New criterion for the stability of a human body in floodwaters

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Abstract: Extreme flood events often lead to heavy casualties, with flood risk to humans varying with the flow conditions and the body attributes. Therefore, it is important to propose an appropriate criterion for the stability of a human body in floodwaters in the form of an incipient velocity. In this study, two formulae for the incipient velocity of a human body for sliding and toppling instability were derived, based on a mechanics-based analysis, and with both formulae accounting for the effect of body buoyancy and the influence of a non-uniform upstream velocity profile acting on the human body. More than 50 tests were conducted in a flume to obtain the conditions of water depth and velocity at instability for a model human body, with the experimental data being used to calibrate two parameters in the derived formulae. Finally, the proposed formulae were validated in detail against existing experimental data for real human subjects, with different stability thresholds being obtained for children and adults in terms of assessing their stability related to floodwaters..

Keywords: human body stability; floodwater; incipient velocity; mechanics-based analysis; flume experiments

1 Introduction

Due to the effects of climate change, the frequency of extreme flood events is expected to increase significantly in future years (IPCC 2007), with annual flood events often leading to significant damage and heavy casualties on a global scale. An analysis of global statistics shows that inland floods caused 175,000 fatalities and affected more than 2.2 billion people between 1975 and 2002 (Jonkman 2005, Jonkman and Vrijling 2008). During the same period, flash floods and urban floods due to heavy rainfall occurred frequently in China, causing considerable loss of life. Statistics from the Ministry of Water Resources of China (MWRC 2011) indicate that the average annual number of fatalities arising directly from floods was 5,500 during the period from 1950 to 1990, with the corresponding number being 3,940 in the 1990s; the average annual number of fatalities since 2000 has reduced to 1,610. However, severe flash floods and debris flows in 2010 led to a loss of more than 2,800 lives (MWRC 2011). More recently, flash flooding occurred in Beijing in July 2012, resulting in about 80 fatalities over two days (Xiao 2012). The safety of people can be compromised when exposed to floodwaters that exceed their ability to remain standing, or moving, with the stability of people in floodwaters being of major concern in the risk management of flood-prone areas (Cox *et al.* 2010). The risk to people in floodwaters is expected to increase in the future owing to the rapid growth in population, the continuous expansion in territories associated with human activity, and the increase in extreme meteorological events. Therefore, it is important to propose a quantitative method of assessing the stability of a human body in floodwaters, which can provide a scientific basis for flood risk management for those people in floodplains and urban areas.

There are two kinds of instability mechanisms identified by existing studies, including sliding (friction) and toppling (moment) instability (Keller and Mitsch 1993, Jonkman and Penning-Rowsell 2008, Cox *et al.* 2010). 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 weight of the body. The risk to a human body in floodwaters 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, such as height and weight. In addition, the risk to a human body is also influenced by psychological factors. For example, an alert and active person knowing the flow regime may be more capable of keeping the body stable when faced with an excessive floodwater force. This variation in the hazard degree of exposure to a human body in floodwaters needs to be estimated for effective flood risk management. Existing criteria for human body stability are represented by the incipient velocities for different depths, as people become unstable in floodwaters. The assessment of human body stability can thus be categorized into two types of criteria. The first type of criteria of human body stability consists of regressed relationships based on a number of laboratory experimental studies, using real human bodies, and the second type comprises empirical or theoretical formulae derived from a mechanics-based analysis (Defra and EA 2006, Cox *et al*. 2010).

The first type of human body stability criteria is mainly presented by Foster and Cox (1973), Abt *et al.* (1989), Takahashi *et al.* (1992), Karvonen *et al.* (2000), and Jonkman and Penning-Rowsell (2008). Foster and Cox (1973) conducted experiments on human stability in a 6 m long flume, with the subjects consisting of 6 boys, aged from 9 to 13 years. However, no quantitative assessment method was obtained from the experiments because the criterion developed for safe and unsafe critical flow conditions depended on the psychological tendency of the test children. Abt *et al.* (1989) reported laboratory experiments of human toppling instability conducted in a 61 m long flume with different ground surfaces, with one concrete monolith and 20 healthy adults being used as the test subjects. An equation defining the threshold of instability of a person in floodwaters was found by linear regression of the experimental data, 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.* (2000) undertook stability tests using seven human bodies aged from 17 to 60 years, standing on a steel grating platform towed in a model ship basin. Based on their experimental data, the product of flow and velocity describing the loss of stability or manoeuvrability of a person was closely related to the height and weight of a human body. Ishigaki *et al.* (2005) conducted laboratory experiments on the evacuation criteria of people from underground spaces in urban floods, and the experimental results indicated that a water depth of 0.3 m was shown to be a critical value for the evacuation from underground spaces through staircases. The Flood Hazard Research Centre in the UK conducted four controlled field tests of human body stability in a natural channel, using a professional stuntman as the test subject. For all of the tests failure was observed to occur for the mode of frictional instability with relatively low water depths and high velocities (Jonkman and Penning-Rowsell 2008). Due to the differences in physical attributes and psychological factors of the human subjects tested in the aforementioned experiments, there exists a wide range of criteria of human body stability in floodwaters. Furthermore, the experimental results indicate that the incoming unit discharge for human body instability was generally proportional to the product of the height and weight of a human body.

The second type of human body stability criteria includes representative studies, such as those of Defra and the EA (2006), Keller and Mitsch (1993), Lind *et al.* (2004), and Jonkman and Penning-Rowsell (2008). Defra and the EA (2006) reported a simple method to determine the rating of flood hazard for people based on velocity, depth and the presence of debris, and the resultant hazard rating can be divided into four corresponding types, ranging from a very low hazard (caution) to danger for all groups (including the emergency services). This criterion assumes that the stability degree of a human body is related only to the hydrodynamic conditions, and hence is independent of a person's physical attributes, such as body height and weight. Therefore, such a criterion is usually applied to a preliminary assessment of people safety in flood risk management. Keller and Mitsch (1993) conducted a purely theoretical study on people stability, and this study accounted for the instability modes of moment and friction of a vertical cylinder intended to represent a human body in floodwaters. The corresponding formula was derived from the equilibrium of forces acting on a flooded person during sliding or toppling, with a uniform velocity profile along the vertical direction being assumed. It should be noted that the derived formula was highly dependent on the selection of friction and drag coefficients. Lind *et al.* (2004) considered the toppling instability of a circular cylindrical, square cylindrical and cylindrical composite bodies, assembled to represent a human body immersed in floodwaters and subjected to drag and buoyancy forces, with the corresponding approximate mechanics-based formulae being established. The experimental data of Abt *et al.* (1989) and Karvonen *et al.* (2000) were used to calibrate and compare these mechanics-based formulae. Jonkman and Penning-Rowsell (2008) discussed two hydrodynamic mechanisms that can cause instability, covering moment instability and friction instability, and then presented the corresponding formulae for these two instability modes, with a uniform velocity profile being assumed and the buoyancy force not being included in the derivation for simplicity. An excessive simplification in the body structure of a human subject was usually made during the derivation of these formulations, based on the theoretical analysis, which led to the neglect, or the inaccurate calculation, of a person's buoyancy force for different water depths. Therefore, these existing criteria cannot be used to assess accurately the degree of human body stability in floodwaters.

All of the analyses reported above indicate that the criteria of human body stability, based on laboratory experiments using real human bodies, are significantly dependent on the physical attributes and psychological factors of the test subjects, while the criteria based on the empirical or theoretical analysis assumes excessive simplifications on the human body structure and the flow conditions. Therefore, it is appropriate to propose a new criterion for human body stability in floodwaters based on further theoretical and experimental studies. In this study, different forces acting on a human body have been analysed, with the corresponding expressions for these forces being presented, and with the formulae of incipient velocity being derived based on instability mechanisms for sliding and toppling respectively. The derived formulae can account for the effect of body buoyancy through calculating the values of the human body volume for different water depths, and can also consider the influence of a non-uniform velocity profile upstream on the stability of the body. 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 model of a human body. The experimental data from this investigation were then used to determine two parameters in the derived formula for each instability mode. Finally, the derived formulae were validated in detail using experimental data obtained from the calculations based on the scale ratios and other existing experimental data for real human subjects, with stability thresholds in floodwaters being proposed for both children and adults.

2 Force analysis and formula derivation

Two possible instability mechanisms are primarily identified, including sliding (friction) and toppling (moment) instability, when considering the stability of a human body in floodwaters. Figure 1 shows a sketch of all the forces acting on a flooded human body for friction and moment instability. Another instability mechanism of floating can occur if the water depth exceeds the height of the body, and thus the stability of the body is no longer subject to the instability calculations of sliding and toppling. In general, the density of a human body is slightly greater than the density of water, and the probability of floating is therefore small in practice. Therefore, the current study only focuses on investigating sliding and toppling instability mechanisms for a human body in floodwaters.

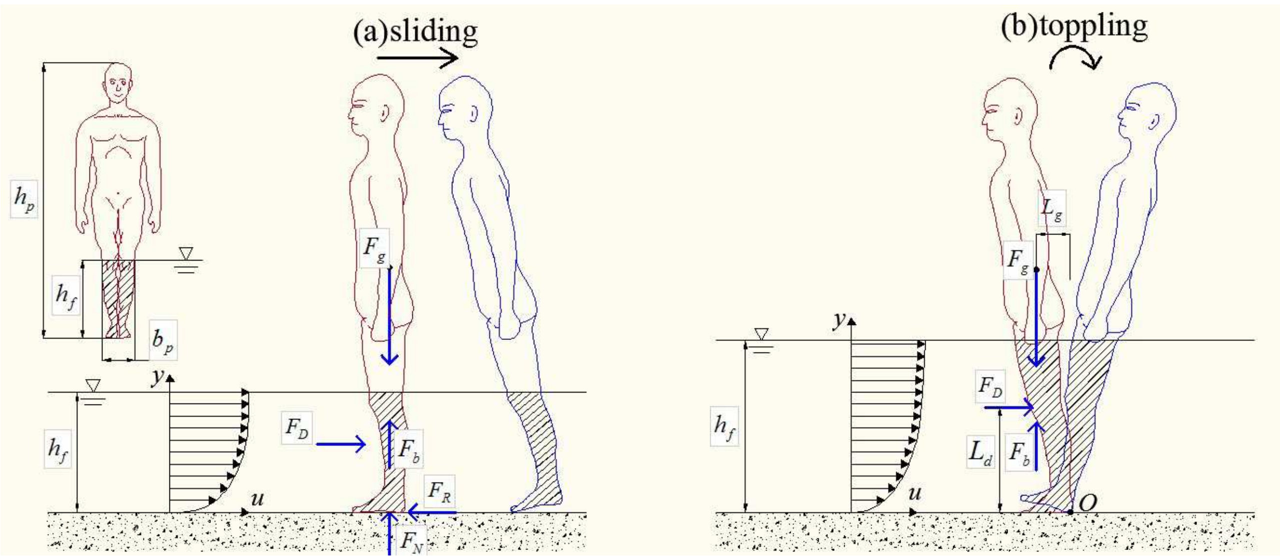

Figure 1 Sketch of governing forces acting on a flooded human body at instability for: (a) friction and (b) moment

2.1 *Forces acting on a flooded human body*

The theoretical analysis of the stability of a human body in floodwaters is approximately similar to the method used for predicting the incipient motion of a coarse sediment particle in analyzing sediment transport in river dynamics (e.g. Zhang and Xie 1993), or deriving the incipient velocity formula for flooded vehicles in flood risk analysis (Xia *et al.* 2011, Shu *et al.* 2011). If a human body stands in floodwaters, then the body needs to be able to withstand the drag force (F_D) of the flowing water and the frictional force (F_R) between the feet of the body and the ground surface in the horizontal direction. Likewise, in the vertical direction, the body experiences its own gravitational force (F_g), its buoyancy force (F_b) and the normal reaction force (F_N) from the ground. Therefore, the stability of a human body subject to flooding is controlled by the above five forces, with the corresponding expression for each force being presented in detail as follows:

(1) Buoyancy force

The calculation of the buoyancy force needs to account for the dimensions 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 size of various segments, such as the shanks, thighs and torso. 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 (Drillis *et al.* 1964, Sandroy and Collison 1966, Guo and Wang 1995). For example, the height from the foot to the knee for a Chinese adult generally ranges from $0.261h_p$ to $0.265h_p$, and the volume of the thighs and shanks approximates to $0.266v_p$.

According to the definition of the buoyancy force, F_b, this can be expressed as:

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

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. It is therefore clear that the magnitude of V_b is related to the values of h_f, h_p and v_p. Hence, an empirical relationship can be established between the buoyancy force exerted by the water upthrust (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 with sufficient accuracy, and with the corresponding expression being written as:

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

where a_1 and b_1 are non-dimensional coefficients, and x is the ratio of the water depth to the body height, with $x = h_f / h_p$. Equation (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 (Guo and Wang 1995), which can be expressed by:

$$v_p = a_2 m_p + b_2 \tag{3}$$

where a_2 and b_2 are coefficients, and these coefficients can be determined for the average attributes of a human body. Therefore, the buoyancy force can be represented as a function of the height (h_p) and the mass (m_p) of a human body, for a given water depth (h_f), and substitution of Eqs. (2) and (3) into Eq. (1) yields:

$$F_b = g\rho_f (a_1 x^2 + b_1 x)(a_2 m_p + b_2) \tag{4}$$

The coefficients a_1 and b_1 in Eq. (2) can be determined from the characteristic parameters of the body structure. The calibrated values of a_1 and b_1 for a typical human body of a Chinese person are 0.633 and 0.367, respectively (Guo and Wang 1995). According to the data on body segment parameters for an American subject, as presented by Drillis *et al.* (1964), the parameters in Eq.(2) can be determined and give the calibrated values for a_1 and b_1 of 0.737 and 0.263, respectively. According to the average body attributes for Chinese people, 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 (Guo and Wang 1995).

(2) Drag force

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

$$F_D = 0.5 A_d C_d \rho_f u_b^2 \tag{5}$$

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 which is used to account for the effect of clothing worn normally on the wetted area, and b_p is the average body width exposed normal to the flow. 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. (5) for the calculation of F_D. As widely known, the value of C_d is a function of the subject shape and the object Reynolds number (R), expressed roughly by $\mathsf{R} = U b_p / \nu$, where ν is the kinematic viscosity of water, and U is the depth-averaged velocity. It is regarded that C_d is independent of the object Reynolds number as R > 2.0×10^4 (Chanson 2004).

For floodwaters occurring in floodplains and urban areas, the magnitude of the velocity will be typically in the range from 0.5 to 3.0 m/s, and the corresponding values of the object Reynolds number will vary typically from 1.5×10^5 to 9.0×10^5, for a mean value of b_p for a real human subject assumed to be 0.30 m. It is therefore assumed that C_d is a constant for large values of the object Reynolds number, and has the same magnitude for the model and prototype (Chanson 2004). Among the studies undertaken for human bodies by Keller and Mitsch (1993), Lind *et al.* (2004), and Jonkman and Penning-Rowsell (2008), constant values of C_d ranging from 1.1 to 2.0 were adopted. 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.

(3) Effective weight

For a human body standing in floodwaters, it is assumed that the action position of the buoyancy force is in line with the centre of gravity of the body, and the forces of F_g and F_b can then be jointly called the effective weight F_G, with $F_G = F_g - F_b$. With Eq. (4) and the expression for gravity in terms of $F_g = g\ m_p$, F_G can be expressed as:

$$F_G = gm_p - F_b = g\left[m_p - \rho_f(a_1x^2 + b_1x)(a_2m_p + b_2)\right] \quad (6)$$

(4) Frictional force

The frictional force is exerted on the interface between the feet of a person and the ground surface, and can be expressed as $F_R = \mu\ F_N$, where F_N is the normal reaction force from the ground surface, and is generally equivalent to the effective weight of a flooded human body, namely $F_N = F_G$, and μ is the friction coefficient between the sole of the feet and the wet ground surface, which is closely related to the ground roughness, shape and degree of wear on the soles. The friction coefficient μ = 0.3 - 1.0 was used in the human stability analyses conducted by Keller and Mitsch (1993), and Jonkman and Penning-Rowsell (2008). Takahashi *et al.* (1992) conducted a series of tests on the friction coefficient for a range of leather and rubber soled shoes on various ground surfaces, and obtained values for the friction coefficient in the range from 0.2 to 1.5. Therefore, the selection of μ needs to be estimated by the roughness of the ground surface and the characteristics of the soles of shoes. With known values for the friction coefficient and the normal reaction force, the expression for the frictional force can be written further as:

$$F_R = \mu F_N = \mu g\left[m_p - \rho_f(a_1x^2 + b_1x)(a_2m_p + b_2)\right] \quad (7)$$

2.3 Formula derivation for different instability modes

The above force analysis for a flooded human body indicates that the occurrence of the two different instability modes depends on the hydrodynamic conditions. The critical condition for sliding instability is that the drag force of the flowing water is equal to the frictional force between the soles and ground surface, which mainly occurs for shallow depths and high velocities. Likewise, the mode of toppling instability occurs when the driving moment induced by the drag force is equal to the resisting force, resulting from the effective weight of the body and which mainly occurs for large depths and low velocities.

(1) Formula for sliding instability mode

The critical condition for sliding instability can be expressed by $F_D = F_R$, as shown in Fig. 1(a), and substitution of Eqs. (5) and (7) into this expression yields:

$$C_d(a_d b_p h_f)\rho_f \frac{u_b^2}{2} = \mu g[m_p - \rho_f(a_1 x^2 + b_1 x)(a_2 m_p + b_2)] \tag{8}$$

Re-arranging Eq. (8) yields the following detailed expression for u_b:

$$u_b^2 = \frac{2\mu g}{\rho_f C_d(a_d b_p h_f)}[m_p - \rho_f(a_1 x^2 + b_1 x)(a_2 m_p + b_2)] \tag{9}$$

It is not easy 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 (Zhang and Xie 1993, Wu 2007). A complex velocity field distribution can form around a human body when it is exposed to floodwater, however, the current study does not consider the detailed complex velocity field around a flooded human subject. Therefore, it is assumed that the incoming flow velocity upstreamis characterized by a power-law distribution of velocity, but β generally deviates from the above value for such a condition. For urban floods the water depth can be larger, sometimes approaching the height of a human body, and the analysis is also based on the concept of incipient motion for a coarse sediment particle in a similar context to river dynamics (Zhang and Xie 1993, Chien and Wan 1999), It is therefore assumed that the representative height for u_b is equal to $a_b h_p$, giving $u_b = (1+\beta)U(a_b h_p/h_f)^{\beta}$, in which a_b is a coefficient related to the body height, which would generally be a very small value of the order to satisfy the condition of $a_b h_p < h_f$. Therefore, the magnitude of u_b is closely related to the values of both h_p and h_f. However, the representative height can also be assumed to be equal to a function of the incoming water depth, with similar formulae being derived. This analysis will be fully considered in future investigations through measuring the detailed velocity profiles around a flooded human body and using an acoustic Doppler velocimeter or similar instruments.

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 related to the body structure. Substituting the expression for u_b and the relationship for b_p into Eq. (9), the incipient velocity (U_c) for a human body in floodwaters at sliding instability can therefore be written as:

$$U_c = \alpha \left(\frac{h_f}{h_p} \right)^{\beta} \sqrt{\frac{m_p}{\rho_f h_p h_f} - (a_1 \frac{h_f}{h_p} + b_1) \frac{(a_2 m_p + b_2)}{h_p^2}} \qquad (10)$$

where $\alpha = \sqrt{2\mu g / (C_d a_d a_p)} / [(1+\beta)(a_b)^{\beta}]$. The determination of the parameters α and β is related to the shape of the body, and the frictional and drag coefficients can be evaluated from the corresponding experimental data. It can be seen from Eq. (10) that the first term inside the root represents the effects of gravity, while the second term is related to the effect of buoyancy. If the buoyancy term inside the root is neglected in the derivation and a uniform velocity profile (i.e. $\beta = 0$) is assumed, then simplification of Eq. (10) would give a similar equation to existing formula widely used (Jonkman and Penning-Rowsell 2008).

(2) Formula for toppling instability mode

When a person stands facing the on-coming flow direction, as shown in Fig. 1(b), 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 $F_D L_d - F_G L_g = 0$, 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_g is the moment arm of the effective weight, with $L_g = a_g h_p$, and a_g is the correction coefficient of the distance between the position of the centre of gravity of the body and the heel. Substitution of the expressions for L_d and L_g and the relationship for b_p for the critical condition for toppling instability yields:

$$[C_d(a_d a_p h_p h_f)\rho_f \frac{u_b^2}{2}](a_h h_f) - (a_g h_p) g [m_p - \rho_f (a_1 x^2 + b_1 x)(a_2 m_p + b_2)] = 0 \tag{11}$$

Re-arrangement of Eq.(11) gives the following expression for u_b:

$$u_b = \sqrt{\frac{2 g a_g}{C_d a_d a_p a_h}} \sqrt{\frac{1}{h_f h_f}[\frac{m_p}{\rho_f} - (a_1 x^2 + b_1 x)(a_2 m_p + b_2)]} \tag{12}$$

Similarly, the depth-averaged velocity in the power-law distribution is used to substitute for u_b in practice, with the relationship between u_b and U being expressed as: $u_b = (1+\beta) U (a_b h_p / h_f)^{\beta}$. Substituting the expression for u_b into Eq. (12), the incipient velocity for a flooded human body at toppling instability can then be written as:

$$U_c = \alpha (\frac{h_f}{h_p})^{\beta} \sqrt{\frac{m_p}{\rho_f h_f^2} - (\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p})(a_2 m_p + b_2)} \tag{13}$$

where $\alpha = \sqrt{2 g a_g / [C_d a_d a_p a_h a_b^{2\beta} (1+\beta)^2]}$. The parameters α and β can be evaluated from the relevant 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. (13), cannot be neglected in the derivation of the formula for the mode of toppling stability.

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 (e.g. the Froude number similarity) (Zhang and Xie 1993, Chanson 2004). The hydraulic model for the stability of a human body in floodwaters 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 for this investigation, and the height and mass of the selected model were 30 cm and 0.334 kg, respectively. For the prototype, the corresponding height and mass were equal to 1.70 m and 60 kg, respectively. According to the conditions for kinematic similarity, the scale ratio for the velocity λ_U was expressed as: $\lambda_U = (\lambda_L)^{0.5} = 2.35$. 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 (Chanson 2004), and it was concluded that C_d for the model was nearly equal to that for the prototype, which led to $\lambda_{F_D} = \lambda_F$. A thin cement layer was specially paved on the bed surface of the flume in order to meet the similarity of the friction roughness, and the measured friction coefficient was about 0.5 between the soles of the model body and the wet cement surface; this corresponded well with the range for the prototype parameters used in the experiments of Takahashi *et al.* (1992). It was deduced that the friction coefficient for the model was nearly equal to that for the prototype, which led to $\lambda_{F_R} = \lambda_F$.

In order to calibrate the parameters for α and β in Eqs.(10) and (13), a series of tests were conducted in a flume in the Sediment Research Laboratory, at Wuhan University, China, to investigate the critical condition of stability for the selected model human body. The horizontal flume was 60 m long, 1.2 m wide and 1.0 m deep, with a cement based bed and two glass sides. Before instability, the model body was kept standing for two postures in the flowing water, with these including : (i) facing the on-coming flow direction, and (ii) with the back of the body directed towards the on-coming flow, as shown in Fig. 2. For each test the water depth and corresponding depth-averaged velocity were recorded when the flooded model body started to become unstable, with the corresponding instability mode of sliding, or toppling, being identified for each test. The depth-averaged velocity was calculated based on the point-velocity profile measured using a propeller-type current meter, and the water depth upstream of the model was measured by a probe-type water level gauge. Due to the approximately flat bed, the flow in the flume was steady and non-uniform. The velocity and depth usually varied as the flow approached the flooded model. Therefore, it was assumed in the analysis that the velocity and depth were measured at a site specified to obtain the characteristic flow parameters acting on the model human body, and this site was located at a distance of 10 cm (about two times the model width) upstream of the flooded subject.

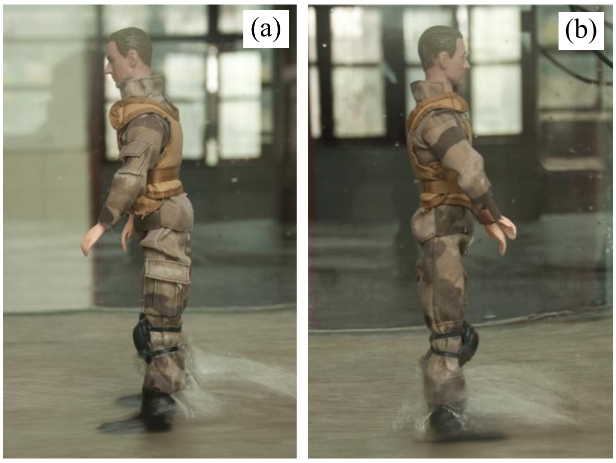

Figure 2 Two standing postures of the model human body in the flume: (a) facing and (b) with the back toward the on-coming flow.

It should be noted that the above tests, using the scale model human body, were different from previous experiments conducted using real human bodies (Abt *et al.* 1989, Karvonen *et al.* 2000). The model body tested in this study could not adjust its standing posture under the action of the flowing water, whereas the real human bodies studied during the stability experiments could adjust their posture and gradually adapt to the on-coming flows. Therefore, the experimental results obtained from the current 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 instability for both sliding and toppling were obtained by studying the response of the model human body in the flume, as shown in Fig. 3. At sliding or toppling instability, the critical velocity is a function of the water depth; with an increase of water depth, the incipient velocity decreases accordingly. It can be seen from Fig. 3 that: (i) only 8 tests were conducted for the mode of sliding instability due to the limited experimental conditions, while 46 tests were conducted for the mode of toppling instability, with sliding instability usually occurring for flows with shallow water depths and high velocities (Fig. 3(a)), and toppling instability generally occurring for the flows with large depths and low velocities (Fig. 3(b)). During the tests, it was not easy to judge the exact type of instability for the model human body as the water depth approached 0.03 m, and there existed an overlap of data for different instability mechanisms in Fig. 3(a) and 3(b).

(ii) the experimental data with the model facing the on-coming flow were slightly different from the data with the model located with the back of the body facing the on-coming flow, indicating that there was no substantial difference in the conditions of incipient motion for these two standing postures; and

(iii) the incipient velocity for the model decreased with an increase in the water depth for each instability mode, which was attributed to two causes. On the one hand, the wetted area increased as the depth increased, which led to an increase in the drag force; whilst on the other hand, the increase in the buoyancy force reduced the effective gravity for a larger depth, resulting in a net decrease in the frictional force resisting sliding or in the moment resisting toppling.

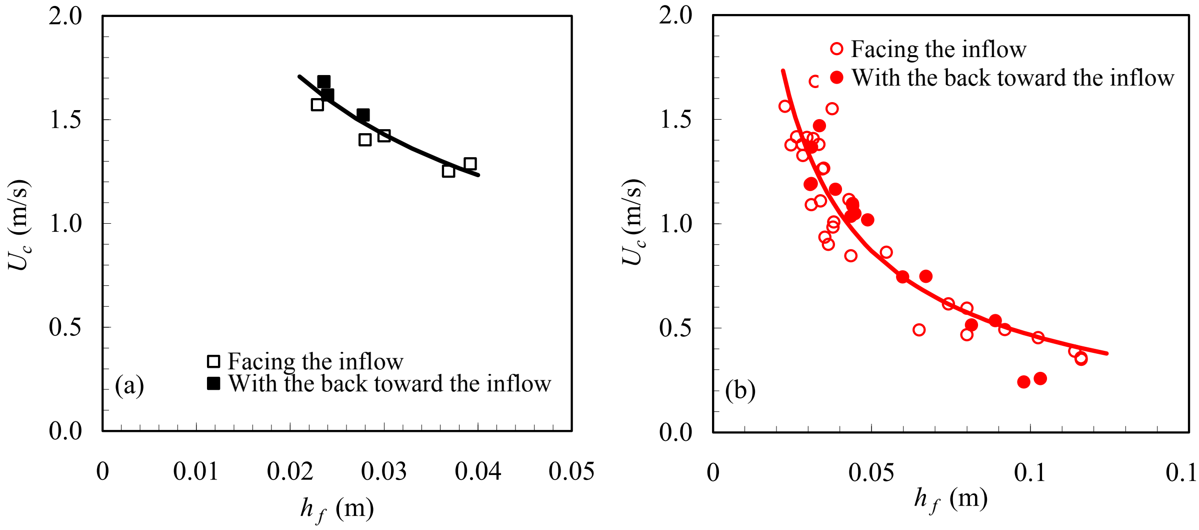

Figure 3 Relationships between the water depth and corresponding incipient velocity for a model human body at instability of: (a) sliding and (b) toppling

3.3 Parameter calibration

The formula structure is relatively complex in Eqs. (10) and (13) due to the introduction of the buoyancy force. In order to determine the parameters of α and β, Eq.(10), or Eq. (13), is transformed to $U_c/\sqrt{m_p/(\rho_f h_p h_f)-(a_1 h_f/h_p+b_1)(a_2 m_p+b_2)/h_p^2}=\alpha(h_f/h_p)^{\beta}$ or $U_c/\sqrt{m_p/(\rho_f h_f^2)-[a_1/h_p^2+b_1/(h_f h_p)](a_2 m_p+b_2)}=\alpha(h_f/h_p)^{\beta}$, respectively. For a particular human body, the values of m_p, h_p, a_1, b_1, a_2 and b_2 are constant. Therefore, both α and β values can be determined by the statistical analysis software package SPSS. The calibrated parameters of α and β 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 formula, with this meaning that a better fit has been obtained using this analysis. Based on the above force analysis, the calibrated value of α is influenced by the shape of the test model, the friction coefficient between the soles and the ground surface, and the drag coefficient. As shown in Table 1, the calibrated value of β is equal to 0.018 for the mode of sliding instability. This instability mode usually occurs for supercritical flow conditions, with low depths and high velocities. For this condition, the vertical distribution of velocity tends to follow a relatively uniform profile, and the magnitude of β approaches a small value. However, the mode of toppling instability generally occurs under subcritical flow conditions, with high depths and low velocities, and therefore the calibrated value of β is in the same range typical of 1/7 to 1/6 for the power-law distribution of velocity for common open channel flows.

Table1 Calibrated parameters in Eqs. (10) and (13) using the experimental data for a model human body

Formula	Parameter calibration		R^2	Instability mode	Number of tests
	α [$m^{0.5}$/s]	β [-]			
Eq. (10)	7.975	0.018	0.883	Sliding	8
Eq. (13)	3.472	0.188	0.853	Toppling	46
Note: other parameters used in formulae, covering: a_1 = 0.633; b_1 = 0.367; a_2 = 1.015×10^{-3} m^3/kg; and b_2 = -4.927×10^{-3} m^3.					

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

$$h_{fp} = h_{fm}\lambda_L \quad \text{and} \quad U_{cp} = U_{cm}\sqrt{\lambda_L} \tag{14}$$

where the subscripts p and m refer to prototype and model parameters, respectively. The scaled-up experimental data obtained using Eq. (14) for the prototype are shown in the scattered points of Fig. 4. In addition, substitution of the parameters for h_p = 1.7 m and m_p = 60 kg for a typical (Chinese) real human body into Eqs. (10) and (13) can be used to obtain the critical velocities for various water depths, using the corresponding values of α and β in Table 1, and as shown for the solid curves in Fig. 4. Figure 4 indicates that the critical conditions obtained using the scale ratios compare well with the calculations from the derived formulae, confirming the accuracy of the critical conditions for the prototype estimated using these two approaches. A fully unbiased validation of the proposed formulae requires additional experimental data for a large-scale model human body, which will be conducted in a future study. 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 Eqs. (10) and (13), with the calibrated parameters in Table 1, would generally be less than the previous experimental data for real human bodies in flumes (Abt *et al.* 1989, Karvonen *et al.* 2000).

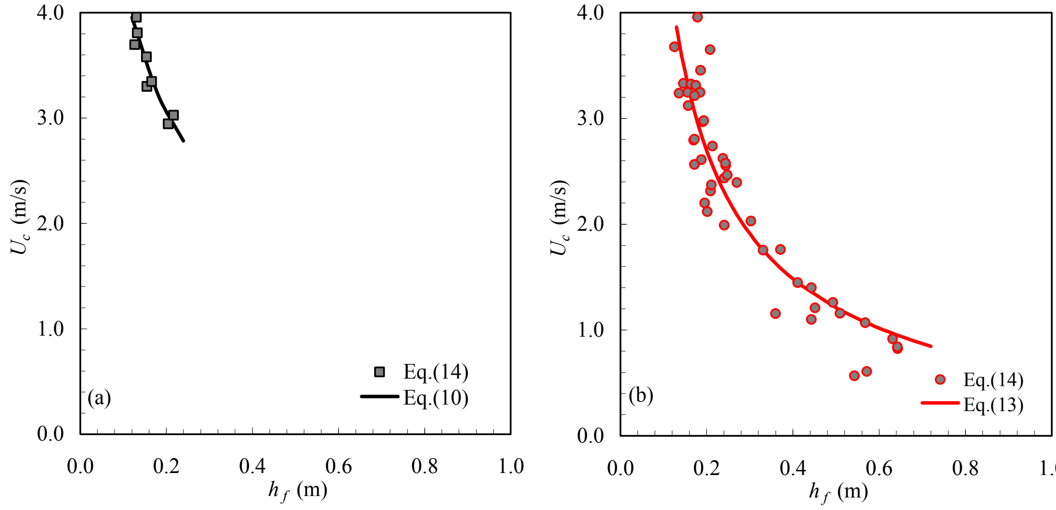

Figure 4 Comparisons between the experimental data using the scale ratios and the calculations using the derived formulae at instability modes of: (a) sliding and (b) toppling

4 Comparison with the experimental data for real human bodies

Existing experimental data for the stability of human bodies in floodwaters using real human subjects are mainly represented using the results of Abt *et al.* (1989) and Karvonen *et al.* (2000). There exists a wide range of measured incipient velocities due to the differences in the experimental conditions and test subjects, with the majority of the experimental data being obtained for the critical conditions at the mode of toppling instability. The incipient velocities for different water depths, obtained from the tests conducted by Abt *et al.* (1989), were generally 30% smaller than the experimental data obtained by Karvonen *et al.* (2000). If the ability of the subject to manoeuvre in the flowing water was included in the derived formulae, it was then appropriate to re-calibrate the parameters for α and β in Eqs. (10) and (13), using the corresponding experimental data for real human subjects. These experiments indicated that sliding instability mainly occurred for flows with shallow depths and high velocities, but with limited test results being obtained. However, it was assumed that from the experiments for real human subjects, there was a strong possibility that if the water depth was less than knee height, then sliding instability was most likely to occur, and the corresponding data were used to re-evaluate the parameters for the mode of sliding instability. The remaining experimental data were used to re-evaluate the parameters for the mode of toppling instability.

4.1 Separate comparison with the tests of Abt *et al.* and Karvonen *et al.*

Abt *et al.* (1989) also conducted experimental studies on the stability of human bodies in floodwaters, using 20 real human subjects, consisting of 18 males and 2 females, with the body weights ranging from 40.9 to 91.4 kg. The flume studies were undertaken for two slopes of 0.5 and 1.5%, with four different bottom surfaces, and with 25 and 46 tests being conducted for each slope respectively. The majority of the water depths were greater than 1.0 m, which led to the dominant mode of instability being due to toppling. Therefore, it was confirmed that the effect of different bottom surfaces on the incipient motion of test subjects was not important (Abt *et al.* 1989, Lind *et al.* 2004). These human subjects were subjected to flow velocities ranging form 0.36 to 3.05 m/s and water depths varying from 0.49 to 1.20 m, and they were allowed to acclimatise and acquire experience in maneuvering in the flow. These subjects were permitted to adjust their standing postures according to the inflow conditions, which led to the result that the incipient velocity for a real human body was greater than the corresponding value for the model human body, as tested in this study.

Based on these experimental data, Abt *et al.* (1989) established an empirical relationship between the product of depth and velocity and the product of height and weight of the subject tested, with the square of the correlation coefficient (R^2) for linear regression being 0.48. The low degree of correlation was attributed to the wide scope of maneuverability of the body in the flow. Jonkman and Penning-Rowsell (2008) developed a formula for predicting the incipient velocity at toppling instability, and $R^2 = 0.34$ was calculated to indicate a poor fit effect according to the tests by Abt *et al.* (1989), which could be partly attributed to the fact that the proposed formula did not account for the effects of the buoyancy force acting on the human body and the non-uniform velocity profile along the vertical direction. If the experimental data of Abt *et al.* (1989) were used to calibrate the parameters in Eq. (13), then values of α = 8.855 m$^{0.5}$/s and β = 0.473 would have been obtained, together with a relatively high value of $R^2 = 0.561$ (Fig. 5a). Therefore, it is appropriate to account for the effects of the buoyancy force and the non-uniform velocity profile in the derived formula for the estimation of the stability conditions of flooded people.

The real seven human subjects (i.e. 5 males and 2 females) in the experimental programme of Karvonen *et al.* (2000) wore survival suits and safety helmets, with the body heights ranging from 1.60 to 1.95 m, and the body weights varying from 48 to 100 kg. The hydrodynamic factors used in the tests included: depths ranging from 0.30 to 1.10 m and velocities varying from 0.60 to 2.71 m/s. Each subject first familiarised himself or herself with the test facility and safety equipment in stagnant water, and the velocity was then gradually increased until the subject lost stability or manoeuvrability. It was observed that some air was trapped inside the suit, causing an increase in the buoyancy force. In addition, the wetted area of a human subject was slightly larger while wearing a survival suit as compared to wearing normal clothing, leading to slightly lower incipient velocities. If only the experimental data of Karvonen *et al.* (2000) are used to evaluate the parameters in Eq. (13), then values of α = 4.825 $m^{0.5}/s$ and β = 0.160 are determined, giving a higher value of R^2 = 0.922 (Fig. 5(b)), which is higher than the value of R^2 = 0.75, calibrated by Jonkman and Penning-Rowsell (2008).

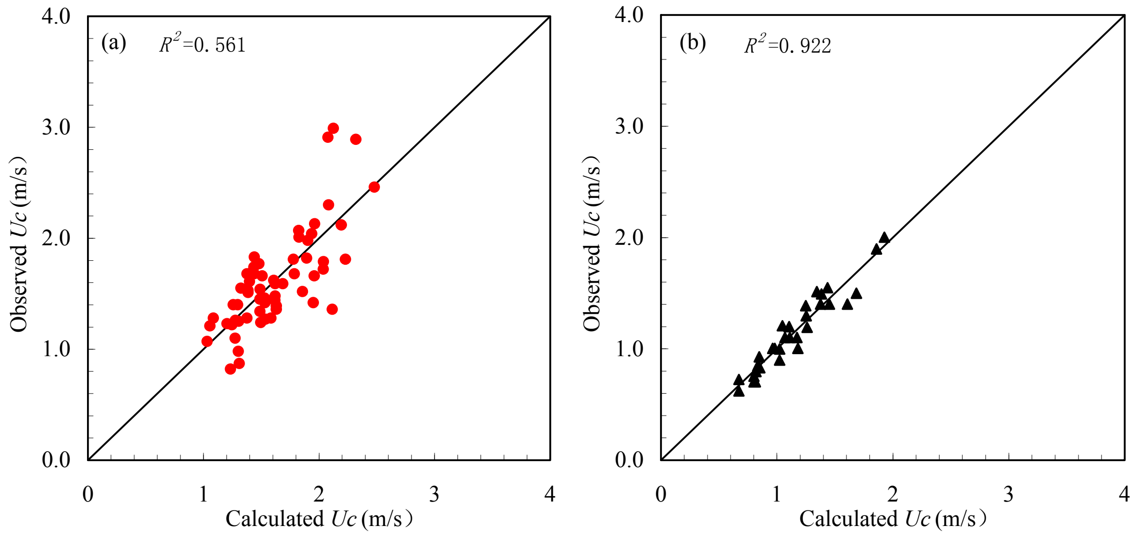

Figure 5 Comparisons between the calculations using further calibrated formulae and the experimental data of: (a) Abt *et al.* (1989), and (b) Karvonen *et al.* (2000)

4.2 Comparison with all the tests

Experimental data for 22 tests at sliding instability using real human subjects (Foster and Cox 1973, Karvonen *et al.* 2000, Yee 2003, Jonkman and Penning-Rowsell 2008) were collected in this study. These data were used to re-evaluate the parameters α and β in Eq. (10), as shown in Table 2. Figure 6(a) shows a significant difference between the experimental data and the predicted incipient velocities for sliding instability using the re-evaluated parameters. This difference is due to: the limited number of tests, the various experimental conditions, and the different criteria for instability. In addition, the experimental data of both Abt *et al.* (1989) and Karvonen *et al.* (2000) have been used to re-evaluate the parameters α and β in Eq. (13), with the calibrated values shown in Table 2, and the comparison between the experimental and predicted data being shown in Fig. 6(b). Figure 6(b) indicates that the experimental results of Abt *et al.* (1989) generally give slightly higher values than the experimental data of Karvonen *et al.* (2000), leading to a lower value of R^2 = 0.465.

Table 2 Re-calibrated parameters in Eq. (10) and Eq.(13) using the experimental data for real human bodies

Formula	Parameter calibration		R^2	Instability mode	Number of tests
	α [m$^{0.5}$/s]	β [-]			
Eq. (10)	10.253	0.139	0.512	Sliding	22
Eq. (13)	7.867	0.462	0.465	Toppling	89

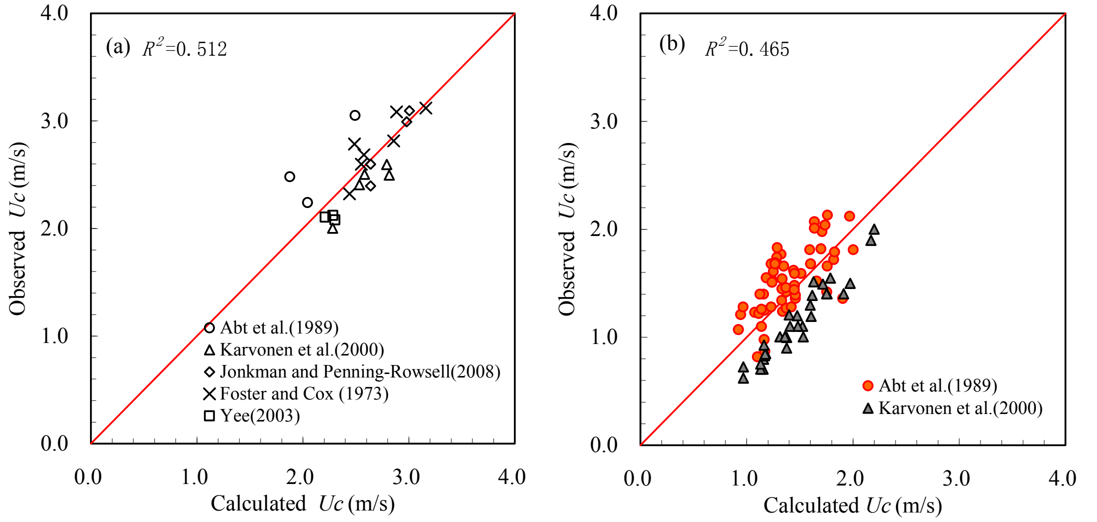

Figure 6 Comparisons between the experimental data for real human bodies and the calculations using the re-calibrated formulae at the instability modes of: (a) sliding and (b) toppling

The above analysis indicates that many factors influence the stability of a real human body when exposed to floodwaters, including: (i) physical attributes of a body such as age, sex, height and weight; (ii) psychological factors, such as the ability to adjust to the standing posture towards the on-coming flow; and (iii) experimental conditions, such as the on-coming flow intensity, ground surface and slope (Lind *et al.* 2004, Cox *et al.* 2010). Although the correlation coefficients cited in Table 2 and obtained from the experimental data for real human bodies are relatively low, these re-evaluated parameters generally account for the critical conditions under different experimental arrangements and various test bodies, which can then be used to predict the incipient velocity at instability for a human body in floodwaters. However, when the re-calibrated values of β are based on experimental data for real human subjects, these values not only account for the effect of a non-uniform velocity distribution along the vertical direction, but they also include the effect of the ability of a human body to adjust to the standing posture, according to the on-coming flow intensity to varying degrees. Therefore, these parameters deviate from the common values, and the results obtained using these parameters would tend to be optimistic, and even potentially dangerous to use in practice, from the viewpoint of flood risk analysis.

4.3 Suggested stability thresholds

There exists a significant difference between the stability thresholds for the model human body and the real human body. The criteria from the tests using the model human body would be more reliable since the model body could not adjust its standing posture according to the flow conditions and therefore becomes unstable for lower velocities. However, the proposed criteria from the tests using real human bodies tended to be more optimistic (and potentially dangerous) due to the inclusion of a person's ability to adapt to the on-coming flow. Based on the calculations using the parameters in Table 1 and Table 2, the toppling stability thresholds for children and adults as suggested in this study, are shown in Fig. 7. The sliding stability thresholds are not included herein, since the mode of sliding instability seldom occurs in practice due to the rare occurrence of low depth and high velocity.

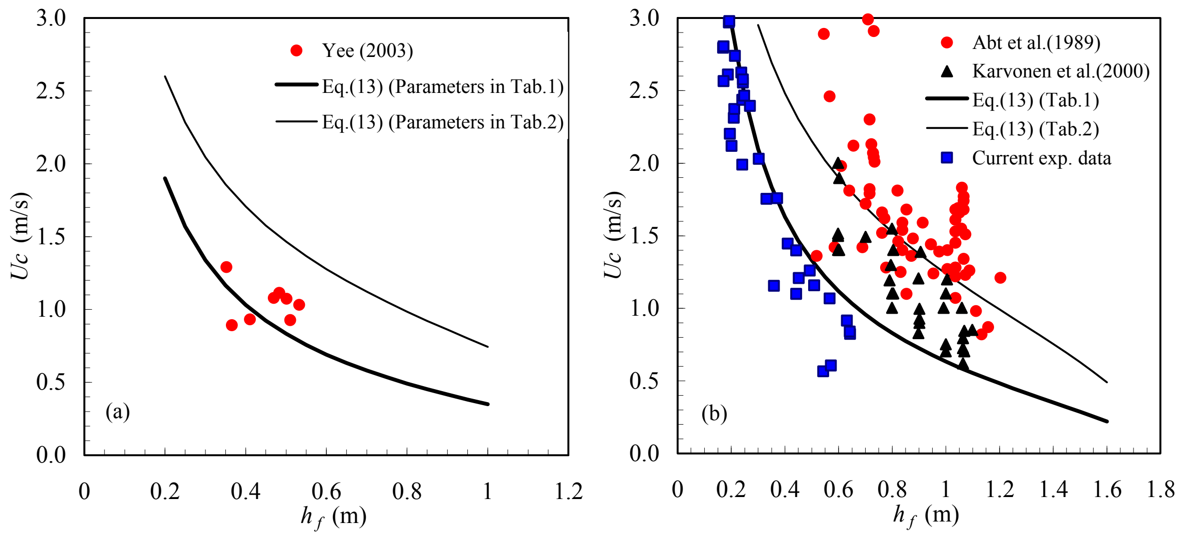

Figure 7 Suggested stability thresholds for: (a) children; and (b) adults

The average parameters for a human body are relevant to Chinese children and adults in the calculations in Fig. 7. Figure 7(a) shows the relationships between the water depth and the incipient velocity, as predicted using the parameters in Table 1 and Table 2, for a typical 7-year old child with a height of 1.26 m and a mass of 25.5 kg. The thin solid curve predicted using the parameters in Table 2 represents the relatively dangerous threshold, while the thick solid curve, predicted using the parameters in Table 1, highlights the relatively safe threshold. The zone between these two curves indicates the moderate hazard region for a child at toppling instability. Figure 7(b) shows similar threshold curves for an adult with a height of 1.71 m and a mass of 68.7 kg. In addition, almost all of the experimental data obtained using the model and real human bodies are included in Fig. 7 as reference values. Therefore, the stability degree for a human body in floodwaters can be assessed using the corresponding curves in Fig. 7(a) or 7(b) according to the inflow conditions.

5 Conclusions

In recent years extreme floods appear to have occurred with increasing frequency and flash floods due to intense rainfall, particularly in urban areas. These floods have been attributed to climate change and have led to serious casualties, and even fatalities, in China and elsewhere. Existing studies have indicated that human bodies have become unstable when exposed to floodwaters under certain conditions, with a considerable increased risk of direct mortality if the person is swept away by the floodwaters. In this study the criterion for the stability of a human body in floodwaters has been investigated using theoretical and experimental studies, combined with a mechanics-based approach. These formulae have been developed based on data acquired for a series of tests undertaken to establish the incipient velocity in a laboratory flume on a scaled model human body. The formulae derived can be used to predict the incipient velocity of a human body at the onset of sliding and toppling. The following key conclusions are drawn from this study:

(i) All of the forces acting on a flooded human body were analysed. It was established that sliding instability mainly occurs for shallow depths and high velocities, with the critical condition being that the drag force induced by the flow is governed by the frictional force between the soles of the feet and the ground surface. In contrast, toppling instability of the body mainly occurs for higher depths and lower velocities, with the critical condition being the driving moment. This moment is governed by equating the product of the drag force and lever arm from the bed to the centre of mass, with the resisting moment, which is determined by the product of the effective weight of the body and the offset lever arm from the centre of mass to the pivot point. Based on the theory developed herein, and similar to the incipient motion for a coarse sediment particle, formulae were derived for the incipient velocity of a human body for the instability modes of sliding and toppling.

(ii) More than 50 tests on the stability of a 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 evaluate the key parameters in the derived formulae, with the evaluated parameters representing relatively safe thresholds. The parameters in the formulae were also evaluated using experimental data for real human bodies published in the literature, which represented more dangerous thresholds due to the ability of the human body to resist sliding or toppling.

(iii) Toppling stability thresholds for children and adults have been proposed in this study, based on the evaluated results obtained using different sets of experimental data, obtained from the literature for real human subjects. The stability thresholds evaluated for real human subjects tend to be more optimistic (and therefore potentially more dangerous), as compared with the stability thresholds obtained for the model human body. This more optimistic threshold occurs because the the real human subject tests account for the ability of the subject to adjust to the standing posture according to the on-coming flow conditions and to redirect the orientation of the body to best suit the direction of the flow.

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Notation

a_1 = coefficient in Eq.(2) (-)

a_2 = coefficient in Eq.(3) (m^3/kg)

b_1 = coefficient in Eq.(2) (-)

b_2 = coefficient in Eq.(3) (m^3)

C_d = drag coefficient (-)

F_b = buoyancy force (N)

F_D = drag force (N)

F_G = effective body weight (N)

F_g = gravitational force (N)

F_N = normal reaction force from ground (N)

F_R = frictional force between feet and ground surface (N)

g = gravitational acceleration (m/s^2)

h_f = water depth (m)

h_p = height of human body (m)

L_d = moment arm of drag force (m)

L_g = moment arm of effective weight (m)

m_p= mass of a human body (kg)

R = object Reynolds number (-)

u_b = representative near-bed velocity (m/s)

U = depth-averaged velocity (m/s)

U_c = incipient velocity for a human body (m/s)

V_b= volume of the displaced water by a flooded body (m^3)

v_p= total volume of a human body (m^3)

α = parameter in Eq. (10) or (13) (m$^{0.5}$/s)

β = parameter in Eq. (10) or (13) (-)

ρ_f = density of water (kg/m^3)

μ = friction coefficient between tyre and ground surface (-)

λ_F = scale ratio of force (-)

λ_L = scale ratio of length (-)

Subscripts

p = prototype (full-scale) (-)
m = model (-)

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