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HUMAN INSTABILITY IN FLOOD FLOWS[1]

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ABSTRACT: Loss of human stability in flood flows and consequent drowning are a high personal hazard. In this paper, we review past experimental work on human instability. The results of new experiments by the Flood Hazard Research Centre (FHRC) are also reported. These new results show that low depth/high velocity flood waters are more dangerous than suggested based on previous experimental work. It is discussed how human instability can be related to two physical mechanisms: moment instability (toppling) and friction instability (sliding). Comparison of the test results with these physical mechanisms suggests that the occurrence of instability in the tests by FHRC is related to friction instability. This mechanism appears to occur earlier than moment instability for the combination of shallow depth and high flow velocity. Those concerned to identify locations where high flood flows could be a threat to human life need to modify their hazard assessments accordingly.

(KEY TERMS: flooding; hydrodynamics; human instability; loss of life; risk assessment.)

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INTRODUCTION

From 1975-2001, 1,816 reported inland flood events, such as flash and river floods, killed over 175,000 people around the world (Jonkman, 2005). Other types of floods, such as dam breaks, storm surges, and tsunamis can be even more catastrophic in terms of loss of life.

Flood mitigation agencies worldwide are increasingly designating floodplains and high hazard zones to identify where the risk of flood damage or loss of life is particularly high. For adequate mapping of such flood hazards it is important to know where the dangerous zones in a potentially flooded area are located. Although flood fatalities can occur because of various other causes such as physical trauma, heart attack, and drowning in cars (Jonkman and Kelman, 2005) loss of human stability and consequent drowning are a high personal hazard.

Other than laboratory experiments by Abt *et al.* (1989) and Karvonen *et al.* (2000), there is little data on what constitute dangerous circumstances (Tapsell *et al.*, 2002), and in particular on the depths and velocities of flood waters that are life-threatening. Jonkman *et al.* (2002) have confirmed this lacunae. In addition, the existing work gives limited attention to the physical mechanisms that cause instability of humans in flood flows.

This paper's objective is to improve the understanding of human instability in flood waters. Results of a new full-scale experiment are reported to provide data to help to define when adult humans are swept away. In addition, the physical mechanisms are elaborated that can lead to instability. The available experimental data are compared with the physical mechanisms.

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PAST WORK ON HUMAN INSTABILITY

Past Work

Several authors have investigated human (in)stability in flowing water within the context of flood hazard analysis. Most authors propose a critical depth-velocity (hv_c) product indicating the combination of depth (h – [m]) and velocity (v – [m/s]) that would lead to a person's instability. Similarly, in analyzing building collapse in flood flows, the hv_c product also tends to be used (e.g., Sangrey *et al.*, 1975; Clausen 1989, Kelman, 2002).

This topic's first experimental study was presumably Abt *et al.* (1989), as they state that "previous work of this nature was not located in literature" (p. 881). They conducted a series of tests in which human subjects and a monolith were placed in a laboratory flume in order to determine the water velocity and depth which caused instability. Equation (1) was derived from the resulting empirical data to estimate the critical product hv_c at which a human subject becomes unstable as a function of the subject's height (L – [m]) and mass (m – [kg]):

$$hv_c = 0.0929(e^{0.001906Lm+1.09})^2 \tag{1}$$

Further tests on humans in laboratory flumes were carried out in the Rescdam project (Karvonen *et al.*, 2000). Depending on the test person's height and mass, critical depth-velocity products were found between 0.64 m^2/s and 1.29 m^2/s. Based on the test data, the authors proposed the following limit for manoeuvrability under normal conditions:

$$hv_c = 0.004Lm + 0.2 \tag{2}$$

In Japan, experiments were conducted on the feasibility of walking through floodwaters. Suetsugi (1998) reports these results in English indicating that people will experience difficulties in walking through water when the depth-velocity product exceeds 0.5 m^2/s.

Different authors have used the available test data to derive empirical functions for determining stability. Lind and Hartford (2000), also see Lind *et al.* (2004), derived theoretical relationships for the stability in water flows of three shapes representing the human body: a circular cylindrical body, a square parallelepiped body, and composite cylinders (two small ones for the legs, and one for the torso). Because of similarities in the stability functions for these shapes, they proposed a limit state in the form of Equation (3). This function is calibrated with the results of the tests by Abt *et al.* (1989):

$$Z(K_0, m, h, v) = K_0 m^{0.5} - hv, \tag{3}$$

where $Z(K_0,m,h,v)$, limit state function for stability [m^2/s]; K_0, constant with an average value of 0.10 $kg^{-1/2}$ m^2/s and a variation coefficient of 0.18 (for derivation, see Lind and Hartford, 2000).

If $Z < 0$, a person loses stability. As the distribution of constant K_0 is given, the probability of losing stability can be determined for a given depth-velocity product (hv). Lind *et al.* (2004) then suggest other variants of the above reliability function, for example, one which is independent of the person's mass.

USBR (1988) gives semi-quantitative criteria that indicate certain hazard ranks (e.g., high and low danger zones) as a function of water depth and flow velocity. Given the lack of experimental data the rankings in USBR (1988) were mainly based on expert judgements of the authors. Similarly, Ramsbottom *et al.* (2004) and Penning-Rowsell *et al.* (2005) have proposed a semi-quantitative equation to relate the flood hazard to people to depth and velocity of the water as well as the amount of debris that is in the water:

$$\text{Flood Hazard} = h(v + 0.5) + \text{DF}, \tag{4}$$

where DF is the debris factor [m^2/s]. From the above flood hazard index, the level of hazard to people can be estimated and then categorized as "low," "moderate," "significant" or "extreme." In the complete proposed methodology, the flood hazard factor can be combined with information on people's and the area's vulnerability to provide an estimate of loss of life caused by a flood, see (Ramsbottom *et al.*, 2004) and Penning-Rowsell *et al.* (2005) for further details, including some modest success in calibration with UK flood fatalities.

Overall, the available studies show that people lose stability in flows in relatively low depth-velocity products. The obtained critical depth-velocity products for standing range from 0.6 m^2/s to about 2 m^2/s. People may experience difficulties in wading through water at lower depth-velocity products. Results from Abt *et al.* (1989) showed that a monolith toppled in much lower depth-velocity products (0.3 m^2/s) than human beings (0.6-2 m^2/s). Abt *et al.* (1989) considered the monolith as "an extremely conservative estimate of the body structure with respect to flood exposure." Human adaptation to flow conditions is likely and it plays an important role in stability estimation. Thus, human actions, such as leaning into the flow, should be taken into account in the physical interpretation of instability.

Review of Experimental Data

Table 1 summarizes the available test data as a basis for further analysis. Results of recent tests by

TABLE 1. Overview of Available Experimental Data on Human Instability.

Reference	Substrate/ Water Conditions	Clothing and Safety Equipment	Test Conditions	Subjects	Number of Measurements	Depth-Velocity Product Statistics
Abt *et al.*, 1989	Grass, concrete, steel, gravel. Water 20-25°C	Jeans and shirt, harness, helmet	2-4 tests in 2 h, v: 0.36-3.05 m/s h: 0.42-1.2 m	20 people, female and male, 19-54 years, good health, m: 41-91 kg; L: 1.52-1.91 m	Monolith: 6 People: 65	People: avg. $hv_c = 1.33\ m^2/s$ SD: $hv_c = 0.28\ m^2/s$
RESCDAM, (Karvonen *et al.*, 2000)	Steel grating-fairly slippery, Water 16°C	Goretex survival suits, helmet, safety ropes, handles	v: 0.6-2.75 m/s h: 0.3-1.1 m	7 people, female and male. Some were professional rescuers. m: 48-100 kg; L: 1.60-1.95 m	People: 38	avg. $hv_c = 0.96\ m^2/s$ SD: $hv_c = 0.16\ m^2/s$

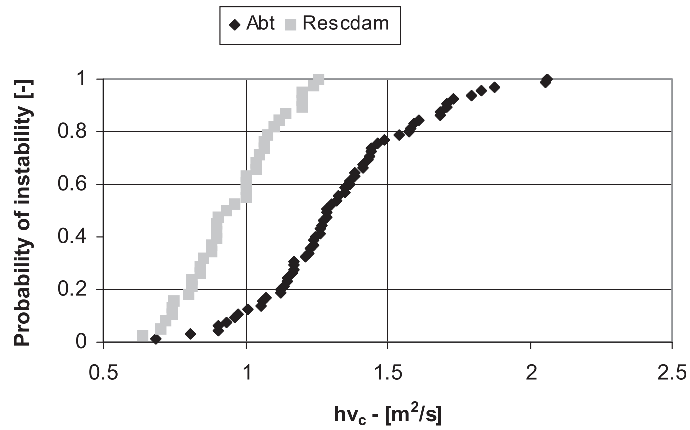

FIGURE 1. Distributions of Critical Depth-Velocity Products for the Available Datasets.

the Flood Hazard Research Centre (FHRC) in the United Kingdom are reported in more detail in the next section.

Figure 1 shows the probability distribution of the critical depth-velocity products for both datasets. The intersection with the horizontal axis indicates the measurement with the smallest hv_c value, while the data point at the probability level of 1 indicates the measurement with the largest hv_c. Both sets of experiments can be approximated with normal distributions, average and standard deviation are indicated in the last column of Table 1.

Figure 1 illustrates that the two datasets are significantly different (see also Ramsbottom *et al.*, 2004). This reflects that the two experiments were carried out under different test circumstances (bottom friction, test configuration) and involved a variety of personal characteristics (weight, height, clothing). For example, the subjects in the tests by Abt *et al.* (1989) wore normal clothing (jeans, shirts), while the subjects in the Rescdam tests (Karvonen *et al.*, 2000) wore survival suits. Also, the people in the Abt *et al.* tests were standing in or wading through the flow, wearing safety harnesses, while subjects in the Rescdam tests were towed through the water on a platform. In the consequent elaboration, both datasets have been analyzed separately to relate the physical mechanisms to the experimental data.

EXPERIMENTS BY THE FLOOD HAZARD RESEARCH CENTRE

Experimental Set-Up

This experiment was designed to replicate as nearly as possible the "real-world" situations where people are faced with flood waters that threatened to "sweep them off their feet."

The experiment was therefore conducted at what is, in effect, a full-scale flume, where sluices control discharge in the river Lea catchment. The sluices operate by restricting the river's flow into the Cattlegate Flood Relief Channel. At times of flood the gates are opened, to activate the Channel, whereas in normal circumstances they are closed to maintain flow through a side weir into the River Lea and to maintain water levels in the Lee Navigation canal. The sluices are motorized, allowing water to pass beneath large rising gates, and the heights of the gates above the channel bed can be readily and rapidly adjusted.

This experiment was not conducted in flood conditions, but when the gates would normally be closed with a substantial head of water accumulated upstream. It was only possible owing to the fact that, by adjusting the distance between the sluice gates and the channel bed, the velocity and depth of water downstream in the Flood Relief Channel can be varied within certain limits. Below the gates, the channel is approximately 70 m wide, in the form of a concrete apron between natural banks. In-channel "spikes" are installed, designed to create a stilling area and restrict the erosion of the Channel's banks.

Our subject was a fully fit 1.7 m tall professional stuntman weighing 68.25 kg. The various tests of his stability in the flood waters were located on the 1:100 (0.01) sloping concrete channel bed some 75 m below the gates (below the in-channel "spikes"). The subject was not connected with restraining safety wires to the bank, or supported in any other way (as in the Abt experiment), and thus was able to move freely. Figure 2 gives an impression of the subject in action in the channel. He was able to communicate with the sluice gate controllers, via wireless radio, and therefore give reactions to the experiments as they unfolded. When he fell, he was rescued by a team of people, including a diver, some 100 m downstream. This assistance was always available during the test and it did mean that it was clear that if he fell, he would not be in any great danger. This is unlikely not to have affected his behavior, which must be a limitation of all such experiments.

Our experiments were conducted in daylight, in early March 1999, such that the water temperature was no more than 10°C. The experiment took the most part of a full day. The subject wore a "drysuit," with rubber soled "wet shoes," but without a helmet. The drysuit was tightly drawn around the man's lower legs, such that his cross-sectional area there was not unduly exaggerated over and above that of a normally clothed individual.

Near the subject, water depth and velocity were continuously measured (the latter averaged across the whole depth), using a *Starflow Ultrasonic Doppler* instrument screwed to the channel bed. This instrument measured flood velocity and depth every five seconds, relaying the data to give a continuous trace of both variables on a bankside recorder. This system for measuring the velocity and depth of water in rivers and streams is suitable for use in a wide range of situations.

The Starflow model used (type 6526) consists of a combination of an ultrasonic transducer assembly (profiled to reduce flow disturbance) and signal processing electronics. It is designed to be placed at (or near) the bottom of the water channel for "upward looking" measurement. A single cable connects the instrument to a 12 V dc power source. Water velocity is measured by the ultrasonic doppler principle, which relies on suspended particles or small air bubbles in the water to reflect the ultrasonic detector

FIGURE 2. Two Pictures Showing the Subject in the Channel: Standing Test (left), Walking Test (right) (Source: BBC 999).

signal. Water depth is gauged by a hydrostatic pressure sensor, referenced to atmospheric pressure through the vented power and signal cable. Water temperature is also measured. This is used to adjust for the change in velocity because of speed of sound and is also available for logging but this variable was not recorded in our experiment. The manufacturer states that velocity is measured with an accuracy of ±2%, and depth with an accuracy of ±0.25%.

After dummy runs for instrument calibration, two standing and four walking tests were undertaken. In the standing tests, the sluice gates were progressively opened until the subject was swept away (to be recovered safely downstream). In the walking tests, he first walked at 90° to the streamflow through progressively deeper water with higher velocities as he neared the channel mid-point. Second, in the last experiment, he sought to move rapidly upstream towards the faster moving water nearer the sluice gates.

Results

In the experiment, the subject was deliberately allowed to react as he felt necessary to avoid falling (and report via the radio the reasons for what he did) rather than being "choreographed." His behavior in the "flume" under increasing water depths and velocities was therefore such as to try to counter the force of the water. In the standing tests, he therefore first stood at right angles to the water flow. As the flow and depth increased, he swiveled so as to stand diagonally to the flow, with one leg in front of the other and with the front leg bent. He then leaned forwards, with his arms extended and pointing downwards, so as to lower his center of gravity.

When he fell, he did so after slipping backwards, and in general, he fell forwards as his feet lost grip. In falling he twisted round to face downstream and "sit" in the water as it carried him downstream: as a stuntman he had been trained to fall safely, and did this twisting automatically.

In the walking tests, he adopted a similar posture, but attempted to move his feet horizontally, by sliding them, rather than raise them higher into the faster flowing water nearer the surface of the stream. He also attempted to stay upright by putting his feet firmly down quickly, so that his movement was staccato rather than normal unfettered walking. He reported that "staying still" was much easier than walking, and that walking through the flowing water was "really exhausting."

In the two standing tests, the numerical results show that, at the water depths investigated (up to 0.35 m), standing remained possible for the subject until the water velocity reached 2.6 m/s (first test) or 2.4 m/s (second test). However, the sliding backwards began at a water velocity of 1.8 m/s and depth of *c.* 0.23 m (both tests), with the subject sliding as much as 7 m backwards before falling.

In the walking tests the channel could be traversed completely, without falling, when the velocity was restricted to 1.7 m/s (depth *c.* 0.26 m). However, the subject consistently fell when the velocity was raised to 3.1 m/s (depth also 0.26 m). In the walking upstream test, the subject again fell, with the velocity at 3.0 m/s. At these velocities and depths, the water flow was turbulent with small waves (and some "white water") making both standing and walking more difficult than had the flow been laminar or nearly so. The combinations of depth and velocity at which actual instability occurred are plotted in Figure 7 and discussed in the section "Comparison of all data sources." In that section also a comparison is made with the results of the Abt *et al.* and Resdam test series.

The subject reported that he thought walking or standing would have been more rather than less difficult had he been carrying extra weight (e.g., carrying a child) because he expected to lose his balance in these conditions. However, these conditions were not tested.

The resistance of the subject to withstand the flow could be dependent on the timing during the test series. In previous experiments it has been reported that people go through a learning phase in which they learn how to stand in or walk through the flow. As the subject was a trained stuntman, it is expected that this effect is relatively limited. In addition, the experiment was conducted during one day and during that time tiredness led to falls with lower hv values in the later measurements. In future tests, this effect could be addressed by using multiple subjects and/or by distributing the tests over multiple days.

INTERPRETATION OF HUMAN INSTABILITY IN FLOOD FLOWS

Physical Interpretation of Human Instability in Flood Flows

Mechanisms for Instability. In the relevant literature the physical interpretation of human instability has received relatively limited attention. Most of the existing criteria for instability (see section "Past Work") are based on a purely empirical analysis of available test data.

Here, however, two hydrodynamic mechanisms that can cause instability are distinguished: moment instability and friction instability. Moment instability, or toppling, occurs when the moment caused by the oncoming flow exceeds the moment because of the resultant weight of the body, see also Abt *et al.* (1989). Friction instability, or sliding, occurs if the drag force induced by the horizontal flow is larger than the frictional resistance between the person's feet and the substrate surface, see also Keller and Mitsch (1993).

For completeness, one other hydrostatic mechanism is mentioned: floating. As the density of the human body is similar to the density of water, floating will usually occur if water depth exceeds a person's height. Then, the person is no longer subject to the moment or friction instability calculations.

Simplified schematic models for the two hydrodynamic mechanisms are shown in Figure 3. These are simple and imperfect models, but they are useful in understanding the physical mechanisms and the most relevant variables. Based on these models, the basic equations for moment and friction instability are derived below. Situations are considered where water depth is less than the person's height. For simplicity, the buoyancy forces are not included in the derivation of the basic equations for moment and friction instability. More complete equations that include buoyancy are reported Jonkman *et al.* (2005). Static models and a constant flow velocity are assumed, but in practice dynamic aspects, such as movement of people, and irregularity of flow, may play a role. The person is represented by a block shape with a certain width and height. An equal distribution of mass over the length of the block shape is assumed, so that the vertical center of a person's mass is located at half of a person's height (This seems reasonable as, more precisely, the body's vertical center of mass is located at approximately 55% of a person's height [Hellebrandt *et al.*, 1938]). The distribution of the velocity of the water flow is assumed to be uniform.

The following expressions are used for the person's weight, the friction force and the horizontal force:

$$F_{\text{person}} = \text{mg} \tag{5}$$

The friction force involves the coefficient of static friction: μ [no units] and equals:

$$F_{\text{friction}} = \mu\text{mg} \tag{6}$$

$$F_{\text{flow}} = 0.5\rho C_{\text{D}} Bhv^2, \tag{7}$$

where B is the average body width exposed normal to the flow [m]. C_{D} is the drag coefficient [no units]. g is the acceleration due to gravity [9.80665 m/s^2], ρ is the density of the flowing fluid [kg/m^3].

In Equation (7), the value of the drag coefficient C_{D} depends on the shape of the exposed object and Bh represents the wetted area's normal projection to the flow.

Moment Instability. For moment instability it is assumed that a person leans forward to counter the moment of the flowing water. To calculate moments it is assumed that the person leans forward and would pivot around their heel (Figure 3a). To obtain

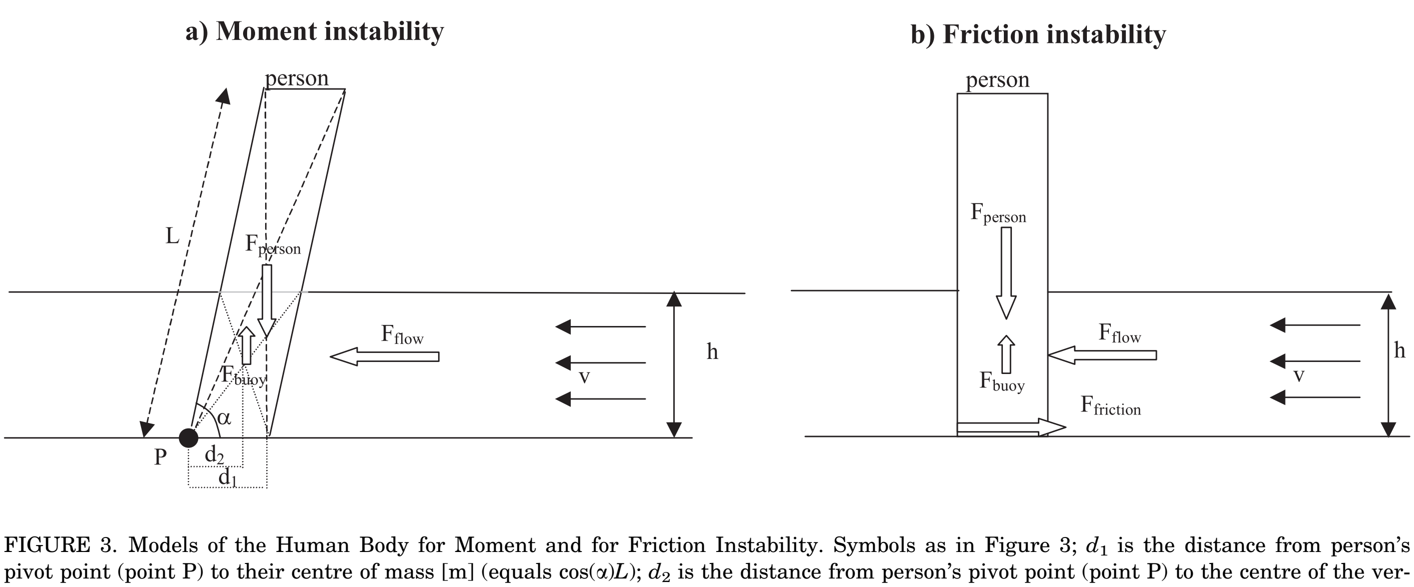

FIGURE 3. Models of the Human Body for Moment and for Friction Instability. Symbols as in Figure 3; d_1 is the distance from person's pivot point (point P) to their centre of mass [m] (equals cos(α)L); d_2 is the distance from person's pivot point (point P) to the centre of the vertical buoyancy force [m]; F_{buoy} is the vertical buoyancy force [N]; F_{flow} is the horizontal force of the flow on an object [N]; F_{friction} is the friction force between a person the stream bed [N]; F_{person} is the person's weight [N]; h is the Water depth [m]; L is the person's height [m]; P is the point in Figure 3 around which a person pivots while leaning into the flow; v is the water flow velocity [m/s]; αis a person's angle of tilt into flowing water [degrees]

instability, the moment associated with incoming flow around pivot point P must equal the resultant moment from the body's weight and buoyancy. This leads to:

$$\sum M_{\mathrm{P}} = 0 \\ F_{\mathrm{person}} d_1 - 0.5 h F_{\mathrm{flow}} = 0 \tag{8}$$

By substitution of Equations (5 and 7) the following expression can be obtained for the value of the critical depth-velocity product for which (moment) instability occurs:

$$hv_{\mathrm{c}} = (2mg\cos(\alpha)L/C_{\mathrm{D}}B\rho)^{0.5} = C_{\mathrm{M}}m^{0.5} \text{ with } C_{\mathrm{M}} = (2g\cos(\alpha)L/C_{\mathrm{D}}B\rho)^{0.5} \tag{9}$$

Equation (9) implies that the critical hv_{c} value can be estimated as a function of a person's mass [Alternatively, it is also possible to express hv_{c} as a function of both mass and length, see (Jonkman *et al.*, 2005).] multiplied by a constant C_{M} with unit $[\mathrm{m}^2/(\mathrm{s\ kg}^{0.5})]$. It also permits including the effects of a sloped bottom, as this directly reduces a person's angle of tilt (α). It is easily shown that the test conditions by Abt *et al.* (1989), with 0.5 and 1.5% slope, will probably have a limited influence on instability as the corresponding angles are small. Overall, the above elaboration shows that the generally used critical depth-velocity product (hv_{c}) is related to moment instability.

Friction Instability. Friction instability occurs if the drag force is larger than the frictional resistance between the person's footwear and the substrate surface (Figure 3b). The critical combination of depth and velocity can be derived from the horizontal force equilibrium:

$$hv_{\mathrm{c}}^2 = \frac{2\mu g}{C_{\mathrm{D}}B\rho} m = C_{\mathrm{F}}m \text{ with } C_{\mathrm{F}} = \frac{2\mu g}{C_{\mathrm{D}}B\rho} \tag{10}$$

The critical value of hv^2 has a linear relationship with mass multiplied by a constant C_{F} with unit $[\mathrm{m}^3/(\mathrm{kg\ s}^2)]$. The critical hv^2 for instability changes for different surfaces and conditions (i.e., for varying values of μ). Endoh and Takahashi (1995) give measured values of μ for different surfaces and shoe types. Values range between 0.38 for concrete covered with seaweed to 1.12 for rough concrete. They suggest $\mu = 0.4$ as a first-order conservative value that can be used to calculate the minimum hv^2 value for instability. Overall, the above elaboration shows that friction instability is related to the product of depth and squared velocity (hv^2), as opposed to hv for moment instability.

Combination of Moment and Friction Instability. Based on the equations derived above it is possible to consider the effects of both moment and friction instability and to identify when a certain mechanism is dominant. From Equations 9 and 10, the values of depth and velocity can be found where moment and friction instability give the same outcome (see also Figure 4):

$$h_{\mathrm{c}} = \frac{C_{\mathrm{M}}^2}{C_{\mathrm{F}}} = \cos(\alpha)\frac{L}{\mu} \\ v_{\mathrm{c}} = \frac{C_{\mathrm{F}}m^{0.5}}{C_{\mathrm{M}}} \tag{11}$$

Assuming realistic values for different input variables the theoretical lines for moment and friction instability have been plotted in the depth-velocity diagram (Figure 4).

For depths larger than h_{c} and velocities smaller than v_{c}, the moment criterion appears to be the dominant mechanism. For water depths smaller than h_{c} and velocities larger than v_{c}, friction instability dominates. Comparison of the two lines shows that, for velocities higher than v_{c}, the moment instability criterion underestimates the combination of depth and velocity that leads to instability. Thus, because of the effects of friction instability, the combination of low depths and high velocities could be more dangerous than would be predicted according to the depth-velocity criterion for moment instability.

Equation (11) also shows that friction instability will become more relevant for slippery surfaces with a low friction coefficient μ. In the conditions that have been investigated in the experiments (i.e., water depths between 0.5 and 1.2 m and velocities between 0.5 and 3 m/s), the moment and friction criteria lie close to each other and they both could lead to instability. In addition, both mechanisms might influence each other. For example, leaning forward to counter the moment decreases friction with the flume or

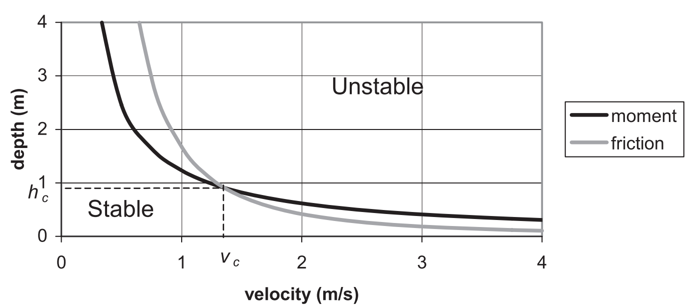

FIGURE 4. Theoretical Boundaries for Moment and Friction Instability (the following input variables have been used: m = 75 kg; g = 9.81 m/s^2; α = 75°; L = 1.75 m; C_{D} = 1.1; B = 0.4 m; μ = 0.5; ρ = 1000 kg/m^3).

channel bottom and induces friction instability. A further comparison between both mechanisms is given in the next section using the experimental data.

Comparison With People Stability Tests

Comparison With the Abt *et al.* and the Rescdam Tests. Available experimental data on human instability has been compared with the above models for moment and friction instability. The datasets of Abt *et al.* and Karvonen *et al.* have been used. For each dataset, coefficients for moment (C_M) and friction instability (C_F) have been derived that result in the best fit with the experimental data using a least square fit. Additionally, the squared correlation coefficient (R^2) is calculated to indicate the goodness of fit. Results are presented in Table 2. For both experimental series, the complete datasets have been analyzed. To investigate the effects of varying bottom material, the most complete subdatasets from Abt *et al.* (1989) have been included for concrete and steel surface with a 1.5% slope (both 14 measurements). For friction instability, an estimate of the friction coefficient is derived using reasonable estimates for the drag coefficient and the width exposed to the flow (C_D = 1.1; B = 0.5 m). The number of measurements from the FHRC experiments is too limited to allow statistical analysis, but these results are discussed separately in the next paragraph.

Moment Instability. To illustrate the results for moment instability, Figure 5 shows the measured depth-velocity products as a function of the person's mass and the derived best-fit trend line for the Rescdam (Karvonen *et al.*, 2000) dataset (C_M = 0.11; R^2 = 0.75).

The analysis shows that there is a good correlation between the observed depth-velocity product for instability and the critical product predicted with Equation (9). It is noted that Lind *et al.* (2004) indicate a major difference between males and

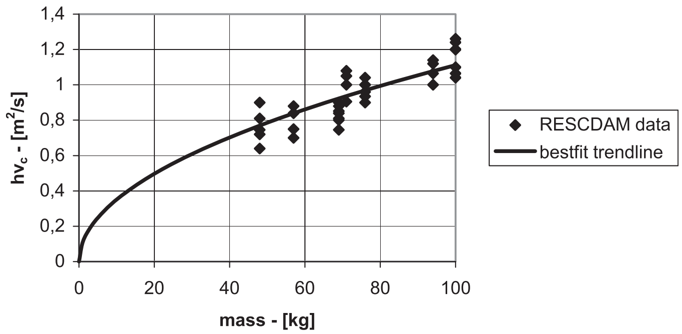

FIGURE 5. Depth-Velocity Product as a Function of Person's Mass for the Rescdam Experimental Data (Karvonen *et al.*, 2000) and the Best-Fit Trend Line.

females in their resistance to withstand the floodwaters. These differences disappear when the experimental results are interpreted with the proposed equations for moment instability, because differences in instability between the two genders are related to different body weights. A similar analysis has been done for the Abt *et al.* dataset leading to C_M = 0.16, but a poorer correlation between observations and model prediction (R^2 = 0.34). This could be due to the larger variations in slope and bottom materials in these tests, suggesting that friction instability could be relevant.

Friction Instability. To further analyse friction instability and the role of the bottom material, two subdatasets from Abt *et al.* (1989) are compared. These are the measurements on 1.5% slope for concrete and steel surfaces. In Figure 6, the measured critical hv^2 values are plotted as a function of a person's mass, together with the two best-fit lines.

For both subdatasets, 14 people were tested. For 11 people, instability occurs at a lower hv^2 product on steel than on concrete, as expected due to steel's lower friction coefficient.

In general, the derived value of the friction coefficient for the Rescdam dataset (μ = 0.49) is smaller than those for the Abt *et al.* (1989) dataset. This

TABLE 2. Derived Coefficients for Moment and Friction Instability Using Experimental Data From Abt *et al.* (1989) and Karvonen *et al.* (2000).

Test	Number of Observations	Moment Instability		Friction Instability		
		C_M [m^2/(s*kg$^{0.5}$)]	R^2	C_F [m^3/(s^2*kg)]	R^2	μ
Abt *et al.* (1989)						
All tests	65	0.16	0.34	0.031	0.36	0.87
Concrete 1.5%	14	0.15	0.62	0.036	0.46	1.01
Steel; 1.5%	14	0.18	0.58	0.030	0.54	0.83
Rescdam, Karvonen *et al.* (2000)						
All tests	38	0.11	0.75	0.018	0.41	0.49

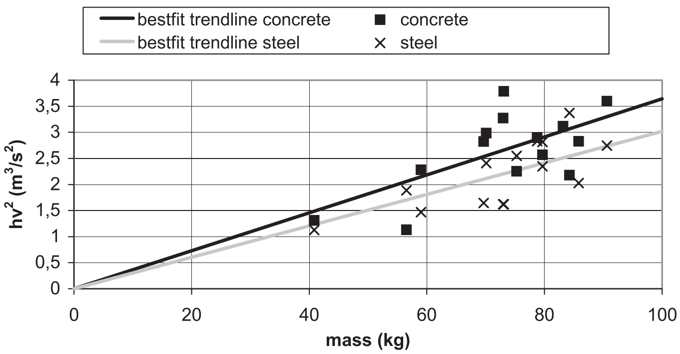

FIGURE 6. Friction Instability: Comparison Between Experimental Data From Abt *et al.* (1989) for Concrete and Steel Bottom and Derived Relationship.

value is representative for slippery surfaces, corresponding with the Rescdam tests being performed on fairly slippery steel.

For the RESCDAM dataset (Karvonen *et al.*, 2000) and the two subdatasets of Abt *et al.* (1989), correlations are lower for friction instability than for moment instability. This could indicate that the experiments were performed in conditions where moment instability is dominating mechanism.

Comparison of All Data Sources. Figure 7 shows the observed combinations of water depth and flow velocity that resulted in instability for the three available experiment series. The plotted data from the full-scale flume experiments by FHRC concern the conditions for which actual instability of the test person (i.e., falling) occurred. In addition, the theoretical lines are shown for moment and friction instability for the constants derived for the Abt *et al.* dataset

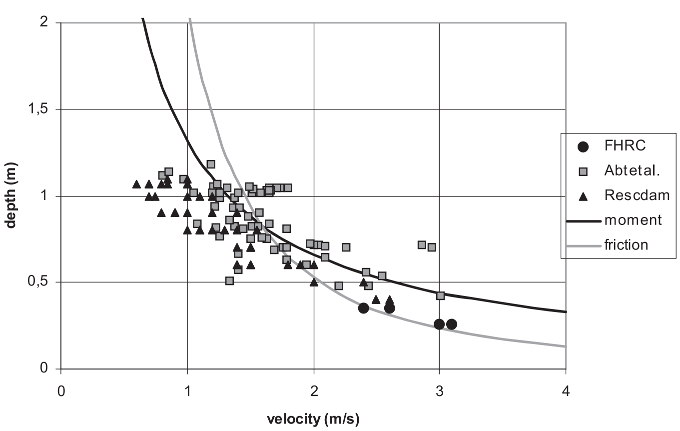

FIGURE 7. Observed Depth-Velocity Combinations That Resulted in Instability for Three Available Experiment Series and Theoretical Lines for Moment and Friction Instability [person m = 68.25 kg; L = 1.70 m; $C_M = 0.16\ m^2/(s*kg^{0.5})$; $C_F = 0.031\ m^3/(s^2kg)$].

and a person with a mass of 68.25 kg (This corresponds to the mass of the test person in the FHRC tests) and a length of 1.70 m. For this person, the hv_c value obtained from the original equation by Abt *et al.* [Equation (2) leading to $hv_c = 1.27\ m^2/s$] is nearly the same as the hv_c value obtained with the equation for moment instability derived in this paper [Equation (9): $hv_c = 1.32\ m^2/s$]. If an equation for moment instability would be derived based on all the available experimental data a critical product value of $hv_c = 1.18\ m^2/s$ would be obtained. This would result in even lower combinations of depth and velocity that would lead to instability.

Comparison of all data sources shows the following:

- For the Rescdam and FHRC tests instability was observed at lower depth-velocity products than would be expected based on the Abt *et al.* data and the derived depth-velocity product. The differences between Abt *et al.* and Rescdam observations could be related to the test circumstances and the type of clothing that test persons were wearing (see also Review of Experimental Data). The FHRC tests considered a fully fit and trained subject that was wearing similar clothing as the persons in the Rescdam tests (i.e., a drysuit).
- In particular, the data by FHRC confirms that, for high velocities and shallow depths, instability occurs earlier than would be expected according to the depth-velocity product for moment instability that is based on the Abt *et al.* data. For the stuntman's weight and height, the depth-velocity product for moment instability based on the Abt *et al.* data predicts that he could stand/walk in water almost twice as deep for the velocities encountered here, or at very much higher velocities for the depths experienced.
- Friction instability is expected to occur earlier than moment instability for the combinations of shallow depth and high velocities. The observations regarding the instability of the subject during the FHRC tests also confirm the relevance of friction instability. The test person first slid in the flowing water, before eventually falling. Overall, based on the results it is expected that friction instability is the dominating instability mechanism for flows with shallow depth and large velocities.

CLOSING DISCUSSION

The insight into human stability in flowing water has been advanced in this paper. It has been shown that two hydrodynamic mechanisms can cause instability in flood flows: moment instability (toppling) and friction instability (sliding). From simplified schematics of the mechanisms, it has been shown that the often-used depth-velocity (hv) product has a physical relationship with moment instability whereas friction instability is more closely related to the hv^2 product.

The results of new full-scale experiments by the FHRC have been reported. These new results, covering circumstances very closely resembling urban flash flooding, show that low depth/high velocity flood waters are more dangerous than suggested by Abt *et al.* (1989). This seems to be due to the effects of friction instability, which appears to occur earlier than moment instability for the combinations of shallow depth and high velocities. Based on these results policy makers should adjust their flood hazard zones accordingly.

We recognize, however, that our knowledge remains rudimentary and, of course, that other mechanisms and circumstances lead to loss of lives in floods. Further theoretical and empirical development and analysis would be useful. Experiments could involve other types of people (e.g., children, subject to ethical concerns) and loading situations (e.g., debris and other ranges of depth and velocity, especially ranges of conditions for which floating becomes important, including high depth/low velocity situations). For a better physical interpretation, more detailed schematization of the mechanical models could be considered, involving body characteristics [see Lind and Hartford (2000) for a discussion] and the flow profile and corresponding drag. Additional monolith tests, also covering different combinations of depth and velocity, are suggested for further verification of the schematic models.

However, the benefit of more refined schematization could be limited, as other phenomena affect human stability in flows (see also Karvonen *et al.*, 2000):

- Bottom characteristics, for instance evenness and obstacles.
- More water characteristics, for instance water temperature, ice, other debris, or even animals (e.g., fish, snakes, alligators) which could cause people to react in a manner other than seeking maximum stability (e.g., by swimming away).
- Human vulnerability factors. Additional loads such as clothing, disabilities, age, fatigue, and hypothermia would reduce ability to lean into the flow. In particular, the tests completed so far with people used healthy adults. Children and the elderly are likely to be particularly vulnerable to instability in flowing water. In flood situations, such as those which happen in the middle of the night, tiredness, disorientation, and mental stress could be significant factors too.
- Physical conditions. Lighting and visibility, wind, waves, and flow unevenness which suddenly changes water velocity and depth.

To transfer these findings to methods to assess the flood risks to people it is also important to consider the correlation between instability and overall risk of being killed in a flood. Losing stability does not necessarily imply drowning. Bern *et al.* (1993) investigated risk factors for flood mortality during the 1991 Bangladesh cyclone by conducting a survey amongst people who were affected by the flood. Of the 285 people who were "swept away" during the storm surge, 112 (39%) died. Numerous first-hand accounts of survivors from the December 26, 2004 Indian Ocean tsunami also point to many people surviving despite being picked up and battered by the tsunami and entrained debris. In many cases, the survivor became unconscious. Additionally, drowning, physical trauma, and hypothermia following instability are only one set of many flood death causes (Jonkman and Kelman, 2005). Thus, for a complete flood hazard analysis, other causes and circumstances should be considered, such as water depth, rise rate of the water and possibilities for warning and evacuation (Jonkman, 2007). Further empirical work could involve data collection on mortality rates in high hazard flood zones, for example near breaches, and could provide information for even more realistic flood hazard analysis.

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