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An Experimental Study on the Effects of Obstacle Diameters on Suspended Sediment Concentration in the Case of Transverse Waves

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A B S T R A C T

There are many cases in open channel flows where the steady flow of water passes through a cluster of vertical cylinders. As a fluid flow is encountered with several obstacles, an overlapping of opposite forces is resulted by vortex shedding, and shear layers in the wake area takes place and transverse waves are formed along the width of the channel. The present study focused on this phenomenon and the effects of obstacle diameters on suspended sediment concentration based on laboratory tests in a rectangular flume. Wooden obstacles were used in an in-line arrangement only in the half part of a channel width divided by putting a plexi glass sheet. Firstly, in the similar condition of discharge, transverse and perpendicular obstacles distances, hydraulic conditions in maximum wave amplitude for different obstacle diameters were determined. Then, the transportation of suspended sediment from upstream to downstream of obstacles and no-obstacle zone for wave modes 1 and 2 was compared to normal flow condition. Along with this, the suspended sediment concentration variations at downstream of obstacles zone were compared to no-obstacle zone. The results showed that transverse waves had a significant impact on reducing the suspended sediment concentration at downstream of obstacles zone rather than no obstacle zone and the maximum of reduced concentration percentages at downstream of obstacles zone versus the condition with no-obstacle zone, for wave modes 1 and 2 was about 11.2% and 8.3%, respectively. Therefore, wave mode 1 had more effect on the reduction of suspended sediment transportation than wave mode 2. In addition, an increase in obstacle diameters cause to increase the maximum values of the dimensionless displacement (A/H) by about 26% and 37% for wave modes 1 and 2, respectively. However, reduced concentration percentages at downstream of obstacles for wave mode 1 and 2 was decreased about 8%.

1. Introduction

When a stationary object is positioned in a fluid stream flow in an open channel, after the stagnation point, boundary layer will be developed around the object. At the point where the boundary layer begins, the thickness of boundary layer is zero and after the development of the boundary layer on the layer of solid object, the boundary layer approaches the point of separation where streamlines are separated from the body (Streeter & Wylie, 1981). Based on Lienhard (1996), a regular pattern of vortexes and shear layers occurs in specific ranges of dimensionless Reynolds number of obstacles in wake zone. In open channels, several cases have been observed where the stream flows over circular obstacles including piles, piers or vegetation across floodplain of a river. The effects of vortexes formed by obstacles result in the formation of surface waves spreading over flow cross section.

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Most studies on vortexes resulting from stream flows over obstacles are related to gas fluid. The results of this kind of researchers can be found in literature, e.g. Fitz-Hugh (1973), Zukauska *et al*., (1983) and Blevins (1997).

On the contrary, few researches have been performed on vortexes resulting from water flow in open channels. The first findings were reported by Crasse (1939). In a similar study, Zima and Ackermann (2002) suggested a formula for simulation of maximum dimensionless values for transverse waves amplitude (A/H). In a recent study by Ghomeshi *et al*., (2007) on the effect of transverse wave in open channel, two equations were proposed to calculate the amplitude of transverse waves. Jafari *et al*., (2010) in a dimensional analysis presented a new formulation to estimate the amplitude of the transverse wave generated by vortex shedding in open channels. Prasanth and Mittal (2009) presented the results of a study on vortex induced vibration of two circular cylinders at low Reynolds number. They found that the in-line arrangement of the two cylinders had a significant effect on the flow. Sadeque *et al*., (2008) experimentally investigated the flow around the cylindrical objects in an open channel. They found that the increase in dimensionless bed-shear stress was inversely related to the level of submergence of the cylinders. Yoon (2009), also, investigated the flow characteristics of two rotating side-by-side circular cylinders. In his research, quantitative information about flow variables such as the pressure coefficient and wall vortices distributions on the cylinders was highlighted. An experimental study on the effects of transverse waves on bed of channels due to vortex shedding was done and results showed that at 70 cm downstream obstacles a ripple bed was formed where most variations were observed in the one-thirds of the side of the channel (Ghomeshi *et al*., 2011). But no study has been focused on the effect of transverse waves and obstacles diameter on the suspended sediment concentration of open channel. Since erosion, scouring and sediment transport in open channels have been of interest to researches for decades, it seems to be the right time to shift the focus towards the effects of obstacles diameter on sediment transportation in condition of overlapping hydraulic forces by vortex shedding.

2. Materials and Methods

An experimental flume with a rectangular cross-section of fixed slope equal to 0.005, 70 cm height, 800 cm length and 100 cm width was used. For the purpose of this study, in order to compare the effects of the transverse waves with condition of the normal flow for different obstacles diameter, width of flume was divided into two equal sections by putting a plexi glass sheet as a wall with a height of 70cm and length of 4m from the middle of flume to end. The flow discharge was equal to 25 L/s throughout the experiments. The discharge was measured and regulated by a flow meter installed at the entrance of the flume. The flow was entered into experimental flume after going through a still tank. The depth and velocity of flow were controlled by a sliding gate which was installed at the end of the flume. In this study, three experiments on average 80 wooden cones with 12, 25 and 42 mm diameter and 30 cm height were used as stream flow obstacles in the half part of a channel width in an in-line arrangement. The bed of flume was covered by plexi glass sheets with a thickness of 10 cm. The sheets were screwed in a grid form in both longitudinal and latitudinal directions at every 3 cm to installation of obstacles at defined transversal (T) and perpendicular (P) intervals in an in-line arrangement on them as shown in Figure 1.

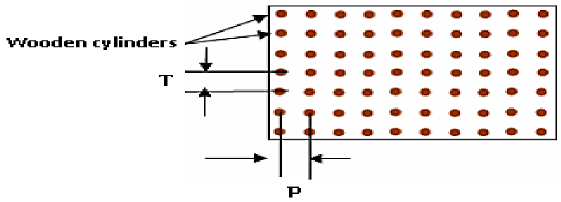

Figure 1. In-line arrangement of the wooden cylinders

Each experiment was conducted in two stages. The aim of the first stage was to find the hydrodynamics of flow in maximum wave amplitude at different modes. This stage included three experiments with different obstacle diameters.

The specifications of experiments are provided in Table 1.

Table 1. The specifications of experiments.

Number of experiments	D mm	T mm	P mm	Obstacles arrangements	B mm	N	Q(lit/s)
1	12	120	120	In-line	1000	4	25
2	25	120	120	In-line	1000	4	25
3	42	120	120	In-line	1000	4	25

In Table 1, the first column shows the number of experiments and the second column presents the diameter of obstacles. Columns 3 and 4 show the transversal (T) and perpendicular (P) distances between obstacles while column 5 shows the obstacles arrangement and column 6 presents the width of experimental flume. Column 7 shows average numbers of obstacles in each row and column 8 shows flow discharges.

After fluid began to flow into the channel, the height of sliding gate was varied from maximum value versus flow depths where transverse waves were formed up to 5 mm steps.

With the gradual reduction of flow depth, two modes of vibration (n=1, 2) were appeared in the experiments. Modes of waves that appear in the laboratory flume are shown in Figure 2.

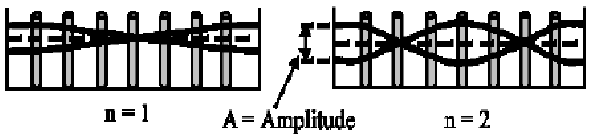

Figure 2. Modes of waves appearing in the laboratory flume

With the gradual reduction of flow depth, wave mode 1 begins to vary with a low amplitude and as the flow depth decreases further, the wave amplitude n=1 widens until it reaches maximum amplitude. As the flow depth continues to decrease, the wave amplitude narrows further until wave n=1 fades away and the amplitude of the waves becomes zero or enters the second mode wave n=2 without becoming zero through a transition stage. As the flow decreases, wave amplitude increases in n=2 and after it reaches a maximum value, it continues to narrow with the decrease in depth.

These two waves possess different characteristics. In this study, the formation of transverse waves is explained by laboratory observations in the first stage.

The hydrodynamics of flow in maximum wave amplitude in different modes are provided in Table 2. Then, nine experiments were conducted during the second stage. In this stage the flume bed was covered by Silica small grain from the upstream of the channel to 100 cm distance from the dividing wall up to 30mm in height. The specifications of silica grain size are shown in Table 3.

Table 2. The hydrodynamics of flow in maximum wave amplitude in different modes

Number of experiments	T/D	P/D	n	A_{av}(mm)	H_{av}(mm)	A/H
1	10	10	1	14	280	0.05
1	10	10	2	11.3	141.2	0.08
2	4.8	4.8	1	31	172.2	0.18
2	4.8	4.8	2	21.7	72.3	0.30
3	2.9	2.9	1	38.7	124.8	0.31
3	2.9	2.9	2	24.1	53.5	0.45

Table 3. Specifications of silica grain size

D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
16.23	118.04	189.45

In maximum wave amplitude in different modes (n=1, 2), wave amplitude and flow depth parameters in flume at three cross-sections (the first, middle and end) in the obstacles zone were recorded and were presented in Table 2. In Table 2, the second column presents the ratio of dimensionless transversal distance to diameter of obstacles and the ratio of dimensionless longitudinal distance to diameter of obstacles is shown in column 3. Column 4 shows the type of observed waves, while column 5 and 6 represent the average maximum wave amplitude and flow depth in the obstacles zone. Column 7 shows the maximum values of the dimensionless displacement (A/H).

As the hydraulic conditions were determined in maximum wave amplitude mode in the first stage of experiments, the sediment was

Laid to cover the upstream bed of the channel. Then, the height of the downstream sliding gate was adjusted, so the waves would form in the maximum amplitude mode. The suspended sediment movement to downstream was investigated under similar conditions.

Experiments of the second stage were performed to measure the suspended sediment concentration transported to downstream in maximum wave amplitude in different modes (n=1, 2). Then, the results were compared to the conditions of the normal flow for different obstacles diameter.

In order to determine the suspended sediment concentration at determined cross-sections, turbidity meter was used to measure the turbidity in NTU in 0.2, 0.6 and 0.8 of flow depth from channel bed.

After calibrating the turbidity meter, the values can be demonstrated in gram/lit.

Flow concentration was measured at upstream and downstream cross-sections in the obstacles and no-obstacle zone after the

Formation of waves with maximum amplitude. Figure 3 presents specifications of experimental flume used in this study.

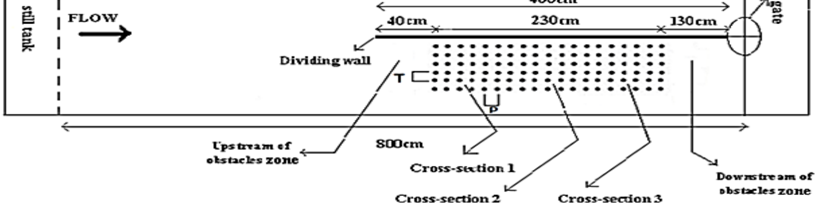

Figure 3. Specifications of experimental flume

3. Results and Discussion

As can be seen in Table 2, obstacles with 12 and 42 mm diameter have the lowest and highest maximum wave amplitude for wave modes 1 and 2, respectively. Thus, in order to understand the flow hydraulic conditions in maximum wave amplitude for obstacle diameters, the variations of A/H against obstacle diameters were depicted in Figure 4.

As shown in Figure 4, an increase in obstacles diameter increased the maximum values of the dimensionless displacement (A/H) by about 26% and 37% for wave mode 1 and 2, respectively.

After the experiments of the second stage finished, the suspended sediment concentration in zone near the obstacles at a distance of 20 cm from their upstream and 40 cm from their downstream and also in no-obstacle zone was investigated. The results show that suspended sediment concentration at downstream of obstacles zone is more than no-obstacle zone in normal flow condition but due to formation of transverse waves, the concentration of suspended sediment at downstream of obstacles zone was decreased rather than no-obstacle zone for wave modes 1 and 2.

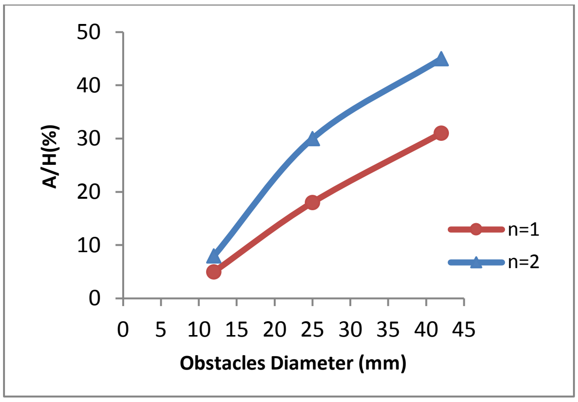

Figure 4. The variations of A/H against obstacles diameter

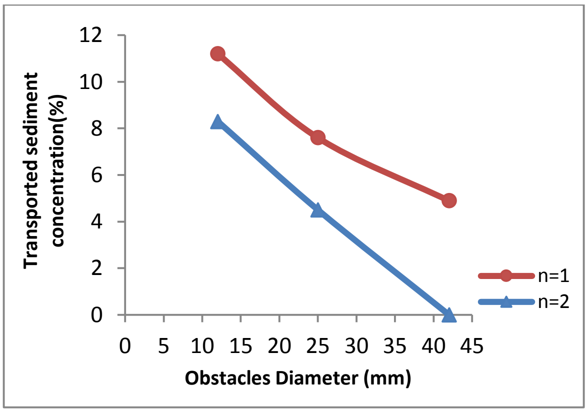

Figure 5. The variations of reduced concentration percentages against obstacles diameter

In order to understand the effects of wave modes 1 and 2 on reducing suspended sediment concentration, the variations of reduced concentration percentages at downstream of obstacles zone rather than no-obstacle zone against obstacles diameter are presented in Figure 5.

As shown in Figure 5, the maximum of reduced concentration percentages at downstream of obstacles zone relative to the condition with no-obstacle zone was about 11.2% and 8.3%, for wave modes 1 and 2, respectively. In addition, an increase in obstacles diameter decreased reduced concentration percentages at downstream of obstacles zone as compared to no-obstacle zone by about 8% for wave mode 1 and 2. Also, according findings, wave mode 1 has more effect to on decreasing suspended sediment transportation as compared to wave mode 2.

4. Conclusions

The results of this study can be summarized as below:

- Suspended sediment concentration at downstream of obstacles zone is higher than no-obstacle zone under normal flow conditions.
- Due to the formation of transverse waves, the suspended sediment concentration at downstream of obstacles zone was decreased as compared to no-obstacle zone and wave mode 1 is more effective on decreasing suspended sediment transportation than wave mode 2.
- An increase in the diameter of the obstacles increases the maximum values of the dimensionless displacement (A/H), whilst. A reduction was observed in reduced concentration percentages at downstream of obstacles zone as compared to no-obstacle zone for wave mode 1 and 2 was observed.

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