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# 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

1 annual number of fatalities arising directly from floods was 5,500 during the period from 1950 to  
2 1990, with the corresponding number being 3,940 in the 1990s; the average annual number of  
3 fatalities since 2000 has reduced to 1,610. However, severe flash floods and debris flows in 2010  
4 led to a loss of more than 2,800 lives (MWRC 2011). More recently, flash flooding occurred in  
5 Beijing in July 2012, resulting in about 80 fatalities over two days (Xiao 2012). The safety of  
6 people can be compromised when exposed to floodwaters that exceed their ability to remain  
7 standing, or moving, with the stability of people in floodwaters being of major concern in the risk  
8 management of flood-prone areas (Cox *et al.* 2010). The risk to people in floodwaters is expected to  
9 increase in the future owing to the rapid growth in population, the continuous expansion in  
10 territories associated with human activity, and the increase in extreme meteorological events.  
11 Therefore, it is important to propose a quantitative method of assessing the stability of a human  
12 body in floodwaters, which can provide a scientific basis for flood risk management for those  
13 people in floodplains and urban areas.

14 There are two kinds of instability mechanisms identified by existing studies, including sliding  
15 (friction) and toppling (moment) instability (Keller and Mitsch 1993, Jonkman and  
16 Penning-Rowsell 2008, Cox *et al.* 2010). Sliding instability usually occurs when the drag force  
17 induced by the incoming flow exceeds the frictional force between the feet of the body and the  
18 ground surface, while toppling instability generally occurs when the moment of the drag force  
19 caused by the inflow exceeds the resisting moment of the effective weight of the body. The risk to a  
20 human body in floodwaters varies both in time and space, due to changes in the hydrodynamic  
21 processes across a flood-prone area, and also due to changes with the different body attributes, such  
22 as height and weight. In addition, the risk to a human body is also influenced by psychological  
23 factors. For example, an alert and active person knowing the flow regime may be more capable of  
24 keeping the body stable when faced with an excessive floodwater force. This variation in the hazard  
25 degree of exposure to a human body in floodwaters needs to be estimated for effective flood risk  
26 management. Existing criteria for human body stability are represented by the incipient velocities  
27 for different depths, as people become unstable in floodwaters. The assessment of human body  
28 stability can thus be categorized into two types of criteria. The first type of criteria of human body  
29 stability consists of regressed relationships based on a number of laboratory experimental studies,  
30 using real human bodies, and the second type comprises empirical or theoretical formulae derived  
31 from a mechanics-based analysis (Defra and EA 2006, Cox *et al.* 2010).

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

27       The second type of human body stability criteria includes representative studies, such as those  
28 of Defra and the EA (2006), Keller and Mitsch (1993), Lind *et al.* (2004), and Jonkman and  
29 Penning-Rowse (2008). Defra and the EA (2006) reported a simple method to determine the rating  
30 of flood hazard for people based on velocity, depth and the presence of debris, and the resultant  
31 hazard rating can be divided into four corresponding types, ranging from a very low hazard (caution)

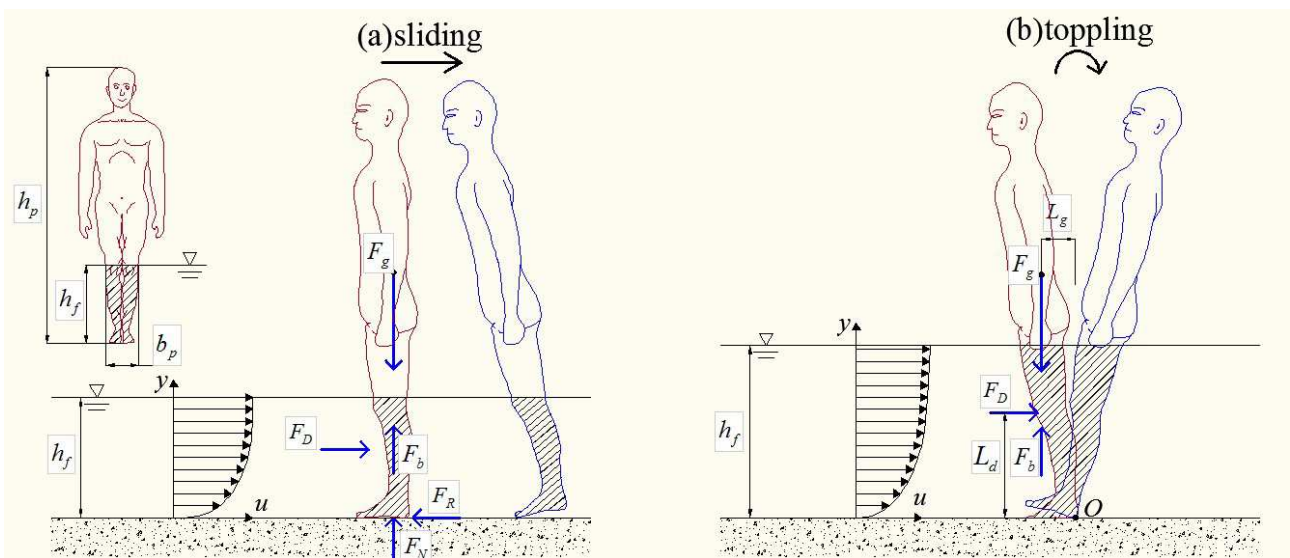
1 to danger for all groups (including the emergency services). This criterion assumes that the stability  
2 degree of a human body is related only to the hydrodynamic conditions, and hence is independent  
3 of a person's physical attributes, such as body height and weight. Therefore, such a criterion is  
4 usually applied to a preliminary assessment of people safety in flood risk management. Keller and  
5 Mitsch (1993) conducted a purely theoretical study on people stability, and this study accounted for  
6 the instability modes of moment and friction of a vertical cylinder intended to represent a human  
7 body in floodwaters. The corresponding formula was derived from the equilibrium of forces acting  
8 on a flooded person during sliding or toppling, with a uniform velocity profile along the vertical  
9 direction being assumed. It should be noted that the derived formula was highly dependent on the  
10 selection of friction and drag coefficients. Lind *et al.* (2004) considered the toppling instability of a  
11 circular cylindrical, square cylindrical and cylindrical composite bodies, assembled to represent a  
12 human body immersed in floodwaters and subjected to drag and buoyancy forces, with the  
13 corresponding approximate mechanics-based formulae being established. The experimental data of  
14 Abt *et al.* (1989) and Karvonen *et al.* (2000) were used to calibrate and compare these mechanics-  
15 based formulae. Jonkman and Penning-Rowse (2008) discussed two hydrodynamic mechanisms  
16 that can cause instability, covering moment instability and friction instability, and then presented the  
17 corresponding formulae for these two instability modes, with a uniform velocity profile being  
18 assumed and the buoyancy force not being included in the derivation for simplicity. An excessive  
19 simplification in the body structure of a human subject was usually made during the derivation of  
20 these formulations, based on the theoretical analysis, which led to the neglect, or the inaccurate  
21 calculation, of a person's buoyancy force for different water depths. Therefore, these existing  
22 criteria cannot be used to assess accurately the degree of human body stability in floodwaters.

23 All of the analyses reported above indicate that the criteria of human body stability, based on  
24 laboratory experiments using real human bodies, are significantly dependent on the physical  
25 attributes and psychological factors of the test subjects, while the criteria based on the empirical or  
26 theoretical analysis assumes excessive simplifications on the human body structure and the flow  
27 conditions. Therefore, it is appropriate to propose a new criterion for human body stability in  
28 floodwaters based on further theoretical and experimental studies. In this study, different forces  
29 acting on a human body have been analysed, with the corresponding expressions for these forces  
30 being presented, and with the formulae of incipient velocity being derived based on instability  
31 mechanisms for sliding and toppling respectively. The derived formulae can account for the effect

1 of body buoyancy through calculating the values of the human body volume for different water  
 2 depths, and can also consider the influence of a non-uniform velocity profile upstream on the  
 3 stability of the body. Laboratory experiments were then undertaken to obtain the conditions of water  
 4 depth and the corresponding velocity at the instant of human instability, using an accurate scale  
 5 model of a human body. The experimental data from this investigation were then used to determine  
 6 two parameters in the derived formula for each instability mode. Finally, the derived formulae were  
 7 validated in detail using experimental data obtained from the calculations based on the scale ratios  
 8 and other existing experimental data for real human subjects, with stability thresholds in  
 9 floodwaters being proposed for both children and adults.

## 10 2 Force analysis and formula derivation

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



20  
 21 Figure 1 Sketch of governing forces acting on a flooded human body at instability for: (a) friction and (b) moment

## 1 **2.1 Forces acting on a flooded human body**

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

### 12 **(1) Buoyancy force**

13 The calculation of the buoyancy force needs to account for the dimensions of each body  
14 segment and the corresponding volume due to the irregular shape of a human body. For a normal  
15 human body there exists a proportional relationship between the size of various segments, such as  
16 the shanks, thighs and torso. The height ( $h_p$ ), or total volume ( $v_p$ ), of a human body can be regarded  
17 as an essential parameter appropriate to determine the size, or volume, of each segment (Drillis *et al.*  
18 1964, Sandroy and Collison 1966, Guo and Wang 1995). For example, the height from the foot to  
19 the knee for a Chinese adult generally ranges from  $0.261h_p$  to  $0.265h_p$ , and the volume of the thighs  
20 and shanks approximates to  $0.266v_p$ .

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

$$22 \quad F_b = \rho_f g V_b \quad (1)$$

23 where  $\rho_f$  is the density of water,  $g$  is the gravitational acceleration, and  $V_b$  is the volume of the  
24 displaced water by the flooded human body. It is therefore clear that the magnitude of  $V_b$  is related  
25 to the values of  $h_f$ ,  $h_p$  and  $v_p$ . Hence, an empirical relationship can be established between the  
26 buoyancy force exerted by the water upthrust ( $F_b$ ) and the water depth ( $h_f$ ), based on the  
27 characteristic parameters of the body structure. This relationship is usually represented by a  
28 quadratic function with sufficient accuracy, and with the corresponding expression being written as:

$$29 \quad V_b / v_p = a_1 x^2 + b_1 x \quad (2)$$

30 where  $a_1$  and  $b_1$  are non-dimensional coefficients, and  $x$  is the ratio of the water depth to the body

1 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  
 2 where  $h_f = h_p$ .

3 The statistics of the segment parameters for a body indicate that there exists an approximately  
 4 linear relationship between the volume  $v_p$  [ $\text{m}^3$ ] and the mass  $m_p$  [kg] of a human body (Guo and  
 5 Wang 1995), which can be expressed by:

$$6 \quad v_p = a_2 m_p + b_2 \quad (3)$$

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

$$11 \quad F_b = g \rho_f (a_1 x^2 + b_1 x) (a_2 m_p + b_2) \quad (4)$$

12 The coefficients  $a_1$  and  $b_1$  in Eq. (2) can be determined from the characteristic parameters of  
 13 the body structure. The calibrated values of  $a_1$  and  $b_1$  for a typical human body of a Chinese person  
 14 are 0.633 and 0.367, respectively (Guo and Wang 1995). According to the data on body segment  
 15 parameters for an American subject, as presented by Drillis *et al.* (1964), the parameters in Eq.(2)  
 16 can be determined and give the calibrated values for  $a_1$  and  $b_1$  of 0.737 and 0.263, respectively.  
 17 According to the average body attributes for Chinese people, the typical parameters in Eq. (3) can  
 18 be evaluated to give:  $a_2 = 1.015 \times 10^{-3} \text{ m}^3/\text{kg}$  and  $b_2 = -4.927 \times 10^{-3} \text{ m}^3$ , respectively (Guo and Wang  
 19 1995).

## 20 (2) Drag force

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

$$22 \quad F_D = 0.5 A_d C_d \rho_f u_b^2 \quad (5)$$

23 where  $u_b$  is a representative near-bed velocity,  $C_d$  is the drag coefficient, which is related to the  
 24 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  
 25 empirical coefficient which is used to account for the effect of clothing worn normally on the  
 26 wetted area, and  $b_p$  is the average body width exposed normal to the flow. For various floodwaters  
 27 it is difficult to determine the exact type of velocity profile, and a characteristic velocity of  $u_b$  is  
 28 often used in Eq. (5) for the calculation of  $F_D$ . As widely known, the value of  $C_d$  is a function of  
 29 the subject shape and the object Reynolds number ( $\mathbf{R}$ ), expressed roughly by  $\mathbf{R} = Ub_p/\nu$ , where  $\nu$  is  
 30 the kinematic viscosity of water, and  $U$  is the depth-averaged velocity. It is regarded that  $C_d$  is



1 independent of the object Reynolds number as  $R > 2.0 \times 10^4$  (Chanson 2004).

2 For floodwaters occurring in floodplains and urban areas, the magnitude of the velocity will  
3 be typically in the range from 0.5 to 3.0 m/s, and the corresponding values of the object Reynolds  
4 number will vary typically from  $1.5 \times 10^5$  to  $9.0 \times 10^5$ , for a mean value of  $b_p$  for a real human  
5 subject assumed to be 0.30 m. It is therefore assumed that  $C_d$  is a constant for large values of the  
6 object Reynolds number, and has the same magnitude for the model and prototype (Chanson 2004).  
7 Among the studies undertaken for human bodies by Keller and Mitsch (1993), Lind *et al.* (2004),  
8 and Jonkman and Penning-Rowsell (2008), constant values of  $C_d$  ranging from 1.1 to 2.0 were  
9 adopted. In this study, it is not necessary to determine the actual numerical value for  $C_d$ , since this  
10 parameter is included in a comprehensive parameter in the formula derivation.

### 11 (3) *Effective weight*

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

$$16 \quad F_G = g m_p - F_b = g \left[ m_p - \rho_f (a_1 x^2 + b_1 x) (a_2 m_p + b_2) \right] \quad (6)$$

### 17 (4) *Frictional force*

18 The frictional force is exerted on the interface between the feet of a person and the ground  
19 surface, and can be expressed as  $F_R = \mu F_N$ , where  $F_N$  is the normal reaction force from the ground  
20 surface, and is generally equivalent to the effective weight of a flooded human body, namely  $F_N =$   
21  $F_G$ , and  $\mu$  is the friction coefficient between the sole of the feet and the wet ground surface, which is  
22 closely related to the ground roughness, shape and degree of wear on the soles. The friction  
23 coefficient  $\mu = 0.3 - 1.0$  was used in the human stability analyses conducted by Keller and Mitsch  
24 (1993), and Jonkman and Penning-Rowsell (2008). Takahashi *et al.* (1992) conducted a series of  
25 tests on the friction coefficient for a range of leather and rubber soled shoes on various ground  
26 surfaces, and obtained values for the friction coefficient in the range from 0.2 to 1.5. Therefore, the  
27 selection of  $\mu$  needs to be estimated by the roughness of the ground surface and the characteristics  
28 of the soles of shoes. With known values for the friction coefficient and the normal reaction force,  
29 the expression for the frictional force can be written further as:

$$30 \quad F_R = \mu F_N = \mu g \left[ m_p - \rho_f (a_1 x^2 + b_1 x) (a_2 m_p + b_2) \right] \quad (7)$$

## 1 2.3 Formula derivation for different instability modes

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

### 9 (1) Formula for sliding instability mode

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

$$12 C_d(a_d b_p h_f) \rho_f \frac{u_b^2}{2} = \mu g [m_p - \rho_f (a_1 x^2 + b_1 x) (a_2 m_p + b_2)] \quad (8)$$

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

$$14 u_b^2 = \frac{2\mu g}{\rho_f C_d(a_d b_p h_f)} [m_p - \rho_f (a_1 x^2 + b_1 x) (a_2 m_p + b_2)] \quad (9)$$

15 It is not easy to determine the effective near-bed velocity  $u_b$  in practice and, for simplicity, the  
16 depth-averaged velocity ( $U$ ) is generally used instead of the characteristic velocity. The incoming  
17 flow velocity upstream of the body is approximately characterized by the power-law velocity  
18 profile, but this refers to the flow velocity distribution before it reaches the effect of the advance  
19 pressure gradient of the body. The power-law distribution of velocity as used in this study can be  
20 expressed as  $u = (1+\beta)U(y/h_f)^\beta$  for open channel flows, in which  $\beta$  is an empirical coefficient  
21 ranging from 1/7 to 1/6,  $y$  is the vertical distance from the bed, and  $u$  is the velocity at elevation  $y$   
22 (Zhang and Xie 1993, Wu 2007). A complex velocity field distribution can form around a human  
23 body when it is exposed to floodwater, however, the current study does not consider the detailed  
24 complex velocity field around a flooded human subject. Therefore, it is assumed that the incoming  
25 flow velocity upstream is characterized by a power-law distribution of velocity, but  $\beta$  generally  
26 deviates from the above value for such a condition. For urban floods the water depth can be larger,  
27 sometimes approaching the height of a human body, and the analysis is also based on the concept of  
28 incipient motion for a coarse sediment particle in a similar context to river dynamics (Zhang and  
29 Xie 1993, Chien and Wan 1999), It is therefore assumed that the representative height for  $u_b$  is equal

1 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  
 2 would generally be a very small value of the order to satisfy the condition of  $a_b h_p < h_f$ . Therefore,  
 3 the magnitude of  $u_b$  is closely related to the values of both  $h_p$  and  $h_f$ . However, the representative  
 4 height can also be assumed to be equal to a function of the incoming water depth, with similar  
 5 formulae being derived. This analysis will be fully considered in future investigations through  
 6 measuring the detailed velocity profiles around a flooded human body and using an acoustic  
 7 Doppler velocimeter or similar instruments.

8 According to the statistics of the segment parameters for a human body, there exists a  
 9 quantitative relationship between the mean body width and body height, expressed by  $b_p = a_p h_p$ ,  
 10 where  $a_p$  is a coefficient related to the body structure. Substituting the expression for  $u_b$  and the  
 11 relationship for  $b_p$  into Eq. (9), the incipient velocity ( $U_c$ ) for a human body in floodwaters at  
 12 sliding instability can therefore be written as:

$$13 \quad U_c = \alpha \left( \frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_p h_f} - \left( a_1 \frac{h_f}{h_p} + b_1 \right) \frac{(a_2 m_p + b_2)}{h_p^2}} \quad (10)$$

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

## 21 **(2) Formula for toppling instability mode**

22 When a person stands facing the on-coming flow direction, as shown in Fig. 1(b), then the  
 23 critical condition for toppling instability is that the human body would pivot around the heel (Point  
 24 O) and would topple backwards as the total moment around the pivot point O is equal to zero,  
 25 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  
 26 the correction coefficient of the height between the centre of the drag force and the ground surface,  
 27  $L_g$  is the moment arm of the effective weight, with  $L_g = a_g h_p$ , and  $a_g$  is the correction coefficient of  
 28 the distance between the position of the centre of gravity of the body and the heel. Substitution of  
 29 the expressions for  $L_d$  and  $L_g$  and the relationship for  $b_p$  for the critical condition for toppling  
 30 instability yields:

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

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

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

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:

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

where  $\alpha = \sqrt{2ga_g / [C_d a_d a_p a_h a_b^{2\beta} (1+\beta)^2]}$ . The parameters  $\alpha$  and  $\beta$  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  $\lambda_L = 5.54$ , 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  $\lambda_U$  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  $\lambda_F$ . Hence, the density of the selected human body model was approximately equal to the density of the

1 prototype, which yielded  $\lambda_{FG} = \lambda_{Fb} = \lambda_F$ .

2 Existing studies indicate that the drag coefficient is regarded as a constant for a specified shape  
3 and relatively high values of the object Reynolds number (Chanson 2004), and it was concluded  
4 that  $C_d$  for the model was nearly equal to that for the prototype, which led to  $\lambda_{FD} = \lambda_F$ . A thin cement  
5 layer was specially paved on the bed surface of the flume in order to meet the similarity of the  
6 friction roughness, and the measured friction coefficient was about 0.5 between the soles of the  
7 model body and the wet cement surface; this corresponded well with the range for the prototype  
8 parameters used in the experiments of Takahashi *et al.* (1992). It was deduced that the friction  
9 coefficient for the model was nearly equal to that for the prototype, which led to  $\lambda_{FR} = \lambda_F$ .

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

27

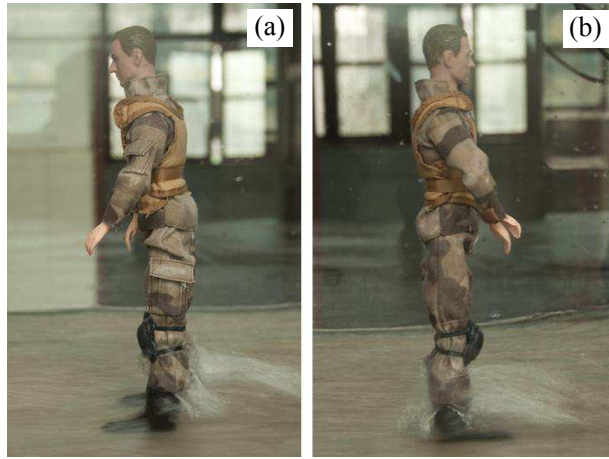


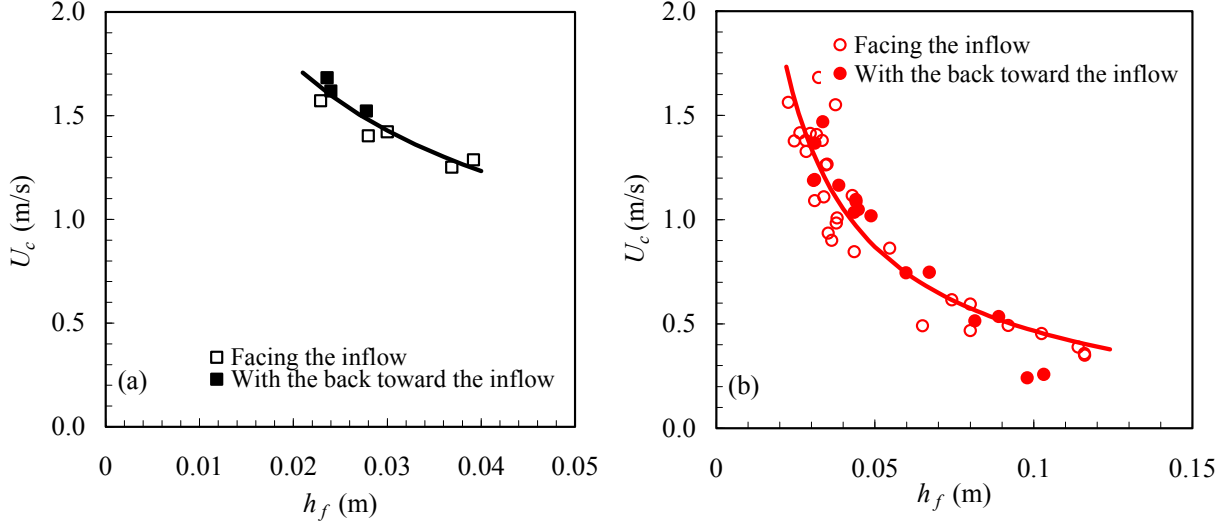
Figure 2 Two standing postures of the model human body in the flume: (a) facing and (b) with the back toward the on-coming flow.

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

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



6  
 7 Figure 3 Relationships between the water depth and corresponding incipient velocity for a model human body at  
 8 instability of: (a) sliding and (b) toppling

### 9 3.3 Parameter calibration

10 The formula structure is relatively complex in Eqs. (10) and (13) due to the introduction of the  
 11 buoyancy force. In order to determine the parameters of  $\alpha$  and  $\beta$ , Eq.(10), or Eq. (13), is  
 12 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  
 13  $U_c / \sqrt{m_p / (\rho_f h_f^2) - [a_1 / h_p^2 + b_1 / (h_f h_p)](a_2 m_p + b_2)} = \alpha (h_f / h_p)^\beta$ , respectively. For a particular human body, the values of  
 14  $m_p$ ,  $h_p$ ,  $a_1$ ,  $b_1$ ,  $a_2$  and  $b_2$  are constant. Therefore, both  $\alpha$  and  $\beta$  values can be determined by the  
 15 statistical analysis software package SPSS. The calibrated parameters of  $\alpha$  and  $\beta$  are shown in Table  
 16 1.

17 From Table 1, the square of the correlation coefficient ( $R^2$ ) is found to be greater than 0.8  
 18 between the measured and predicted velocities for each formula, with this meaning that a better fit  
 19 has been obtained using this analysis. Based on the above force analysis, the calibrated value of  $\alpha$  is  
 20 influenced by the shape of the test model, the friction coefficient between the soles and the ground  
 21 surface, and the drag coefficient. As shown in Table 1, the calibrated value of  $\beta$  is equal to 0.018 for

1 the mode of sliding instability. This instability mode usually occurs for supercritical flow conditions,  
 2 with low depths and high velocities. For this condition, the vertical distribution of velocity tends to  
 3 follow a relatively uniform profile, and the magnitude of  $\beta$  approaches a small value. However, the  
 4 mode of toppling instability generally occurs under subcritical flow conditions, with high depths  
 5 and low velocities, and therefore the calibrated value of  $\beta$  is in the same range typical of 1/7 to 1/6  
 6 for the power-law distribution of velocity for common open channel flows.

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

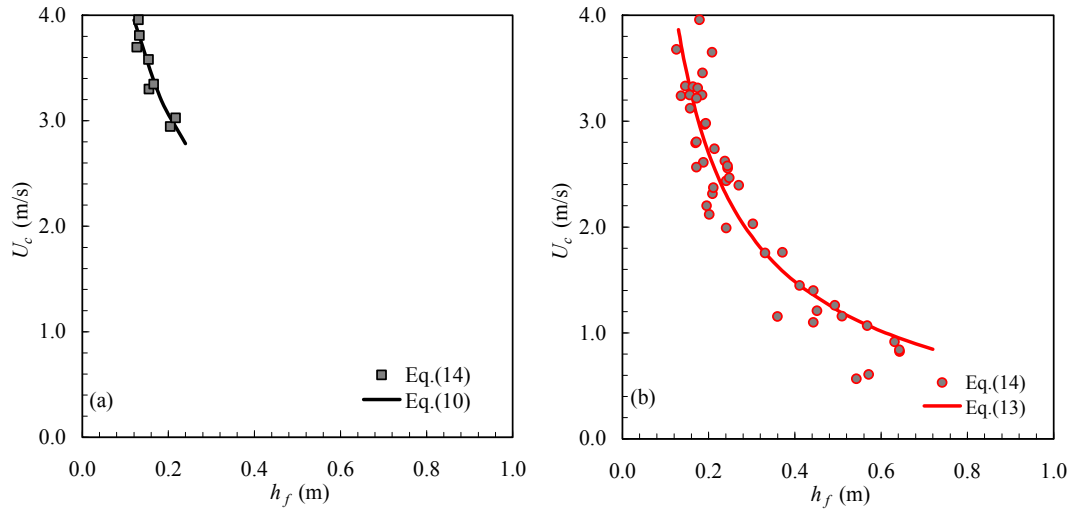
Formula	Parameter calibration		$R^2$	Instability mode	Number of tests
	$\alpha$ [m <sup>0.5</sup> /s]	$\beta$ [-]			
Eq. (10)	7.975	0.018	0.883	Sliding	8
Eq. (13)	3.472	0.188	0.853	Toppling	46
Note: other parameters used in formulae, covering: $a_1 = 0.633$ ; $b_1 = 0.367$ ; $a_2 = 1.015 \times 10^{-3}$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

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

$$12 \quad h_{fp} = h_{fm} \lambda_L \quad \text{and} \quad U_{cp} = U_{cm} \sqrt{\lambda_L} \quad (14)$$

13 where the subscripts  $p$  and  $m$  refer to prototype and model parameters, respectively. The scaled-up  
 14 experimental data obtained using Eq. (14) for the prototype are shown in the scattered points of Fig.  
 15 4. In addition, substitution of the parameters for  $h_p = 1.7$  m and  $m_p = 60$  kg for a typical (Chinese)  
 16 real human body into Eqs. (10) and (13) can be used to obtain the critical velocities for various water  
 17 depths, using the corresponding values of  $\alpha$  and  $\beta$  in Table 1, and as shown for the solid curves in  
 18 Fig. 4. Figure 4 indicates that the critical conditions obtained using the scale ratios compare well  
 19 with the calculations from the derived formulae, confirming the accuracy of the critical conditions  
 20 for the prototype estimated using these two approaches. A fully unbiased validation of the proposed  
 21 formulae requires additional experimental data for a large-scale model human body, which will be  
 22 conducted in a future study. It should be noted that the model human body could not respond to the  
 23 incoming flows in the physical and psychological attributes, and the incipient velocities calculated  
 24 using Eqs. (10) and (13), with the calibrated parameters in Table 1, would generally be less than the  
 25 previous experimental data for real human bodies in flumes (Abt *et al.* 1989, Karvonen *et al.* 2000).





1  
2 Figure 4 Comparisons between the experimental data using the scale ratios and the calculations using the derived  
3 formulae at instability modes of: (a) sliding and (b) toppling

#### 4 **4 Comparison with the experimental data for real human bodies**

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

##### 21 **4.1 Separate comparison with the tests of Abt *et al.* and Karvonen *et al.***

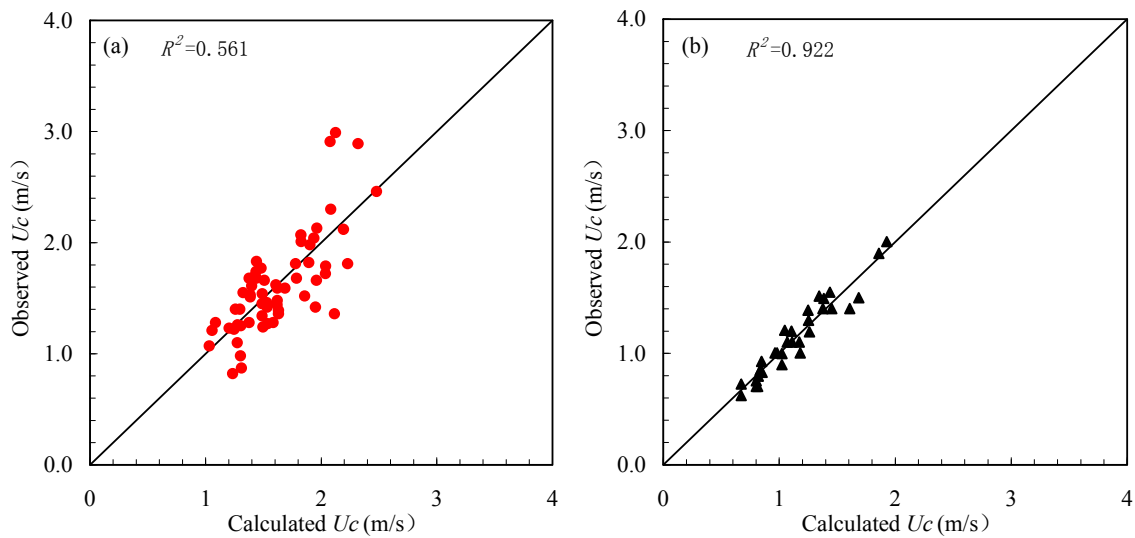
22 Abt *et al.* (1989) also conducted experimental studies on the stability of human bodies in  
23 floodwaters, using 20 real human subjects, consisting of 18 males and 2 females, with the body

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

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

25 The real seven human subjects (i.e. 5 males and 2 females) in the experimental programme of  
26 Karvonen *et al.* (2000) wore survival suits and safety helmets, with the body heights ranging from  
27 1.60 to 1.95 m, and the body weights varying from 48 to 100 kg. The hydrodynamic factors used in  
28 the tests included: depths ranging from 0.30 to 1.10 m and velocities varying from 0.60 to 2.71 m/s.  
29 Each subject first familiarised himself or herself with the test facility and safety equipment in  
30 stagnant water, and the velocity was then gradually increased until the subject lost stability or

1 manoeuvrability. It was observed that some air was trapped inside the suit, causing an increase in  
 2 the buoyancy force. In addition, the wetted area of a human subject was slightly larger while  
 3 wearing a survival suit as compared to wearing normal clothing, leading to slightly lower incipient  
 4 velocities. If only the experimental data of Karvonen *et al.* (2000) are used to evaluate the  
 5 parameters in Eq. (13), then values of  $\alpha = 4.825 \text{ m}^{0.5}/\text{s}$  and  $\beta = 0.160$  are determined, giving a  
 6 higher value of  $R^2 = 0.922$  (Fig. 5(b)), which is higher than the value of  $R^2 = 0.75$ , calibrated by  
 7 Jonkman and Penning-RowSELL (2008).



8

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

## 11 4.2 Comparison with all the tests

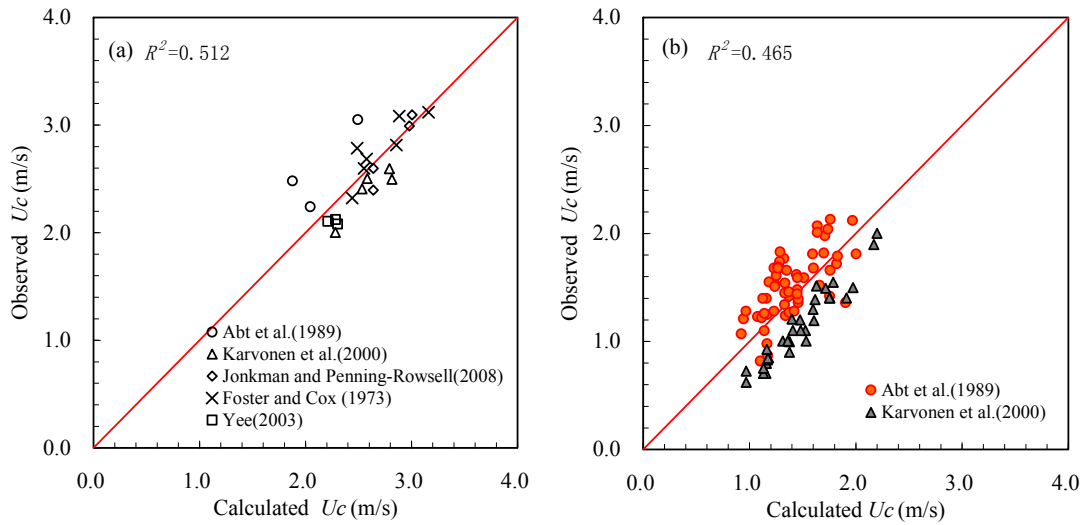
12 Experimental data for 22 tests at sliding instability using real human subjects (Foster and Cox  
 13 1973, Karvonen *et al.* 2000, Yee 2003, Jonkman and Penning-RowSELL 2008) were collected in this  
 14 study. These data were used to re-evaluate the parameters  $\alpha$  and  $\beta$  in Eq. (10), as shown in Table 2.  
 15 Figure 6(a) shows a significant difference between the experimental data and the predicted incipient  
 16 velocities for sliding instability using the re-evaluated parameters. This difference is due to: the  
 17 limited number of tests, the various experimental conditions, and the different criteria for instability.  
 18 In addition, the experimental data of both Abt *et al.* (1989) and Karvonen *et al.* (2000) have been  
 19 used to re-evaluate the parameters  $\alpha$  and  $\beta$  in Eq. (13), with the calibrated values shown in Table 2,  
 20 and the comparison between the experimental and predicted data being shown in Fig. 6(b). Figure  
 21 6(b) indicates that the experimental results of Abt *et al.* (1989) generally give slightly higher values  
 22 than the experimental data of Karvonen *et al.* (2000), leading to a lower value of  $R^2 = 0.465$ .

1  
2

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
	$\alpha$ [ $m^{0.5}/s$ ]	$\beta$ [-]			
Eq. (10)	10.253	0.139	0.512	Sliding	22
Eq. (13)	7.867	0.462	0.465	Toppling	89

3



4

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

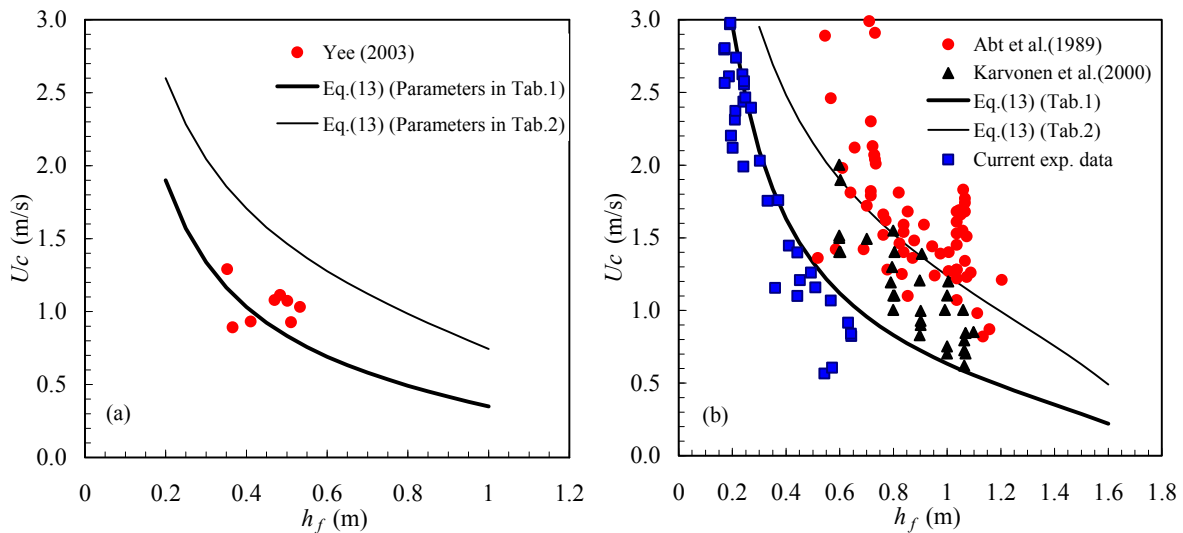
7 The above analysis indicates that many factors influence the stability of a real human body  
8 when exposed to floodwaters, including: (i) physical attributes of a body such as age, sex, height  
9 and weight; (ii) psychological factors, such as the ability to adjust to the standing posture towards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

1 obtained using these parameters would tend to be optimistic, and even potentially dangerous to use  
 2 in practice, from the viewpoint of flood risk analysis.

### 3 4.3 Suggested stability thresholds

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

14



15

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

17 The average parameters for a human body are relevant to Chinese children and adults in the  
 18 calculations in Fig. 7. Figure 7(a) shows the relationships between the water depth and the incipient  
 19 velocity, as predicted using the parameters in Table 1 and Table 2, for a typical 7-year old child with  
 20 a height of 1.26 m and a mass of 25.5 kg. The thin solid curve predicted using the parameters in  
 21 Table 2 represents the relatively dangerous threshold, while the thick solid curve, predicted using  
 22 the parameters in Table 1, highlights the relatively safe threshold. The zone between these two

1 curves indicates the moderate hazard region for a child at toppling instability. Figure 7(b) shows  
2 similar threshold curves for an adult with a height of 1.71 m and a mass of 68.7 kg. In addition,  
3 almost all of the experimental data obtained using the model and real human bodies are included in  
4 Fig. 7 as reference values. Therefore, the stability degree for a human body in floodwaters can be  
5 assessed using the corresponding curves in Fig. 7(a) or 7(b) according to the inflow conditions.

## 6 **5 Conclusions**

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

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

29 (ii) More than 50 tests on the stability of a human body were conducted in a flume using a  
30 scaled model body, with the incipient velocities being measured for a range of different water

1 depths. The experimental data were used to evaluate the key parameters in the derived formulae,  
2 with the evaluated parameters representing relatively safe thresholds. The parameters in the  
3 formulae were also evaluated using experimental data for real human bodies published in the  
4 literature, which represented more dangerous thresholds due to the ability of the human body to  
5 resist sliding or toppling.

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

14  
15

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22 and the Associate Editor for their constructive comments in improving the paper.

23

## 24 **Notation**

25

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

27  $a_2$  = coefficient in Eq.(3) ( $\text{m}^3/\text{kg}$ )

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

29  $b_2$  = coefficient in Eq.(3) ( $\text{m}^3$ )

30  $C_d$  = drag coefficient (-)

31  $F_b$  = buoyancy force (N)

- 1  $F_D$  = drag force (N)  
 2  $F_G$  = effective body weight (N)  
 3  $F_g$  = gravitational force (N)  
 4  $F_N$  = normal reaction force from ground (N)  
 5  $F_R$  = frictional force between feet and ground surface (N)  
 6  $g$  = gravitational acceleration ( $\text{m/s}^2$ )  
 7  $h_f$  = water depth (m)  
 8  $h_p$  = height of human body (m)  
 9  $L_d$  = moment arm of drag force (m)  
 10  $L_g$  = moment arm of effective weight (m)  
 11  $m_p$  = mass of a human body (kg)  
 12  $R$  = object Reynolds number (-)  
 13  $u_b$  = representative near-bed velocity (m/s)  
 14  $U$  = depth-averaged velocity (m/s)  
 15  $U_c$  = incipient velocity for a human body (m/s)  
 16  $V_b$  = volume of the displaced water by a flooded body ( $\text{m}^3$ )  
 17  $v_p$  = total volume of a human body ( $\text{m}^3$ )  
 18  $\alpha$  = parameter in Eq. (10) or (13) ( $\text{m}^{0.5}/\text{s}$ )  
 19  $\beta$  = parameter in Eq. (10) or (13) (-)  
 20  $\rho_f$  = density of water ( $\text{kg/m}^3$ )  
 21  $\mu$  = friction coefficient between tyre and ground surface (-)  
 22  $\lambda_F$  = scale ratio of force (-)  
 23  $\lambda_L$  = scale ratio of length (-)  
 24 *Subscripts*  
 25  $p$  = prototype (full-scale) (-)  
 26  $m$  = model (-)  
 27

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