POLISH MARITIME RESEARCH 1 (105) 2020 Vol. 27; pp. 53-59
10.2478/pomr-2020-0006

EXPERIMENTAL STUDY OF DAM-BREAK-LIKE TSUNAMI BORE IMPACT MECHANISM ON A CONTAINER MODEL

Cheng Chen[1,2]
Jun Chen[3]
Peng Lin[1]
Chiwei Chen[1]
Haozhe Chen[2]
[1] College of Civil Engineering, Fuzhou University, Fuzhou, China
[2] Key Laboratory of Coastal Disaster and Defence of Ministry of Education, Hohai University, Nanjing, China
[3] The Pearl River Hydraulic Research Institute, Guangzhou, China

ABSTRACT

Tsunami disasters have frequently occurred in recent years. More and more researchers are focusing on this topic. To investi-gate the tsunami bore impact mechanism on a container model, a multi-functional slope-changing tsunami flume is built in this study. To simulate a tsunami bore, a dam-break wave was generated by a free-falling gate in a reservoir. A needle water level gauge and a high-speed camera were used to measure the tsunami wave heights and velocities for different storage water levels in the test flume, and the corresponding Froude numbers of tsunami waves were also calculated. The factors af-fecting the movement distance of the tsunami wave impacting the container model are explored in this experiment, and the results show that the movement distance is positively correlated with the storage water level, and negatively correlated with the container density and the coast slope.

Keywords: tsunami bore; dam break; container; Froude number; movement distance; coast slope

INTRODUCTION

Tsunami disasters have frequently occurred in recent years, and tsunami waves are characterised by fast propagation velocity [1], wide influencing areas and large released energy [2, 3]. It is difficult to generate large-scale broken-state tsunami waves, so dam-break waves have been used by international scholars to simulate tsunami waves after breakage and good simulation results have been obtained. Chanson found that tsunami waves propagate ashore in the form of breaking waves [4]. By observing and analysing the Indian Ocean tsunami, the results show that the analytical solution of dam-break waves is in good agreement with tsunami waves. Imamura et al. found that the process of coastal propagation such as tsunamis and tidal bores is consistent with dam-break flow in the physical mechanism [5]. Therefore, under laboratory conditions, this method of tsunami wave generation has been adopted by many researchers.

A tsunami wave is a highly destructive natural disaster. Saatcioglu et al. [6] found that great damage will be caused to structures during a tsunami. When the tsunami is near the shore, the damage may take the form of impacting and carrying away heavy objects. Shafiei et al. [7] found that tsunamis usually produce breaking waves near the shore, and then, in the form of high-speed water, impact and carry away heavy objects such as box structures, floating driftwood, vehicles and other. Numerous scholars have done research on tsunami waves impacting coastal structures. Robertson et al. [8] set up a test of tsunami waves acting on a composite wall/building system, finding that even in the same test settings, the initial impact pressure changes greatly, which is because the tsunami waves have been completely broken, with strong turbulent characteristics, while this instability is more obvious when tsunami waves propagate over the water. Chock et al. [9] also studied the mechanism of the tsunami wave force on a composite plate/wall system, with the plate height, wave height and hydrostatic depth as variables, and also put forward the design envelope on the basis of the pressure coefficient of the uplift forces.

Saatcioglu et al. [6] studied the load of a tsunami wave impacting a box structure. While the relationship between the tsunami wave intensity and the box structure changed, the change in the relationship between the flume slope and the box structure was not discussed. In this paper, the motion characteristics of a container model under the impact of dam-break waves made in the laboratory to simulate tsunami waves will be observed. Finally, the factors affecting the impact and movement mechanism of tsunami waves on the container model will be revealed.

EXPERIMENTAL FLUME AND MODEL SETTING

FLUME SYSTEM OF TSUNAMI WAVE

This experiment was carried out in a multi-functional slope-changing flume in the open channel of the Water Conservancy Hall of Fuzhou University. The flume system structure of the tsunami wave is shown in Fig. 1. The dimensions of the experimental flume are 4.40 m in length, 0.30 m in width and 0.30 m in height, with the maximum working water level of 0.265 m. The flume is made of plexiglass, and the bottom and wall of the flume are smooth to reduce the influence of the boundary effect. The flume is divided into a storage section and test section, and a free-falling sluice is set between the two, with a thickness of about 20 mm. The upstream storage water level can be controlled by a gate switch. When the gate is laid down freely, the water in the storage tank collapses and is released, forming the broken-state tsunami wave similar to a dam-break in the downstream flume, and then flows out from the end of the flume after passing through the downstream dry bed, which is a self-circulating device as a whole.

MODEL STRUCTURE SETTING

The container model is 0.13 m in length, 0.037 m in width and 0.04 m in height, and filling material can be added inside the structure to change the density of the model. In reality, containers, vehicles, houses and other box structures are located on the dry bed of the coast, so the dry bed environment in the downstream of the flume is maintained in the experiment. The frictional coefficient between the container and its bottom is around 0.1–0.3. In order to measure the factors influencing the change in the container model caused by the impact and carrying of the tsunami wave, different test conditions are set up: (1) The initial locations of the containers are 0.5 m and 1.0 m behind the gate of the storage tank; (2) the storage water level is respectively taken as 0.13 m, 0.14 m, 0.15 m, 0.16 m and 0.17 m, thus generating tsunami waves of different intensity; (3) the container density ranges from 1,150 to 1,550 kg/m^3, with intervals of 50 kg/m^3, so as to explore the influence of the container density on the change; (4) the bed slope is taken as flat (0°) and climbing (1°), in order to explore the sensitivity of the container change to the bank slope. Repeatability tests are conducted at least five times for each group of experimental conditions, and the final data are averaged.

MEASUREMENT OF KEY FACTORS IN EXPERIMENT

During the experiment, the physical quantities that need to be measured include the tsunami wave height, velocity, movement distance of the container model, etc. The highest tsunami wave height of 0.40 m can be measured by a needle water level gauge in the multi-functional slope-changing

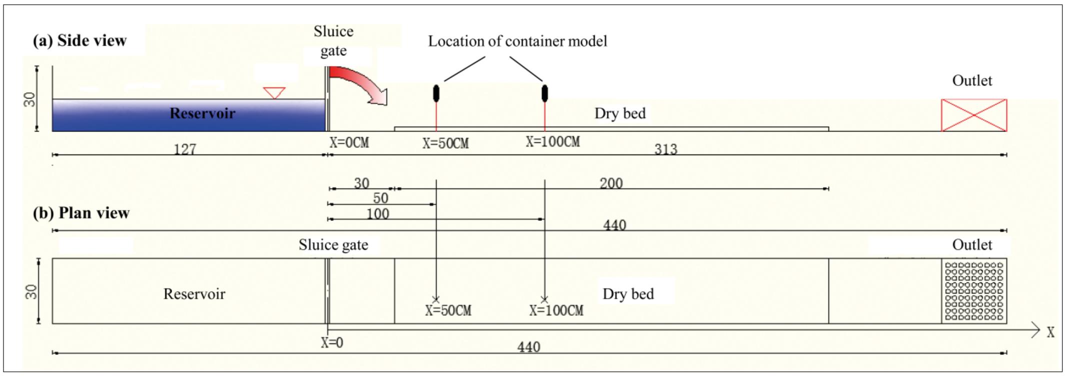

Fig. 1. Schematic of tsunami wave flume system

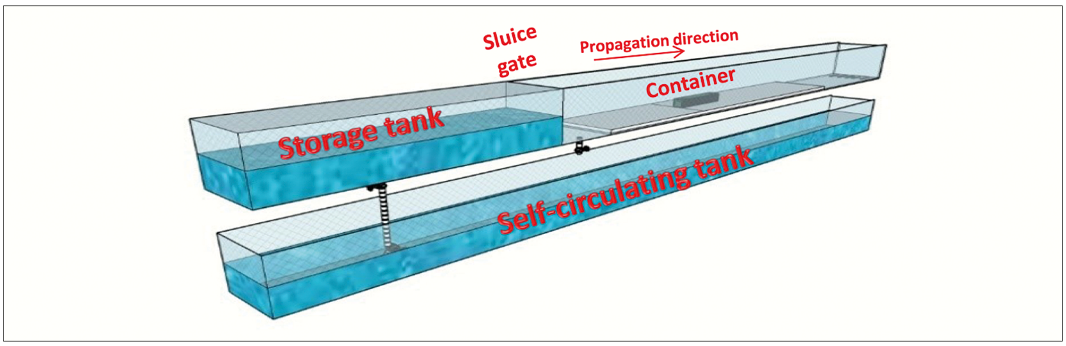

Fig. 2 Stereogram of the test flume and set-up of the model

flume. The tsunami wave heights under different conditions can be measured by setting the needle water level gauge in the dry bed areas and cooperating with a high-speed camera for confirmation. The time interval between adjacent needle water level gauges of the tsunami waves is recorded by the high-speed camera so as to calculate the movement velocity of the tsunami waves. The movement distance of the container can be measured after draining the residual water in the test area at the end of each impact process.

EXPERIMENTAL RESULTS AND DISCUSSION

WAVE HEIGHT AND VELOCITY

Through the different combinations of the storage water level and flume gradient, eight groups of tsunami wave current conditions with different states were produced in this experiment. With the increase of the tsunami wave height in the flume (0.033 m to 0.048 m), the tsunami wave velocity also increases (0.53 m/s to 1.00 m/s). The tsunami wave's Froude number characterises the motion characteristics of the wave, and its calculation formula is as follows:

$$Fr_b = \frac{u_b}{\sqrt{hg}} \tag{1}$$

where Fr_b is the tsunami wave Froude number, u_b is the tsunami wave velocity, h is the tsunami wave height and g is gravity acceleration.

In reality, the tsunami wave's Froude number depends on the conditions near that point, such as the bed slope, surrounding terrain or obstacles. The Froude number in this experiment is taken from 1 m away from the gate. The wave heights and velocities with different intensities produced in this experiment are shown in Table 1, and the numerical range of Froude numbers in the test condition is calculated to be between 0.93 and 1.52. It can be seen from the table that when the storage water level is low (0.13–0.15 m), the Froude number is close, slightly greater than 1, which belongs to the category of torrent. When the storage water level is high (0.16–0.17 m), the Froude number increases suddenly and jumps to more than 1.20, which indicates that the flow pattern of the tsunami wave is more acute at a high storage water level, and the inertia force action is obviously greater than the action of gravity. In addition, it can be seen from the table that at the same storage water level, the Froude numbers of the tsunami wave in a climbing state are all less than the values in the flat state.

VARIATION IN WATER FLOW PATTERN AT THE GATE

For the experiment on the dam-break physical model, the gate is a very important and special position, which controls the upstream initial water level and bears the water pressure imposed by the water tank, so the variation in water level here often reveals the hydrodynamic characteristics of tsunami waves.

The water flow patterns of tsunami generation and propagation are different, so it is necessary to observe the water flow pattern at the gate (Fig. 3). After the dam-break, due to a large number of water dislocations, water flows rapidly from upstream to downstream, forming the tsunami waves, which then move rapidly downstream due to the effect of gravity and inertia. In the process of tsunami wave generation at the gate, the upstream initial water levels in the three groups of experiments are 0.13 m, 0.15 m and 0.17 m, respectively, and the variation in water level at the gate at the moment of dam-break can be obtained by using the image information. The higher the upstream water level, the faster the dam breaks. By comparing the results of theoretical solutions, it can be concluded that the water level at the gate satisfies three changing processes: a rapid descent stage, a relatively stable stage and a slow descent stage.

Rapid descent stage (Fig. 3(a)): Once the gate falls down at the bottom of the flume representing a dam-break, a water level difference of about 30 mm near the gate causes strong turbulence.

Tab. 1. Moving directions of tropical cyclones in Guangdong coastal areas

Bore strength case	Bottom bed slope	Storage water level (m)	Wave height (m)	Wave velocity (m/s)	Froude number
1	Flat slope	0.13	0.035	0.59	1.01
2	Flat slope	0.14	0.037	0.63	1.05
3	Flat slope	0.15	0.041	0.67	1.06
4	Flat slope	0.16	0.042	0.77	1.20
5	Flat slope	0.17	0.044	1.00	1.52
6	Climbing slope 1°	0.13	0.033	0.53	0.93
7	Climbing slope 1°	0.15	0.040	0.63	1.01
8	Climbing slope 1°	0.17	0.048	0.83	1.21

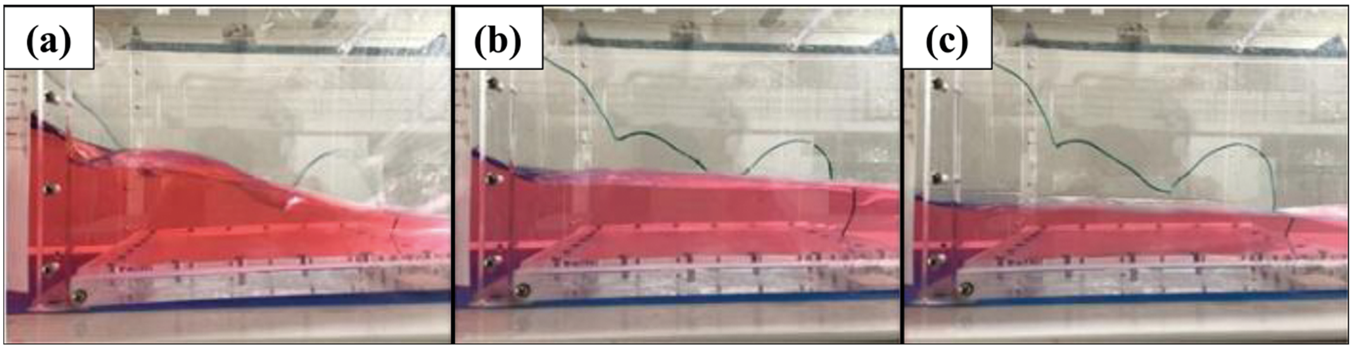

Fig. 3. Variation in water flow at the gate

Relatively stable stage (Fig. 3(b)): The dam-break flow in the flume is concentrated in the middle and forms an arc-shaped flow pattern.

Slow descent stage (Fig. 3(c)): The higher the upstream initial water level and the longer the duration, the smaller the impact of the water flow in this stage on the downstream structure. Due to the limited length of the flume, the reflected wave will soon return to the gate during the slow descent stage of the water level at the gate, and the water level difference caused by the gate factor will gradually disappear. At this time, the dam-break wave will not have the effect of carrying the container model.

FLOW PATTERN OF TSUNAMI WAVE IMPACTING CONTAINER MODEL

The process of the tsunami wave impacting and carrying the container model is characterised by short time, high intensity and fast change of the flow pattern. Through the high-speed camera observation, it can be divided into the following five typical processes:

Impact stage of wave front (Fig. 4(b)): The wave foot of the tsunami waves first touched the lower part of the container model, but at this moment the wave did not impact the whole container model, so the impact area was limited. Under this condition, the container model was still stationary because it was impacted by the tsunami wave foot, which was not enough to counteract the weight of the container model and the ground friction.

Splashing stage of wave front (Fig. 4(c)): After the tsunami was hindered by the container model, the water flow along the original central axis of the flume changed its direction of travel and splashed upwards to form a water wall, which reached two to three times the height of the container model. In the process of water flow movement, the high-jumping water flow was mixed with a large amount of air. The flow on both sides of the flume did not change the direction of travel, but continued to move forward. Under this condition, the container model, affected by the impact of the tsunami wave, its self-weight and the friction between the container model and the base plate, may or may not move, depending on the density of the container model, the initial section area and other factors.

Rising water level stage (Fig. 4(d)): In this stage, the splashing of the water wall along the wave front fell down to the area behind the container model, and the water flow on both sides of the model also reached behind the model. The main body of the tsunami wave submerged the container model and began to carry the model away. At this time, the water level in front of the container model rose rapidly, forming a difference with the water level behind the model. Under this condition, the container model was subjected to the impact force of the tsunami current and the residual water pressure in the front and rear of the model, while the above resultant force was greater than the ground friction force. In addition, because the container model was submerged in water, the existence of buoyancy reduced the friction between the model and the base plate, which made the model most prone to accelerated movement.

Quasi-constant stage (Fig. 4(e)): The water level in front of the container model has gradually risen to a stable value, and the water level difference between the front and rear of the model has gradually decreased. The large-scale white hat phenomenon disappeared, and there was only a small-scale white hat phenomenon behind the container model caused by falling water. The flow pattern tended to be stable, and the container model continued to move in the direction of the water flow. The wave height and velocity decreased, but this stage lasted the longest. Under this condition, the container model was mainly affected by the impact force and buoyancy of the water flow, and the change speed of the model gradually became the tsunami velocity. After that, the water level dropped slightly and the buoyancy decreased slightly, which led to the increase of ground friction, so the moving speed of the container model finally decreased.

Water recession stage (Fig. 4(f)): This stage marks the end of the tsunami. Due to the closure of the gate and the drainage facilities installed downstream of the flume, the water level in the flume began to decline, while the tsunami gradually weakened and finally completely receded. Under this condition, the carrying capacity of the tsunami water was gradually weakened, and the weight of the container model and the ground friction were gradually restored to the dominant position. Finally, the carrying capacity was less than the maximum static friction, and the container model slowed down gradually until it stopped. It can be concluded that the movement distance of the container model can be used to roughly retrieve the intensity and duration of the tsunami waves.

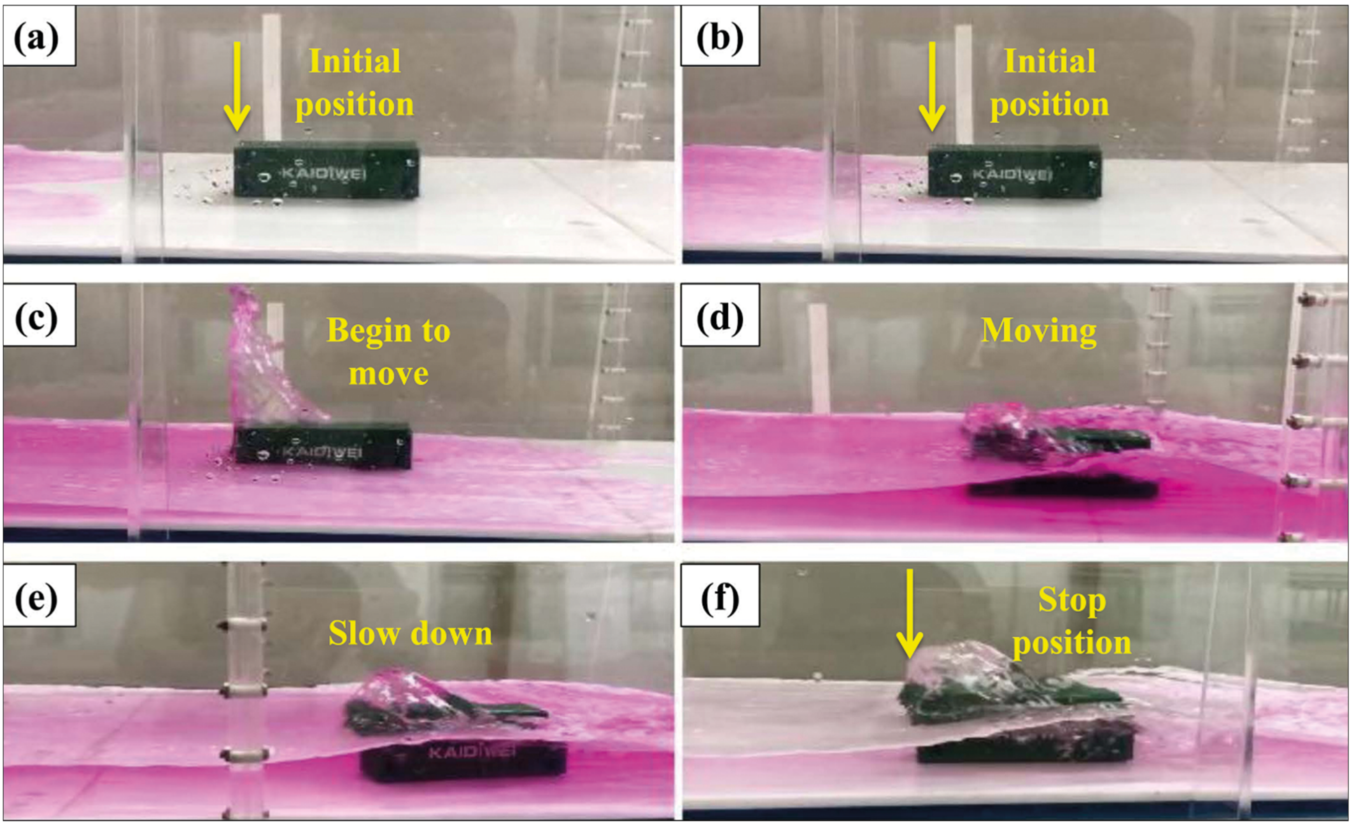

Fig. 4. Process of tsunami waves impacting container model

EXPLORATION ON INFLUENCING FACTORS OF CONTAINER MODEL MOVEMENT

This experiment is to explore the factors affecting the change of the impact of the tsunami wave on the container model, including the storage water level (tsunami wave intensity), container density and bed slope.

(1) Storage water level

Fig. 5 shows the movement distance of the container model on a flat bed (Fig. 5(a) and Fig. 5(b)) and a climbing slope (Fig. 5(c)), in which Fig. 5(a) shows the case when the initial position of the container is 0.5 m behind the gate, and Fig. 5(b) and Fig. 5(c) show the case when the initial position of the container is 1.0 m behind the gate. When the movement distance of the container exceeds the length of the test section in the flume (in Fig. 5(a) 1.75 m, in Fig. 5(b) and Fig. 5(c) 1.25 m), the measured data only take the range value. By comparing Fig. 5(a) with Fig. 5(b), it can be concluded that the farther the initial position is from the gate, the larger the migration distance is, which is because the tsunami wave grows along the way after being generated behind the gate, and also because the tsunami wave gathers in the process of coastal propagation.

It can be seen from Fig. 5 that the movement distance of the container model is greatly affected by the storage water level (tsunami wave intensity), and there is a linear positive correlation between the storage water level and the movement distance on both the flat bed and the climbing slope. Taking the container density of 1400 kg/m^3 in Fig. 5(a) as an example,

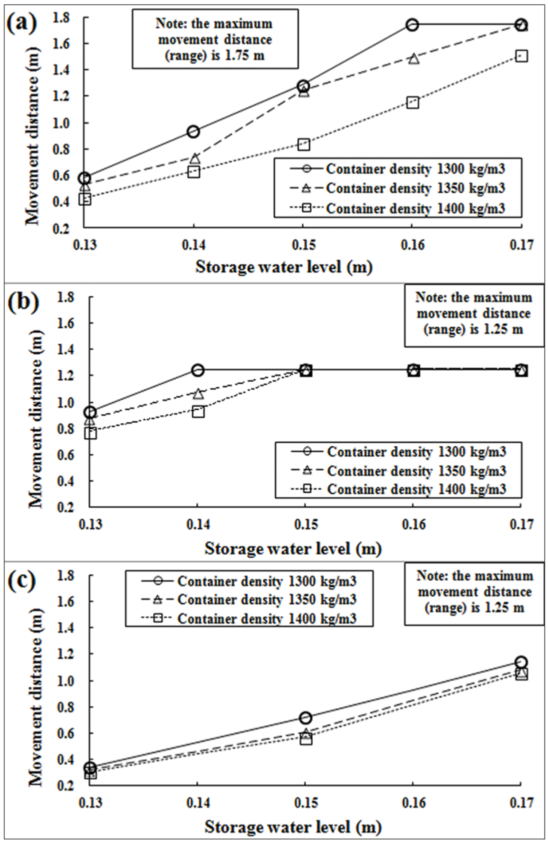

Fig. 5. Influence of storage water level on movement distance: (a) for initial container position 0.5 m behind gate, and for flat bed; (b) for initial container position 1.0 m behind gate, and for flat bed; (c) for initial container position 1.0 m behind gate, and for climbing slope

when the storage water level increases from 0.13 m to 0.17 m, the container movement distance increases approximately linearly from 0.43 m to 1.51 m. The origin of the linear influence of the tsunami wave height on the container movement distance is as shown in Eq. (1); when the Froude number Fr_b does not change much, the tsunami wave height (h) is approximately proportional to the tsunami wave energy ($1/2mu^2_b$), with the result that the container movement distance is also proportional.

It should be noted in Fig. 5(b) that, after the storage water level of 0.15 m, the movement distance does not change because of the limitation of the flume bed length. To be more specific, the total length of the flume bed is 2.25 m, and the initial position of 1.0 m behind the gate results in a maximum movement distance of 1.25 m.

(2) Container density

The container density is also the influencing factor of movement. At the same storage water level, the larger the container density, the smaller the movement distance.

Fig. 6 shows the movement distance of the container model on the flat bed (Fig. 6(a)) and on the climbing slope of 1° (Fig. 6(b)), and the initial state of the container is taken from 1 m behind the sluice. It should be noted in Fig. 6(a) that the maximum movement distance is 1.25 m because of the limitation of the flume bed length, as detailed above.

Taking Fig. 6(b) as an example, it shows the movement of the container with different densities in the climbing state. It can be seen that the data have a certain randomness and discreteness, but the overall trend shows that the container density has a negative correlation with the movement distance. When the three storage water levels impact the container, their movement distances all decrease with the increase of container density.

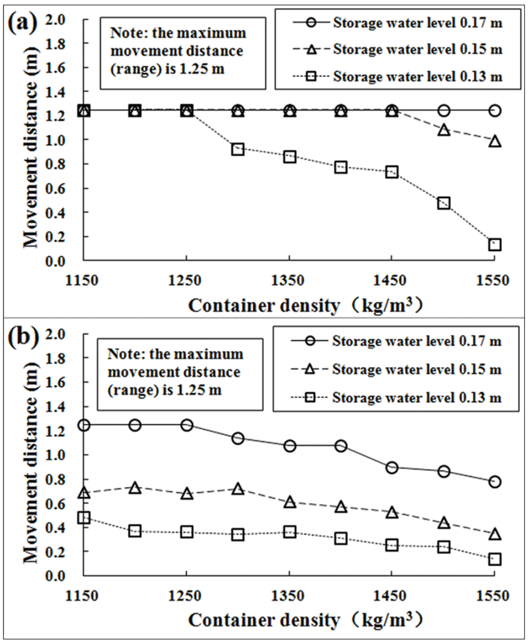

Fig. 6. Influence of container density on movement distance: (a) for initial container position 1.0 m behind gate, and for flat bed; (b) for initial container position 1.0 m behind gate, and for climbing slope

(3) Bed slope

Fig. 7 compares the movements of the container on the flat bed and climbing slope (1°) (taking the storage level of 0.13 m as an example). The results show that, on the flat bed, the increase of container density can significantly reduce the movement distance. However, on the climbing slope, the increase of container density only slightly reduces the movement distance. On the other hand, the smaller the container density is, the more sensitive it is to the change of the bed slope; the larger the container density is, the less significant the bed slope factor of the container movement is.

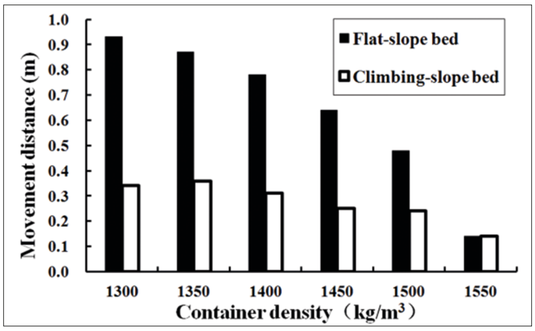

Fig. 7. Influence of bed slope on movement distance

CONCLUSIONS

A tsunami wave is generated in a test flume by using a dam-break wave to study the mechanism of the tsunami wave impacting a container model. The result shows that the tsunami wave's Froude number is slightly greater than 1 at a low storage water level, but increases significantly at a high storage water level. The Froude number of the tsunami wave in climbing state is less than that in the flat bed state. When the tsunami wave is generated, the water flow at the gate of the energy storage tank can be divided into three stages, respectively a rapid descent stage, relatively stable stage and slow descent stage. The process of the tsunami wave impacting the container model can be divided into an impact stage of the wave front, a splashing stage of the wave front, a rising water level stage, a quasi-constant stage and a water recession stage. In the process of the tsunami wave impacting and carrying away the container model, the main driving force is the wave's impact and buoyancy, while the main resistance is from the gravity of the container model and ground friction. This experiment explores the factors that affect the movement distance of the container model, including the storage water level, container density and coastal slope, while the movement distance is positively correlated with the storage water level, and negatively correlated with the container density and coastal slope.

ACKNOWLEDGEMENTS

The work was financially supported by the National Natural Science Foundation of China (Grant No. 51809047); Fujian Natural Science Foundation (2019J05029); Educational Research Projects of Young and Middle-aged Teachers in Fujian Education Department (JT180049).

REFERENCES

1. Nandasena N., Sasaki Y., Tanaka N. (2012): *Modeling field observations of the 2011 Great East Japan tsunami: Efficacy of artificial and natural structures on tsunami mitigation*. Coastal Engineering, 67, 1–13.

2. Ghobarah A., Saatcioglu M., Nistor I. (2006): *The impact of the 26 December 2004 earthquake and tsunami on structures and infrastructure*. Engineering Structures, 28(2), 312–326.

3. Chen C., Melville B., Nandasena N. A. K., Farvizi F. (2018): *An experimental investigation of tsunami bore impacts on a coastal bridge model with different contraction ratios*. Journal of Coastal Research, 34(2), 460–469.

4. Chanson H. (2006): *Tsunami surges on dry coastal plains: Application of dam break wave equations*. Coastal Engineering Journal, 48(4), 355–370.

5. Imamura F., Goto K., Ohkubo S. (2008): *A numerical model for the transport of a boulder by tsunami*. Journal of Geophysical Research: Oceans, 113(C01008), 1–12.

6. Saatcioglu M., Ghobarah A., Nistor I. (2005): *Effects of the December 26, 2004 Sumatra earthquake and tsunami on physical infrastructure*. ISET Journal of Earthquake Technology, 42(4), 79–94.

7. Shafiei S., Melville B. W., Shamseldin A. Y., Adams K. N., Beskhyroun A. S. (2016): *Experimental investigation of tsunami-borne debris impact force on structures: Factors affecting impulse-momentum formula.* Ocean Engineering, 127, 158–169.

8. Robertson I., Riggs H., Mohamed A. (2008): *Experimental results of tsunami bore forces on structures*. International Offshore Mechanics and Arctic Engineering Conference, 2008.

9. Chock G. Y. K., Robertson I., Riggs H. R. (2013): *Tsunami structural design provisions for a new update of building codes and performance-based engineering*. Solutions to Coastal Disasters, 2013, 423–435.

CONTACT WITH THE AUTHORS

Cheng Chen
e-mail: chencheng_1117@163.com

College of Civil Engineering
Fuzhou University
No.2, Wulongjiang North Avenue, 350108 Fuzhou
China
Key Laboratory of Coastal Disaster and Defence of Ministry of Education,
Hohai University
No.1, Xikang Road, 210098 Nanjing
China

Jun Chen
e-mail: 861702955@qq.com

The Pearl River Hydraulic Research Institute
Pearl River Water Conservancy Building
No.80, Tianshou Road, 510611 Guangzhou
China

Peng Lin
e-mail: 1047823595@qq.com

College of Civil Engineering
Fuzhou University
No.2, Wulongjiang North Avenue, 350108 Fuzhou
China

Chiwei Chen
e-mail: 490248527@qq.com

College of Civil Engineering
Fuzhou University
No.2, Wulongjiang North Avenue, 350108 Fuzhou
China

Haozhe Chen
e-mail: 107012487@qq.com

Key Laboratory of Coastal Disaster and Defence of Ministry of Education,
Hohai University,
No.1, Xikang Road, 210098 Nanjing
China