [6]. The authors in [7] divided the front into three distinct regions: energy-conserving region, dissipative wake region and tail. They concluded that only the energy-conserving region has a velocity roughly equal to the front speed. The head is a region of intense mixing. There are two main types of instabilities that are

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responsible for mixing in the frontal region [2]: firstly, Kelvin-Helmholtz billows which are responsible for mixing behind the head. These types of billows are formed at the interface between two fluids of different density, moving relative to each other. Secondly, a shifting pattern of lobes and clefts that is caused by the displacement of ambient fluid by the head. The lobe-cleft patterns are stable during head evolution [8]. Head velocity of saline currents is defined as a function of head height and reduced gravity [9]. According to [10], for low slopes (angle < 2.3°) the head velocity is independent of slope. The deposition process decreases the head velocity and increases the thickness of current front [11]. The key role of bed materials in self-reinforcing mechanism of the head is explained in [12]. A self-a1ccelerating current is a particle-driven gravity current whose velocity increases while moving downstream. It means that the gravity current erosion of bed materials outweighs its deposition onto the bed. The suspended materials increase the density and thus the speed of the current. In [13], experiments have been done with a smooth bed as well as two bed roughness (0.7 and 4.5 mm) that were made out of sand with different mean diameters. They observed that as the roughness increases the head velocity decreases. To the authors' knowledge no experiments were performed on the head moving over cylindrical roughness.

In the present paper, turbidity currents head motion over artificially roughened beds is investigated experimentally. Cylindrical roughness elements in three different heights were employed in order to study effect of roughness on head characteristics. The main objective of this research is to evaluate the effect of bed roughness on hydraulic parameters of turbidity currents head.

This paper is organized as follows: Section 2 explains experimental setup and procedure. Section 3 discusses the influence of head concentration, head height and bed slope on head velocity for smooth and rough beds. This paper is concluded in Section 4.

MATERIALS AND METHODS

Experiments were performed in Physical Hydraulic Modelling Laboratory at Shahid Chamran University of Ahvaz, Iran. The experimental facility is schematically illustrated in Figure 1. It was composed of three main components: the glass-wall flume, the mixing system and the head tank. The flume was 7.8 m long, 0.35 m wide and 0.7 m deep with variable bed slopes. The flume was divided into two parts by a sliding vertical gate placed

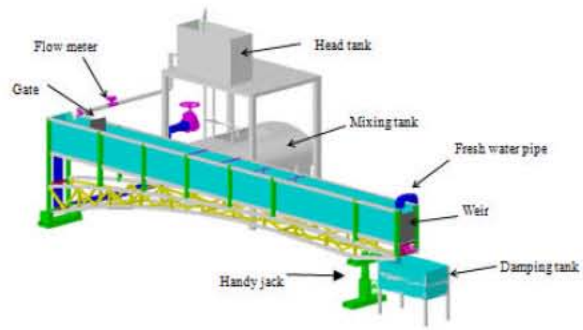

Fig. 1: Schematic of experimental apparatus

at a distance 0.8 m from the upstream end of the flume. The left part was filled with dense fluid, whilst the right part was filled with tap water. The height of ambient fluid was kept constant during each experiment by the means of a weir at the downstream end of the flume. Dense mixtures of water and suspended sediments were created in a mixing tank. In the mixing tank, sediment particles were kept in suspension by constant mixing over the course of experiments. The dense fluid was pumped to a head tank which was installed above the mixing tank. The head tank was employed for transferring the dense fluid to the flume with a fixed head. The flow discharge could be measured by an electromagnetic flow meter before entering to the flume. The experiments started with the sudden opening of the gate and ended when the head reached the downstream end of the flume. The gate was opened 10 cm. The temperatures of both dense and ambient fluids were measured using a digital thermometer prior to opening the gate. The temperature difference between the dense and ambient fluids was less than 1°C for all experiments. Moreover, the dense fluid and fresh water had the same depth when the gate was suddenly lifted up so that the head motion was not affected by the difference in depths.

A total of 36 experiments were carried out over three rough beds as well as a smooth bed. The length of all rough beds was 3.75 m with roughness elements starting at 1.56 m from the gate. The desired roughness was obtained by gluing cylindrical roughness elements on the bed in staggered form. The canter-to-canter spacing between two consecutive rows of roughness elements and two neighbouring roughness elements within a row were 7.5 and 3 cm, respectively. The roughness elements and an artificially roughened bed are shown in Figures 2 and 3, respectively.

Experiments were carried out at a fixed discharge of 1 L/S and with three slopes (0.5%, 1.25% and 2%). Dense fluids with three different concentrations were

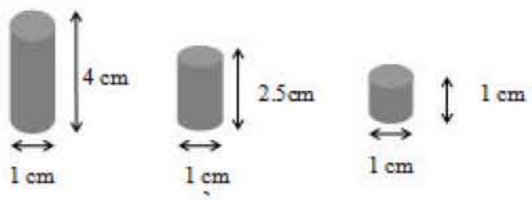

Fig. 2: Illustration of geometric parameters of roughness elements

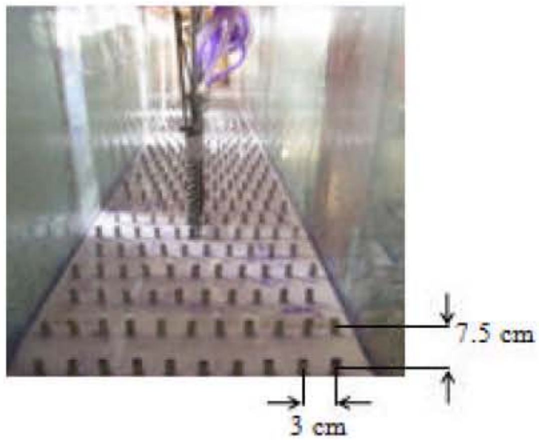

Fig. 3: An artificially roughened bed using 2.5 cm roughness elements

Table 1: Characteristics of the sediment

Type	D10 (μm)	D50 (μm)	D90 (μm)	Density (kg/m^3)
Microsilica	2.18	13.56	44.76	2650

prepared by mixing 20, 30 and 40 kg of noncohesive sediments in 2 m^3 of tap water. The characteristics of sediment particles are provided in Table 1.

During experiments, the evolution of the head was recorded by videotaping and the head height and velocity were extracted from the films. Turbidity current head samples were obtained at distances of 1.8 cm and 4.8 from the bed by four rakes of siphons located 2.25, 3, 3.75, 4.5 meters from the sliding gate. The siphons were constructed from copper tubes with the external diameter of 6mm and 5mm internal diameter.

The head velocity depends on head characteristics (height and concentration), ambient fluid properties (height and concentration), reduced gravity, bed slope and height of roughness elements. Using dimensionless analysis, Equation 1 can be obtained.

$$\frac{U_h}{\sqrt{g' H_h}} = f\left(\frac{C_h}{C_a}, S, \frac{H_r}{H_h}, \frac{H_h}{H_a}\right) \qquad (1)$$

where U_h is head velocity, $g' = (\rho_h - \rho_a)/\rho_a$ is reduced gravity, H_h is head height, C_h is head concentration, C_a is ambient fluid concentration, S is bed slope, H_r is height of roughness elements and H_a is ambient fluid height.

RESULTS AND DISCUSSION

Effect of Head Concentration on Head Velocity: Normalised head velocity as a function of head concentration for smooth and rough beds is illustrated in Figure 4 and 5, respectively. In terms of smooth bed, it is noticed that dimensionless head velocity increases as the normalized head concentration rises. The driving force of gravity currents is the density difference between the current and ambient fluid. Consequently, the head speeds up when it is of more concentration. Based on the Figure 4, normalized head velocity grows sharply when its concentration exceeds 8.25. This can be attributed to the considerable density difference between the head and fresh water in such concentrations.

According to Figure 5, cylindrical roughness reduces the normalized head velocity in comparison with the smooth bed. Furthermore, they managed to control the head, i.e. dimensionless head velocity remains almost

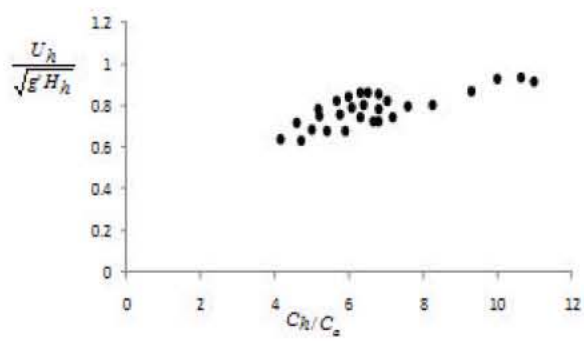

Fig. 4: Dimensionless head velocity plotted against normalized head concentration for smooth bed

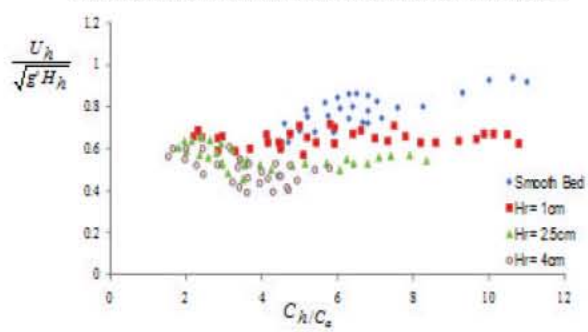

Fig. 5: Dimensionless head velocity plotted against normalized head concentration for rough beds

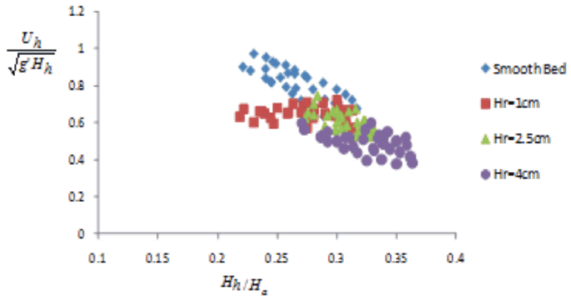

Fig. 6: Normalized head velocity versus dimensionless head height

constant despite of growth in frontal concentration. The non-dimensional frontal velocity at 2.5 cm cylindrical roughness elements is less than their 1cm counterparts; however, the velocity at 4 cm roughness is roughly the same as 2.5 cm cylindrical roughness.

The similar function of 2.5 cm and 4 cm cylindrical roughness elements is due to a new phenomenon which is going to be introduced in this paper and is given the name of "Head Rise" by the authors. It occurs when the size of roughness elements which is in interaction with head is less than its actual size due to upward movement of the head. As it was previously mentioned, density currents can occur even with a minor density difference of a few percent. Therefore, they can potentially rise when they faces roughness elements higher than a critical value. In the present study, the effective height of cylindrical roughness elements lessens for 4 cm roughness and their performance is similar to 2.5 cm roughness as it is observed in Figures 5. It seems that during the head rise, the head of turbidity current moves over roughness elements instead of moving among them and hence the effective height of the roughness is less that its actual height. The head rise is an extremely important phenomenon that should be taken into consideration in possible practical projects for controlling turbidity currents using artificial roughness.

Effect of Head Height on Head Velocity: Figure 6 shows the influence of head height on head velocity for smooth and rough beds. In the smooth bed, dimensionless head velocity decreases with increasing normalised head height. The normalised height for 1cm roughness elements is similar to that of the smooth bed and it is thought that the similarity is due to the minimal size of such roughness elements. The normalised velocity for 1cm roughness elements remains almost constant even as the dimensionless head height changes. In contrast, for 2.5 and 4 cm roughness elements, the normalized velocity decreases as the dimensionless height increases. The head enlarges with increasing surface roughness. The experiments were performed at a fixed discharge of 1 L/S; consequently, the growth in head height is attributed to the reduction of frontal speed. It means that the head speed decreases due to influx of fresh water into the head and hence the head height increases.

Effect of Bed Slope on Head Velocity: As it was previously mentioned, the experiments were conducted at three slopes: 0.5%, 1.25% and 2%. The influence of bed slope on normalized head velocity is illustrated in Figure 7. It is observed that dimensionless head velocity remains almost unchanged over the range of slopes in the smooth bed. There are some fluctuations in the dimensionless head velocity at rough beds; nevertheless, no particular trend is observed and therefore dimensionless head velocity seems to be nearly independent of the slope. For the sake of further analysis of the slope effects on the head velocity, the sensitivity of normalized head velocity toward slope alterations is investigated in the following part of this paper.

Developing an Equation for Head Velocity: Using non-dimensional parameters, Equation 2 predicts the head velocity for rough beds. Error (*E*) and Coefficient of determination (R^2) are presented for this equation. The error shows the amount by which observations differ from their expected values and R^2 provides a measure of how well future outcomes are likely to be predicted by the equation.

$$\frac{U}{\sqrt{g'H_h}} = 17.585 \times \left(\frac{C_h}{C_a}\right)^{-0.124} \times S^{0.281} \times EXP\left(-0.688\frac{H_r}{H_h} - 6.155\frac{H_h}{H_a}\right) \quad (2)$$

$R^2=0.795$ $\quad$ $E=12.2\%$

The results of sensitivity analysis of normalized head velocity are shown in Figure 8. It is evident that the normalized head velocity is only weekly dependent on slope (*S*) and dimensionless head concentration $\left(\frac{C_h}{C_a}\right)$. Therefore, these parameters were omitted and Equation 3 was driven.

$$\frac{U}{\sqrt{g'H_h}} = 1.147 \times EXP\left(-1.464\frac{H_r}{H_h} - 1.416\frac{H_h}{H_a}\right) \quad (3)$$

$R^2=0.75$ $\quad$ $E=14.2\%$

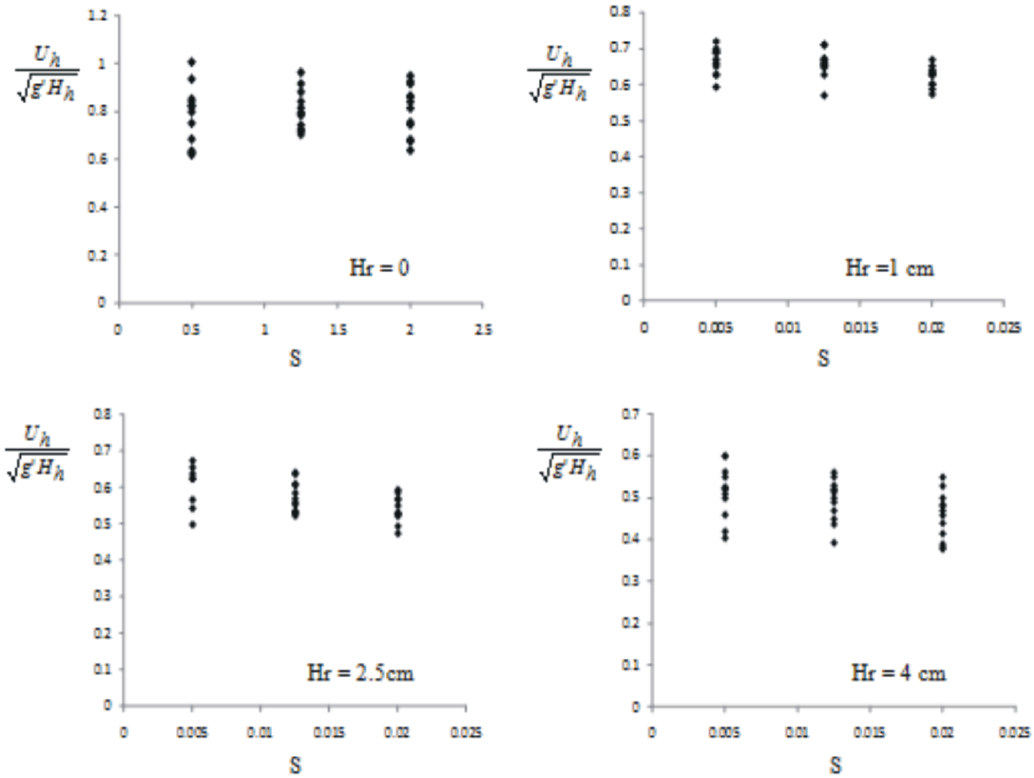

Fig. 7: Normalized head velocity against slope

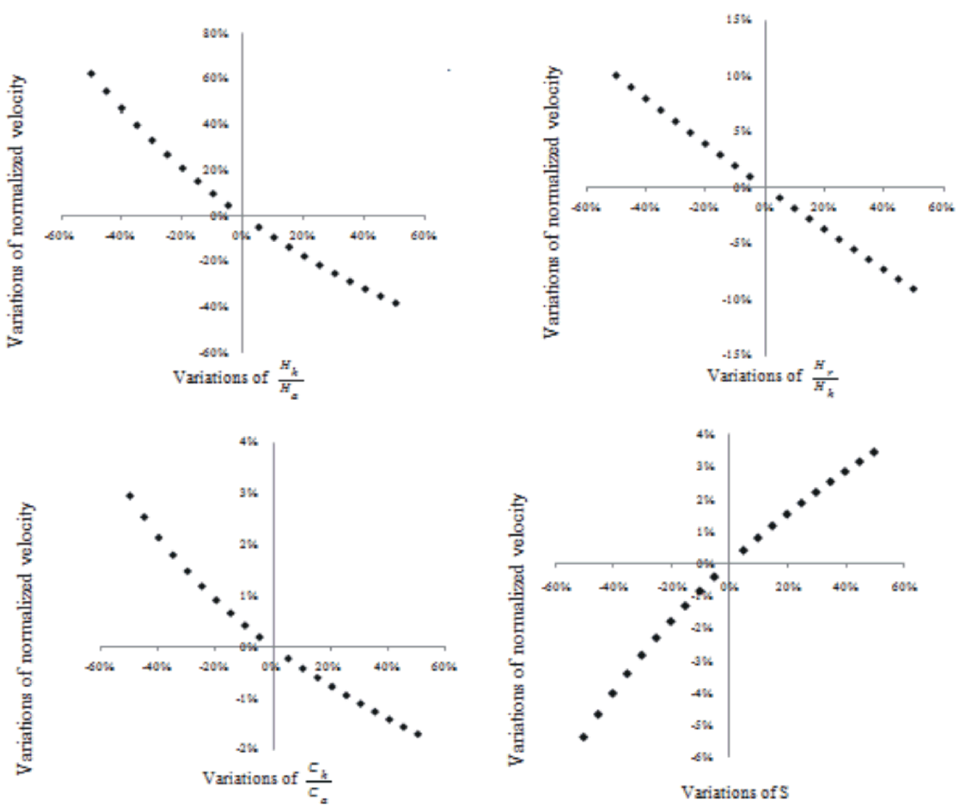

Fig. 8. Results of sensitivity analysis

CONCLUSION

This paper investigates turbidity currents head velocity over artificially roughened beds with cylindrical roughness elements. Experiments were conducted using three rough beds as well as a smooth bed. The following conclusions can be drawn:

- In the smooth bed, dimensionless head velocity rises as the normalized head concentration increases.
- All rough beds reduce the normalized head velocity in comparison with the smooth bed. Cylindrical roughness elements managed to control the head, i.e. normalized head velocity remains almost unchanged even with growth in head concentration.
- The dimensionless frontal velocity at 2.5 cm roughness elements is less than their 1 cm counterparts. Nevertheless, the velocity at 4 cm roughness elements is nearly the same as 2.5 cm roughness. It seems that the head rises when it faces 4 cm roughness elements so that effective height of roughness elements decreases.
- In the smooth bed, dimensionless head velocity decreases as normalised head height increases.
- Normalized head height increases as the beds get rougher.
- Normalized head velocity is almost independent of slope for the smooth bed and all artificially roughened beds.

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