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Effects of cylindrical and cubic piles on motion of density currents

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Research Paper

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Density current is the motion of a fluid in another fluid of a different density, with frequent negative environmental impacts. According to the deposition problems caused by density currents in the vicinity of dam bodies, attempts are usually made to weaken or eliminate these types of currents in the middle of the reservoir. Appropriate barriers are placed in the middle of the reservoir for this purpose. The effects of cylindrical and cubic obstacles on the motion of the head of the saline density current are experimentally investigated in this study. The results show that the effect of cubic obstacles on current parameters is greater compared to cylindrical obstacles.

Key words:

saline density current, turbidity current, head of density current, cylindrical obstacles, cubic obstacles

Prethodno priopćenje

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Utjecaj valjkastih i kockastih pilota na gradijentne struje

Gradijentno strujanje je gibanje fluida kroz neki drugi fluid drugačije gustoće, uz često negativan utjecaj na okoliš. Zbog problema taloženja uzrokovanih djelovanjem gradijentnih struja u blizini tijela brana, često se poduzimaju odgovarajuće mjere kako bi se ublažio ili eliminirao utjecaj takvih struja u srednjem dijelu akumulacija. U tom se smislu u sredini akumulacije postavljaju odgovarajuće prepreke. U ovom se radu eksperimentalno istražuje utjecaj valjkastih i kockastih prepreka na kretanje prednje fronte (glave) gradijentnih struja. Rezultati istraživanja pokazuju da je utjecaj kockastih prepreka na parametre strujanja veći od utjecaja valjkastih prepreka.

Ključne riječi:

gradijentna struja gustoće, struja zamućenja, glava gradijentne struje, valjkaste prepreke, kockaste prepreke

Vorherige Mitteilung

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Einfluss von Walzen Pfählen auf die Gradientenströme

Die Gradientenströmung stelle die Bewegung von Flüssigkeiten durch eine andere Flüssigkeit mit der anderen Art der Dichtigkeit dar, wobei oft ein negativer Umwelteinfluss entsteht. Wegen der Probleme der Ablagerung, welche durch die Wirkung von Gradientenströmen in der Nähe von Talsperrenkörpern verursacht wurden, werden oft entsprechende Maßnahmen eingeleitet, damit die Wirkung von solchen Strömen im mittleren Teil von Akkumulationen gemildert oder beseitigt wird. In diesem Sinne werden in der Mitte der Akkumulation entsprechende Hindernisse aufgestellt. In dieser Arbeit wird experimental der Einfluss von Walzen- und Würfelhindernissen auf die Bewegung der vorderen Front (des Kopfes) von Gradientenströmen erforscht. Die Forschungsergebnisse zeigen, dass der Einfluss von Würfelhindernissen auf die Strömungsparameter höher als der Einfluss von Walzenhindernissen ist.

Schlüsselwörter:

Gradientenstrom mit der Dichtigkeit, Trübungsstrom, Kopf des Gradientenstromes, Walzenhindernisse, Würfelhindernisse

1. Introduction

Density currents are produced where gravity acts upon a density difference between one fluid and another; such currents are also called gravity currents [1]. The density difference can be caused by suspended materials, temperature gradients, dissolved contents, or a combination of these causes. In this process, the entrant fluid is called the dense fluid and the clear fluid is called the ambient fluid.

These currents are known as turbidity currents in which the main driving mechanism is obtained from suspended sediments. The most common type of a density current is an underflow that is produced when a flow enters into an ambient fluid of a lower density. This type of current is also studied in this research.

A density current is often established during a flood at a point where a river reaches a reservoir at plunge point, and then the density current is moved to the bottom of the reservoir [2, 3]. If the slope of the bottom is high (higher than 0.001) or if it is narrow, the density current continues to move over a long distance [4].

Turbidity currents decrease reservoir volume by sedimentary deposition, pose the risks of water inlet structures blockage, facilitate sediment entrance into power plants, and prevent the extraction of water for irrigation [5].

During a great flood, turbidity currents can entrain considerable amounts of the existing sediment deposits and transport such sediments to an area of deposition near the dam. An optimum opening time of bottom outlets can be determined as the time needed to transport a significant quantity of sediments by means of turbidity currents during floods [6].

The loss of storage in reservoirs, related to the deposition of fine sediments due to density currents, is a subject of great concern to agricultural and environmental engineers and is still a topic of ongoing research. In dam reservoirs, turbidity currents are mostly underflows, which consist of following parts (Figure 1).

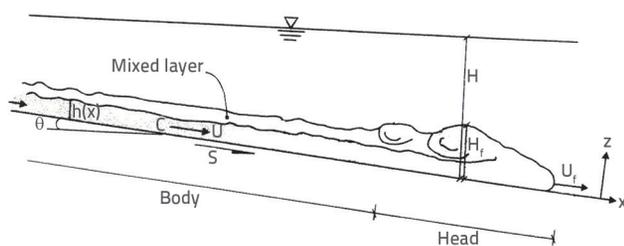


Figure 1. Schematic view of a density current [7]

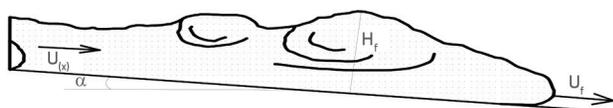


Figure 2. A view of head of a density current [9]

Density currents penetrate inside the stationary fluid through their head. The head has special characteristics, which distinguish it from body, including the height (H_r) exceeding that

of the body, lower velocity (U_r), and a nose which is situated a little above the bed (Figure 2) [8].

The head is a region of intense mixing. the head of the current is irregular. Its motion is unsteady and the gradient resulting from specific mass difference between the head and fluid moves it through the fluid [10]. Many studies have been performed by researchers on hydraulic parameters of the head of density currents and on its velocity. In most research conducted so far, the velocity of the head of saline currents has been described as being a function of head height and reduced gravity [11, 12]. Density currents rank among factors that are important for the transport of sediments in lakes and man-made reservoirs. One of the methods for controlling this current is to use obstacles along its course. The obstacles can control the current either relatively or fully, and they can cause it to change direction [13]. Recently, this method has been considered experimentally in a flume; the first coherent research on this issue has been conducted by Oehy (According to Asghari Pari) [14].

In order to control sedimentation in reservoirs, Oehy [15] modelled the effects of obstacles on turbidity (density) currents through physical experiments and numerical simulations and, in a case study on Grimsel Reservoir, he evaluated possible effects on density currents with submerged embankment dams using numerical models. The results showed that, due to the effect of dam block, sediments could be settled and kept locally, protected by the inlet and outlet. He concluded that the formation of obstacles in subcritical flows is suitable for controlling this current. In addition, experimental investigation on the effects of permeable and impermeable obstacles showed that the efficiency of entrapping is considerable in impermeable obstacles; moreover, an optimum height for these obstacles provides maximum capacity at the upstream [16].

Marousi et al. [17] investigated the efficiency of solid obstacles in the control of turbidity currents and the results showed that the use of solid obstacles decreases sediment transport. Sequeiros et al. [18] performed some experiments with saline and sedimentary density currents, and studied the combined effect on moving beds with several types of aggregates. The results of these experiments showed that form of generated bed has a great influence on velocity profiles and enhances the place of formation of maximum speed. Nasrollahpour and Ghomeshi [19] studied the effect of the roughness of geometry on the characteristics of the density-current head and concluded that the concentration and velocity of the density-current head decreases and its height increases with an increase in the height of roughness and with an increase in the surface area of roughness of constant height.

In recent research on the effects of concentration and bed slope, the velocity of head of density currents has been specified for a bed without any obstacles, at constant concentration. The results showed that the velocity of head increases with an increase in slope and, at a constant slope, the velocity of head increases with an increase in concentration [13, 20].

Qorban Moghadam [13] investigated the effect of the arrangement of cylindrical obstacles on the motion of head of saline density currents. These obstacles were made of PVC, and

measured 1 cm in diameter and 30 cm in height. Longitudinal and lateral centre-to-centre distances between individual obstacles were 8 cm. The obstacles were applied in the area 4 m long and 35 cm wide. The results demonstrated that the velocity of the head of density currents in a bed with obstacle has a decreasing trend just like in an obstacle-free bed, but the decrease in a bed with obstacles is faster than an obstacle-free bed. The decrease in velocity of the density current head is the highest in the 4×4 arrangement, and it decreases in the 8×4 and 4×8 arrangements, up to 8×8 arrangement when it reaches the lowest value because of the density of obstacles.

Yaghubi et al. [21] examined by physical experiments the effect two consecutive right-angled triangular obstacles with various heights have on turbidity current. The result showed that in the presence of obstacle the average upstream velocity between the obstacles is dramatically lower compared to downstream. In addition, as the obstacle height increases the velocity decreases in the lower region of the current while increasing in the upper zone.

Asghari Pari et al. [22] studied various effects obstacles have on the control of density currents. The result showed that the use of obstacles affects density current parameters, and that a certain height of an obstacle is required to completely control the density current at each slope.

Huang et al. [23] conducted an experimental study on the influence of the height and position of obstacles on the behaviour of density currents. They concluded that the presence of obstacles blocks the progress of density currents. Moreover, the higher the obstacle the more visible is the density current reducing effect.

Literature review shows that most investigations on the effect of obstacles on density currents are restricted to obstacles that have the width equal to that of the flume, and that only one obstacle that covered the entire width of channel was used [10, 16, 21].

In the research about density currents, no study has been found on the effects of cubic and cylindrical piles with rough surfaces, which are placed in large numbers along the length of the channel, with the height exceeding that of the head and body of density currents. Thus, considering the importance of controlling density currents in reservoirs using methods such as construction of obstacles in reservoirs, the effect of cylindrical and cubic obstacles (such as piling) on the motion of density currents in reservoirs is investigated in this paper to highlight their effect on hydraulic parameters of currents. The head of a density current has three main features: concentration,

velocity, and height. The main objective of this research is to study the influence of obstacles in staggered arrangement, with the height exceeding that of the density current.

2. Physical model and experimental procedure

The experiments were conducted at Sediment Centre Laboratory of Khuzestan Water and Power Organization in Ahvaz, Iran. The experiments were conducted in a flume measuring 12.5 m in length, 30 cm in width, and 40 cm in height, with variable bed slopes. The experimental setup used in this study is schematically shown in Figure 3a. A Plexiglas sheet 1 cm in thickness was placed at the bottom of the flume to enable installation of obstacles. A Plexiglas sluice gate, with the width equal to the width of the flume, was made in order to perform this experiment. The flume has four tanks, a flow meter, and a manual slope-changing jack (Figure 3a & 3b).

The municipal drinking water system and laboratory tap water were used for supplying the water needed for the experiments; moreover, two pumps were installed for the acceleration of the filling process. In all experiments, the height of ambient fluid was kept constant thanks to a weir installed at the downstream of the flume. The density current was prepared with water, edible salt, and colouring

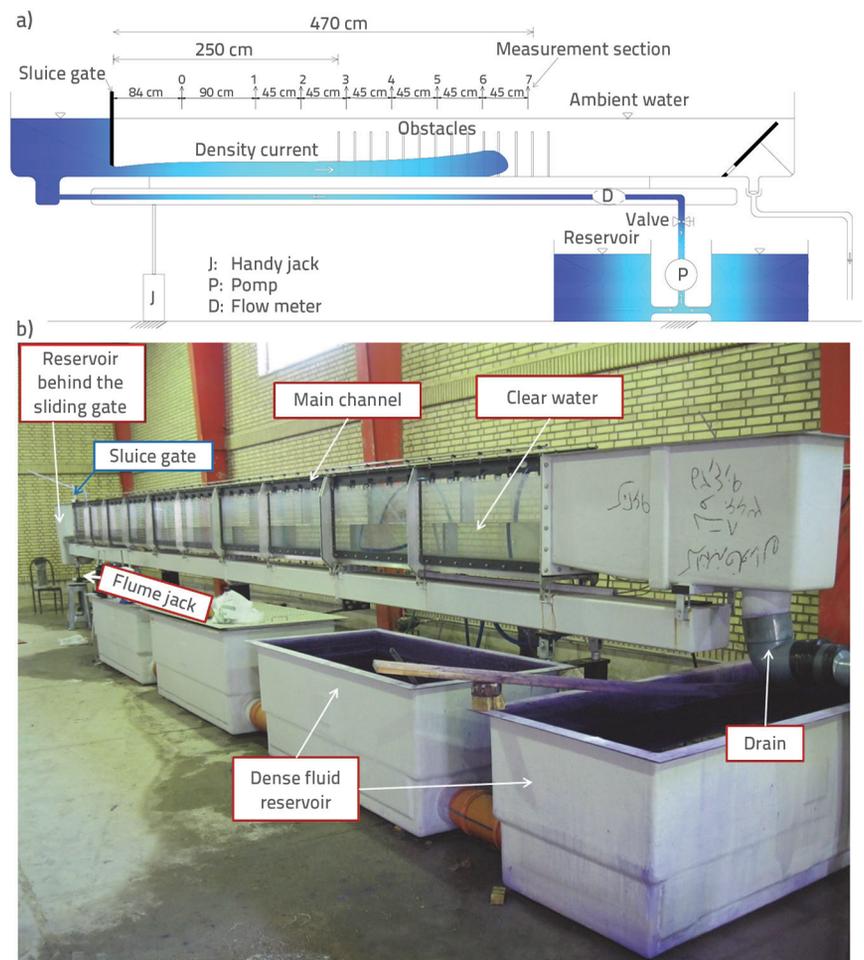


Figure 3. a) Schematic view of the flume and connected devices; b) Experimental setup

agent (the colouring agent had no effect on the concentration). The colouring agent was used in order to specify the current and to make it traceable. The salt and water were mixed in four tanks connected to the flume. The density current was then transferred at a constant rate, using the main pump and a pipeline, to a tank at the back of the sluice gate separating the density current and ambient clear water. An electromagnetic flow meter was used for adjusting the discharge of the density current entering the flume. Before the start of each experiment, the concentration and temperature of the ambient water and density current were measured and controlled by Ec Meter. After aligning the level of density current behind the gate with that of ambient water in the flume, the sluice gate was suddenly opened and experiments started and ended when the head reached the downstream end of the flume. The head of the density current is shown in Figure 4. The height of the opening gate was adjusted to 5 cm. Due to sudden opening of the gate, the density current moved under the ambient water.

To avoid the turbulent effect due to entering flow near the gate and the complete formation of density current, obstacles were positioned in the area ranging from 2.5 m to 4.7 m from the gate, and so the length of the area covered with obstacles was 2.2 m (Figure 3a and 5).

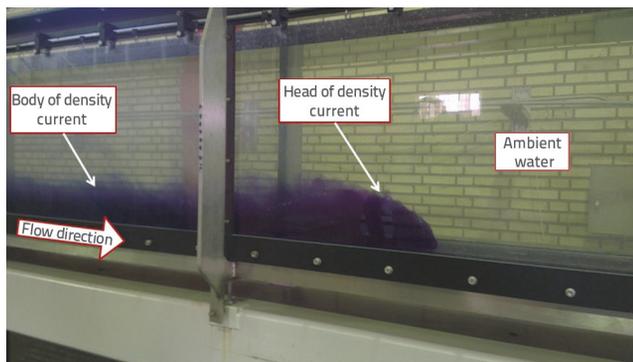


Figure 4. Head and body of density current



Figure 6. Bed with cylindrical obstacles

Twenty-seven experiments were conducted, with three bottom slopes (0.2 %, 0.5 %, 1 %), three different initial concentrations (15, 20, and 25 g/l) and three different discharge rates (0.27, 0.55, and 0.83 l/s). At a particular concentration and slope, three experiments were done with different discharge rates and without the presence of obstacle (control experiments), three experiments were conducted with the same characteristics in the presence of cylindrical obstacles, and three other experiments were made with the same specifications with the cubic obstacles. Then, the slope of the flume was changed and these experiments were repeated and the final tests were performed by changing the flow concentration.

The obstacles are made of wood with rough surfaces. The height of the obstacles was selected in such a way that in all experiments the height of the head of the density current was lower than the height of obstacles. The longitudinal and lateral centre-to-centre distance between individual obstacles was 3cm. 323 cylindrical obstacles 1cm in diameter and 30cm in height were placed on the bed of the rectangular flume in a staggered arrangement and, in the next step, the same number of 1x1 cm cubic obstacles measuring 30 cm in height were similarly placed on the bed of the rectangular flume. The bed with cylindrical and cubic obstacles is shown in figures 6 and 7. The height of the head of the density current was recorded

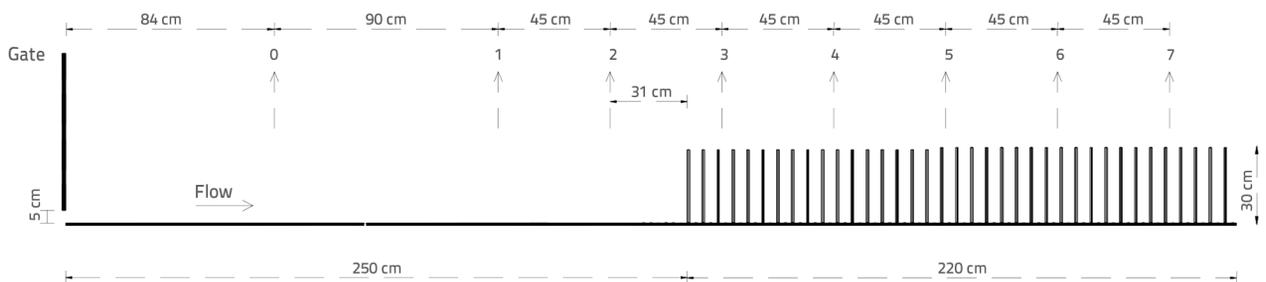


Figure 5. Sampling sections of the flume and arrangement of obstacles

by reading marks from rulers installed on the body of the flume in seven sections with definite distances from the gate, spaced 45 cm from each other (Figure 3a and 5). The concentration of density current was also measured in three sections along the flume (Figure 7). In addition, velocity of the head of the density current was measured by distance-time method using two cameras and a chronometer. After the end of each experiment, the valve that controls entry of the density current was closed, the flume was drained through its end gate, and all devices were carefully inspected, cleaned and adjusted. Figure 8 shows how the density current moved and how it dealt with obstacles.

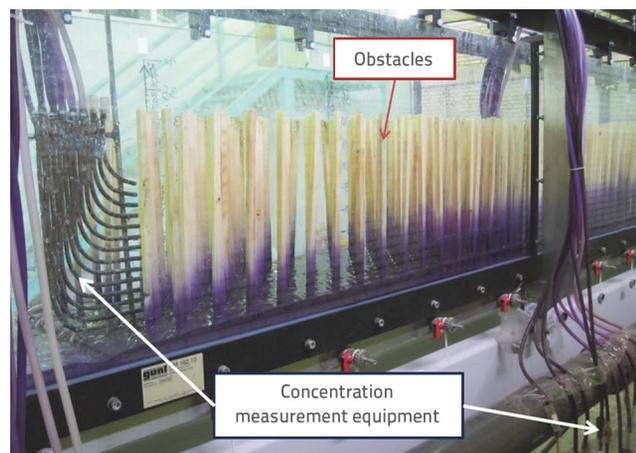


Figure 7. Cubic obstacles and concentration measurement equipment

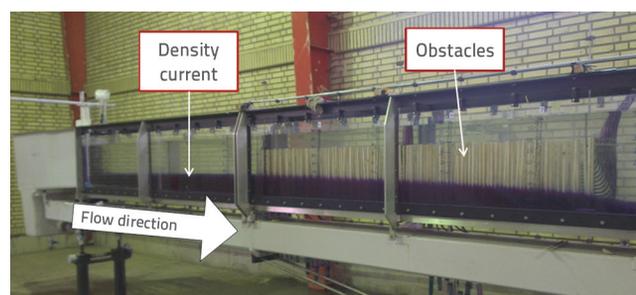


Figure 8. Motion of density current and its passage through obstacles

3. Results and discussion

Some experimental results showing the effect of cylindrical and cubic obstacles on the height and velocity of the head of density current are given in Tables 1 and 2.

3.1. Height of head

Considering the experimental results given in Tables 1 & 2 and their graphical representation presented in Figure 9, it can be observed that, for a given slope and concentration, the height of the head of density current has an ascending trend along the direction inside the flume with an obstacle-free bed. It seems quite reasonable considering the mixing of the density current and the ambient stationary fluid. Certainly, molecular diffusion is also involved in this process, but due to the fact that the presence and movement of the head of the density current in the flume is short, the effect of this parameter can be ignored. This statement has also been confirmed by other research [13, 24]. However, under similar conditions of concentration, slope and discharge in beds with obstacles, this trend is completely reversed and the height of the head reduces along the length of the flume (the amount of decrease in height of the head relative to an obstacle-free bed was about 50 % and 70 % for cylindrical samples and cubic samples, respectively). This is also due to the presence of obstacles that improved the amount of mixing ambient fluid with dense fluid to such level that dense fluid was separated from the front of head of the current and faded in clean fluid. This is the reason why the volume of the head of density current reduced, and its height was reduced accordingly. According to the experiments, the decrease in cubic obstacles is greater compared to cylindrical obstacles (by about 30 %). This may be due to hydrodynamic difference between the cubic and circular obstacles.

According to figures 3a and 5, the obstacles start between section 2 and section 3 (at the distance of 250cm from the gate). This means that results of initial sections in beds with obstacles

Table 1. Values measured in various experiments, without the presence of obstacle

Exp. no.	Obstacle	C (slanost) [g/l]	Slope [%]	Distance 90 cm		Distance 180 cm		Distance 270 cm		Distance 360 cm	
				H_h [cm]	V_h [cm/s]	H_h [cm]	V_h [cm/s]	H_h [cm]	V_h [cm/s]	H_h [cm]	V_h [cm/s]
1.	No obstacle	15	0.2	13.5	5.625	14	5	14.25	5	16	4.736
2.			0.5	13	6	13.5	5.625	14	5.294	15	5.294
3.			1	12.9	6.428	13	6	13.5	5.294	14	5.294
4.		20	0.2	11	6.923	11.7	6.428	12.7	6	13.9	6
5.			0.5	11	6.923	11.5	6.923	12	6.428	13	6.428
6.			1	11	6.923	11	6.428	11.5	6.428	12.5	6.428
7.		25	0.2	10.5	7.5	11.5	7.5	12	6.923	13	6.923
8.			0.5	10.3	7.5	11.25	7.5	12	7.5	12.5	6.923
9.			1	10.3	7.5	11	7.5	11	6.923	12	6.923

Table 2. Values measured in various experiments with the presence of obstacles

Exp. no.	Obstacle	C [g/l]	Slope [%]	Distance 90 cm		Distance 135 cm		Distance 180 cm		Distance 225 cm		Distance 270 cm		Distance 315 cm		Distance 360 cm	
				H _h [cm]	V _h [cm/s]												
10.	Cylindrical	15	0.2	13	5.625	13.2	5.625	13	5	10.5	4.5	10	4.09	7	3.75	6.5	3.214
11.			0.5	13	6	13	5.625	11.75	5.625	10	5	7	4.09	6	3.75	6	3.214
12.			1	12.75	6.428	13	5.625	11.5	5.625	10	5	7	4.5	5.5	3.75	5.25	3.461
13.		20	0.2	11	6.923	11	6.428	11	6.428	10	5.625	9	4.5	6.5	4.09	6	4.09
14.			0.5	11	6.923	11	6.428	11	6.428	10	5.625	7	5	6.5	4.09	6	4.09
15.			1	11	6.923	10.8	6.428	11	6.428	9.8	5.625	6	5	5.5	4.09	5	4.09
16.		25	0.2	10.3	7.5	10.5	7.5	10	7.5	8.5	6.428	6	5	5	4.5	5	4.09
17.			0.5	10	7.5	10.5	7.5	9	7.5	8	6.428	5.9	5	5	4.5	4.7	4.09
18.			1	9.75	7.5	10	7.5	9	7.5	7.7	6.428	5.5	5.625	5	5	4.5	4.5
19.	Cubic	15	0.2	13	5.625	13.2	5.625	12.5	5	9	4.5	6	4.09	5	3.461	4	3
20.			0.5	13	6	13	5.625	11.25	5.625	8.7	4.5	6	4.09	5	3.461	4	3
21.			1	13	6.428	13	5.625	11	5.625	8.5	4.5	6	4.09	4.8	3.75	4	3.214
22.		20	0.2	11	6.923	11	6.428	9.8	6.428	9	4.5	6	4.09	5	3.75	4	3.214
23.			0.5	11	6.923	11	6.428	10	6.428	8.5	5.625	6	4.5	5	4.09	4	3.461
24.			1	11	6.923	10.75	6.428	10	6.428	8.25	5.625	6	5	4.7	4.09	3.75	3.461
25.		25	0.2	10.3	7.5	10.5	7.5	9.8	7.5	8	5.625	5.5	5	5	4.5	4	3.75
26.			0.5	10	7.5	10.5	7.5	9	7.5	8	5.625	5.5	5	5	4.5	4	3.75
27.			1	9.75	7.5	10	7.5	8.5	7.5	7.7	6.428	5.25	5	5	5	3.75	3.75

and in beds without obstacles are nearly the same. Also it should be noted that the zero number shown in the x-axis of diagrams in figures 9, 10, and 11, is located 0.84 meters away from the

gate, and that no readings were made in the zone up to 0.84 m from the gate. Graphs shown in Figure 9 show the process of changing height of head of the density current in three forms of

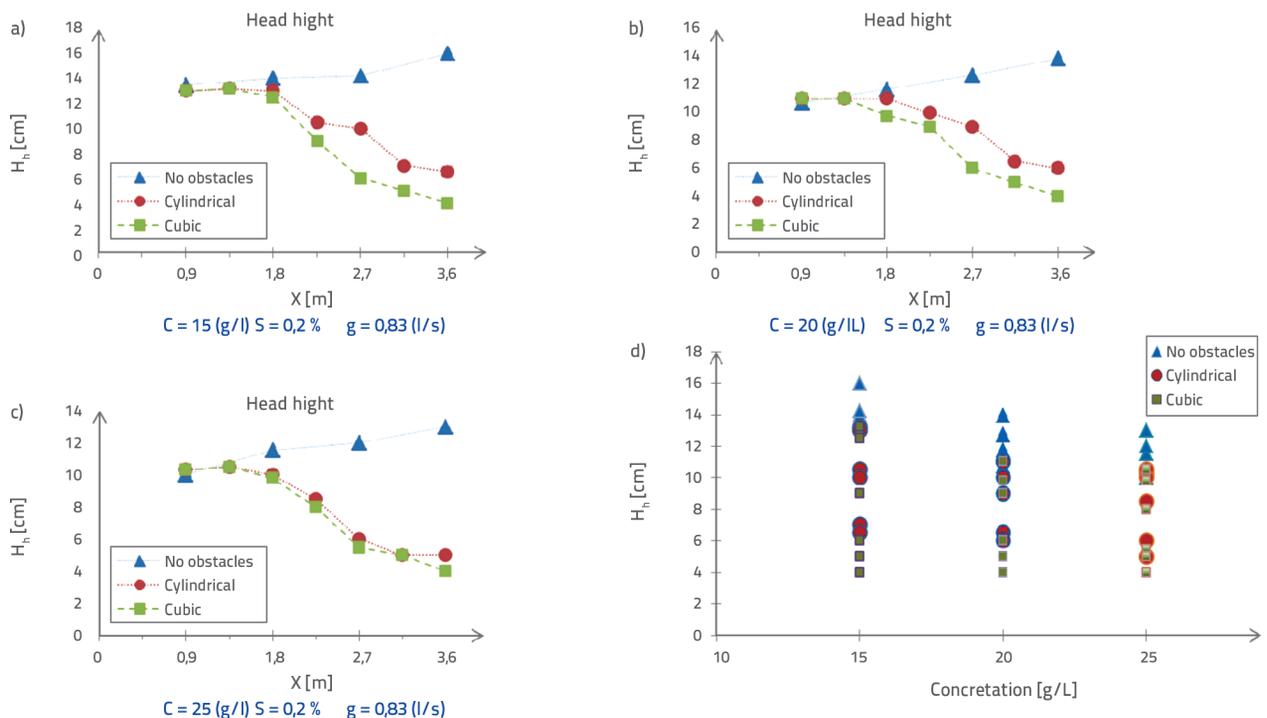


Figure 9. Graph of changes in height of head of density current along the length of the channel

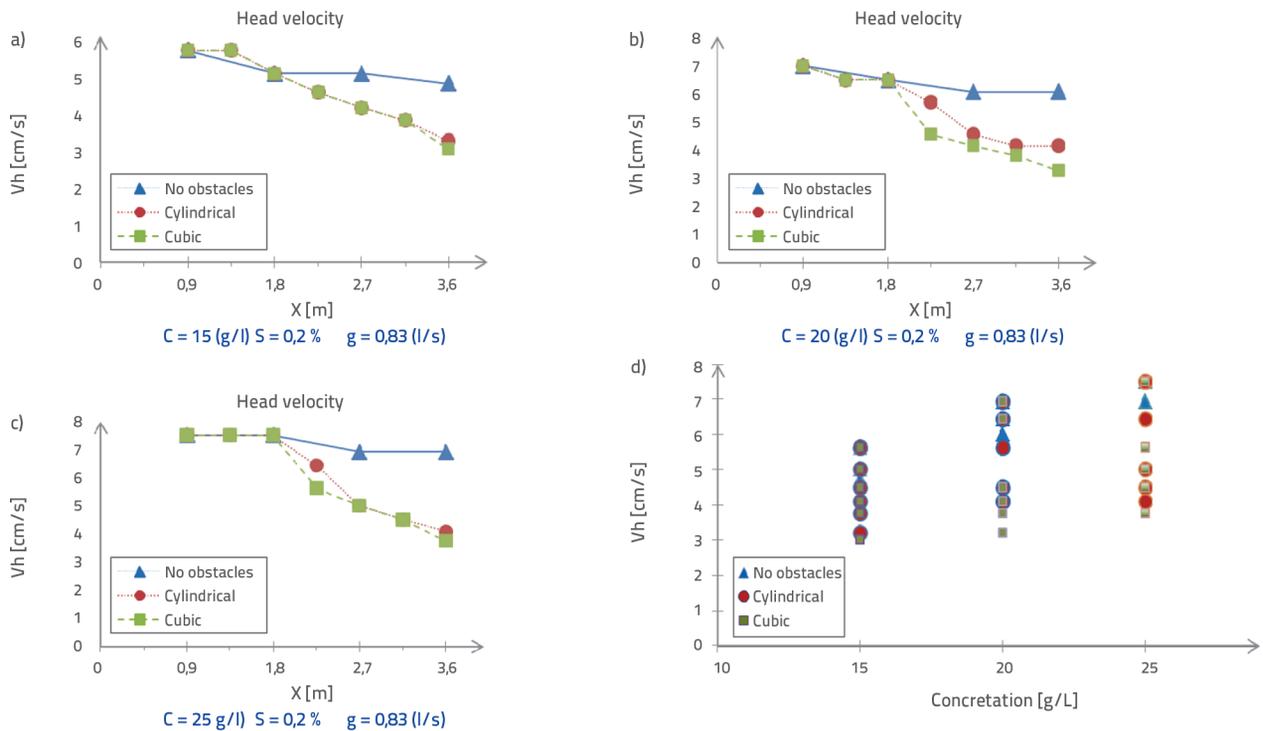


Figure 10. Graph of velocity changes of the head of density current along the length of the channel

bed without obstacles, with cubic obstacles, and with cylindrical obstacles at the slope of 0.2 %, for the discharge equal to 0.83 l/s, and for three concentrations 15, 20 and 25 g/l.

As shown in Figure 9, the height of the head of the density current decreases with an increase in concentration of density current owing to the effect of gravity on the current, and according to the continuity law, its speed must be increased to maintain continuity of the current. According to Figure 9 and the above description, at similar distances along the X-axis, the height of the head of the density current decreases as the concentration increases. For example, at the highest concentration of 25 g/l (Figure 9-C), all head heights are lower than the head heights at lower concentration of 15 g/l (Figure 9-A). The data presented show good accordance of results of this study with the results of other research [14, 25].

Also, at a given concentration and discharge, the change in slope, for example, an increase in slope, just like an increase in concentration, leads to a decrease in the height of the head of density current.

3.2. Velocity of head

Velocity changes of the head of density current, for the constant slope of 0.2 %, for the discharge of 0.83 l/s, and for three concentrations of 15, 20, and 25 g/l, are graphically presented in Figure 10. The graphs demonstrate a decreasing trend of velocity of the head of density current along the flume from the gate (from upstream toward downstream) in a bed with and without obstacles.

A decrease in velocity of the head of density current is observed at an obstacle-free bed. This decrease is due to the entry of

some quantity of ambient fluid into the head during motion of the density current. However, the amount of decrease in velocity of the head along the direction of flow is higher for the bed with obstacles, as this decrease in velocity is about 30 % for bed with cylindrical obstacles while it is about 45 % for cubic obstacles. Due to their geometric form, cubic obstacles have a larger wake space than cylindrical obstacles. This leads to more mixing of the ambient fluid with density fluid, consequently reducing the volume of density fluid at the head making it more watery, and thus the velocity of the head of density currents in cubic obstacles decreases more along the direction of the bed compared to cylindrical obstacles. In addition, due to their geometric form (a complete face with orthogonal angles along the direction perpendicular to the motion of the current) cubic obstacles cause an increase in friction coefficient and consequently a higher shear stress in comparison with cylindrical obstacles. In addition, the variation in velocity of the head of density currents against entrance concentration is presented graphically in Figure 10. This figure shows that an increase in concentration leads to an increase in velocity of the head of density current. Thus, when the concentration of entrance density fluid increases, the density difference between the density current and ambient fluid increases as well. Therefore, the gradient of pressure will increase and, considering that the main reason of motion of head of density current is the gradient of pressure resulting from specific mass difference between head and ambient fluid [26, 27], the velocity of the head of density current will increase. This statement has been confirmed by results obtained in similar research [14, 20, 24]. Graphs of the change in head velocity against slope change are shown in Figure 11. These graphs show

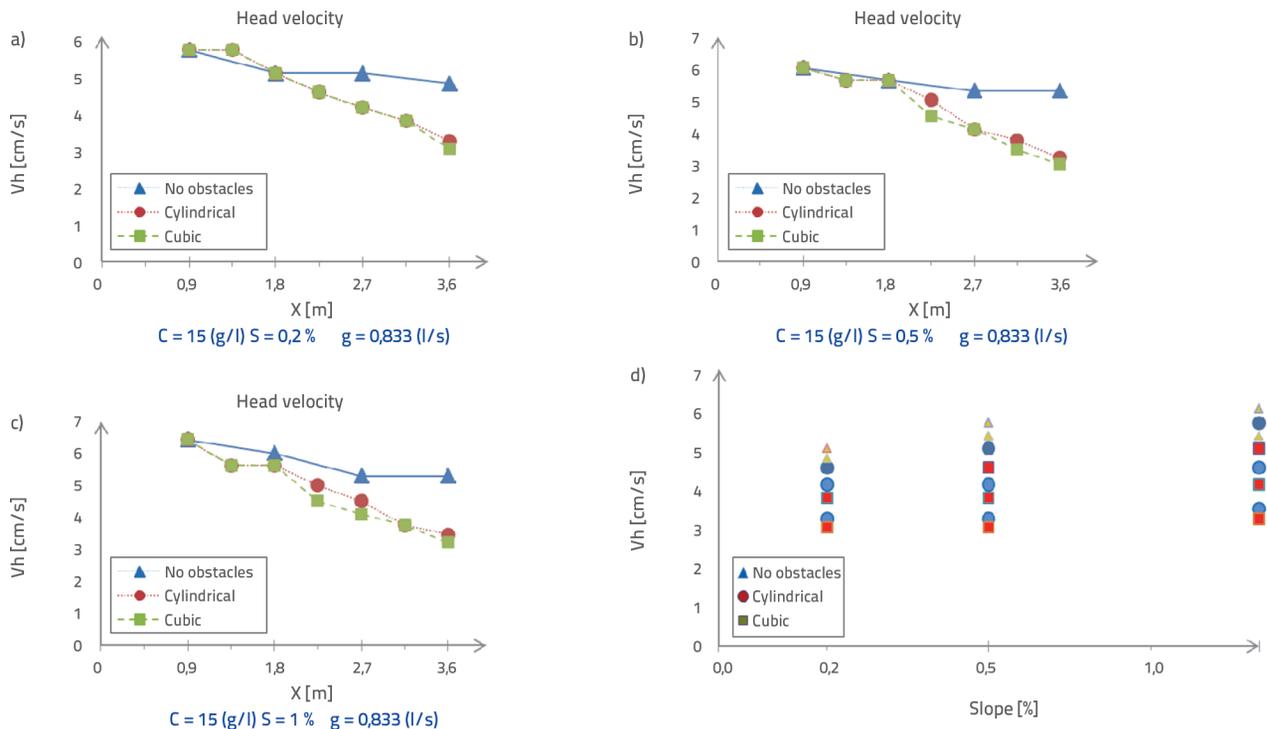


Figure 11. Graphs showing change of head velocity against change of channel slope

that the velocity of the head of density current increases with an increase in the slope of the channel, because an increase in slope increases the effective component of the weight force. On the bed with obstacles, the rate of an increase in velocity of the head of density current, which is due to an increase in the slope of the bed, decreases compared to the bed without obstacles. The reason could be a considerable mixing of the head of density current with clear ambient fluid on beds with obstacles.

4. Conclusion

The effects of cylindrical and cubic obstacles on the motion of the head of saline density currents are experimentally investigated in this study. Experiments were performed for three cases: (1) obstacle-free bed, (2) bed with cylindrical obstacles, and (3) bed with cubic obstacles. Measurements were performed at various inlet concentrations of density currents and slopes. The results point to the following conclusions:

- On the obstacle-free bed, the height of the head of density current along the channel had an ascending trend.
- On the bed with obstacles, the height of the head of density current decreased along the channel. The amount of decrease is higher in the case of cubic obstacles compared to cylindrical ones. In beds with obstacles, under similar conditions of concentration, slope and discharge, this decrease is about 50% in cylindrical obstacle, while it is about 70% in cubic obstacles, compared to the obstacle-free bed.
- The effect of changes of concentration of the current and slope of the bed on the height of the head was similar.

An increase in values of these two parameters led to a decrease in height of the head of density current in both forms (with obstacles and without obstacles).

- The process of changing velocity of the head of density current along the bed with and without obstacle was descending. The amount of decrease in head velocity along the direction of the channel was much higher for the bed with obstacles compared to the bed without obstacles. This amount of decrease was greater in cubic obstacles than in cylindrical obstacles so that cubic obstacles and cylindrical obstacles decreased the head velocity of density current by 45% and 30%, respectively.
- At a constant slope, the velocity of the head increases with an increase in concentration.
- Head velocity of density current in both forms (with obstacles and without obstacles) increased at constant concentration with an increase in slope. On the bed with obstacles, the rate of increase in head velocity of density current, which is due to increase in the slope of the bed, decreased more compared to the bed without obstacles.

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