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Stability of Individuals during Urban Inundations: What Should We Learn from Field Observations?

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Abstract: The flooding of urbanized areas constitutes a major hazard to populations and infrastructure. Flood flows during urban inundations have been studied only recently and the real-life impact of fluid flows on individuals is not well understood. The stability of individuals in floodwaters is re-assessed based upon the re-analysis of detailed field measurements during a major flood event. The results emphasized that hydrodynamic instabilities, linked to local topographic effects and debris, constitute major real-world hazards. A comparison between a number of flow conditions deemed unsafe for individuals, along with guidelines, suggests that many recommendations are over-optimistic and unsafe in real floodwaters and natural disasters. A series of more conservative guidelines is proposed, particularity relevant to flood events.

Keywords: urban inundation; Human body stability; incipient velocity; turbulence; field observations; flood events

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1. Introduction

Flooding is one of the most frequently occurring natural disasters in the world [1,2]. Flooding induced by dam failures caused the loss of life of more than 10,000 people between 1870 and 1990, outside of China [3]. It is expected that flooding will occur even more frequently in the future as a result of climate change [4–7]. In addition to the expected increase in the magnitude and frequency of future flooding, there will also be an increase in the world's population from the current level of 7.3–9.7 billion by 2050 [8]. Current projections indicate that 66% of the world's population will live in urban areas by 2050 [9], with 40% of the global urban land located in areas highly prone to flooding [10]. The number of people affected annually by flooding and natural disasters will increase significantly in the very near future. Floods through urban environments constitute a major hazard to infrastructure and people. Flood flows during urban inundations have been studied only recently, and few studies considered the impact of water flows on populations, including residents, emergency, and swift rescue personnel [11–15]. The risk to the populations is expected to increase with urban developments in flood-prone areas, while squatting areas in some countries is highly vulnerable to flooding [5,16].

Individuals' stability and safety may be adversely impacted in flowing waters, preventing their ability to stand, move or evacuate in an inundated environment. Experimental investigations under controlled conditions [11,17–19] tested the stability of individual adults and children in flumes and channels, with recent studies undertaken with scaled models [14,20]. Most results indicated that, considering a human body in floodwaters, the main mechanisms of instability are sliding and tumbling [21,22] (Figure 1). Observations suggested that sliding is most common in high-velocity shallow waters, and tumbling (or toppling) is more frequent in deeper waters [15,23,24]. During an inundation, an individual in floodwater is subjected to several forces, including its weight, a buoyancy force, a normal reaction force, the resultant of the pressure forces, and the surface friction on the floor [11,14,21,25]. The sliding resistance of an individual body is linked to the balance between the streamwise hydrodynamic force, the bottom friction, and the weight force component along the flow direction, when the floor is inclined (Figure 1 Left). The rotational stability of the individual is the resultant of the forces acting at the downstream bottom edge of the body, for an individual facing the flow (Point O in Figure 1 Right). Toppling or tumbling may occur when the moment of the hydrodynamic force resultant exceeds the moment due to the resultant weight of the body. Figure 1 presents a schematic of a standing individual facing flowing waters.

Further, a broad variety of human and environmental factors may impact the stability of individuals in water [25–28]. These could include the body shape, size, mass, balance, strength, foot size, state of mind, and body response, as well as climatic conditions (darkness, temperature, and rain) and environmental hazards (water turbidity, and debris). For an idealised situation, dimensional considerations show that the stability of an unassisted individual in floodwaters is a function of the human body's characteristics (height H, density ρ_H), fluid and physical properties (density ρ, viscosity μ, gravity acceleration g), bottom surface and slope (θ), water flow characteristics, and the type of gait [22,29]. Focusing on the most relevant factors, this yields:

$$\text{Stability threshold} = F(H, \rho_H, \rho, \mu, g, \text{bed surface}, \theta, d, V, V', d, d', \text{gait type}) \tag{1}$$

where d is the water depth, V is the water velocity (Figure 1), d' is a characteristic water depth fluctuation, and V' is some characteristic velocity fluctuation. A number of experimental studies were conducted with adults, children, and scale models. Despite very different settings, the results yielded some threshold for the stability of adults and children in floodwaters in the form of a relationship between a characteristic depth-averaged velocity V_c for individual stability and the corresponding water depth d (Figure 2). Typical results are presented in Figure 2a,b for children and adults, respectively, in the form of a comparison between field data, full-scale tests, scaled model data, and a semi-analytical relationship. The data are presented in a dimensional form at full-scale, regrouping both sliding and tumbling instability modes.

All the data indicated that, for an unassisted individual, the onset velocity for instability V_c decreased with increasing water depth, and the results were irrespective of the instability mode, sliding or tumbling (Figure 2). Importantly, the observations presented a significant scatter, reflecting differences in experimental conditions. For example, some experiments were performed with a stuntman, others with trained emergency personnel, e.g., swift water rescue and fire fighters, and fit young adults, while some were with children of various ages and sizes. Another point is that all the full-scale experiments with individuals were conducted in secured conditions (e.g., harness), in daylight and good lighting conditions, with clear water, and in the absence of debris. These test conditions were ideal, and guidelines derived from these data may be overly optimistic to be applied during a natural disaster. It is the aim of this contribution to review the stability of individuals in floodwaters based upon the re-analysis of well-documented field measurements during major flood events. Special attention is paid to the role of water velocity and water depth fluctuations.

2. Field Observations and Materials

Two field observation data sets were re-analyzed in the present contribution [27,29]. A key aspect of the data re-analysis is the first-hand experience of the authors who worked in an inundated urban environment and have a physical understanding of the flow hydrodynamics and fluid-body interactions.

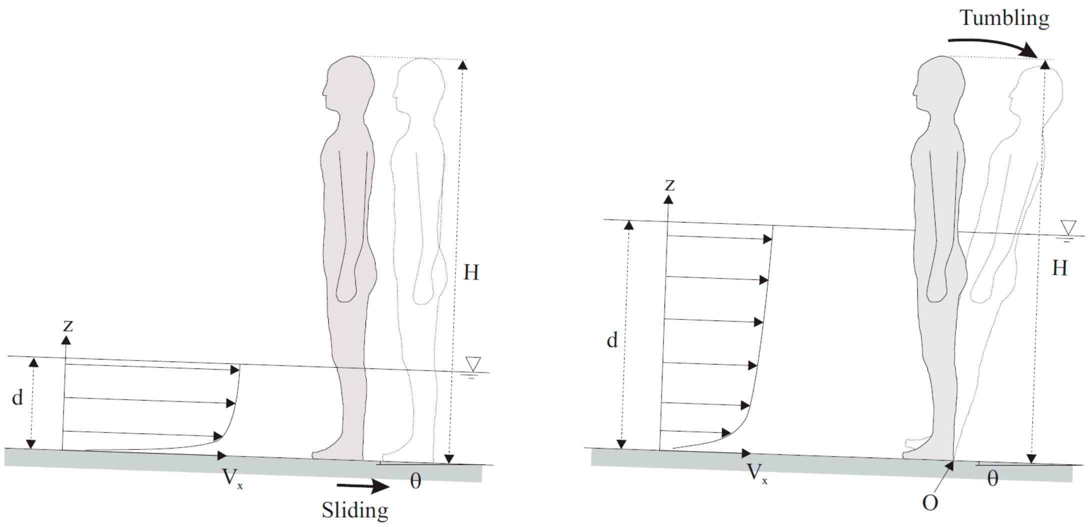

Figure 1. Definition sketch of forces acting on a stationary individual in floodwaters.

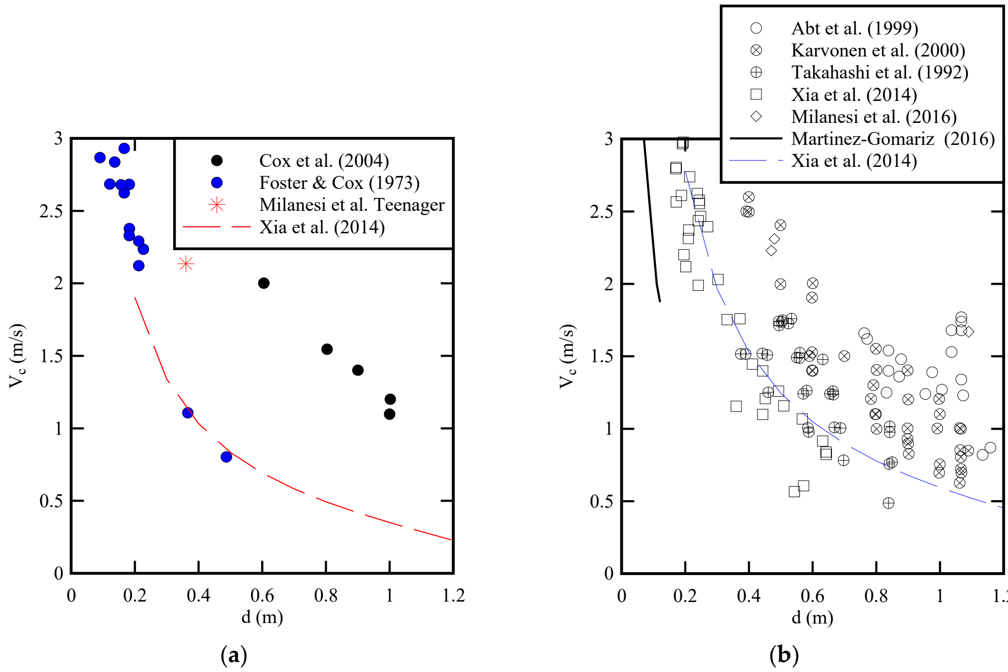

Figure 2. Relationship between characteristic flow velocity and water depth for stability of (**a**) children and (**b**) adults. Comparison between field data [27], full-scale tests [11,17–19,23], scaled model data of [12], and semi-analytical relationship proposed by [12].

In January 2011, the city of Brisbane (Australia) experienced a major flood [30,31]. The peak flood flow took place on 12 January afternoon and 13 January morning (Figure 3). The event affected many people (12,000 homes) causing in excess of $500 million of flood damage [32]. A series of detailed velocity measurements were conducted in an inundated section of the city about the peak of the flood of the Brisbane River [33]. The instantaneous velocity components were recorded continuously at a relatively high frequency (50 Hz) using an acoustic Doppler velocimeter (ADV) for three periods, before and after the peak of the flood (Table 1). The sampling locations were at the edge of a covered car park (Figure 4) along a street (Figure 4, Left). The sampling detailed, as listed in Table 1, includes the sampling elevation measured above the bed (Column 2) and the longitudinal velocity information (mean value, standard deviation, and range of data). As part of the fieldwork, the authors experienced the impact of the flood flow during the preparation and installation of the instrumentation. Namely, shortly before the start of data sets T2, T4, and T5 (Table 1). For each instance, the individuals used secured safety ropes and safety handrails to work safely in the inundated Gardens Point Road. All together, three people were involved working in the floodwaters, and they were assisted by three other people safely located above the floodwaters. The three individuals in the waters comprised two university academic staff and a senior technical staff, who had about 40 cumulative years of fieldwork experience in rivers and estuaries. Their body characteristics are listed in Table 2. These individuals were not specifically trained, they did not have swift water rescue training and they had no previous experience working in floodwaters during a natural disaster.

The second data set is a series of flood-related videos analyzed by [27], focusing on the data listed as "incipient of instability". All events were reviewed by the authors. Only natural major flood event observations were retained, and data for individuals using secured ropes and assistance were considered unsafe and unstable situations.

Table 1. Field measurements of instantaneous longitudinal velocity in Gardens Point Road, Brisbane on 12 and 13 January 2011.

Period	Z_{ADV} (m)	Velocity Data Set	Water Depth (m)	Mean Velocity (m/s)	Std Velocity (m/s)	Velocity Data Range (m/s)	Individual Stability
T2	0.35	800,000 samples (4.4 h)	0.8–1.0	0.454	0.170	−0.36/+1.17	Unstable & Unsafe
T4	0.083	685,884 samples (3.8 h)	0.6–0.4	0.455	0.123	−0.23/+1.09	Unstable & Unsafe
T5	0.083	196,762 samples (1.1 h)	0.3–0.1	0.0065	0.031	−0.12/+0.15	Stable & Safe

Table 2. Characteristics of individual researchers who worked in floodwaters at Gardens Point Road, Brisbane on 12 and 13 January 2011.

No.	Height (m)	Mass (kg)	Age	Male/Female
1	1.75	75	49	M
2	1.75	74	51	M
3	1.79	120	60	M

(**a**)

(**b**)

Figure 3. Inner city of Brisbane, Australia during the 2011 Brisbane River flood inundation. (**a**) Intersection of Margaret and Albert Streets on 12 January 2011 at 16:30. (**b**) Submerged intersection of Milton Road and Eagle Terrace on 13 January 2011 at 05:35.

Figure 4. Velocity measurement locations along Gardens Point Road in Brisbane Central Business District, Australia on 13 January 2011 at 11:40. Looking upstream at the acoustic Doppler velocimeter (ADV) sampling sites during periods T2 & T4—T5. The water depth was about 1 m at the time of photograph.

3. Results: Stability of Individuals in Floodwaters

Following the field deployment in Brisbane (12–14 January 2011), a discussion with all individuals who worked in the floodwaters indicated that the flow conditions were unsafe to work without secured ropes and handrails during the periods T2 and T4 (Table 1). These hydrodynamic conditions would have been totally inappropriate for any form of evacuation in the inundated urban environment. The flow conditions were most unsafe because the intense turbulence and water surges created very hazardous and treacherous conditions. These resulted in very large fluctuations in velocity, as reported in Table 1 (columns 6 and 7). The environmental conditions were unstable, with the individuals losing their footing and balance during the water surges. These surges were induced by local topographic effects, namely choking flow conditions induced by building structures upstream of the observation site [32]. The people who assisted, from above, listed further risks associated with large debris regularly passing in Gardens Point Road. These included trees, branches, logs, plastic containers, and rubbish bins. Figure 3a shows a rubbish bin (i.e., wheelie bin) floating at a street intersection, while Figure 3b shows floating debris in the foreground. Further, the works undertaken in the water at twilight and in the early evening were very difficult, despite the artificial lighting available, because of the risk of spatial disorientation and loss of peripheral awareness.

The second data set [27] included several flood flow situations that were unstable. In a few instances, the waters were sediment-laden and turbid, hampering any advance on the irregular bed. In several cases, fairly significant differences were observed between different individuals subjected to the same flood hazard. While not all data could be quantitatively re-analyzed, the materials showed qualitative contrasting behaviors, depending upon the situation, flow conditions, and individual attitudes.

Both field observation data sets are regrouped in Figure 5. In Figure 5, the bars for the Brisbane River data indicate the range of instantaneous depth and velocity measurements. The re-analyzed data are compared to data for the stability threshold of adults obtained under controlled conditions (see above), typically undertaken with constant water velocity and low water turbulence. The comparison between field observations, typically deemed unstable by the authors, and earlier guidelines demonstrate that many recommendations would be inappropriate in the context of the field observations. In practice, the current guidelines might not be relevant to natural disaster situations, in particular floods in urban settings with large turbulence levels. It is believed that criteria based simply upon the water velocity and depth do not account for many hazardous factors encountered in natural catastrophes, inclusive of fluctuations in depth and velocity, as well as high turbulence levels. In Brisbane, the experimental observations indicated a median acceleration amplitude about 0.46 m/s^2 and a median jerk amplitude of 19 m/s^3. Further, current guidelines do not take into account many risks associated with flowing debris, such as trees, logs, branches, bins, and industrial containers entrained in floodwaters. They also ignore any sense of insecurity associated with the absence of secured ropes and harness, water turbidity, and darkness.

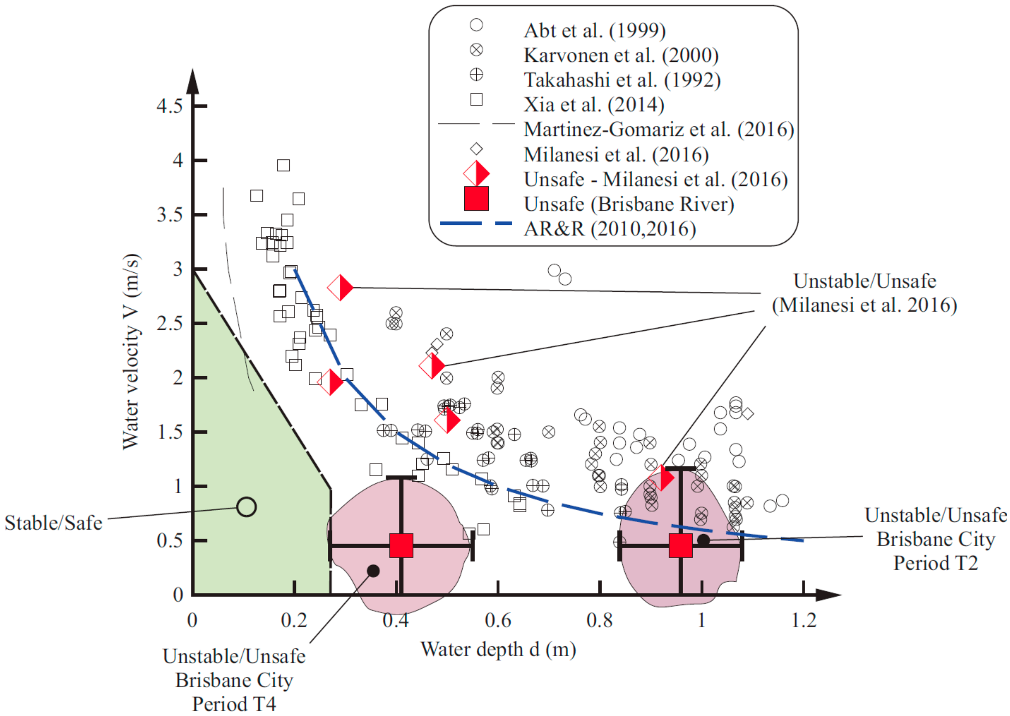

Figure 5. Relationship between water velocity and water depth for stability of human body in floodwaters. Comparison between field observations deemed unsafe for evacuation (Red symbols), full-scale tests with adults [11,18,19,23], model data of [14], current guidelines ([13,34] {Low hazard}) and new guidelines (Equation (2)). Scatter bars show the range of instantaneous velocity and water depth measurements.

Based upon the re-analyzed field observations, new and more conservative guidelines for human body safety in floodwaters are proposed:

$$d < 0.27 \text{ m} \qquad \text{for } V < 1 \text{ m/s} \tag{2a}$$

$$V < 3 - 7.4 \times d \qquad \text{for } d < 0.3 \text{ m} \tag{2b}$$

with the water depth d and water velocity V in m and m/s, respectively. Equation (2) is shown in Figure 5 and corresponds to the stability of individuals in floodwaters, in the absence of large suspended debris. Equation (2) should be considered as a set of conservative recommendations, encompassing natural disaster situations in urban environments.

In Figure 5, the scatter bars represent the full range of instantaneous water depth and velocity measurements. These large fluctuations in depth and velocity significantly complicate any prediction to assess where a situation is safe/unsafe for evacuation.

4. Discussion and Concluding Remarks

Flooding in urbanized settings create hazardous situations for the population, leading too many times to the tragic loss of lives. The stability of individuals in floodwaters is re-assessed based upon the re-analysis of detailed field measurements during a major flood event. The results emphasized that hydrodynamic instabilities linked to local topographic effects and debris constitutes major real-world hazards. A comparison between a number of flow conditions deemed unsafe for individuals, along with guidelines, suggests that many recommendations are overly optimistic and unsafe in real floodwaters and natural disasters.

Flood flow situations in inundated urban environments can be treacherous because of intense turbulence and water surges—as observed in Brisbane City in January 2011. A critical review of past data and recommendations demonstrates that too many tests were conducted in idealized situations, with fit individuals working in secured conditions, good weather conditions, and in the absence of debris. The experience gained by the authors and the re-analysis of real flood disaster data shows that, during a natural disaster, the flood flow conditions can be treacherous and dangerous. New recommendations are derived from field observations (Equation (2)) and the present results suggest that a number of guidelines for human body stability in floodwaters need to be critically reviewed.

Finally, although swift water flood rescue courses are available, no clear guidance and procedure directly relevant to such a floodwater research study has been published, to the best knowledge of the authors. The lack of appropriate guidance for working in floodwaters highlights a need for further studies in this field.

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