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Analyses of the stability of submerged ice blocks*

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Abstract: This paper proposes the critical conditions for a submerged ice block beneath an intact ice cover to become unstable, as a fundamental component of any numerical model to successfully predict the ice jam formation or the ice jam release events. The flume model experimental and numerical simulation methods are both applied to analyze the stability of submerged ice blocks. The flume model experiment is first conducted, and the experimental results indicate that the influencing factors of the stability of a submerged ice block include the relative length, the relative water depth and the relative width. It was shown that the effect of the relative width on the stability of submerged ice blocks was not well studied. Based on the experimental results, the k - ε turbulence model is applied to establish a 3-D numerical model for studying the pressure distribution beneath submerged ice blocks. The effects of the relative width on the Venturi pressure and the leading edge pressure are evaluated. Finally, according to the force balance equation and the moment balance equation, this paper proposes a computational formula for the sliding and underturning critical conditions of submerged ice blocks, and the results are in good agreement with the experimental results.

Key words: Submerged ice, river ice, ice block stability

Introduction

The ice jams and the ice dams in rivers will cause a significant rise of the water levels. Under extreme conditions, the ice flooding may occur during winter or early spring. The breakup of ice on rivers has numerous socio-economical and ecological impacts[1-3]. The transport and the accumulation of ice are complicated problems of river ice hydraulics because of the complex fluid dynamics surrounding individual ice floes[4-8]. The critical condition is a fundamental component of any numerical model to successfully predict the river ice processes. In the practical context of the transport and the accumulation of ice, it is a primary issue whether the floating ice floes approaching an ice cover will become a part of the cover or whether they will be entrained in the flow, and whether the entrained ice floes will be transported or deposited beneath the ice cover, to form an ice jam. This paper focuses on the stability of submerged ice blocks, which is important for preventing ice damage.

A variety of methods were developed to monitor the surface ice conditions in rivers. For example, the satellite imagery was utilized recently to determine the velocity of ice floes[9,10]. Some studies examined the stability of floating ice blocks[11-13]. However, because of the inherent theoretical difficulties and the safety considerations when trying to measure the dynamic ice processes in the field, much of the knowledge of these processes is qualitative. It is particularly difficult to study ice blocks transported beneath an ice cover. Therefore, most investigations of this phenomenon focused on the critical condition at which the floating ice blocks at the leading edges of intact ice covers were submerged[14-16]. Jasek[17] noted that when large ice floes were transported downstream under an ice jam past its toe, these floes would likely be propelled upward, impacting the underside of the intact solid ice cover.

With recent advances in numerical and experimental technologies to allow for better visualization and determination, one may explore the mechanics of the problem in more detail. This paper proposes the

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critical conditions for a submerged ice block beneath an intact ice cover to become unstable. A flume model experiment is first conducted to determine the influencing factors for the stability of the submerged ice blocks. Based on the experimental results, a 3-D numerical model is established for studying the pressure distribution beneath submerged ice blocks. The effects of the relative width b/B (block width/flume width) on the Venturi pressure and the leading edge pressure are discussed. Finally, the computational formulas for the sliding and underturning critical conditions of the submerged ice blocks are proposed and the results are in good agreement with the experimental results.

1. Methods

In this paper, the flume model experiment and numerical simulation methods are both applied to analyze the stability of submerged ice blocks. The flume model experiment is first conducted to analyze the influencing factors for the stability of submerged ice blocks. Based on the experimental results, the k - ε turbulence model is applied to establish the 3-D numerical model for studying the pressure distribution beneath submerged ice blocks. According to the force and moment balance equations, a computational formula for the stability of submerged ice blocks is proposed.

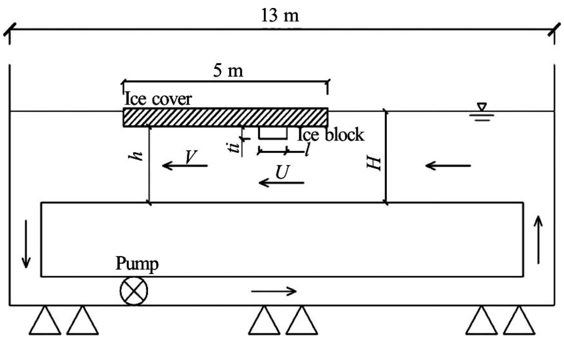

Fig.1(a) Experimental setup

Fig.1(b) (Color online) Functional flume

1.1 *Flume model experiment*

The experiment is performed in the 13 m long recirculating flume located in the State Key Laboratory of Hydraulic Engineering Simulation and Safety at the University of Tianjin in China. This rectangular flume, as shown in Fig.1, is 0.47 m high and 0.6 m in width. The pump is controlled by a variable frequency drive with a maximum velocity of 5.0 m/s.

Table 1 Summary of the experimental conditions

Run number	h /m	Submerged ice block t_i /m	l /m	b /m	Density/ $m^3 \cdot kg^{-1}$
1	0.200	0.02	0.06	0.04	0.913
2	0.251				
3	0.300				
4	0.350				
5	0.200	0.02	0.06	0.06	0.914
6	0.251				
7	0.300				
8	0.350				
9	0.200	0.02	0.08	0.04	0.913
10	0.251				
11	0.300				
12	0.350				
13	0.200	0.01	0.03	0.02	0.921
14	0.251				
15	0.300				
16	0.350				
17	0.030	0.01	0.02	0.02	0.921
18		0.01	0.03	0.01	0.922
19		0.01	0.03	0.02	0.921
20		0.01	0.03	0.03	0.922
21		0.01	0.04	0.02	0.923
22		0.01	0.06	0.03	0.920
23		0.01	0.06	0.04	0.921
24		1.00	0.08	0.04	0.921
25		0.02	0.02	0.02	0.912
26		0.02	0.04	0.04	0.913
27		0.02	0.06	0.03	0.912
28		0.02	0.06	0.04	0.913
29		0.02	0.06	0.05	0.914
30		0.02	0.06	0.06	0.914
31		0.02	0.08	0.04	0.913
32		0.02	0.08	0.06	0.913
33		0.03	0.06	0.03	0.926
34		0.03	0.06	0.04	0.927
35		0.03	0.08	0.04	0.926
36		0.03	0.08	0.06	0.927
37		0.03	0.09	0.08	0.928
38		0.03	15.00	0.10	0.926

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