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STABILITY CRITERION FOR A FLOODED HUMAN BODY UNDER VARIOUS GROUND SLOPES

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ABSTRACT: Extreme flood events often lead to heavy casualties, with flood risk to humans varying with the flow conditions, the body attributes, and the ground slopes. Therefore, it is important to propose an appropriate stability criterion for a flooded human body under various ground slopes. In this study, a formula for the incipient velocity of a flooded human body at toppling instability was derived, based on a mechanics-based analysis. The effect of body buoyancy and the influence of a non-uniform upstream velocity profile acting on the flooded human body under a sloping ground were considered in the formula derivation. 186 tests were conducted in a flume to obtain the conditions of water depth and velocity at instability for a model human body under three ground slopes, with the experimental data being used to calibrate two parameters in the derived formula. Finally, the proposed formula was used to estimate the critical velocities under different depths for real human subjects, in terms of assessing their stability related to floodwaters.

KEYWORDS: human body stability; floodwater; incipient velocity; mechanics-based analysis; sloping ground

1 INTRODUCTION

The frequency of extreme flood events is expected to increase significantly in future years due to the effects of climate change and human activities, with annual flood events often leading to severe damage and heavy casualties on a global scale [1]. The Ministry of Water Resources of China reported that the average annual number of fatalities arising directly from floods was 5500 during the period 1950-1990, and this number has reduced to 1610 [2]. However, severe flash floods and debris flows in 2010 led to a loss of more than 2800 lives [2]. More recently, flash flooding occurred in Beijing in July 2012, resulting in about 80 fatalities in two days [3]. The safety of people can be compromised when exposed to floodwaters, with the people stability in floodwaters being of major concern in the risk management of flood-prone areas [4,5]. The risk to flooded people is expected to increase in the future owing to the rapid growth in population, the continuous expansion in territories associated with human activities, and the increase in extreme meteorological events. Therefore, it is important to propose a quantitative method of assessing the stability of a flooded human body under various ground slopes.

There are two kinds of instability mechanisms identified by existing studies, including sliding (friction) and toppling (moment) instability [4,6-7]. Sliding instability usually occurs when the drag force induced by the incoming flow exceeds the frictional force between the feet of the body and the ground surface, while toppling instability generally occurs when the moment of the drag force caused by the inflow exceeds the resisting moment of the effective body weight. The risk to a flooded human body varies both in time and space, due to changes in the hydrodynamic processes across a flood-prone area, and also due to changes with the different body attributes and ground slopes. Existing observations show the mode of toppling instability for a flooded human subject is more popular in urban and floodplain floods, and existing stability criteria for a flooded human body are represented by the incipient velocities for different depths, based on the experimental data in flume [7-9]. Foster and Cox [8] conducted experiments on human stability in a flume using the subjects of 6 boys, and no quantitative assessment method was obtained. Abt et al. [9] reported laboratory experiments of human toppling instability conducted in a long flume with different ground surfaces, and an equation defining the threshold of instability of a flooded person was developed, which indicated that the unit discharge at instability was a function of the product of the height and mass of a human body. Karvonen et al. [10] undertook stability tests using seven human bodies, and the product of flow and velocity describing the loss of human stability was closely related to the height and weight of a human body, based on the experimental data. Due to the differences in physical attributes and psychological factors of the human subjects tested in these experiments, there exists a wide range of stability criteria for a flooded human body. In addition, the effect of various ground slopes on the stability criteria has not been investigated in detail.

Therefore, it is appropriate to propose a stability criterion for a flooded human body under various ground slopes. In this study, different forces acting on a flooded human body under a sloping ground have been analysed, with the formula of incipient velocity at toppling instability being derived. Laboratory experiments were then undertaken to obtain the conditions of water depth and the corresponding velocity at the instant of human instability, using an accurate scale human body model in a flume. The experimental data were then used to determine two parameters in the derived formula. Finally, the derived formula was validated using the experimental data obtained from the calculations based on the scale ratios, with stability thresholds in floodwaters being proposed for both children and adults.

2 FORCE ANALYSIS AND FORMULA DERIVATION

2.1 Forces acting on a flooded human body

The theoretical analysis of the stability of a flooded human body at toppling is approximately similar to the method used for predicting the incipient motion of a coarse sediment particle at rolling in river dynamics [11]. If a human body stands in a floodwater, the body needs to be able to withstand the drag force (F_D) of the flowing water in the streamwise direction. In the vertical direction, the body experiences its own gravitational force (F_g), its buoyancy force (F_b) and the

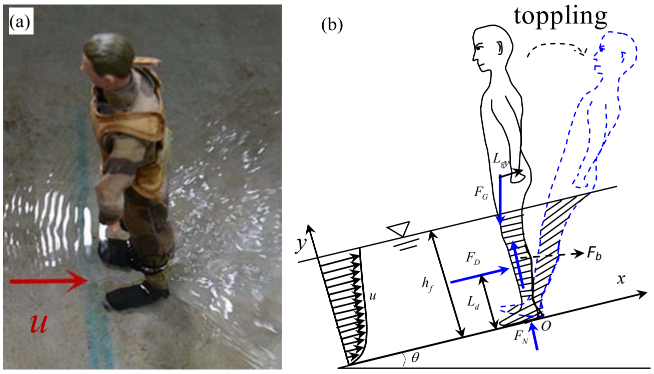

Figure 1 Sketch of governing forces acting on a flooded human body

normal reaction force (F_N) from the ground. Therefore, the stability of a flooded human subject at toppling is controlled by these four forces, as shown in Figure 1.

2.1.1 Buoyancy force

The calculation of the buoyancy force needs to account for the dimension of each body segment and the corresponding volume due to the irregular shape of a human body. For a normal human body, there exists a proportional relationship between the sizes of various segments. The height (h_p), or total volume (v_p), of a human body can be regarded as an essential parameter appropriate to determine the size, or volume, of each segment [12-14]. According to the definition of the buoyancy force, F_b can be expressed by:

$$F_b = \rho_f g V_b \tag{1}$$

where ρ_f is the density of water, g is the gravitational acceleration, and V_b is the volume of the displaced water by the flooded human body.Therefore, the magnitude of V_b is related to the values of h_f, h_p and v_p. An empirical relationship can be established between the buoyancy force (F_b) and the water depth (h_f), based on the characteristic parameters of the body structure. This relationship is usually represented by a quadratic function:

$$V_b / v_p = a_1 x^2 + b_1 x \tag{2}$$

where a_1 and b_1 are non-dimensional coefficients, and x is the ratio of the water depth to the body height, with $x = h_f / h_p$. Eq. (2) indicates that the value of V_b is equal to that of v_p for the case where $h_f = h_p$.

The statistics of the segment parameters for a body indicate that there exists an approximately linear relationship between the volume v_p [m^3] and the mass m_p [kg] of a human body [14], which can be expressed by $v_p = a_2 m_p + b_2$, where a_2 and b_2 are coefficients. These coefficients can be determined from the average attributes of a human body. Therefore, the buoyancy force is a function of the height (h_p) and the mass (m_p) of a human body for a given water depth (h_f), and it can be written as:

$$F_b = g\rho_f (a_1 x^2 + b_1 x)(a_2 m_p + b_2) \tag{3}$$

where a_1 and b_1 in Eq. (2) or (3) can be determined from the characteristic parameters of the body structure. According to the average body attributes for Chinese people, the values of $a_1 = 0.633$ and $b_1 = 0.367$ are calibrated, respectively, and the typical parameters in Eq. (3) can be evaluated to give $a_2 = 1.015\times10^{-3}$ m^3/kg and $b_2 = -4.927\times10^{-3}$ m^3, respectively [14].

2.1.2 Drag force

In the streamwise direction, the drag force (F_D) acting on a flooded human body can be written as:

$$F_D = 0.5 A_d C_d \rho_f u_b^2 \tag{4}$$

where u_b is a representative near-bed velocity; C_d is the drag coefficient, which is related to the flow pattern and the body shape; and A_d is the wetted area, with $A_d = a_d(b_p h_f)$, where a_d is an empirical coefficient, and b_p is the average body width exposed normal to the flow. According to the statistics of the segment parameters for a human body, there exists a quantitative relationship between the mean body width and body height, expressed by $b_p = a_p h_p$, where a_p is a coefficient. Therefore, the expression of $A_d = a_d\ a_p\ (h_p h_f)$ can be obtained. For various floodwaters it is difficult to determine the exact type of velocity profile, and a characteristic velocity of u_b is often used in Eq. (4) for the calculation of F_D, and it is regarded that C_d is independent of large values of object Reynolds number [15]. In this study, it is not necessary to determine the actual numerical value for C_d, since this parameter is included in a comprehensive parameter in the formula derivation.

2.1.3 Effective weight and normal reaction force

The gravity can be expressed by $F_g=gm_p$, with the corresponding components of F_{gx} ($=F_g\sin\theta$) and F_{gy}($=F_g\cos\theta$) in the x and y directions, where θ is the angle of a sloping ground. For a flooded human body standing on a sloping ground, it is assumed that the action position of the buoyancy force is in line with the component of the body gravity along the y direction. The forces of F_{gy} and F_b can then be jointly called the effective weight in the y direction (F_{Gy}), with $F_{Gy}=F_{gy} - F_b$, namely:

$$F_{Gy} = gm_p\cos\theta - F_b = g\left[m_p\cos\theta - \rho_f (a_1x^2 + b_1x)(a_2m_p + b_2)\right] \tag{5}$$

The component of F_g in the x direction can be written as:

$$F_{Gx} = gm_p\sin\theta \tag{6}$$

F_N is the normal reaction force from the ground surface, and is generally equivalent to the effective weight of a flooded human body along the y direction, namely $F_N = F_{Gy}$.

2.2 Formula derivation for toppling instability mode

The mode of toppling instability occurs when the driving moment induced by the drag force is equal to the resisting moment resulting from the effective weight of the body, which mainly occurs for large depths and low velocities. When a person stands facing the oncoming flow direction, as shown in Figure 1, then the critical condition for toppling instability is that the human body would pivot around the heel (Point O) and would topple backwards as the total moment around the pivot point O is equal to zero, namely:

$$F_{Gy}L_{gy} + F_{Gx}L_{gx} - F_D L_d = 0 \tag{7}$$

where L_d is the moment arm of the drag force, with $L_d = a_h h_f$, and a_h being the correction coefficient of the height between the centre of the drag force and the ground surface; L_{gx} is the moment arm of the effective weight along the x direction, with $L_{gx} = a_{gx}h_p$, and a_{gx} is the correction coefficient of the distance between the gravity centre of the body and the bottom, which is approximately equal to 0.55 based on the studies of Hellebrandt [16]; L_{gy} is the moment arm of the effective weight along the y direction, with $L_{gy} = a_{gy}h_p$, where a_{gy} is the correction coefficient of the distance between the position of the gravity centre of the body and the heel. According to the statistics of body structure, the value of a_{gy} ranges around 0.05. Substitution of the expressions for L_d, L_{gx}, and L_{gy} into the critical condition yields:

$$\begin{gathered}\left[m_p g\cos\theta - \rho_f g(a_1x^2 + b_1x)(a_2m_p + b_2)\right]a_{gy}h_p \\ +(m_p g\sin\theta)a_{gx}h_p - (0.5A_d\rho_f C_d u_b{}^2)a_h h_f = 0\end{gathered} \tag{8}$$

Re-arrangement of Eq. (8) gives the following expression for u_b:

$$u_b = \sqrt{\frac{2g}{a_d a_p a_h C_d}}\sqrt{\frac{\left[m_p\cos\theta - \rho_f(a_1x^2 + b_1x)(a_2m_p + b_2)\right]a_{gy} + m_p a_{gx}\sin\theta}{h_f^2\rho_f}} \tag{9}$$

It is difficult to determine the effective near-bed velocity u_b in practice and, for simplicity, the depth-averaged velocity (U) is generally used instead of the characteristic velocity. The incoming flow velocity upstream of the body is approximately characterized by the power-law velocity profile, but this refers to the flow velocity distribution before it reaches the effect of the advance pressure gradient of the body. The power-law distribution of velocity as used in this study can be expressed as $u = (1+\beta)U(y/h_f)^\beta$ for open channel flows, in which β is an empirical coefficient ranging from 1/7 to 1/6; y is the vertical distance from the bed; and u is the velocity at elevation y [11,17].Substituting the expression for u_b into Eq. (9), the incipient velocity for a flooded human body at toppling instability can then be written as:

$$U = \alpha(\frac{h_f}{h_p})^{\beta} \sqrt{\frac{m_p}{h_f^2 \rho_f}(\cos\theta + \gamma \sin\theta) - (\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p})(a_2 m_p + b_2)} \tag{10}$$

where $\alpha = \sqrt{2ga_{gy}/(a_d a_p C_d a_h)}/[(1+\beta)a_b{}^{\beta}]$, $\gamma = a_{gx}/a_{gy}$. According to the values of a_{gx} and a_{gy}, the value of γ is set to a constant of 10.0 during this preliminary investigation. The parameters α and β can be evaluated from the experimental data. As mentioned above, toppling stability usually occurs for large water depths, and the magnitude of the buoyancy force can account for more than 60% of the body weight as the water depth approaches the height of the waist. Therefore, the effect of the buoyancy force, as presented by the second term inside the root in Eq. (10), can not be neglected in the formula derivation.

3 FLUME EXPERIMENTS AND PARAMETER CALIBRATION

3.1 Model design and experiment description

In a physical hydraulic model, the flow conditions are ideally similar to those in the prototype if the model displays the principles of geometric, kinematic and dynamic similarity [11,15]. The hydraulic model for the stability of a flooded human body was designed to be an undistorted model, with a geometric scale of λ_L = 5.54, according to the comprehensive considerations of the experimental conditions and the available size of models. A model human body which strictly followed geometric similarity in each dimension was selected, and the height and mass of the model were 30 cm and 0.373 kg, respectively. For the prototype, the corresponding height and mass were equal to 1.70 m and 63.4 kg, respectively. According to the conditions for kinematic similarity, the scale ratio for the velocity λ_U was expressed by $\lambda_U = (\lambda_L)^{0.5} = 2.35$.

Based on the conditions for dynamic similarity, the ratio of the prototype to model force was equal to the same scale ratio of λ_F. Hence, the density of the selected human body model was approximately equal to the density of the prototype, which yielded $\lambda_{F_G} = \lambda_{F_b} = \lambda_F$. Existing studies indicate that the drag coefficient is regarded as a constant for a specified shape and relatively high values of the object Reynolds number [15], which led to $\lambda_{F_D} = \lambda_F$.

In order to calibrate the values of α and β in Eq. (10), a series of tests were conducted in a flume in the Hydraulic Laboratory of Wuhan University, China, to investigate the critical condition of stability for the model human body. The flume was 24 m long, 1.0 m wide and 1.0 m deep, with a cement-based bed and two glass sides. Before instability, the model body was kept standing on a flat or sloping ground for a specified posture in the flowing water, facing the oncoming flow direction. In this study, similar incipient motion experiments using the model body were conducted in the flume under three slopes of flat ground, 1:50, and 1:25, with the corresponding test runs of 45, 49 and 81, respectively. It should be noted that the above tests, using the scale model human body, were different from previous experiments conducted using real human bodies [9-10]. The model body tested in this study could not adjust its standing posture, whereas the real human bodies studied during the stability experiments could adjust their postures and gradually adapt to the oncoming flows. Therefore, the experimental results obtained from this study would tend to be safer from the viewpoint of flood risk analysis.

3.2 Analysis of experimental data

The incipient velocities for different water depths at toppling instability were obtained by studying the response of the model human body in the flume, as shown in Fig. 2a. It can be seen from Fig. 2a that: (i) under each ground slope, the critical velocity is a function of the water depth; with an increase of water depth, the incipient velocity decreases accordingly; and (ii) in the case of incoming depth of 0.1 m, the critical velocities for the model human body at toppling instability were 0.24, 0.31, 0.38 m/s under three slopes, respectively. When the ground

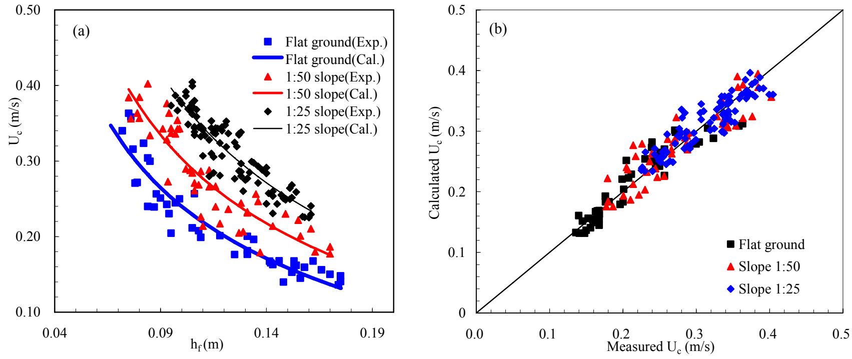

Figure 2 Calibration of Eq. (10) using the experimental data: (a) relationships between h_f and U_c for a model human body under three ground slopes; (b) comparison between the calculated and measured incipient velocities.

slope is at an angle θ, the resisting moment preventing the human body from toppling is increased by $(gm_p \sin\theta)L_{gx}$. Therefore, the increase in the resisting moment leads to an increase in the incipient velocity on a sloping ground, as compared with the value on a flat ground.

3.3 Parameter calibration

The formula structure is relatively complex in Eq. (10) due to the introduction of the buoyancy force and the ground slope. For a particular human body, the values of m_p, h_p, a_1, b_1, a_2 and b_2 in Eq. (10) are constant. Therefore, both α and β values in Eq. (10) can be determined by the statistical analysis software package SPSS, using the experimental data under each ground slope. The calibrated parameters of α and β for each ground slope are shown in Table 1. From Table 1, the square of the correlation coefficient (R^2) is found to be greater than 0.8 between the measured and predicted velocities for each ground slope, with this meaning that a better fit has been obtained using this analysis. Figure 2b shows that the calculated critical velocities compared well with the measured data for each ground slope.

Table1 Calibrated parameters in Eq. (10) for three ground slopes

Ground slope	Parameter calibration		γ	R^2	Number of tests
	α [m$^{0.5}$/s]	β [-]			
Flat ground	1.705	0.197	—	0.884	45
1:50 slope	1.882	0.173	10.0	0.820	49
1:25 slope	2.09	0.150	10.0	0.823	92
Note: other parameters used in formulae, covering: $a_1 = 0.633$; $b_1 = 0.367$; $a_2 = 1.015\times10^{-3}$ m^3/kg; and $b_2 = -4.927\times10^{-3}$ m^3.					

3.4 Application to real human bodies

Since the model tests strictly followed the principles of geometric, kinematic and dynamic similarity, the incipient velocities measured for the different water depths could be used directly to estimate the incipient motion conditions for the prototype, according to the scale ratios of depth and velocity. These scaling relationships are written as

$$h_{fp} = h_{fm}\lambda_L \quad \text{and} \quad U_{cp} = U_{cm}\sqrt{\lambda_L} \tag{11}$$

where the subscripts p and m refer to prototype and model parameters, respectively. The

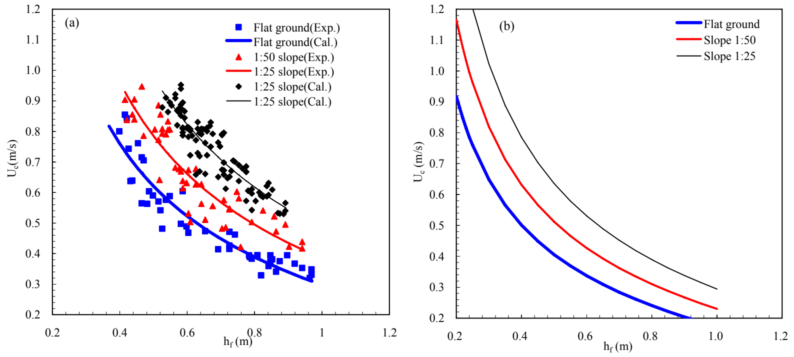

Figure 3 Suggested stability thresholds for (a) adults and (b) children

scaled-up experimental data obtained using Eq. (11) for the prototype are shown in the scattered points of Fig. 3a. In addition, substitution of the parameters for h_p = 1.7 m and m_p = 63.4 kg for a typical real human body into Eq. (10) can obtain the critical velocities for various water depths, using the values of α and β in Table 1, and as shown for the solid curves in Fig. 3a. Figure 3a indicates that the critical conditions obtained using the scale ratios compare well with the calculations from the derived formula under each ground slope. It should be noted that the model human body could not respond to the incoming flows in the physical and psychological attributes, and the incipient velocities calculated using Eq. (10) and the parameters in Table 1, would generally be less than the previous experimental data for real human bodies [9-10].

Figure 3b shows the relationships between the water depth and the incipient velocity under three ground slopes, as predicted using Eq. (10) and the parameters in Table 1, for a typical 7-year old child with a height of 1.26 m and a mass of 25.5 kg. It can be seen from Fig. 3 that for the same incoming depth of 0.60m, the estimated critical velocity for an adult is 0.52 m/s, which is greater than the corresponding value of 0.34 m/s for a child. Therefore, the stability degree for a flooded human body can be assessed using the corresponding curves in Fig. 3a or 3b according to the inflow conditions and the ground slopes.

4 CONCLUSIONS

In this study the criterion for the stability of a flooded human body has been investigated using theoretical and experimental studies. The formula has been developed based on a series of tests that were undertaken to establish the incipient velocity in a laboratory flume on a scaled model human body under three slopes. The following conclusions are drawn from this study:

(i) All of the forces acting on a flooded human body at toppling instability were analysed, with the corresponding formula being derived. Toppling instability of the body mainly occurs for higher depths and lower velocities, with the critical condition of the driving moment equaling the resisting moment.

(ii) 186 tests on the stability of a flooded human body were conducted in a flume using a scaled model body, with the incipient velocities being measured for a range of different water depths. The experimental data were used to calibrate two parameters in the derived formula, with the calibrated parameters representing relatively safe thresholds.

(iii) Toppling stability thresholds under different ground slopes for children and adults have been proposed, based on the parameters of body height and mass for real human subjects.

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