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Forces on surface-piercing vertical circular cylinder groups on flooding staircase

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ABSTRACT

Flooding into underground spaces has become a common threat and caused significant damages and casualties in the past decades. To improve the understanding of people walking through the flooding staircase, a 1:2-scale physical model of a staircase with rest platform was assembled. An instrument was developed to measure the hydrodynamic forces acting on individual vertical circular cylinders, as well as cylinder groups arranged side-by-side, in tandem and staggered cylinder arrays on the flooding staircase. The results show that the horizontal hydrodynamic force on a cylinder increases rapidly with the increasing of the inundated depth on the entrance of the staircase. With a side-by-side tight cylinder array, the force on the central cylinder is always larger than an isolated one. The force on the downstream cylinder in tandem cylinder array is always smaller. However, the drag coefficients of both cases are much larger than the corresponding ones in a horizontal bed channel. For the case of staggered cylinder array, the force on the downstream cylinder varies with the change of the transverse spacing and the longitudinal distance between cylinders.

1. Introduction

Urban flooding during last two decades, owing to the rapid urbanization and the climate change, has caused widespread devastation, economic damages and even the loss of human lives. Some works have been done to try to better understand urban flooding and to help evacuating the people trapped in the flooding water. Most of these works were focused on the human safety in the floodways that happens on the flat ground (Foster and Cox, 1973; Keller and Mitsch, 1992; Takahashi et al., 1992; Shand et al., 2010) or the ground with small bed slopes (Abt et al., 1989; Jonkman and Penning-Rowsell, 2008).

With the rapid expansion of underground spaces, underground flooding has become a new challenge for the urban flooding management. Some flooding events intruding into underground spaces were reported (CCIDUS, 2002; Ishigaki et al., 2008; Higo et al., 2011; Teng et al., 2006; Toda, 2007). More attentions have also been paid on the safety evacuation of trapped people in the flooding underground space (Inoue et al., 2003; Ishigaki et al., 2005, 2008; Kotani et al., 2012; Oertel and Schlenkhoff, 2008; Shao, 2010).

To ensure the safety of people in the flooding water, two safe evacuation indicators have been proposed for the trapped people walking through the flooding water. The first indicator is the one for people walking through the flooding staircase with no rest platform, v^2y (where v is the water velocity on the step and y is the water depth on step) (Inoue et al., 2003; Ishigaki et al., 2005). There will be a danger for evacuation once v^2y exceeds 1.5 m^3/s^2 based on the investigation of people walking on a 1:3-scale

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staircase model (Inoue et al., 2003). However, Ishigaki et al. (2005) concluded that v^2y should not exceed 1.2 m^3/s^2 by testing the stability of people walking on a flooding real-scale staircase model, which could be more suitable for human evacuation behavior because it was obtained in the real-scale staircase and safer for the evacuators. The second indicator is the one for people walking in the flooding flow in a flat flume (RESCDAM, 2000), *SN* ($SN=vy$). Generally, people can withstand an *SN* of 0.64–1.26 m^2/s (RESCDAM, 2000).

Therefore, the most important parameters for evaluating safety in the flooding water are water velocity v and water depth y as indicated in the above-mentioned two indicators. On the other hand, the resultant force on the human body by the flooding flow is the main factor affecting the human safety through the flooding staircase, and is much easier to be measured in the experiments. Ishigaki et al. (2005) had ever tested the forces on a leg model with different kinds of footwears settled at different steps of a real-size staircase model and obtained a critical force, 42.4 N, for people safety evacuation. The force acting on the human body is similar to the parameters v^2y proposed by Inoue et al. (2003) and Ishigaki et al. (2005) because it is directly related to $\rho v^2 y$ and the diameter of the cylinder. Therefore, the force acting on the cylinder, instead of the indicator of v^2y, has been chosen as the indicator in this paper to judge the safety of evacuators.

When two or more people walk through the flooding staircase at the same time, the force acting on the human body varies due to the flow disturbance created by other people. Besides, the staircases leading to the underground space usually have one or more rest platform(s) that separate staircase into several segments (BUEDRI, 2003; MOHURD, 2005). As a consequence, it may exert considerable extra force on the evacuators walking through the flooding staircase and threaten the safety of the evacuators.

In the laboratory, the force on a human leg can be simplified as the force on a surface-piercing cylinder in the open channel flow or in the flooding flow on staircase. The former has been broadly investigated and discussed (Akilli and Rockwell, 2002; Chaplin and Teigen, 2003; Noack et al., 1993; Ozgoren, 2006; Sadeque et al., 2008; Shao et al., 2013). However, few works on the force on the protruding cylinder located at the flooding staircase can be found (e.g. Inoue et al., 2003; Ishigaki et al., 2005). Therefore, this paper is to present an experimental study regarding the hydrodynamic force on protruding circular cylinders arranged on the flooding staircase. The hydrodynamic forces on an isolated circular cylinder located at different steps of the staircase were first investigated and the effects of the rest platform were evaluated. Then, the forces on several cylinder groups arranged in four different arrays were observed and discussed. Finally, the drag coefficients were obtained and compared with those in a flume with horizontal bed reported in the literatures.

2. Experimental set-up

2.1. Experiment unit

The experimental unit, a 1:2-scale model of a prototype entrance/exit of subway station, was assembled at Zhejiang University with 20 m long, 1.2 m wide and 3.5 m high as shown in Fig. 1. The experiments in this study were conducted mainly on the part of 0.8 m wide staircase. It includes 26 identical steps ($s=0.08$ m, $l=0.14$ m, where s and l are the height and length of the steps, respectively) and one rest platforms. The staircase was separated by the rest platform into two segments, each segment is composed of 13 identical steps, and has a slope of 29.7° based on the pseudo-bottom connected by the step edges. The steps, together with the rest platforms, are numbered from No. 1 to No. 28 sequentially from top to bottom in the flow direction as shown in Fig. 1.

2.2. Force Measurement Instrument

The forces exerted on the legs of the trapped people walking through the flooding steps include hydrodynamic force in the flow direction, buoyancy force in the positive z-direction and the weight of people in the negative z-direction

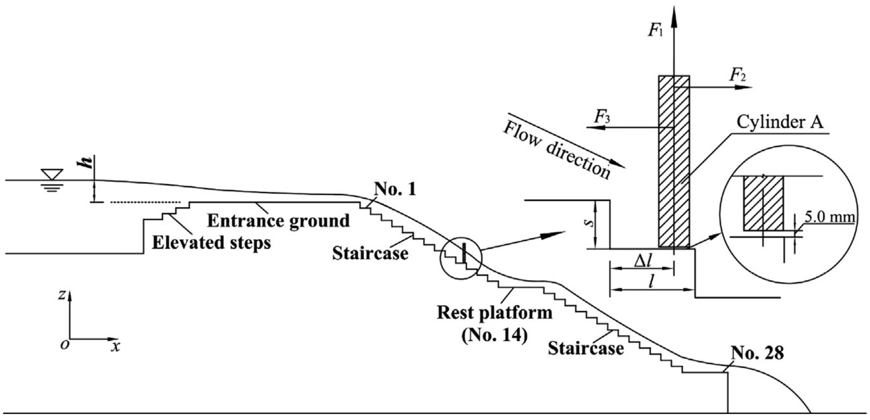

Fig. 1. Experimental setup of the staircase model and the arrangement of a single cylinder on the step.