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Turbulence characteristics of flows passing through a tetrahedron frame in a smooth open-channel

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ABSTRACT

The turbulence characteristics of flows passing through a tetrahedron frame were investigated by using a 2-dimensional fiber-optic laser Doppler velocimeter (2-D FLDV). Experiments for uniform flows with different bed slopes under both submerged and un-submerged conditions were carried out in a re-circulating flume with glass side walls. The experimental bed was a smooth fixed bed. It was observed that with the tetrahedron frame the mean longitudinal velocity decrease in the retardation zone. However, both the longitudinal and the vertical turbulence intensities are larger than those for the undisturbed approach flow. The tetrahedron frame may reduce the probability of sediment entrainment by retarding the flow and reducing the boundary shear stress. In addition, it may induce sediment deposition in a sediment laden flow by changing the flow direction and increasing the energy dissipation.

1. Introduction

Armoring countermeasures such as rock gabions and dumped riprap have been extensively used throughout the world for stabilizing channel beds, protecting river banks and minimizing scour at bridge foundations [1,2]. However, these countermeasures can enhance further local scour at the edge of the protection elements, often resulting in significant edge-induced failure, as shown in Fig. 1. As an alternative to armoring countermeasure, Chang [3] has reported that some flow-altering devices in the form of permeable structures, such as timber pile dike and steel jack, have been used in river engineering practice. Ghisalberti and Nepf [4] investigated aquatic flows over a submerged vegetation canopy, and found that the dominant mixing mechanism of the flow adjacent to a permeable medium is the vortex generated by the inflectional velocity profile. Permeable structures used in river engineering, like submerged vegetation, also permit through flow and cause velocity reduction, thereby minimizing scour and causing sediment deposition.

Interactions between permeable structures and fluid flows have been studied in different disciplines [5–8]. Leenders et al. [6] pointed out that shrubs had a significant effect in reducing flow velocities near the ground level, which implied that the bed shear stress could also be reduced. Recently, a type of permeable countermeasure, known as tetrahedron frames, has been used with reasonable success to prevent bank erosion in China [9]. Based on the field experiments, they found that the tetrahedron frames can retard local flow velocities and enhance sediment deposition and new land creation.

In addition, similar frame-type structures were developed to serve as submerged breakwaters in Japan [10]. Recently, Lu et al. [11] and Tang et al. [12], respectively, reported that tetrahedron frames can be successfully used as a scour countermeasure to protect grade-control structures (GCS) and reduce pier-scour depth. The laboratory results of the former showed that tetrahedron frames can be used to achieve an average scour depth reduction of about 83%. Fig. 2(a) contains one of their typical experimental results, showing a comparison of the scour depths downstream of a grade-control structure with and without tetrahedron frames under clear-water conditions. The result reveals that the tetrahedron frames can effectively reduce the scour depth downstream of a GCS. Fig. 2(b) shows the corresponding photograph of the experimental result (top view) after 2 h of clear-water scour. The photograph reveals how deposition has occurred downstream of the first scour hole with the placement of the tetrahedron frames.

Notwithstanding these reported successes in tetrahedron frame applications as an effective scour countermeasure, the flow mechanism involved has not been thoroughly investigated to-date. As a result, researchers and engineers are faced with the question on how interactions between the porous obstacles and turbulence flow field affect sediment transport, and finally arrest scouring

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Fig. 1. Edge failure at Lung-En Weir in Taiwan (2009).

and erosion. The present study aims to provide an improved understanding on the flow mechanism around a tetrahedron frame.

2. Experimental setup and procedure

The experiment was conducted in a re-circulating flume with glass bottom and side walls. It is 12.0 m long, 0.25 m wide and 0.5 m high, and consists of a slope-adjustable (0–2%) bed. In order to prevent impurities from flowing into the flume, a filter was installed at the settling tank. Moreover, a honeycomb was placed at the entrance of the flume to regulate the flow. A fully developed, uniform flow was established at the test section located at a distance 8.5 m downstream from the flume entrance.

Fig. 3(a) shows the experimental setup of this study. As shown in the figure, the tetrahedron frame is arranged with its vertex pointing downstream (→▷), which is the optimum orientation suggested by Zhou et al. [13]. Moreover, this orientation has been confirmed by the results of Lu et al. [14] based on the movable bed experiments. Fig. 3(b) shows a schematic diagram of the tetrahedron frame model adopted in this study. It comprises six identical rods, each with a square cross-section (3 × 3 mm), and length $L = 40$ mm. The length-to-width ratio (L/B) of the rod is 13.33, which is within the optimum range suggested by Xu and Zhang [15] for high flow retardation effect. The height, K_t of the tetrahedron frame used in this study is 37.6 mm.

Flow measurements were conducted by using a 2-dimensional fiber-optic laser Doppler velocimeter (2-D FLDV) along the centerline of the flume both upstream and downstream of the tetrahedron frame. The sampling frequency of the FLDV application was 100 Hz and the sampling duration was approximately 3 min for each measurement. The transverse and conjugate diameters of the measuring volume were 2.66 mm and 0.19 mm, respectively. A 3-dimensional traversing system was used to move the probe of the 2-D FLDV to the desired location. As shown in Fig. 3, a total of nine cross sections, including two upstream, one at the center and six downstream of the tetrahedron frame, were measured. For each location, about 18,000 instantaneous velocities for both the longitudinal and vertical directions were recorded. The flow depth was measured with an ultrasonic water gauge.

The experiments were conducted with two different longitudinal bed slopes of 0.1% and 1%, which are typical river bed slopes in Taiwan. They are, respectively, called mild slope and steep slope in this study. The flows are subcritical ($0.48 \leqslant Fr \leqslant 0.77$, where Fr = flow Froude number) for the mild slope, and supercritical for the steep slope ($1.69 \leqslant Fr \leqslant 2.15$). Moreover, the extent of submergence of the tetrahedron frame, i.e., whether the frame is fully or partially submerged, also constitutes another variable. Hence two different frame submergences are tested in this study. Table 1

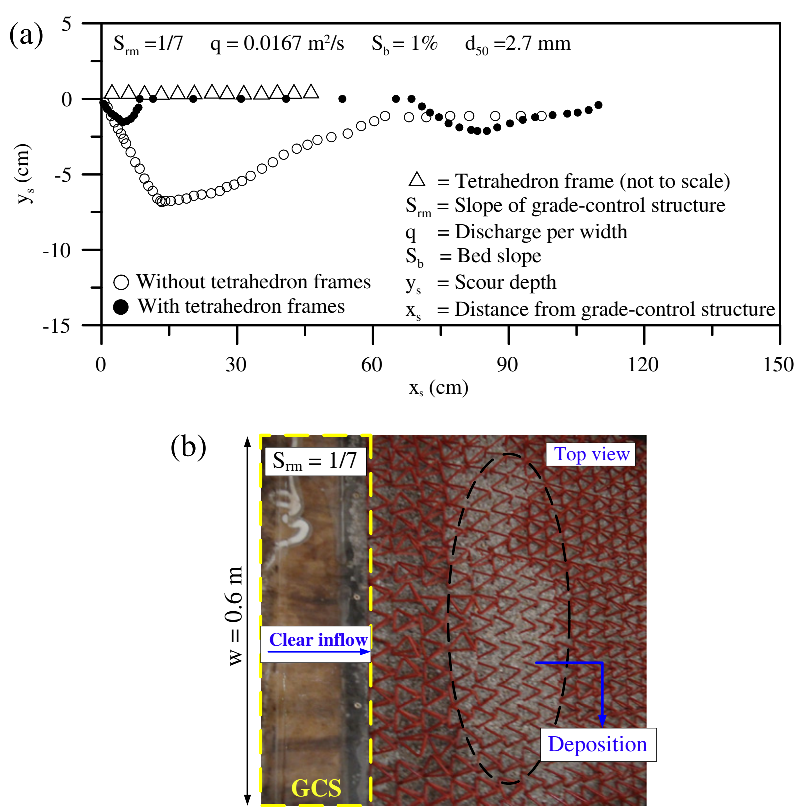

Fig. 2. (a) Scour depth downstream of a grade-control structure with and without tetrahedron frame protection [11]; (b) photograph of the experimental result with tetrahedron frames.