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ORIGINAL ARTICLE

Survey Simultaneous effect of Bed Slope and Roughness on Density current frontal velocity with Physical Modeling

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ABSTRACT
The useful life reduction of dams occurs due to filling their reservoirs with sediment. Since the velocity of water in the dam reservoir is closed to zero, the main factor of sediments movement is a phenomenon called density current. So the exact understanding of this phenomenon can significantly help control the density current and increase the service life of dam. In this study, the simultaneous effect of bed slope and roughness on frontal velocity of density current was assessed. The experiments were done in a flume with the length of 780 cm and width of 35cm and the height of 70 cm with four sizes of roughness height (0cm,0.5cm, 1cm, 1.5cm) which were placed on the wall area and with four slopes(0%, 1.5%, 2.5%, 3.5%). Also, in all experiments, two concentrations of 20g and 40g per liter of the sediment density current was used. A total of 32 series of experiments was conducted. The obtained results showed that by increasing roughness height, the head velocity of density current decreases, also by increasing slope. More over in presence of roughness, kulgan coefficient was estimated about 4 percent. Finally using the SPSS and Data fit software, some relation were presented in order to predict the frontal velocity of density current with respect of roughness and slope.
Key words: density current, bed slope, roughness, frontal velocity

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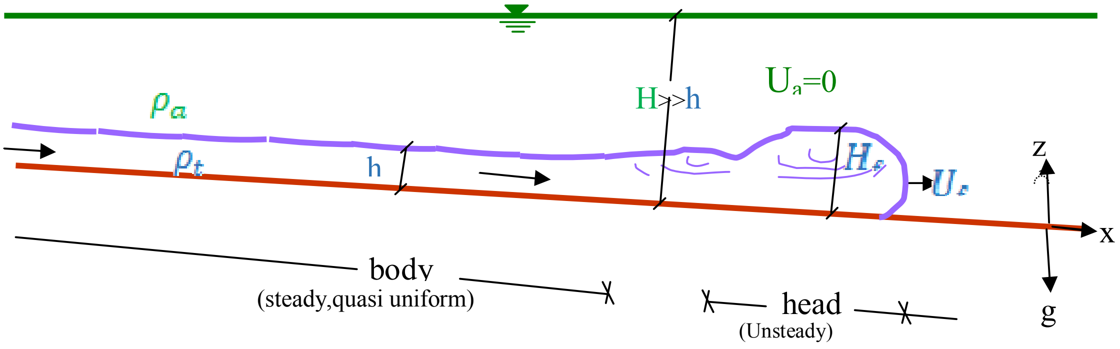
INTRODUCTION

Today reserving surface waters through dam construction is one of the significant methods in order to manage using of this water supply resource. The reduction of dam's service life, occurs due to sedimentation in dam reservoir. The main factor of grained sediments movement in dam reservoirs is a phenomenon called density current. Density current or gravity current is a current with a ρ_t density which inherently occurs due to effect of density difference for two fluid on the gravity acceleration. This means that gravity force has decreased in proportion of $\Delta\rho/\rho_a$. Density current has many similarities with currents in open-channels, with a difference that in density currents, surrounding fluids has a decreasing effect on gravity force and decrease coefficient is in the form of $\Delta\rho/\rho_a$. Therefore, gravity acceleration affecting currents which states as driving force in density currents, states as follows:

$$g' = g\frac{(\rho_t - \rho_a)}{\rho_a} = g\frac{\Delta\rho}{\rho_a} = gC_S\frac{\rho_s - \rho_w}{\rho_w} \qquad (1)$$

Where g' is decreased gravity acceleration, C_s is average volume tric concentration of non-sticky sediments, ρ_a is density of surrounding fluid, ρ_s is density of dense fluid, ρ_w is density of water and ρ_s is density of sediment particles (It's 2650 kg/m^3 for most natural sediments). A schematic of density current movement is illustrated in figure 1.

Figure (1) - A schematic of density current movement (Asgharipari [1])

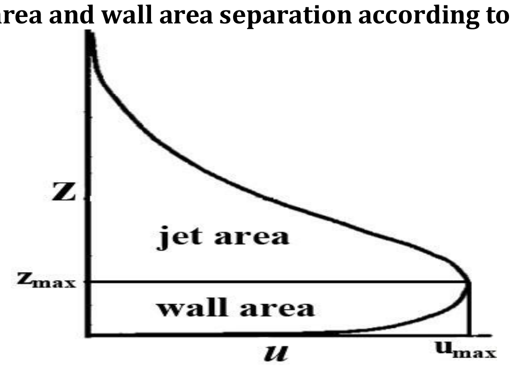


There have been many studies to understand this phenomenon and many empirical relations have presented in order to predict its pattern. Density has been stated first by Johnson (1939). Piper and Normark [2] studied the processes that lead to creation of density current. Siqueiros et al. [3] studied accelerating density current resulted from suspended particles entering into current. They concluded that properties of bed materials play an important role in formation of this phenomenon. Mohammadnezhadet and Shamsai [4] studied the properties of salt and sediment density current velocity on moving bed. They considered two regime of flow - sub critical and super critical-in their experiments. The results of their study showed that based on regime of flow and time duration, the bed may remain unchanged or formed. These bed formed, will effect on vertical profile of velocity. Islam and Imran [5] conducted experimental studies on average velocity and turbulence structure of stable density current. They used acoustic velocity meter in their experiments. Wells et al [6] conducted experimental studies about relationship between coefficient of sediment entering into density current and coefficient of density current velocity. Siqueiros et al [7] studied the bed load transfer and also bed resistance with regard to density current. Milberg and Kneller [8] studied density current and their deposits. Barbosa and Mauad [9] studied density current in steady states by using numerical methods. There are many theoretical and empirical relations regarding frontal velocity in density current. Initially, Kulgan(1957) studied the frontal velocity of density current and presented the following relation:

$$U_f = C_c\sqrt{g' H_f} \qquad (2)$$

Where U_f is frontal velocity of density current, C_c is constant coefficient and is g' decreased gravity acceleration which is calculated based on relation (1). Kulgan was suggested the value of constant coefficient equal 0.7. Also, other researchers including Middleton [10], Oehy and Schleiss [11] and Ghomeshi [12] offered values between 0.63 and 0.75 for this coefficient. Altinakar et al [13] divided the density current body into two parts. first part is from the floor to the height in which the velocity of density current reaches maximum (wall area) and second part is from where in which the velocity of density current is maximum to the end of body height (jet area). They believed that current turbulence at wall area, was resulted from bed effects. Also, sedimentation occurs in this area, while turbulence at jet area is resulted from friction between current and surrounding fluid (figure 2).

Figure (2) - jet area and wall area separation according to velocity profile

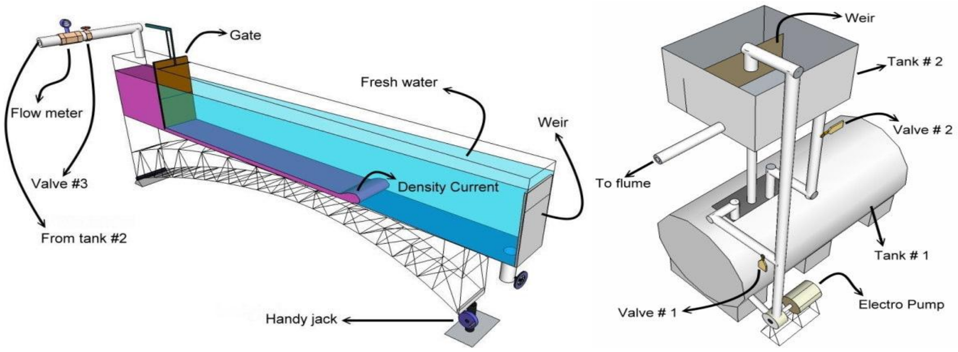


MATERIALA AND METHODS

As stated before, the objective of the present study is to investigate the simultaneous effect of roughness and bed slope on dense flow frontal velocity. Flume and materials used in this study are shown in figure

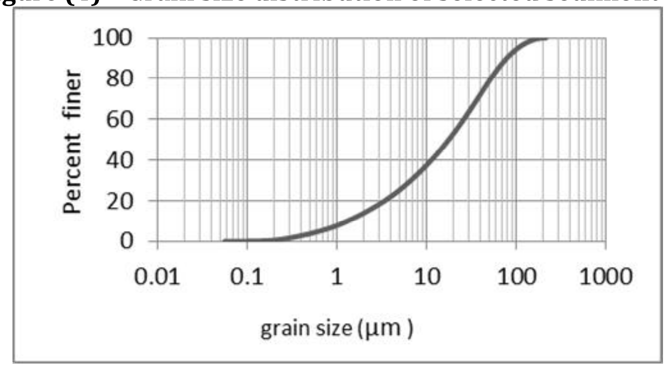
(3). In order to conduct experiments, first density current was prepared in reservoir by combining water and stone powder with favorable density and transferred to upper reservoir through pumping in order to reach a constant head, then in flow rate into flume was controlled by using a valve and electromagnetic flow meter. At first, flume was divided into two parts by a gate and therefore density current separated from surrounding fluid and at early stage of experiment, this gate raised to a definite height by using a lever and density current entered the surrounding fluid.

Figure (3) -a view of reservoir and flume



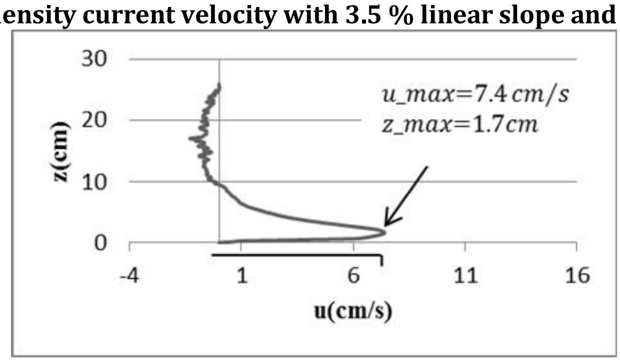
A curve of used materials grading is presented in figure (4). With regard to figure (4), average size of particles: D_{50} is about 17 μm (Micrometer), D_{84} is about 63 μm and D_{16} is about 3 μm.

Figure (4) – Grain size distribution of selected sediment



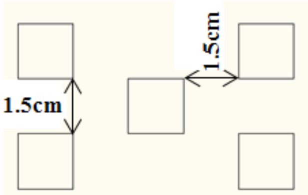
To determine roughness heights, an experiment was conducted in which minimum (Z_{max}) formed according to figure 5, with bed slope of 3.5 percent and density of 20 g per liter. The height of used roughness in this study was consider less than Z_{max} in this area. In figure 5 profile of density current velocity has presented. In order to determine the profile of density current velocity, DOP 2000 device has been used. As it's shown in figure 5, Z_{max} is 1.7centimeter. Therefore, the maximum roughness height is considered 1.5 cm in wall area. So all the roughnesses placed in density curent body. Also other roughness heights (0, 0.5, and 1 cm) were selected according to it. Length and width of roughnesses were considered 1.5 according to length and width of the flume.

Figure (5) – profile of density current velocity with 3.5 % linear slope and density of 20 g per liter



In order to determine velocity and height of head density current, recording by digital camera was used during experiments. Roughness arrangement was considered as zigzag with longitudinal and latitudinal distance of 1.5 cm according to figure (6).

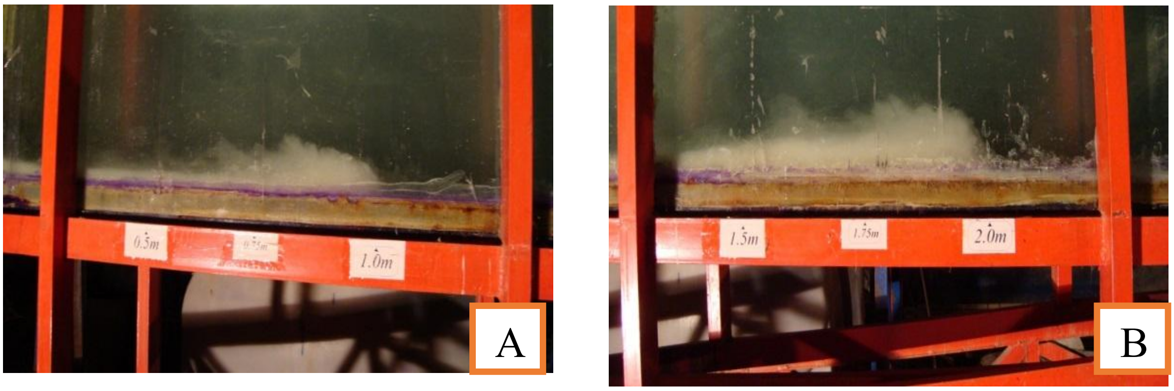
Figure (6) – roughness arrangement



Conclusion AND DISCUSSION

Frontal and body of density current before and after contacting roughness is presented in figure (7).

Figure (7) –frontal of density current (A) before reaching to roughness,(B) after reaching to roughness



Changing procedure of slope and roughness for two density include 10 and 20 g per liter has presented in figures (8) and (9).

Figure 8- frontal velocity of density current changes against roughness height increase (density of 10 g per liter)

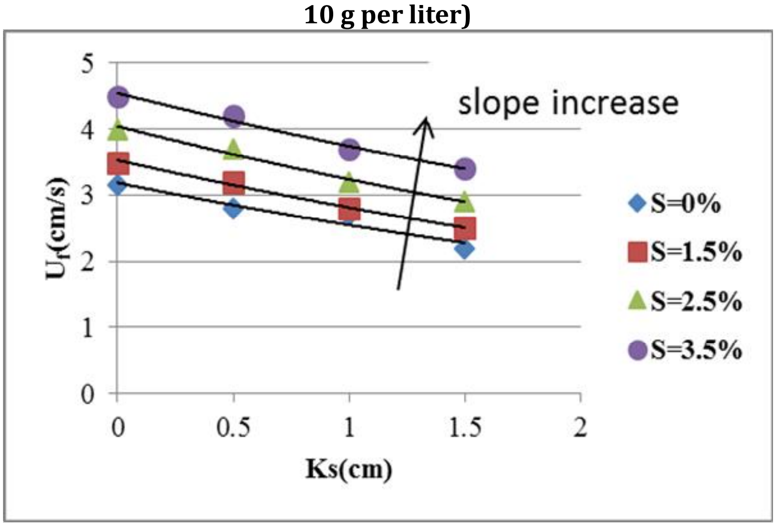
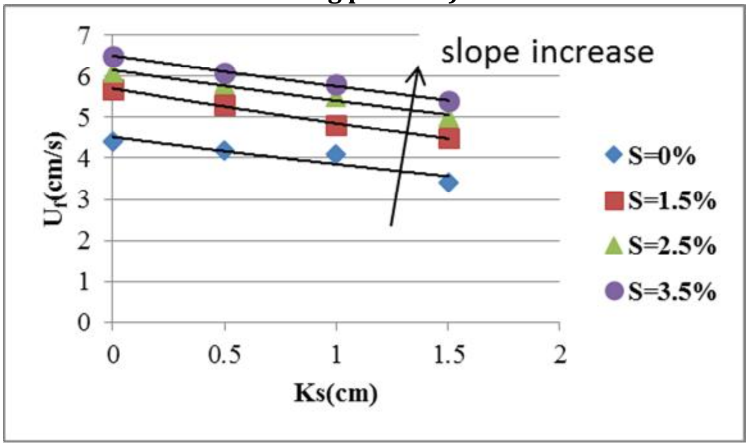


Figure 9- frontal velocity of density current changes against roughness height increase (density of 20 g per liter)



According to these figures we can see that when roughness increase, the frontal velocity of current will reduce. The reason for this phenomenon is that roughness existence in addition to its resistance nature against current, also results in sediment deposition in the current path. This cause density of current to be reduced in the movement path and consequently reduced difference of the current density with surrounding fluid. This is main factor of density current movement, and thus, frontal velocity of density current is reduce. Also, according to figures (8) and (9), it's shown that when slope increases, the head velocity of density current will increase that is has been proved. However, what is necessary to mention in this regard is that when slope increases, the effect of roughness increasing in the frontal velocity of density current reduction will reduce. The reason for this phenomenon is that by increasing the slope, the flow velocity will increase which results in current momentum increase. This momentum increasing cause roughness resistance to be reduced against density current progress. Also, with regard to these figures it is observed that when density increases, the frontal velocity will increase that is a result of an increase in density of current density difference with surrounding fluid. The result obtained from changes percent of frontal velocity of density current have presented in table 1 and 2.

Table (1)- changes of head velocity of density current by changing slope and roughness in percent (density of 10 g per liter)

	frontal velocity of current reduction percent			
Roughness(cm) / slope (%)	0	0.5	1	1.5
0	-	11	20	31
1.5	-	8	18	28
2.5	-	7	15	27
3.5	-	6	12	24

Table (2)- changes of head velocity of density current by changing slope and roughness in percent (density of 20 g per liter)

	frontal velocity of current reduction percent			
Roughness(cm) / slope (%)	0	0.5	1	1.5
0	-	9	16	22
1.5	-	7	15	21
2.5	-	5	10	18
3.5	-	3	7	17

For example in a density current with density of 10 g per liter at 0% slope, an increase in roughness height from 0 to 1.5 cm causes the frontal velocity to be reduced 31%. While the same increasing in roughness height at a slope of 3.5 % cause, frontal velocity to be reduced about 24%. Also, in a dense flow with density of 20 g per liter at 0% slope, an increase in roughness height from 0 to 1.5 cm causes the frontal velocity to be reduced 22%. While the same increasing in roughness height at a slope of 3.5 % cause, the frontal velocity to be reduced 17%.

DIMENSIONAL ANALYSIS

In order to present some relations to predict the frontal velocity of density current with respect to simultaneous effect of roughness and slope, dimensional analysis was done. The existing variables in dimensional analysis for frontal velocity of density current are according relation (3). It should be noted that whereas current discharge is considered constant in all experiments, so it's not considered as a variable.

$$f(U_f, k_s, H_f, \rho_a, \rho_s, g, S, \nu_s) = 0 \qquad (3)$$

In above relation, k_s is hight roghness, S is bed slope and ν_s is kinematic mucilage of denseflow, Other parameters are according to figure (1).After dimensional analysis by using Buckingham π method, relation (4) obtained as follows:

$$U_f = f_1\left(\frac{k_s}{H_f}, S\right)\sqrt{g'H_f} \qquad (4)$$

As it's observed, relation (4) is similar to Kulgan relation (2). Using the obtained results of conducted experiments, Kulgan coefficient for this research is estimated about 0.4 which its value reduction comparing to other researcher's results is due to applying roughness in these experiment. In this relation, coefficient of term $\sqrt{g'H_f}$ is a function of $(k_s/H_f, S)$ for frontal velocity. In order to determine this coefficient Data fit software was used. The resulting relation is as follows:

$$U_f = \left[0.43 + 1.74(S) - 1.47\left(\frac{k_s}{H_f}\right)\right]\sqrt{g'H_f} \qquad (5)$$

In fact above relation is the same as Kulgan relation which coefficient is a function of k_s/H_f and S. In order to assess the relation (5) accuracy, statistical methods were used which are presented as follows:

1- R^2 and α which are square of correlation coefficient and the slope of regression line($\alpha = U_m/U_P$) respectively. Prediction accuracy of each relation depends on above parameters, in a way that as much as R^2 and α be closer to one, that relation would better estimate the frontal velocity and body of density current values.

2-Error percent ($\%E$) which is defined as follows:

$$\%E = \frac{\sum_{i=1}^{N}|U_{mi} - U_{pi}|}{\sum_{i=1}^{N} U_{mi}} \times 100 \qquad (6)$$

3- Mean chi-square error (RMSE) which is defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(U_{mi} - U_{pi})^2}{N}} \qquad (7)$$

Where N: number of data, U_m frontal velocity of density current measured in the laboratory, and U_p is the frontal velocity of density current predicted by the formula. In each formula which calculated values for $\%E$ and RMSE be closer to zero, it's more accurate. A summary of statistical analysis results are presented in table (3).

Table (3)- results of statistical analysis of formula(5)

RMSE	**%*E***	α	R^2	
0.005	7.5	0.94	0.97	**Formula(5)**

According to above table it seems that relation (5) is able to predict the frontal velocity arte of density current, with acceptable accuracy.

CONCLUSION

In this research, the simultaneous effect of roughness and slope on frontal velocity of density current was investigated. In order to do that, experiments were conducted considering 4 roughness height, 4 bed slope, and 2 densities. Following are main results of this research:

1- Roughness existence in the current path causes resistance against density current progress, which results in reduction of frontal velocity of dense flow.
2- Roughness existence in the current path cause sediments to be deposited. So difference of density with surrounding fluid will be reduced, that is results in reduction of frontal velocity of density current.
3- When concentrations increases, the frontal velocity of density current will increase.
4- When slope increases, the effect of roughness in reduction of frontal velocity of density current will decrease.
5- Regarding roughness, the Kulgan coefficient in this research estimated to be about 0.4.
6- Using the Datafitsoftware, the Kulgan coefficient was presented as a function of $\frac{k_s}{H_f}$ and S, and obtained relation is able to predict the frontal velocity of density current with acceptable accuracy.

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