An experimental study to determine the obstacle height required for the control of subcritical and supercritical gravity currents

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Turbidity currents are important phenomena involved in sediment processes in long and deep reservoirs. Deviation or dissipation of the turbidity currents in reservoirs can be achieved by using obstacles. In this paper, we study the effects of obstacle height on complete control of both subcritical and supercritical gravity currents ($0.7 \leq Fr_d \leq 1.37$) with various inflow characteristics by means of a physical model. First, a gravity current with different concentrations and discharges without using an obstacle is measured along a flume with three different slopes. Then, the height required to block the gravity current is determined by taking into account inflow characteristics and other results reflected in the literature. Finally, using the obstacle same as embankment barrier with various heights, the effects of obstacle height on the gravity current are studied in both subcritical and supercritical flows. The results specify what obstacle height is required for complete blockage of subcritical and supercritical gravity currents.

Keywords: obstacle height; reservoir; subcritical; supercritical; gravity current

1. Introduction

Sedimentation resulted from turbidity currents has been considered for a long time as a fundamental cause of shortening reservoirs lifetime. A large number of reservoir dams around the world have been filled with accumulated sediments. Turbidity currents develop due to the gravitational force acting on the density difference caused by suspended particles in the flow. Since the gravitational force acts on this type of currents, the turbidity currents are underflows of gravity currents. The occurrence of the turbidity currents in dam reservoirs transfers sediments to near body of dams which poses substantial threats to water release facilities like intakes and bottom outlet. The control of such currents has always been a problem in dam operation. The location of sediment accumulation is another factor greatly affecting the operational lifetime of a dam. Different techniques exist in sediment control management of reservoirs. Construction of obstacles in reservoirs is one of the methods to control or divert such currents. It also reduces concentration and density of the current passed over the obstacle. As a result, much of the sediment is deposited behind the obstacle; however, a portion of the current which passes over the obstacle would dissipate due to the reduction of current relative density.

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When the gravity current encounters an obstacle, depending on the obstacle height and inflow conditions, different cases can occur which can be classified into four cases. The theory of these cases has been broadly discussed by Asghari Pari et al. (2010) and briefly presented in Figure 1. This figure presents flow regime passing over the obstacle in a two-layer flow with unlimited upper layer for densimetric Froude number \((Fr_d)\) as a function of relative obstacle height \(H_m = h_m/h\). The first case occurs when the height of obstacle is low (the amount of energy at the obstacle section is more than the minimum energy in the current conditions). In this case, the current passes over the obstacle thoroughly. This case corresponds to regions A, B and C in Figure 1. The second case happens when the obstacle height is such that the current with critical depth passes over the obstacle completely. The third case occurs when the obstacle height is such that the current even with critical depth cannot pass over the obstacle. In this case, a portion of the current passes over the obstacle and the rest of it travels upstream in the form of a reflected bore or a hydraulic jump. Such a jump results in energy dissipation and adjusts flow conditions in upstream and downstream. This case corresponds to region D in Figure 1.

The fourth case happens when the obstacle is high enough to block the current totally (region E in Figure 1). Since in the first two cases, the current remains in steady state and the relative blockage of the current does not happen, these two cases do not affect sedimentation pattern (Bursik and Woods (2000)). Therefore, such cases do not fall into the scope of this research. In this research, all experiments have been accomplished in conditions in which the relative or complete blockage of the current can occur (i.e. regions D and E) and in range of \(Fr_d\) between .7 and 1.37.

The rest of this paper is organised as follows. In Section 2, we review the previous researches. The methodology of the experiments of this research is presented in

![Figure 1](image-url). Flow regime passing over the obstacle for \(Fr_d\) as a function of relative obstacle height \((H_m = h_m/h)\) in a two-layer flow with unlimited upper layer.
Section 0. In Section 4, we investigate the effect of obstacle on blocking both subcritical and supercritical turbidity currents. Finally, Section 5 concludes the paper.

2. Previous studies

Long (1954, 1970) reviewed a single-layer and a two-layer current with unlimited depth in upper layer using an obstacle. Greenspan and Young (1978) studied the effects of obstacle on the current with the impact angles of 30, 60 and 90°. Rottman, Simpson, Hunt, and Britter (1985) resolved analytically the two-step current over the horizontal slope with the presence of an obstacle in steady and unsteady currents and concluded that if the obstacle height is twice its current thickness, the current can be fully blocked. Lane-Serff, Beal, and Hadfield (1995) studied theoretically and experimentally two-dimensional gravity currents over obstacles with limited and unlimited upper layers. It was mentioned that when the gravity current interacts with an obstacle, a part of the flow may pass over the obstacle, while the remaining is scattered back as a bore. By means of theoretical model, they predicted the proportion of the flow that continues over the obstacle as well as the speed and the depth of the reflected flow. Prinos (1999) has studied the effects of semicircle and triangle shapes for the obstacle as well as the position of the obstacle in horizontal slope for densimetric Froude number in the range of .7–.8 and concluded that the obstacle shape does not have any effect on blocking the turbidity current. Bursik and Woods (2000) conducted a series of laboratory experiments that illustrated the influence of changes in channel topography (depth or width) on the sedimentation patterns produced by steady, particle-laden currents. Since the current was not blocked to produce a bore, topographic features consisting of constrictions, ridges and sudden openings caused no significant deviation from exponential deposit thinning or discontinuity in thickness. The observation was the same even when there was a transition in flow regime caused by the topographic feature. In contrast, if the topographic changes were large enough to partially reflect the flow producing an upstream-propagating bore, the deposit did not thin exponentially.

Oehy and Schleiss (2007) have studied the impact of obstacle construction and screen on controlling the turbidity current in dam reservoirs. Their investigations showed that turbidity currents can be considerably slowed down by obstacles or permeable screens and that most of the sediments can be retained on their upstream side. They also stated that both technical measures seem to be adapted for subcritical and supercritical approaching flow conditions; however, the obstacle showed slightly higher retention rates than the geotextile screen. Other researches including Kneller, Edwards, McCaffrey, and Moore (1991) and Alexander and Morris (1994) investigated the effect of oblique reflection and sea floor topography on turbidity currents. Kubo (2004) has examined topographic effects on deposition of turbidity currents experimentally and numerically. The experiments have been carried out on a series of humps with the heights equal to 1.2 and 3.6 cm. The author has provided results showing that deposit distribution on the upstream of a hump is increased locally and stated that increased deposit on the upstream of a hump is attributed not only to partial blocking of the current at the hump crest, but also to the differential deposition due to deceleration on the upslope. Toniolo, Parker, Voller, and Beaubouef (2006), Toniolo, Parker, and Voller (2007) have considered theoretically and numerically the trap efficiency of mud in dam reservoirs. De Cesare, Oehy, and Schleiss (2008) observed that obstacles with reasonable heights (at least twice the current height) are efficient for blocking the currents. Their investigation also showed that in certain configuration, turbidity current can be
considerably slowed down by a geotextile or an inclined water jet screen and therefore, most of the sediments can be retained upstream. Gonzalez-Juez, Meiburg, and Constantinescu (2009) numerically investigated the flow of gravity currents passing a circular cylinder mounted above a wall and focused on the influence of the gap separating the cylinder from the wall. Gonzalez-Juez and Meiburg (2009) also considered the problem of a partial-depth lock-exchange gravity current passing an isolated obstacle. They extended the shallow-water models proposed by Rottman et al. (1985) and Lane-Serff et al. (1995) and predicted the height and front speed of the downstream current as functions of the inlet Froude number and the ratio of the obstacle height to the current height. Jenzer Althaus, De Cesare, Boillat, and Schleiss (2009) presented case studies turbidity currents and their sedimentation in reservoirs with the aid of case studies and numerical simulation to determine the effect of submerged obstacles on reservoir sedimentation. Nasrollahpour and Ghomeshi (2012) have investigated the influence of roughness geometry on the head concentration. Oshaghi, Afshin, and Firoozabadi (2013) carried out a series of laboratory experiments with various obstacle heights and different inlet densimetric Froude numbers. Experiments showed that the density current with lower inlet Froude number reacts to the presence of the obstacle more rapidly compared to the currents with higher values of inlet Froude number.

In general, the results of studies show that the specific obstacle height capable of controlling and blocking the gravity current depends totally on inflow characteristics. According to what mentioned above, no comprehensive research has been conducted on a given height of obstacle which can completely block the gravity current under different inflow conditions and in subcritical and supercritical flows. Since the construction of an obstacle in dam reservoir is a new technique in reducing turbidity current impacts, more studies need to be conducted in this respect. In the present research, a physical model is used to study the effect of a given height of obstacle which can block the gravity current for different concentrations, discharges and slopes.

3. Methodology

Initial variables used in experiments with gravity current include current thickness \( h \), current body velocity \( u \), density of ambient water \( \rho \), density of turbidity current \( \rho' \), fluid kinematics viscosity \( \nu \), obstacle height \( h_m \), gate opening \( Z \), reservoir depth \( D \) and gravity \( g \). By dimensional analysis, the relative obstacle height can be derived as follows:

\[
H_m = \frac{h_m}{h} = \frac{1}{f} \left( R_e = \frac{uh}{\nu}, \quad Fr_d = \frac{u}{\sqrt{g' h}}, \quad r = \frac{h}{D}, \quad S \right)
\]

(1)

where \( R_e \) is Reynolds number, \( Fr_d \) is densimetric Froude number, \( r \) is the dimensionless coefficient representing the ratio of current thickness to the reservoir depth, \( g' = g \frac{\rho' - \rho}{\rho} = g \frac{h_0}{h} \) and \( S \) is the slope of flume floor. The objective of this research is to create varying flow conditions with different concentrations and to control turbidity currents with the use of an obstacle. Hence, the experiments were carried out by means of a flume of 8 m in length, 70 cm in height and 35 cm in width. The saline current was used as a turbidity current in the experiments, and it was continuous release. The water depth in clear current tank was constant and equal to 66 cm. For the gate opening, two series of experiments were performed in which we changed the size of gate opening. In the first series, gate opening was 3, 5 and 8 cm (can be seen in Supplement data, experiments No. 9–11); and for the second series, gate opening was 3 and 8 cm (can be seen
in Supplement data, experiments No. 2 and 3). For both series of mentioned experiments, we observed that the gate opening only influenced the flow for the first .5 m after the gate and no significant changes was observed after 1.2 m away from the gate. Since we did not observe any significant changes in the flow by changing the size of gate opening ($Z$), we considered it as fixed at 3 cm for the rest of experiments. Furthermore, since the water depth in reservoir was also fixed at 66 cm during the experiments, the parameter $Z/D$ is constant and not an effective parameter in this research. During the experiments, three flow discharges with various concentrations on three different slopes were used for the inflow. As mentioned before, the height of obstacle blocking the gravity current depends on the inflow conditions. Therefore, the experiments were carried out first without the presence of obstacle under all flow conditions. Considering the results of experiments and taking into account the constraints proposed by other researchers and results of analytical solutions based on simplified assumptions (Figure 1), 2, 3 or 4 heights were determined for each case. The shape of the obstacle in all experiments was a trapezoidal cross-section with a 1:1 slope on both sides. The velocity profile at two sections, one at upstream of the obstacle and the other one at downstream of the obstacle (the location of probes in Figure 3), was measured by Acoustic velocity meter DOP2000. The DOP transducers had an angle of 20° looking downstream, an emission frequency of $f = 4$ MHz with diameter of 5 mm. The temperatures of gravity current and ambient water were measured to ensure that the gravity current is due to difference between concentrations of saline water and clear water. During the experiments, the maximum temperature difference was 2°. The densities of gravity current and fresh water were measured by a hydrometer device. In order to enhance the accuracy of experiments especially for the current head velocity measurements, the flume gate was designed such as it can be adjusted to the respective opening immediately. In order to control the inflow in the flume, an electromagnetic flowmeter was used and the outlet check valve was calibrated by considering the water stage. Inflow and outflow discharges were constant during all experiments, hence the water stage was kept constant during experiments. A schematic view of the flume and connected devices as well as a schematic view of flume dimension and probes location has been shown in Figures 2 and 3, respectively. The experiment has been accomplished for three flume slopes of 0, 1.93 and 3.86%; three discharges of .9, 1.4 and 2 l/s; and three concentrations of 8.3, 16.7 and 25 kg/m$^3$. Table 1 presents the range of variations in parameters of this
In the experiments, the average velocity and depth of the turbidity current were calculated using the Ellison and Turner (1959) equations as follows,

$$U = \frac{\int_0^\infty u^2 \, dz}{\int_0^h u \, dz} = \frac{\int_0^h u^2 \, dz}{\int_0^h u \, dz}$$  \hspace{1cm} (2)

**Figure 3.** Schematic view of the dimension of flume and probes location.

**Table 1.** The results of all experiments in the form of dimensionless parameters.

| S (%) | Q (l/s) | Fr|d | Hm  | r   | Δρ/ρ |
|-------|---------|----|----|-----|-----|------|
| 0     | .9      | .7 | 1.87 | .11 | .006 |
| 1.93  | 1.4     | .76 | 2 | .16 | .006 |
| 1.93  | 2       | .9 | 2.65 | .18 | .006 |
| 0     | .9      | .79 | 1.99 | .08 | .01  |
| 0     | 1.4     | .83 | 2.3 | .1 | .01 |
| 0     | 2       | .93 | 2.75 | .15 | .015 |
| 0     | .9      | .83 | 2.16 | .07 | .015 |
| 0     | 1.4     | .91 | 2.54 | .09 | .015 |
| 0     | 2       | .94 | 2.77 | .13 | .017 |
| 1.93  | .9      | 1.2 | 3.55 | .1 | .006 |
| 1.93  | 1.4     | 1.03 | 3.27 | .16 | .006 |
| 1.93  | 2       | .99 | 3.56 | .21 | .006 |
| 1.93  | .9      | 1.29 | 3.81 | .08 | .011 |
| 1.93  | 1.4     | 1.15 | 3.97 | .11 | .011 |
| 1.93  | 2       | 1.1 | 3.64 | .15 | .011 |
| 1.93  | .9      | 1.36 | 3.48 | .06 | .016 |
| 1.93  | 1.4     | 1.24 | 4 | .09 | .016 |
| 1.93  | 2       | 1.17 | 4 | .13 | .017 |
| 3.86  | .9      | 1.21 | 4.17 | .12 | .007 |
| 3.86  | 1.4     | 1.11 | 4 | .19 | .007 |
| 3.86  | 2       | 1.08 | 3.97 | .24 | .007 |
| 3.86  | .9      | 1.31 | 4.58 | .1 | .011 |
| 3.86  | 1.4     | 1.19 | 4.42 | .15 | .01 |
| 3.86  | 2       | 1.14 | 4.23 | .2 | .011 |
| 3.86  | .9      | 1.37 | 4.45 | .08 | .017 |
| 3.86  | 1.4     | 1.32 | 4.59 | .12 | .015 |
| 3.86  | 2       | 1.25 | 4.94 | .14 | .017 |
\[
\bar{h} = \frac{\int_0^\infty u\,dz}{\int_0^\infty u^2\,dz} = \frac{\int_0^{h_i} u\,dz}{\int_0^{h_i} u^2\,dz}
\] 

(3)

where \( h_i \) is the thickness of the current as velocity is zero.

Due to lack of space, the flow conditions with and without the presence of obstacle have been given in the Supplemental data Section.

4. Results and discussion

When the current encounters the obstacle, a portion of current passes over the obstacle. After passing the obstacle, this part of the current forms gravity current similar to the initial current but with a lower velocity. This process has been illustrated in Figures 4(a)–(h). The current passing over the obstacle includes two parts: the first part is the head of the current and the second part is the body of the current coming after the head. However, in the cases when the current head passes over the obstacle and the current body is blocked, the current head can only be observed. As mentioned above, when the current encounters the obstacle, a portion of the current travels upstream in the form of a reflected bore. In supercritical currents, this bore is in the form of an acute head with a height corresponding to the obstacle height. Such a bore can actually be considered as

![Figure 4. Schematic view of a gravity current encountering an obstacle in the horizontal slope (a–f) and the conditions of the reflected bore from the obstacle in subcritical (g) and supercritical (h) currents.](image)

Notes: Figures (a–g) correspond to test No. 51 and Figure (h) belongs to test No. 111.
a moving hydraulic jump (Figure 4(h)). In subcritical currents (horizontal slope case), the reflected bores are observed in the form of a series of undular bore, at the head of which the variations in the height are gradually and smooth unlike the supercritical currents (Figure 4(g)). In this case, at the top of the obstacle, the critical flow depth occurs and a quasi-steady current is formed over the obstacle when the bore travels upstream. In the case that moving hydraulic jump travels upstream, depending on the flow conditions, this jump can be transformed into a fixed hydraulic jump and the current turns into a steady current. In all experiments performed in this research (except for one case), adequate distance in the upstream for forming the fixed hydraulic jump has not been available. Therefore, the moving hydraulic jump reaches the gate and after encountering the gate (In this state, the current after the gate turns from free flow into a submerged form), it travels towards the obstacle in the form of a new bore. When this bore reaches the obstacle, the discharge of the gravity current passing over the obstacle increases. Such a sweep movement of bores continues until the steady current is formed. In this research, measuring the discharge passing over the obstacle has been considered as the criteria for the calculations to measure the amount of flow that has been stopped by the obstacle. In the tests, the velocity profile at the first section (i.e. the location of the first probe in Figure 3) has been measured in the time interval between the moment when the current encounters the obstacle and before the arrival of reflected bore from the obstacle. Furthermore, the velocity profile at the second section (i.e. the location of the second probe in Figure 3) has been measured in the time interval after the head of current reaches the end of flume and before the arrival of reflected bore from the end of flume. Figure 5 shows the measured velocity profiles at the upstream of obstacle (the location of probe 1). These profiles are averaged using Equations (2) and (3) and discharges are calculated for each case using certain equation. For all experiments, dimensionless parameters (that shown in Equation (1)) have been calculated. In the experiments, Reynolds number belongs to the interval (2800, 15000) and since the flow

![Figure 5. Vertical velocity profiles of gravity currents for test No. 43, test No.50, test No. 93 and test No. 23 at the location of probe 1.](image-url)
in this range is turbulent and we could not find any especial trend between $H_m$ and $R_e$ (not shown here), it was suggested that $R_e$ is not an effective parameter and was omitted from the list of parameters affecting the relative height of obstacle. In the experiments, the depth of inert water at the location of probe 1 has been used to measure $r$ parameter. Other dimensionless parameters calculated from the results have been illustrated in Table 1. It should be mentioned that the values of $H_m$ presented in this table are related to the obstacle heights which resulted in total blockage of the current.

The results of all experiments in this research show that when slope and discharge were constant, by increasing the concentration, the gravity current depth decreases which can lead to reduction of the obstacle height required for the blockage of the current. On the other hand, the results indicate that as the concentration rises, densimetric Froude number of the inflow increases causing the relative obstacle height to increase. Therefore, concentration variations (in the range of present research) cannot be effective as an independent parameter in determining the relative height required for the blockage of the current.

In order to study the effect of densimetric Froude number of the inflow on the relative obstacle height, the results have been shown in Figure 6. Such results have been also presented for various amounts of slope and $r$ in Figures 7 and 8, respectively. The theoretical line shown in Figures 6–8 is as the same as the line separated E section in Figure 1. The equation of this line is as follows (Asghari Pari, Kashefipour, Ghomeshi, & Bajestan, 2010 and Rottman et al., 1985):

$$Fr_{d1}^2 = (H_m - 1)^2 \left( \frac{H_m + 1}{2H_m} \right)$$

where $Fr_{d1}$ is densimetric Froude number of approaching flow before the obstacle.

![Figure 6](image_url)
Henceforth, the line separating regions D and E in Figure 1 is called theoretical line. This line has been depicted in Figures 6–8. The left side of this line is the region of relative blockage of the current and the right side of the line specifies the region of complete blockage of the current. The results of this research located in the right side of the theoretical line thoroughly indicate that as the densimetric Froude number of the inflow increases, the relative obstacle height required for blockage of the current rises. As can be seen in Figure 6, by increasing densimetric Froude number of the inflow, the curve belonging to the results of this research diverges from the theoretical line. This can be due to increase of entrainment rate and the effect of such an increase on controlling the gravity current using an obstacle. According to Figure 6, the curve of the results of present study correlates with the theoretical line for the values of densimetric Froude number smaller than .7 and this is due to the fact that for such values, the effect of ambient fluid can be disregarded. Therefore, the theoretical line can be used for the values of densimetric Froude number smaller than .7. Furthermore, the results of this research indicate that a relative obstacle height of 2 ($H_m = 2$) can block the gravity current completely for the values of densimetric Froude number smaller than .8 ($Fr_d < .8$). This result corresponds to that obtained by Lane-Serff et al. (1995), Prinos (1999) and Rottman et al. (1985). Additionally, it can be seen from Fig. 6 that when $0.7 < Fr_d < 1$, the relative obstacle height required for completely controlling the current is between 1.8–3 and as the densimetric Froude of the current increases, the required $H_m$ value grows faster compared to supercritical range ($1 < Fr_d < 1.37$). In terms of $r$, Figure 7 indicates that for the same inflow characteristics and a constant densimetric Froude number, as the value of $r$ increases, the relative obstacle height required for blockage of the current slightly rises; however, the sediment deposition upstream of the obstacle will reduce its blocking efficiency with time. In terms of $S$, Figure 8 shows that by increasing the slope, and thus converting subcritical current to supercritical current, the effect of obstacle height on blocking the current decreases.

Figure 7. Experimental results for total blockage of the gravity current for various values of $r$.  

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In order to derive an expression to estimate the relative height required for complete blockage of the current in different inflow characteristics, statistical analysis has been used. In this regard, various statistical models have been tested by means of SPSS software. According to the results, the following form of equation was suggested to relate the relative height of obstacle to the effective parameters, including $Fr_d$, $r$ and $S$,

$$H_m = 2.297Fr_d^{897} (S + 1)^{157} e^{1.422r}$$

This equation was developed using about 80% of existing measured data, and was verified by the rest of measured values. Statistical calculations showed that the absolute error of estimating the relative height ($H_m$) required for complete blockage with the verification data is 6.75% and with all data, 5.4% showing a remarkable accuracy. Also the remaining 20% data have been utilised to estimate the accuracy and correctness of Equation (5) by means of Root Mean Summation of Square Error method, with this statistical parameter being calculated .23. It should be mentioned that Equation (5) was obtained for $0.7 \leq Fr_d \leq 1.37$, $0\% \leq S \leq 3.86\%$ and $0.06 \leq r \leq 0.24$. It should be also noted that this equation is applicable to describe the flume experiments and not for general cases. Considering the densimetric Froude number, slope of the flume floor ($S$), and ratio of current thickness to the reservoir depth ($r$) as well as the variations range of these parameters in the present research, it was observed that densimetric Froude number is about 2 times as effective as two other parameters in Equation (5). Hence, densimetric Froude number of the inflow is the predominant parameter in determining the obstacle height required for controlling the gravity current. This equation also indicates that not only as the slope increases but also when $r$ increases, the relative obstacle height required for complete blockage of the current rises. On the other hand, according to Equation (5) with decreasing the value of $r$ (i.e. higher depth of reservoir), the effect of this ratio goes to the zero and the same conclusion exists when the bed slope is zero. Furthermore, the effect of concentration as an independent dimensionless parameter ($\Delta \rho/\rho$) has been investigated. Sensitivity analysis indicated that the effect of $\Delta \rho/\rho$ as an
independent parameter is zero. This result is due to the fact that the effect of this parameter has been considered in the densimetric Froude number of the inflow.

5. Conclusion
Construction of obstacle with the right design is considered as one of the methods of controlling or deviating the turbidity currents. In this paper, we have studied the obstacle height required for the complete blockage of the gravity current in various conditions. The conclusions of our study can be summarised as follows:

- A power relationship between densimetric Froude number \( .7 \leq Fr_d \leq 1.37 \), slope of the flume floor \( 0 \leq S \leq 3.86\% \) and the ratio of current thickness to the reservoir depth \( .06 \leq r \leq .24 \) has been derived for estimating relative obstacle height required for complete blockage of the gravity current, and the error rate of estimation by this relationship is 5.4\%. It is applicable to describe the flume experiments and not for general cases.
- Densimetric Froude number is around two times as effective as slope of the flume floor \( S \) and the ratio of current thickness to the reservoir depth \( r \). Hence, densimetric Froude number of the inflow is the predominant parameter in determining the relative obstacle height required for controlling the gravity current.
- In order to block the subcritical gravity currents, the obstacle height of 2–2.75 times as high as the current body height is required and to block the supercritical gravity currents (for the range of densimetric Froude number in the present research), the obstacle height of 3.2–5 times as high as the current body height is required.
- By increasing densimetric Froude number of the inflow \( .7 \leq Fr_d \leq 1.37 \), the relative obstacle height required for blockage of the current rises and the curve belonging to the results of this research diverges from the theoretical line (that is suitable for lower limit in subcritical gravity current).
- As the ratio of current thickness to the reservoir depth \( r \) increases, the relative obstacle height required for blockage of the current rises.
- A relative obstacle height of 2 \( (H_m = 2) \) can block the gravity current completely for the values of densimetric Froude number smaller than .8 \( (Fr_d < .8) \). This result completely conforms to that obtained by previous researchers.

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Supplemental data
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