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Mechanism of toppling instability of the human body in floodwaters

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Abstract. Extreme urban flood events occur frequently in China, often leading to heavy casualties. Thus, it is of great importance to study the mechanism of the instability of the human body in floodwaters. The results of such research can provide scientific reference for city flood control standards. In this paper, a formula for the incipient velocity of the human body, during toppling instability in floodwaters, was derived based on mechanical characteristics, instability mechanism, and critical conditions during instability. A series of flume experiments were conducted to investigate the incipient velocity of two 3D printed human body models of different sizes; the resultant experimental data was used to determine parameters in the derived formula. Additionally, grip strength was taken as a standard of a person's ability to withstand floodwaters. Finally, crowd factors were introduced, and based on this study, a criterion for the toppling instability of different subjects in floodwaters was proposed. Compared to the results of previous studies, the proposed formula can better predict the instability of the human body in floodwaters.

1. Introduction

Statistics from the *Emergency Events Database* indicate that the loss of life and property caused by floods, ranks highest among all natural disasters [1]. According to an in-depth investigation conducted by the *Ministry of Housing and Urban-Rural Development*, of the 351 cities investigated in China, 62% of them were hit by urban water disasters between 2008 and 2010. Even worse, 137 of these cities were struck more than three times [2, 3]. Unfortunately, the situation became more serious in 2011 when many cities, including Beijing, Chengdu, Wuhan, and Hangzhou, suffered rainstorms, which lead to severe urban water-logging disasters [4]. On July 21, 2012, Beijing suffered its biggest rainfall since the establishment of PRC [5, 6]. In recent years, urban floods have become more frequent, leading to traffic paralysis, serious adverse effects on the normal operation of cities, and an increasing threat to human lives. The safety of the inhabitants on floodways is a big problem of urban storm water design and flood plain management. According to the statistics provided in 2011 by *China's State Flood Control and Drought Relief Headquarters and Ministry of Water Resources*, the number of dead and/or missing, as a result of flash flooding, is on the rise; in 2010 alone, the death toll reached 3,222. Populations living in flood zones are expected to increase in the coming decades due to the effects of climate change, the rapid growth in population, and the expansion of urbanization [8]. Hence, the instability mechanism of the human body during a flood disaster is an important issue to be studied.

Existing research on the body's instability in floodwaters is insufficient, and the topic is only vaguely mentioned in flood risk management protocols. Most references to this serious issue are expressed by the relationship between incipient velocities and water depths. The main existing research ideas are as follow.

- *Experimental testing.* Foster, *et al.* [9] performed experiments on human stability in a flume 6 meters long, 0.6 meters wide, and 0.75 meters deep, with the subjects consisting of six male children aged 9 to 13 years old. However, there was no quantitative evaluation method, because the criteria developed for stability and instability flow conditions were based on the personal tendency of the experimenter. Based on the earlier work of Foster and Cox, Yee [10] expanded on the research by experimenting the stability of four children. Abt, *et al.* [11] undertook laboratory experiments on human instability in a flume 61 meters long, 2.24 meters wide, and 1.22 meters deep with different surfaces; the subjects consisted of twenty adults. A formula defining the critical value of instability of a human body in floodwaters was obtained, which included the height and mass of the experimenter, and the flow depth and velocity of the water. The equation was as follows:

$$hv_c = 0.0929(e^{0.001906Lm+1.09})^2$$

According to experiments on human stability, Suetsugi [12] believed that conditions became unsafe when the product of flow depth and velocity reached 0.5 m^2/s. A movable platform, 1.17 meters long, inside a test water basin was used to test the stability of rescue workers by Karvonen, *et al.* [13]. Rescue workers were represented by seven participating adults. The research method of Karvonen, *et al.* was unique because the platform was moving through stagnant water, as opposed to the subjects being exposed to flowing water. Based on their experimental data, the equation derived by Abt, *et al.* was improved upon, as follows:

$$hv_c = 0.004Lm + 0.2$$

Jonkman, *et al*. [14] reported on a study conducted by FHRC in the UK, in which a professional stuntman was subjected to different flowing water within the channel. In all of the tests, instability reportedly occurred after the subject slipped backwards in the relatively high velocities and low water depths. The experimental results indicated that the condition of flow, describing instability or maneuverability of a human body, is closely related to a subject's height and weight. However, there is no known theory for the parameters of friction and drag coefficients.

- *Empirical and theoretical analysis.* Based on the experimental results of Abt, *et al.*, Takahashi, *et al.* [15] developed a computational model for human stability which included friction, drag force, and weight. For any given person's weight and height, computational resolution of frictional force, drag force, and weight facilitated the calculation of critical velocity for either sliding or toppling modes of instability in a given water depth. In water depths less than 0.48 of a subject's height, only the feet and legs were exposed to drag forces, which led to discrepancies between computational results and the experimental results obtained by Foster and Cox. Keller, *et al.* [16] undertook a theoretical analysis of human body stability, and one formula was derived. However, this purely theoretical method was highly dependent on the friction and drag coefficient values. The friction coefficient and drag coefficient were 0.3 and 1.2 respectively in the study, which did not match the general values of friction and drag coefficient measured by Takahashi, *et al.* [15]. Lind, *et al.* [17] considered the toppling instability of a circular cylindrical body, a square parallel pipe, and composite cylinders for the torso and two legs, assembled to represent a person immersed in floodwaters and subjected to buoyancy and drag forces; four formulae were established. The experimental data of Abt, *et al.* [11] and Karvonen, *et al.* [13] was used to calibrate and compare these formulae. It should be noted that the geometrical similarities of the study objects were not accurate. Consequently, Ramsbottom, *et al.* [18] and Penning-Rowsell [19] proposed an equation to judge the risk level of a human body in floodwaters, found by semi-quantitative assessments including flow depth and velocity.

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According to the equation, several risk levels were ranked, including low risk, moderate risk, significant risk, and extreme risk, and a division chart of risk level for Britishmen was developed. Compared to other equations, the equation written by Penning-Rowsell was superior because it was clear that the stability of a human body in floodwaters was not only about the product of their weight and height, but was also related to the ground features. Cao, *et al.* [20] identified two types of instability mechanisms of a person standing still in floodwaters, which included sliding and toppling instability. A formula for the incipient velocity of a human body for toppling and sliding instability in floodwaters was derived. At the same time, a dynamic equation for a person walking in floodwaters, considering only one generalized coordinate, was derived based on the Lagrange method. The numerical solution was presented through the higher-order Runge-Kutta method. Cao, *et al.* asserted that sliding instability usually occurred when the flow velocity was <0.25 m/s while toppling instability generally occurred when the flow velocity was >2.5 m/s. They suggested values of flow depths of 0.8-0.9 m for human walking instability research in floodwaters.

- *Combination of theoretical analysis with flume experiments.* Recently, Xia [21,22] achieved results by conducting research on a human model, with a scale of 1:5.54, and by considering the threshold of motion of coarse sediment. The derived method was mentioned by Jianheng Xie [23] in Mechanics of Sediment Transport. However, there was no theory for the values of height and weight of the model in the experiments.

Unfortunately, the decrease in flood diversion areas, such as rivers and farmland, caused by increasing urbanization and economic growth, and the increase in impermeable surfaces, further exacerbates urban flood risks and places people's lives and property in growing danger. All of the above-mentioned research, based on experimental tests using actual people, was significantly dependent on the psychological factors and physical attributes of the test subjects. In addition, the research based on laboratory experiments, using models of human bodies, was less precise because the geometrical attributes of the study subjects were dissimilar. Research projects based on theoretical analysis, combined with flume model experiments, are more scientific than other research methods. However, there is still no known theory for the selection of values for height and weight of a model in experimentations, and the existing research does not take varied subjects into account. Thus, it is necessary to further study the mechanism of instability of the human body in floodwaters, in order to provide scientific reference for the implementation of city flood control standards.

2. Force analysis and mechanism of instability

2.1. Force analysis

If a person stands facing upstream in floodwater, the water depth doesn't surpass their head. Therefore, the stability of a human body subjected to flooding is determined by the drag force, frictional force, its own gravitational force and buoyancy force. Figure 1 shows the forces acting on a submerged human body during a moment of instability.

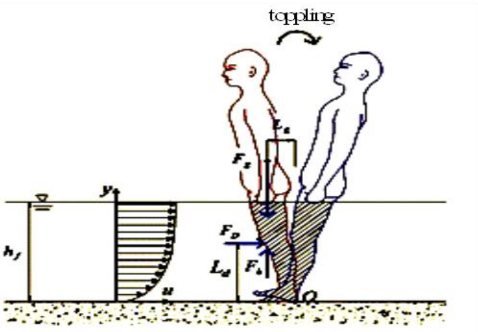


Figure 1. Forces acting on a submerged human body for toppling instability.

- Drag force. In the horizontal direction, the drag force (F_D) acting on a flooded human body can be expressed as follows [21, 22]:

$$F_D = A_d C_d \gamma_f u_b^2 / 2g \tag{1}$$

where u_b is the near-bed velocity; C_d is the drag force coefficient; γ_f is the unit weight of the flow; and A_d is the stressed area, $A_d = a_d(b_p \times h_f)$. It is well known that the value of C_d is closely related to the shape of the subject and the object Reynolds number. According to the test of drag force, the value of C_d is inversely proportional to the Reynolds number when the Reynolds number is <20,000, and the value of C_d is regarded as a constant number, 1.08, when the Reynolds number is >20,000.

- Buoyancy force. It is assumed that the distribution of the volume of the human body in the height direction is a smooth curve. As such, F_b can be expressed by the following:

$$F_b = \rho g V_b \tag{2}$$

According the study conducted by Xia [21, 22], V_b can be expressed by the following:

$$V_b/V_p = 0.633\left(\frac{h_f}{h_p}\right)^2 + 0.367\frac{h_f}{h_p} \tag{3}$$

where $V_p = 0.0008m_p + 0.0092$ (according to the research conducted by Zhao, 2005; ρ is the density of water, g is the gravitational acceleration, V_b is the submerged volume of the human body, V_p is the volume of the human body, and h_p is the height of the person. Equation (3) proposes that the action of gravity will reduce, because the buoyancy force increases as the depth of flow rises; therefore, buoyancy exerts a significant effect on a submerged human body, which cannot be ignored.

- Gravity force. The gravity force can be expressed as follows:

$$F_g = m_p g \tag{4}$$

Where m_p is the mass of human body.

- Frictional force. According to the research of Xia [21,22], the frictional force expression can be written as follows:

$$F_R = \mu g(m_p - \rho V_b) \tag{5}$$

2.2. Mechanism of instability of a submerged human body

Existing research shows that sliding and toppling instability are the two instability mechanisms. Sliding instability generally occurs in cases of low water depths and high flow velocities, meaning $F_D>F_R$. Toppling instability usually occurs in cases of high water depths and low flow velocities, meaning $F_D>F_g$. Hydrologic features of urban floodwaters are usually high water depths at low flow velocities; as such, this study focused on toppling instability.

When a human stands facing upstream in the urban flood, as shown in figure 1, the toppling instability critical condition of the human body would be the heel (O) and would overturn the total torque backward around the pivot point O ($\sum M_O = 0$), namely $F_D \cdot a_h h_f - F_g \cdot a_g h_p = 0$, where a_h and a_g are the correction coefficients [21,22]. Using equations (1) and (5), a deformation equation can be derived for u_b, as follows:

$$u_b = \sqrt{\frac{2ga_g}{a_d a_p a_h}} \sqrt{\frac{1}{h_f{}^2}(\frac{m_p}{\rho} - V_b)} \sqrt{\frac{1}{C_d}} \tag{6}$$

Analogously, using the average velocity instead of the representative near-bed velocity, which can be expressed as $u_b = (1+\beta)(a_b h_p / h_f)^{\beta} U$ and by substituting $u_b = (1+\beta)(a_b h_p / h_f)^{\beta} U$ into the equation (6), the incipient velocity of the toppling instability for a submerged human body can then be expressed as follows:

$$U = \alpha(\frac{h_f}{h_p})^{\beta} \sqrt{\frac{1}{h_f{}^2}\left(\frac{m_p}{\rho} - V_b\right)} \sqrt{\frac{1}{C_d}} \tag{7}$$

where $\alpha = \frac{1}{1+\beta \ \ a_b^{\beta}} \sqrt{\frac{2ga_g}{a_p a_h a_d}}$ and the unit is $m^{0.5}s^{-1}$. Parameters α and β are closely related to the human body friction coefficient and drag coefficient; the values of α and β can be determined according to the experimental data of the flume.

3. Flume experiments

3.1. Model design

According to *The China National Physique Monitoring Report* in 2010 and 2014, the height range of adult males in China was 1.65 m-1.72 m, with an average of about 1.69 m (figure 2). The weight range of adult males in China was 61.5 kg-71.5 kg, with an average of about 68.9 kg (figure 3). The physical model for the instability of a submerged human body was designed into two different models, with geometric scales of λ_L=4 and λ_L=8. The outstretched arms of the model were designed with 70 degrees of angle on the left arm and 10 degrees of angle on the right arm, with both arms forming an angle of 100 degrees, according to the action of inertia of a human body in floodwaters (figure 4). The size and scale of the model was in line with the average size of a Chinese adult, taking national standard *GB1000-88*, *The China National Physique Monitoring Report* in 2014, and the monograph written by Qingshan Guo [25] for reference. Figures 5 and 6 illustrate the human body models used in this study, which were created by 3D printing using photosensitive resin. The hollow insides of the models were filled with steel balls with a diameter of 2 mm, and sealed with waterproof material in order to mimic the distribution of gravity on a real human. The basic parameters are shown in table 1.

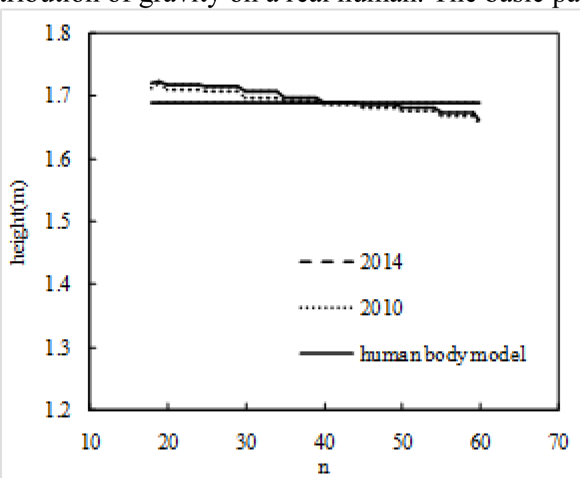


Figure 2. Average height distribution of adult males in China.

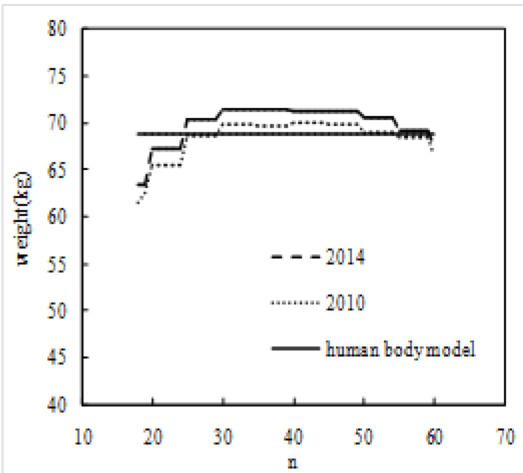


Figure 3. Average weight distribution of adult males in China.

Figure 4. Action of inertia on a human body in floodwaters.

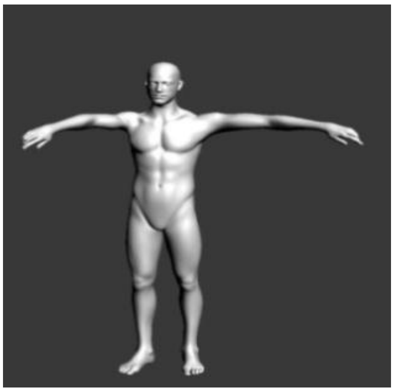


Figure 5. Model of the human body.

Figure 6. 3D printed model of the human body.

According to the study conducted by Xia [21, 22], the prototype and the physical model must conform to the principles of geometric, kinematic, and dynamic similarities. The model used in this study strictly followed geometric similarities; therefore, the scales of length, width, and height were equal. For example, the model with the scale of $\lambda_L = 4$ can be expressed as follows:

$$\lambda_L = \lambda_W = \lambda_H = 4 \tag{8}$$

The model needed to satisfy the principles of kinematic similarities, so the scale ratio for the velocity λ_U can be written as follows:

$$\lambda_U = \lambda_L^{1/2} = 2 \tag{9}$$

According to the principles of dynamic similarities, the scale ratio of the force λ_F was written as follows:

$$\lambda_F = \lambda_L^3 = 64 \tag{10}$$

The density of the model and the prototype almost unanimously, hence the following was true:

$$\lambda_{F_g} = \lambda_{F_b} = \lambda_F = 64 \tag{11}$$

According to Xia's [21, 22] analysis:

$$\lambda_{F_D} = \lambda_F \tag{12}$$

According to the principles of the friction roughness similarities, the following was true:

$$\lambda_{F_R} = \lambda_F = 64 \tag{13}$$

Table 1. Basic parameters of the model.

Scale	Prototype	Model	
	1:1	1:4	1:8
Height (cm)	169.02	42.26	21.13
Weight (g)	68900	1076.56	134.57
Palm volume	$V_1 = 0.00566V_p$		
Forearm volume	$V_2 = 0.01702V_p$		
Upper volume	$V_3 = 0.03495V_p$		
Thigh volume	$V_4 = 0.0924V_p$		
Shank volume	$V_5 = 0.04083V_p$		
Trunk volume	$V_6 = 0.6132V_p$		
Palm length	$L_1 = 0.109h_p$		
Forearm length	$L_2 = 0.157h_p$		
Upper length	$L_3 = 0.1172h_p$		
Thigh length	$L_4 = 0.232h_p$		
Shank length	$L_5 = 0.247h_p$		
Trunk length	$L_6 = 0.300h_p$		

3.2. Experiments

Experiments were conducted in a flume in the State Key Laboratory of Water Resources and Hydropower Engineering Science at Wuhan University to investigate the critical condition of toppling instability for the model of the human body. The horizontal flume was 6.0 meters long, 1.2 meters wide, 0.8 meters deep with a slope of 0.5%, and was equipped with a glass bed and glass sides, and an adjustable tail gate; the water temperature was 21.5° C to 21.6° C. The model was placed at the base of the flume, in the center, in order to reduce impacts on the flume walls. The adjustable quantity of flow in this experiment was 0-100 L/s, which was gradually increased every 90 s from the initial depth of 0.01 m. At the same time, the tail gate was adjusted and the state of the model was observed. Each test was conducted three times; the flow and corresponding water depth and velocity were recorded as the submerged model went from stable to unstable, and the arithmetic average was calculated.

3.3. Analysis of experimental results

Thirty groups of effective data were collected from the models for toppling instability in this study, including fifteen groups of data using the model with $\lambda_L = 4$ and fifteen groups using the model with $\lambda_L = 8$. The relationship of the incipient velocities for different water depths at toppling instability is shown in figure 7, with the horizontal axis representing critical depth of the water h_f (m) and the vertical axis representing the corresponding velocity U_c(m). The following information can be drawn from figure 7:

- The incipient motion of the two models was basically the same, and the incipient velocity for the models decreased with increases in the water depth. This was because when the water depth increased, the wetted area increased, resulting in an increasing drag force. When the effective gravity decreased, friction for resisting sliding decreased.
- The smaller the mass of the model, the easier it was to move when the models faced the same direction, because the effective gravity becomes smaller when the mass of model decreases with the proximity of the buoyancy force of the models in the same water depth.

The law of incipient motion, concluded from the experimental results, was consistent with the changing law of the curve of incipient velocity formula for a submerged human body. Therefore, the structure of equation (7) was reasonable.

4. Criteria for toppling instability of a human body in floodwaters

4.1. Parameter calibration

A formula for toppling instability was derived, which was relatively complex because of more variables. Therefore, equation (7) was transformed to the following:

$$U/\left(\sqrt{\frac{1}{h_f^{\,2}}\left(\frac{m}{\rho}-V_b\right)}\sqrt{\frac{1}{C_d}}\right)=\alpha\left(\frac{h_f}{h_p}\right)^{\beta} \tag{14}$$

where the relation between $U/\left(\sqrt{\frac{1}{h_f^{\,2}}\left(\frac{m}{\rho}-V_b\right)}\sqrt{\frac{1}{C_d}}\right)$ and $\frac{h_f}{h_p}$ represents a power function.

According to Xia's [21, 22] research, the prototype, and the physical model, must conform to the following scale ratios of water depth and velocity:

$$\begin{cases} h_{fp}=h_{fm}\times\lambda_L \\ U_{cp}=U_{cm}\times\sqrt{\lambda_L} \end{cases} \tag{15}$$

where the subscripts p and m refer to the prototype parameters and model parameters. The scaled-up experimental data, obtained from 30 tests using equation (15) for the prototype, is shown in the points of figure 7. The experimental parameters $h_p = 1.7m$ and $m_p = 68kg$ were used for real human bodies in the study by Jonkman and Penning-Rowsell, while $h_p = 1.69m$ and $m_p = 68.9kg$ were used in this study. Hence, the experimental data obtained from Jonkman and Penning-Rowsell was applicable in this study. A statistical analysis software package, SPSS, was used to determine α and β, as follows: $\alpha = 1.915$ and $\beta = -0.391$.

Figure 7 shows that the critical instability conditions, obtained using the scale ratios, matched well with the calculations from equation (7), confirming the accuracy of the critical conditions for the prototype.

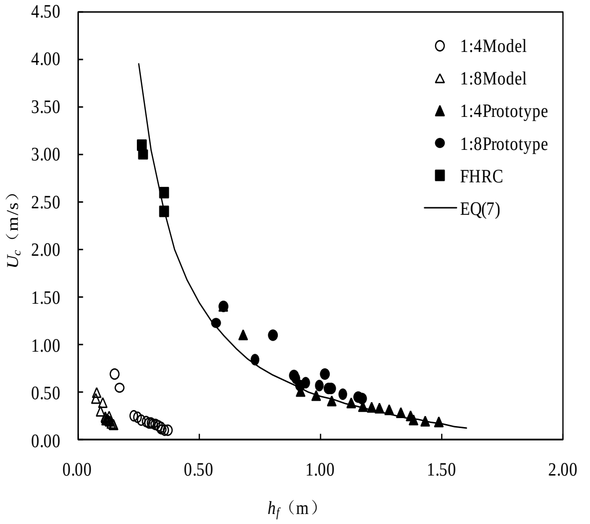


Figure 7. Comparisons the critical conditions between the experimental data and the calculations using the derived formula.

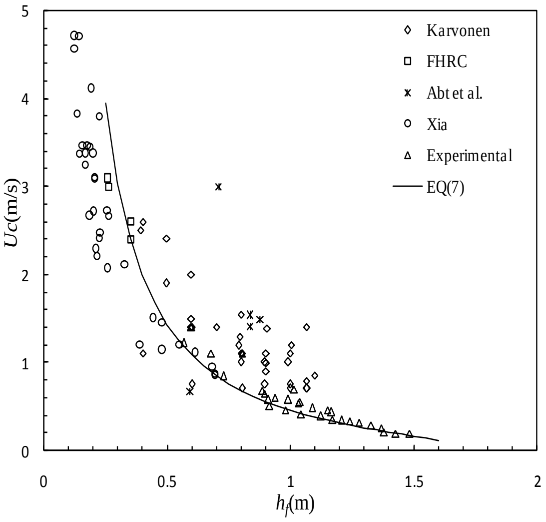


Figure 8. Comparison to previous results.

4.2. Comparison with previous achievements

Most existing research on the instability of the human body in floodwaters neglected to investigate the effects of body buoyancy. However, buoyancy exerts a significant effect on a submerged human body, as confirmed by Xia. Buoyancy can be ignored only when the depth of floodwater is shallow enough. Thus, research that does not consider buoyancy is not applicable when the depth of the floodwater is higher, such as in the results obtained by Abt, *et al*., Takahashi, *et al.* and so on.

Existing experimental data for the instability of human bodies in floodwaters using prototypes are mainly represented by the results of Abt, *et al.* [11], Karvonen, *et al.* [13], Jonkman and Penning-Rowsell[14], and Xia[21,22]. Twenty real humans were used to conduct experimental research on the instability of the human body in floodwaters in the study of Abt, *et al.*[11]. Flume studies were undertaken on four different bottom surfaces in over 70 tests. In the experimental program of Karvonen, *et al*. [13], seven real humans wore survival suits and safety helmets. Four controlled field tests of human body stability in a natural channel were conducted by FHRC in the UK using a stuntman as the test subject. The subject completed maneuvers, including standing and walking at right angles and walking into the flow of the water (Jonkman and Penning-Rowsell), Xia conducted 54 tests on the instability of humans in a flume using a human body model with $\lambda_L = 5.54$. Before the model became unstable, it was placed in two positions in the flowing water including facing upstream in floodwater and with its back to the oncoming flow direction. Comparisons to the results of the above-mentioned studies are shown in figure 8. As shown in figure 8, in conditions of the same depth, the scattered points of the previous experimental data for real humans in flumes were higher than the points of the experimental data in this study, which meant that the incipient velocities in this study were generally lower than those of the experimental data regarding real humans. The reason may be that the model lacked the ability to resist floodwaters subjectively and actively, making it less stable than a real human in floodwaters. The scattered points of the experimental data given by Xia were below the points in this study, which may be because the weight of the prototype model used by Xia was 60 kg, which was less than the weight of prototype used in this study (68.9 kg). Therefore, compared to the stability of the model in this study, the stability of the model used by Xia was worse. Hence, the formula derived in this study was more reliable for predicting the toppling instability of the human body in floodwaters.

4.3. Extensive application

Because the human body model used in this study was based on the average height and weight of adult males, equation (7) derived herein based on the experimental data cannot be used to reflect the instability of the entire population in floodwaters because the values of children, adults, elderly, males, and females are different. As such, crowd factors K_r were introduced into the formula derivation of the toppling instability for varied population, in order to make the formula closer to reality.

The strength of the upper limb muscles can be represented by grip strength. Therefore, grip strength, which is generally related to the weight of the tested person, can be evaluated in a physical fitness test, through which a scientific physical assessment can be made [26, 27]. Thus, the grip strengths of different people were used as criteria for the resistant ability of a human in floodwaters. The measurement of grip strength was conducted with a hand grip dynamometer, which tested 218 volunteers of different ages, consisting of 106 males and 112 females. The grip strength values of the males' and females' left and right hands are plotted in figure 9. As shown, the grip strengths of the left and right hands were evenly distributed close to the line y=x, which showed that the grip strengths of the left and right hands were approximate to each other. Thus, the average grip strengths of the left and right hands were used in this study.

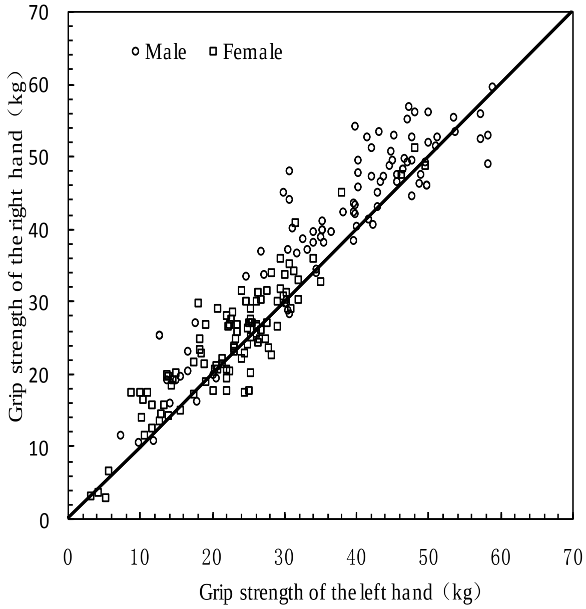
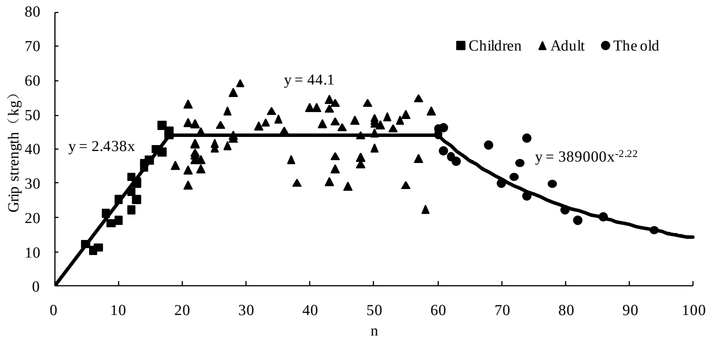


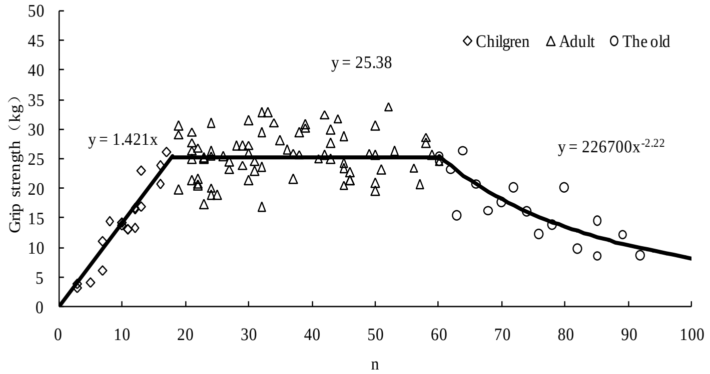
Figure 9. Grip strength of left and right hands.

According to the *United Nations Convention on the Rights of the Child*, which was passed in November 20th, 1989, individuals under the age of 18 are deemed as children, and above the age of 60 are deemed as elderly [28]. Therefore, people aged 18 to 60 were deemed as adults in this study.

Figure 10 shows the distribution of average grip strength of males and females, among which the grip strength of children basically met the linear relationship. The average grip strength for adult males and females was 44.1 kg and 25.38 kg, respectively, all fitting within the standard of grip strength set in The China National Physique Monitoring Report in 2014 released by the General Administration of Sport of China. Therefore, the crowd factors K_r of varied population were calculated according to the distribution of the grip strength, which is shown in table 2.



(a) Male



(b) Female

Figure 10. Distribution of grip strength.

Table 2. Crowd factors K_r

Population	Crowd factors	K_r
Male	Children	0.0553 n
	Adult	1
	Elderly	8821 $n^{-2.22}$
Female	Children	0.0323 n
	Adult	0.576
	Elderly	5140 $n^{-2.22}$

Note: n-age

Substituting crowd factors K_r into equation (7), the incipient velocity for a submerged human at toppling instability can be expressed as follows:

$$U = 1.915K_r(\frac{h_f}{h_p})^{-0.391}\sqrt{\frac{1}{{h_f}^2}\left(\frac{m}{\rho}-V_b\right)}\sqrt{\frac{1}{C_d}} \quad (16)$$

In 2010, there were 85.02 million disabled persons in China, accounting for 6.34% of the total population [29]. Therefore, equation (16) has wide application.

5. Conclusions

In this study, the mechanism of toppling instability of the human body in floodwaters was researched using theoretical analysis and flume experiments combined with a force analysis. A formula was derived based on data acquired from the flume experiments undertaken to establish the incipient velocity on two human body models of different scales. The formula can be used to predict the incipient conditions (the flow depth and velocity of the water) of the toppling instability of the human body in floodwaters. The following statements refer to the analytical and experimental tests conducted in this study:

- In this paper, the experiment assumed people were uninjured during the flood. The outstretched arms of the model were designed with 70 degrees of angle in the left arm and 10 degrees of angle in the right arm with both arms together forming an angle of 100 degrees. The slope of the flume was 0.5%, the water temperature was 21.5° C to 21.6° C, and human body model was without clothes.
- The strength of the upper limb muscles can be represented by the grip strength; therefore, grip strength, which is generally related to the weight of the tested person, was evaluated in physical fitness testing through which scientific physical assessments were made. With this data, the grip strengths of different people were used as criteria for the resistant ability of the human body in floodwaters.
- Considering the human body's action of inertia in floodwaters, it was more practical to make a human body model with 3D printing, which was closer to reality, thus ensuring the experimental data was more accurate.
- Various forces acting on a submerged human body were analyzed and the crowd factors were further improved and became more reasonable, forming a wide formation from children to the elderly. A formula of incipient velocity for a submerged human body at toppling instability was derived consisting of crowd factors K_r and the drag coefficient C_d, and parameters of the formula were derived using the experimental data. Compared to previous research results, it was confirmed that the derived formula was reliable in predicting the toppling instability of the human body in floodwaters.
- In addition to the factors of flow conditions, the gender and the physical characteristics of the subject, such as height and weight, there are many other factors that influence the stability of a human body in floodwaters, including the clothing worn by the subject, the slope of the flume, turbulence characteristics, water temperature, fatigue, and so on. Hence, further research with additional experiments on large-scale human body models, or real human bodies, in real floodwaters is needed to further improve the formulae of incipient velocity of a submerged human body in different environmental conditions.

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