An Experimental Analysis of the Impact of the Transverse Distance of Cubic Obstacles on the Hydraulic Characteristics of Transverse Waves in Staggered Arrangements

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Abstract

Transverse waves are formed by obstacles such as vegetation, bridge pier and dock in the flow path. present study investigated the effect of transversal distance of cubic obstacles on the hydraulic characterization of transverse waves with four wave modes in resonance. The obstacles were arranged staggered at two transversal distances and a constant longitudinal distance. All experiments were performed in a flume with a length of 16 m, a width of 1.25 m, and a height of 0.6 m. The flow discharge was varied between 30 and 38 lit/s in the experiments. The results showed that flow regime was turbulent and sub-critical in experiments. In resonance, the Obstacle Reynolds Number and Froude Number were within the range of $2319<Re<5627$ and $0.055<Fr<0.210$ respectively. In resonance, relative amplitude of the wave increases by increasing the transversal distance of obstacles (decreasing the density of obstacles) and the highest relative amplitude of 33% was obtained for T/D=9.6, wave mode IV and Q=30 lit/s. With the increase in discharge, the relative amplitude of the wave in each transversal distance and all four wave modes decreased.

KEYWORDS

Transverse waves, Cubic obstacles, Transversal distance, Staggered arrangement, Strouhal number

Introduction

The construction of any obstacle to the water flow path disturbs the flow lines and contributes to the formation of swirling flows. This phenomenon, in turn, exerts two oscillating forces on the obstacle; one aligns with the water flow and another perpendicular to the flow. The water passing through the obstacles downstream creates a type of disturbance called vortex. With the reciprocation of oscillating forces and their collision with the channel wall, the water surface also tends to start rippling. In certain conditions, resonance is formed if the frequency of the vortex created by the obstacle is the same as the natural frequency of oscillation in the structure, leading to transverse waves with the maximum amplitude formed across the channel. Transverse waves are also very important in terms of issues such as the stability of hydraulic structures, lateral erosion, and deposition in the bed. Thus, identifying such waves can account for the occurrence of some phenomena. In their experimental study, Poustizadeh and Ghomeshi [1] investigated the effect of transverse waves on the concentration of suspended sediments downstream of obstacles with a staggered arrangement in a rectangular flume and concluded that in the absence of waves, suspended sediments are equally or more concentrated at the end of the channel with obstacles than the end of the obstacle-free channel, and transverse waves, especially wave mode I, reduce the suspended sediment transport in the obstacles and decrease the concentration of suspended sediments downstream of the obstacles. Strouhal Number is used in the analysis of phenomena under the influence of vortices and time-dependent phenomena. Indeed, the Strouhal Number is considered the size of the dimensionless frequency of the oscillations in this phenomenon. The present study aimed to investigate the characteristics of transverse waves in staggered arrangements with changes in the transverse distance of obstacles and the discharge rate using a physical model.

Methodology

All experiments were performed in a rectangular flume with a length of 16 m, a width of 1.25 m, a height of 0.6 m, and a slope of 0. The flume was equipped with a weir in to regulate the water flow depth for forming transverse waves in different modes. A digital electromagnetic flow meter (RPOMAG 53, precision: ±0.001 lit/s) installed at the flume inlet was used to measure the discharge. The experiments were performed at three discharges of 30, 34, and 38 lit/s. Wooden cubic obstacles (flow collision to the vertex) were used. The obstacles with square cross-sections with a side of 2.5 cm and a height of 40 cm were installed perpendicular to the flow direction. The obstacles were arranged staggered at transversal distances of 12 and 24 cm and constant longitudinal distance of 12 cm. A total of 24 experiments were performed. At the beginning of each experiment, the flow entered the flume by adjust the discharge. The weir was adjusted to the height that the water level reached the upper edge of the obstacles. No wave was formed in this case. The weir was gradually brought down so that the wave mode I started to oscillate with low amplitude. The velocity increased as the weir was pushed down gradually, and the formed wave appeared in a more clear shape, and its amplitude was gradually increased to maximize the oscillation amplitude of wave mode I. For each weir height along the obstacle placement area, the highest and lowest water levels during an oscillation on the flume wall were recorded to determine the wave amplitude and mean flow depth. As the weir height was further lowered and the flow velocity increased, the amplitude of wave mode I started to decrease. In other words, the wave amplitude started to decrease in the opposite direction as the weir height further decreased, and the wave mode I disappeared. All the above stages were repeated to form wave modes II, III and IV. The time for 15 oscillations was recorded using a chronometer to calculate the frequency of the vortex created by the obstacle.

Results and Discussion

From a physical perspective, in the flow of water passing through the piers, when the frequency caused by the vortex of the obstacle is equal to the natural frequency caused by the oscillation in the structure, resonance occurs and causes the oscillation of the water level with the maximum amplitude [2]. In this case, a correct number of nodes are placed in the width of the channel, and their number is the same as the wave mode. The flow regime in the experiments was turbulent and subcritical. The range of Obstacle Reynolds Number and Froude Number in resonance for different waves is presented in Table 1. The hydrodynamics of transverse waves suggest that they are formed in subcritical conditions, and transverse waves can only be analyzed in subcritical conditions. Furthermore, if a wave is formed in supercritical conditions, the effect of friction on the bed increases due to the low depth of the water flow. Thus, the transverse wave is not stable under these conditions and disappears quickly. In addition, Von Karman oscillating paths occur when the Obstacle Reynolds Number is within the two ranges of $40<Re<3\times10^5$ or $Re>3.5\times10^6$ [3]. In the present study, the Obstacle Reynolds Number in the resonance was in the range of $2319<Re<5627$, which indicates the existence of strong vortices behind each obstacle.

Table 1. Range of Obstacle Reynolds Number and Froude Number in resonance

n	Reynolds Number	Froude Number
1	2319 - 2566	0.055 - 0.062
2	3688 - 3989	0.110 - 0.123
3	4609 - 5142	0.156 - 0.192
4	5421 - 5627	0.186 - 0.210

To assess the effect of the transverse distance of cubic obstacles on the relative amplitude of the wave in the resonance, the graph for changes in the relative amplitude of the wave (*A/H*) with the changes in the dimensionless transverse distance (*T/D*) for each wave mode at different discharge rates is shown in Fig. 1. As can be seen, with an increase in the transverse distance of the obstacles, the relative amplitude of the wave increased for all waves. Thus, for each wave mode, the relative amplitude for *T/D*=9.6 is higher than *T/D*=4.8. Accordingly, the findings showed that the relative amplitude of transverse waves has an inverse relationship with the number of obstacles in each row and a direct relationship with their distance in each row. The highest relative amplitude of the wave in the experiments was equal to 33% for *T/D*=9.6, wave mode IV and discharge rate of 30 lit/s, and the lowest was equal to 10.8% for *T/D*=4.8, wave mode IV, and discharge rate of 38 lit/s. In addition, Purmohammadi et al. [4] reported that the maximum relative amplitude was equal to 61% for cylindrical obstacles formed in *T/D*=2.4, in-line arrangement, and at a width of 74 cm. as the *T/D* value increased from 4.8 to 9.6, the highest increase in the relative amplitude of the wave was equal to 30%, which corresponds to the discharge rate of 38 lit/s and the wave mode IV, and the lowest relative amplitude was equal to 2.7% that occurred at a discharge rate is 34 lit/s in wave mode III.

As displayed in Fig. 1, as the discharge rate increased from 30 to 38 lit/s, the relative amplitude of the wave decreased in both transverse distances and all four wave modes. For *T/D*=4.8, the highest reduction rate in the relative amplitude of the wave was equal to 26% as the discharge rate increased from 30 to 38 lit/s in wave mode IV, and the lowest decrease was equal to 3% as the discharge rate increased from 34 to 38 lit/s in wave mode I. In addition, for *T/D*=9.6, the highest reduction rate in the relative amplitude of the wave was equal to 11% as the discharge rate increased from 30 to 38 lit/s in wave mode IV, and the lowest decrease was equal to 1.6% as the discharge rate increased from 34 to 38 lit/s in wave mode I.

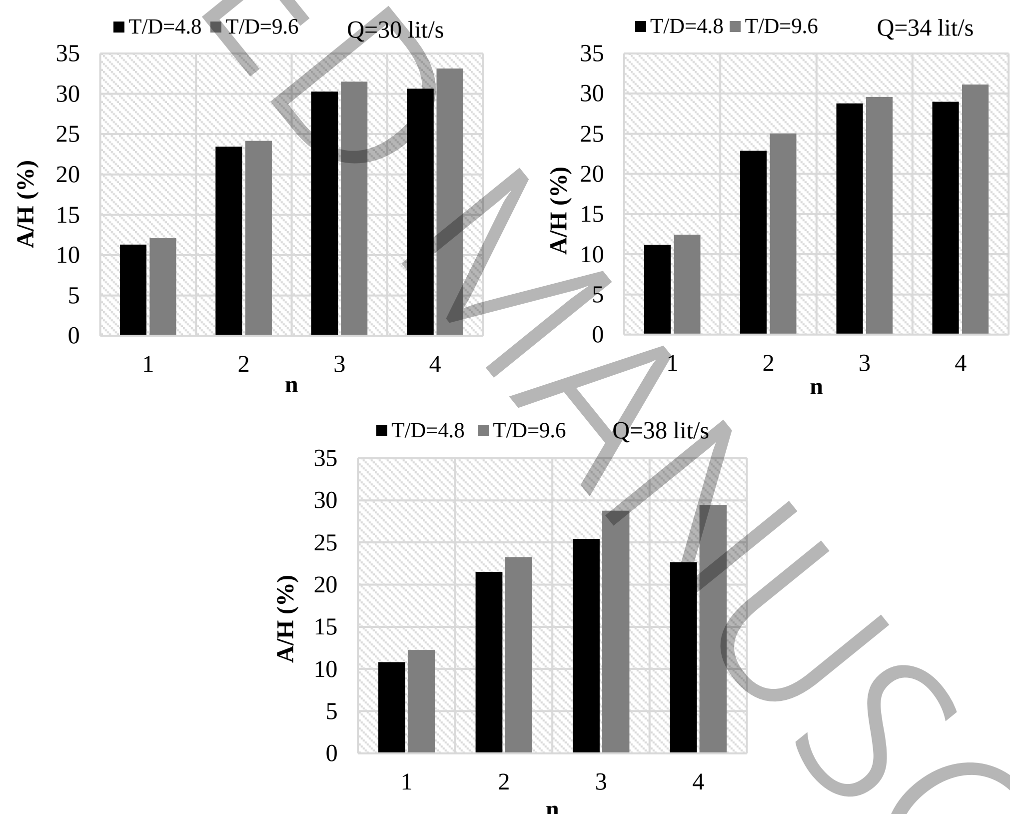

Fig. 1. Variations of relative amplitude of the wave (A/H) by changing the dimensionless transversal distance (T/D) in different discharges

Conclusion

The present study examined the impact of the transverse distance of cubic obstacles with staggered arrangements on the characteristics of transverse waves in a wide flume. The findings indicated that the flow regime in the experiments was turbulent and subcritical in the resonance, the Obstacle Reynolds Number and Froude Number were in the range of $2319<Re<5627$ and $0.055<Fr<0.210$, respectively. Furthermore, as the transverse distance of the obstacles increased, the relative amplitude of the wave increased. In other words, the relative amplitude of transverse waves has an inverse relationship with the number of obstacles in each row and a direct relationship with their distance in each row. The highest relative amplitude of the wave formed in the experiments was equal to 33% for *T/D*=9.6, wave mode IV, and a discharge rate of 30 lit/s. As the discharge rate increased from 30 to 38 lit/s, the relative amplitude of the wave in each transverse distance and all four wave modes also decreased.

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