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Human body stability in floodwaters: the 2011 flood in Brisbane CBD

H. Chanson[1], R. Brown[2] and D. McIntosh[2]
[1]The University of Queensland, School of Civil Engineering
Brisbane QLD 4072
AUSTRALIA
E-mail: h.chanson@uq.edu.au
[2]Queensland University of Technology, Faculty of Science and Engineering, Brisbane QLD 4000, Australia

Abstract: *.The flooding of urbanised areas constitutes a hazard to the population and infrastructure. Floods through inundated urban environments have been studied recently and the potential impact of flowing waters on pedestrians is not well known. Herein the stability of individuals in floodwaters is reviewed based upon the re-analysis of detailed field measurements in an inundated section of the central business district of the City of Brisbane (Australia) during the 2011 flood. Detailed water elevation and velocity data were recorded. On-site observations showed some hydrodynamic instability linked to local topographic effects, in the form of a combination of fast turbulent fluctuations and (very) slow fluctuations of water level and velocity associated with surges. The flow conditions in Gardens Point Road was unsafe for individuals and a review of past guidelines suggests that many previous recommendations are over-optimistic and unsafe in real floodwaters.*

Keywords: *Floodwater, Human body stability, Incipient velocity, Turbulence, Brisbane River, 2011 flood, Field measurements*

1. INTRODUCTION

The flooding of urban environments constitutes a major hazard to the population. Floods through inundated urban areas have been studied only recently and few considered the impact of flowing waters on pedestrians including residents, emergency and swift rescue personnel (Abt et al. 1989, Asai et al. 2010, AR&R 2010, Xia et al. 2014). The risks of people caught in floodwaters are expected to increase with the build-up of populations and urban developments in flood prone areas, while urban squatting in some countries is highly vulnerable to flooding (Kundzewicz 2008).

The eastern Australian continent received some extraordinary rainfalls between November 2010 and January 2011 causing some major floods in the states of Victoria, Tasmania, New South Wales and Queensland (BOM 2011, Chanson 2011). In Queensland, 78% of the state was declared disaster zone and the flood reconstruction costs were estimated to be in excess of $5 billions (QFCI 2011). Thirty three lives were lost and three remain missing (QFCI 2011, Agnew P&F Association 2011), among which are several people who were washed away in the floodwaters.

On 12-14 January 2011, the City of Brisbane was affected by a major flood causing over $500 millions of damage (Fig. 1). During the event, some field measurements were conducted in an inundated street of the central business district (CBD) (Brown and Chanson 2013). The results are re-analysed herein with a focus on the flow turbulence and the implication in terms of human body stability in floodwaters in an inundated urban setting. It is the purpose of this contribution to discuss the current recommendations on human body stability and their relevance in the context of the January 2011 flood in Brisbane, based upon the field experience and detailed measurements during the event.

Figure 1 – People in floodwaters during the 2011 Brisbane River flood (Australia) - (A) Indooroopilly Road on 12/1/2011 afternoon about 14:50; (B) Indooroopilly Rd on 12/1/2011 morning (Courtesy of K. Clarke); (C) Chelmer Street East on 13/1/2011 at 11:34 (Courtesy of F. Reid); (D) Moggill Road on 12/1/2011 about 17:00

2. BASIC CONSIDERATION

Considering a human body in floodwaters, there are two main mechanisms of instability: i.e., sliding and tumbling (Fig. 2). Past studies suggested that sliding was common in high-velocity shallow waters, while tumbling (or toppling) was more frequent in deeper waters (Cox et al. 2004, Xia et al. 2014). During a flood event, an individual is subjected to several forces, namely its weight, a buoyancy force, the reaction force including a normal reaction force and surface friction on the floor, and the resultant of the pressure forces (Abt et al. 1989, Takahashi et al. 1992, Xia et al. 2014). The sliding resistance of the body is linked to the balance between the streamwise hydrodynamic force, the bottom friction, and the weight force component along the flow direction (if the floor is inclined). The rotational stability of the body is the resultant of the forces acting at the downstream bottom edge of the body (Point O, Fig. 2). Toppling or tumbling may occur when the moment of the hydrodynamic force resultant exceeds the moment due to the resultant weight of the body.

Dimensional considerations show that the stability of a human body in flood waters is a function of the body characteristics (height H, density ρ_H), fluid and physical properties (density ρ, viscosity μ, gravity acceleration g), bed surface and slope (θ), flow properties and the type of gait:

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

where d and V are respectively the flow depth and velocity (Fig. 2), and d' and V' are some characteristic depth fluctuation and velocity fluctuation respectively. 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 and the water depth d (Fig. 3). Typical results are presented in Figures 3A and 3B for children and adults respectively. The data are presented in a dimensional form at full-scale and regroup both sliding and tumbling instability modes.

All the results indicated that the onset velocity for instability V_c decreased with increasing water depth, and the results were irrespective of the instability mode (Fig. 3). The data presented some scatter reflecting differences in experimental conditions. For example, some experiment was performed with a stuntman, others with trained emergency personnel (e.g. swift water rescue, fire fighters) and fit young adults, and some with children of various sizes. Another aspect is that all the experiments with individuals were conducted in secured conditions (e.g. harness), in daylight and good lighting conditions, and in absence of debris. Thus these conditions were ideal and the guidelines presented in Figure 3 may be over-optimistic to be applied during a natural disaster.

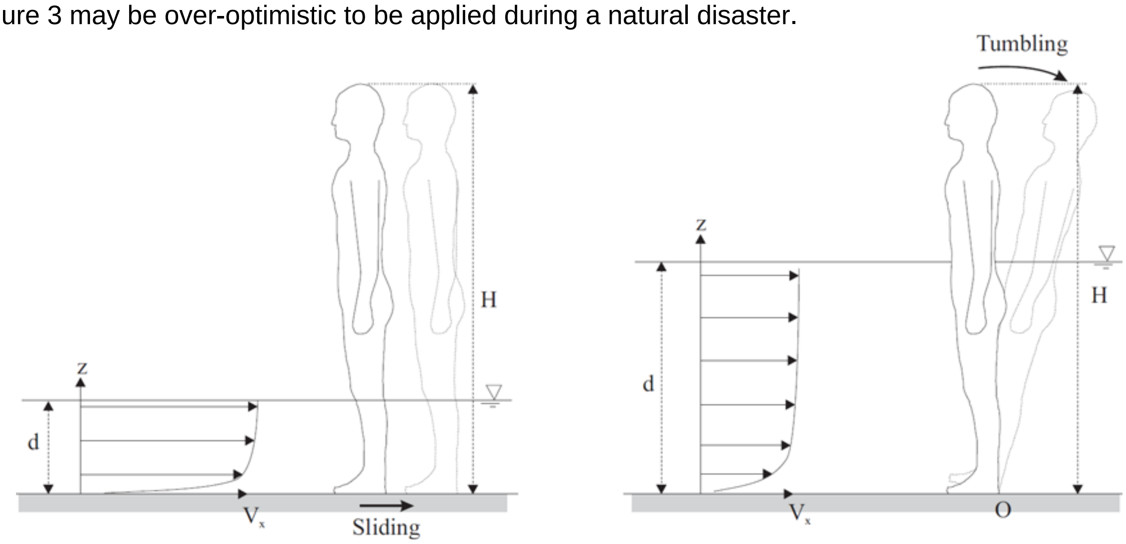


Figure 2 – Sketch of the forces acting on a human body in floodwaters

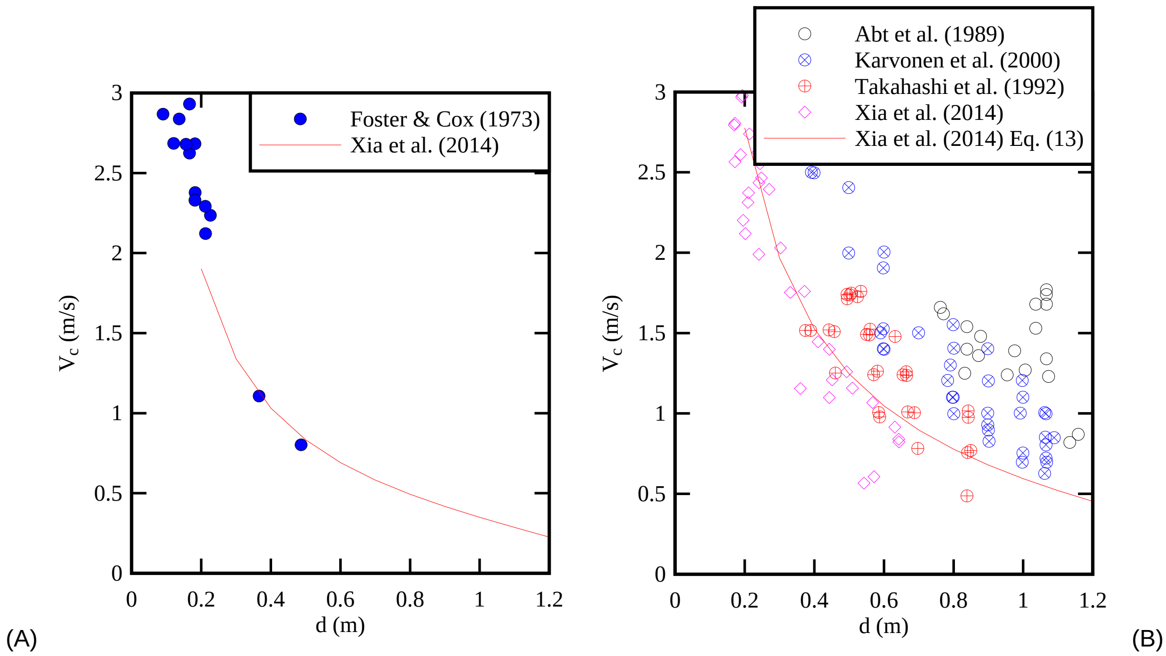


Figure 3 – Relationship between characteristic flow velocity and water depth for stability of (A) children and (B) adults - Comparison between full-scale tests (Foster and Cox 1973, Abt et al. 1989, Karvonen et al. 2000, Takahashi et al. 1992), model data of Xia et al. (2014), and semi-analytical relationship proposed by Xia et al. (2014)

3. FIELD OBSERVATIONS IN BRISBANE CBD

Some water level data and turbulent velocity measurements were conducted in the inundated Gardens Point Road, Brisbane CBD on 12 to 14 January 2011 (Brown and Chanson 2013). The velocity components were recorded at 50 Hz using a Sontek™ microADV for 3 periods (Table 1) before and after the peak of the flood. The sampling locations were at the edge of a covered car park (Fig. 3, Right) along Gardens Point Road (Fig. 3, Left), and the sampling volume elevation above the bed is listed in Table 1 (Column 2). During the field study, the water depth ranged between 1 m and zero when the flood receded. All the acoustic Doppler velocimeter (ADV) data underwent a thorough post-processing (Brown and Chanson 2013).

Figure 3 – Gardens Point Road (Brisbane CBD, Australia) on 13/1/2011 at about 11:00. Looking upstream at ADV sampling sites (T2: Red arrow; T4-T5: Blue arrow) - The water depth in the foreground was about 1 m

During the rising stage of the flood, the river swelled and inundated Gardens Point Road and the surrounding car parks. A relatively fast flow motion was observed along Gardens Point Road from Parliament House to the Goodwill Bridge. The river surface was brown and the waters were heavily sediment-laden. The river started to recede on 13 January morning, and it left a 2-10 cm thick layer of soft mud on Gardens Point Road and the car parks on 14 January 2011 morning.

During the flood, the authors went into the floodwaters to install the ADV system and later to re-locate the unit. They observed some hydrodynamic instabilities linked to some local topographic effects (Brown and Chanson 2013). Namely a combination of fast turbulent fluctuations together with some (very) slow fluctuations of water level and longitudinal velocity associated with some water surges. These instabilities were recorded by the ADV signal. The velocity data were decomposed to separate the contributions of the slow and fast fluctuations to the turbulent kinetic energy:

$$V_i = \langle V_i \rangle + [V_i] + v_i \qquad (2)$$

where V is the instantaneous velocity component data, <V> is the low-pass filtered component, [V] the band-pass filtered component, v is the high-filtered turbulent fluctuation component, i = x,y,z, x is the longitudinal direction positive downstream, y is the horizontal transverse direction and z is the vertical direction positive upwards. The threshold frequencies were selected as 0.002 Hz and 0.33 Hz, and [V] characterised the (very) slow fluctuations in velocity, observed with periods between 50 and 100 s.

The results showed that the slow fluctuations in velocity contributed to 90 to 95% of the turbulent kinetic energy (Brown and Chanson 2013). Some data are reported in Table 1 (Columns 7 to 10). In Table 1, the data for period T5 differed substantially from earlier results. This was caused by the retreat of the flood waters when Gardens Point Road became disconnected from the main river channel and the velocity magnitude dropped drastically (Fig. 4A).

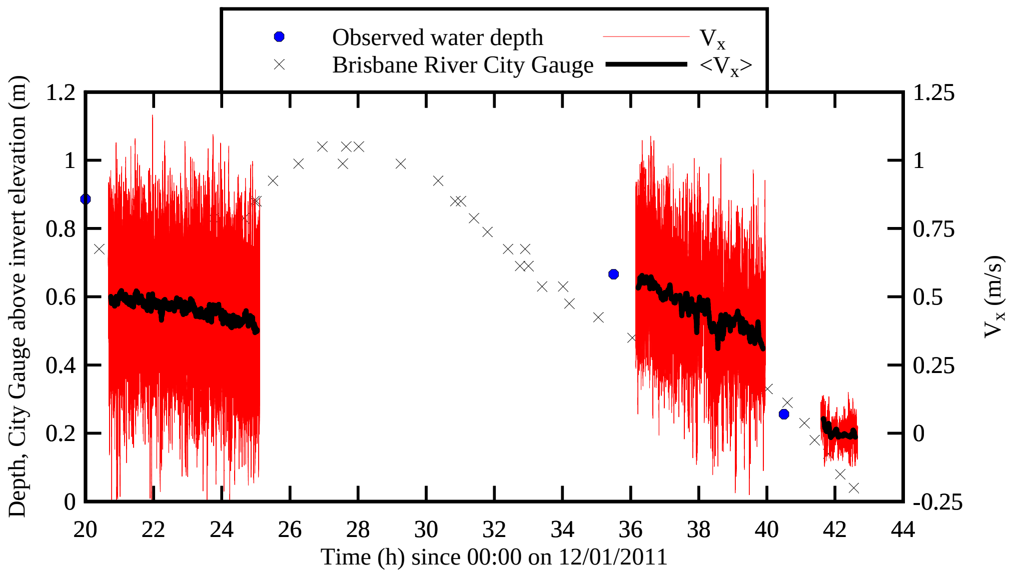
Table 1 - Field measurements at Gardens Point Road during the Brisbane River flood in January 2011

Period	z_{ADV} (m)	Sampling rate (Hz)	Sample	Depth (m)	$\overline{V_x}$ (m/s)	$(V_x-<V_x>)'$ (m/s)	v_x' (m/s)	v_y'/v_x'	v_z'/v_x'	Human body safety
T2	0.35	50	800,000 samples, from 20:40:08 on 12/1/2011	0.8-1.0	0.454	0.163	0.035	0.96	1.14	Unsafe / Unstable
T4	0.083	50	685,884 samples from 12:08:55 on 13/1/2011	0.6-0.4	0.453	0.123	0.027	0.76	0.84	Unsafe / Unstable
T5	0.083	50	196,762 samples from 17:34:40 on 13/1/2011	0.3-0.1	0.006	0.031	0.006	0.76	0.68	Safe / Stable

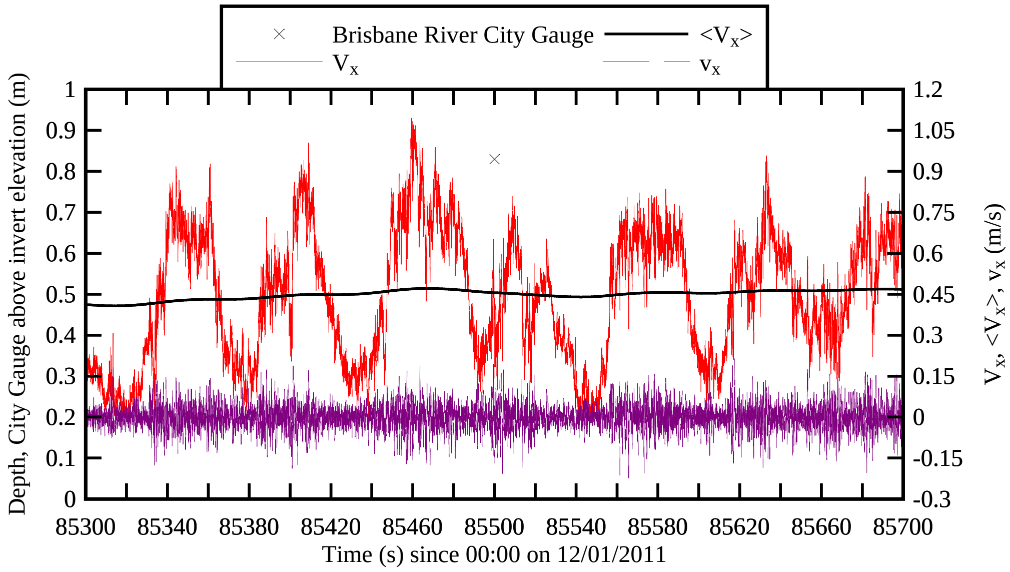
3.1. Turbulence characteristics

The water elevation data were consistent with the City Gauge data, collected 1.55 km downstream of the sampling site, while the velocity data showed large fluctuations of all components (Fig. 4). This is illustrated in Figure 4A in terms of V_x for the entire data set. In Figure 4A, the City Gauge data are presented relative to the invert elevation at the sampling site (i.e. 3.42 m AHD). Figure 4B shows some details of the longitudinal velocity fluctuations, highlighting some slow fluctuations about the mean trend with a period of about 60 s. The fast turbulent fluctuations (v_x) are also shown in Figure 4B.

A conditional analysis was applied to characterise some turbulent bursting events in terms of the product $v_x \times v_z$, where v is the (high-pass filtered) turbulent velocity fluctuation (Eq. (2)). This technique, called quadrant analysis, is commonly used in boundary layer flows (Willmarth and Lu 1972, Nakagawa and Nezu 1977). Four types of bursting events are characterised: outward interaction $v_x > 0$ & $v_z > 0$ (Q1), ejection and lift-up of low-speed streaks of fluids for $v_x < 0$ & $v_z > 0$ (Q2), inward interaction for $v_x < 0$ & $v_z < 0$ (Q3), and sweep for $v_x > 0$ & $v_z < 0$ (Q4). Herein the contribution of $v_x \times v_z$ to each quadrant was analysed for $|v_x \times v_z| > Ho \times |\overline{v_x \times v_z}|$ with Ho an arbitrary value, called hyperbolic hole size.



(A) Water depth, V_x, $<V_x>$ and Brisbane City gauge data (above Gardens Point Road invert elevation)



(B) Detailed time-variations of V_x, $<V_x>$ and v_x during data set T2

Figure 4 – Water depth and longitudinal velocity in Gardens Point Road on 12-14 January 2011

Figure 5 shows a typical plot of results in terms of the fractional contributions to the tangential stress $v_x \times v_z$ with the hyperbolic central region omitted for various values of the hole size Ho. In the present data set, the contributions of all four quadrants were comparable independently of the hole size (Fig. 5). Also shown on Figure 5 is a curve representing the percentage of time that the signal $v_x \times v_z$ remains in the hole $|v_x \times v_z| < \text{Ho} \times |\overline{v_x \times v_z}|$. For a large fraction of the time, $|v_x \times v_z|$ is very small relative to shorter intervals of intense activity (i.e. bursting events). Roughly speaking, the smallest events occupying 80% of total time made less than 30% of the total contribution to the Reynolds stress $v_x \times v_z$, on average, for all three data sets (Table 1). The present data differed substantially to boundary layer data and open channel flow measurements, both qualitatively and quantitatively (Nakagawa and Nezu 1977). Both sweep and ejection events contributed about the same levels as inward and outward interactions, in contrast to boundary layer flows. The contrasting differences might reflect the complexity of the flow hydrodynamics, including the influences of the surrounding buildings, concrete columns and walls, handrails and signpost poles.

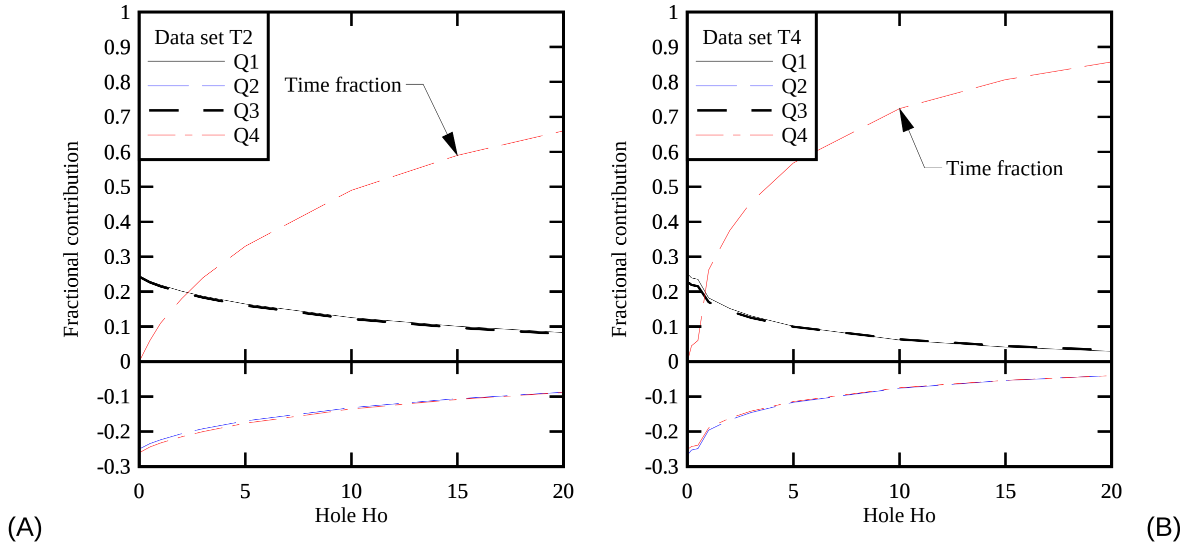


Figure 5 – Fractional contribution to Reynolds stress $v_x \times v_z$ and fraction of time spent in hole as function of the hole size - Gardens Point Road on 12-14 January 2011: (A) period T2; (B) period T4

4. HUMAN BODY STABILITY

The authors experienced the force of the flood flow in Gardens Point Road during the installation and checking of the equipment: i.e., shortly prior to the start of data sets T2, T4 and T5 (Table 1). They used secured safety ropes and safety handrails to work safely in the flood waters. Altogether three people worked in the flood waters, while they were assisted by three more people safely located in the building level 2. The three people in the waters included two academic staff and a senior technical staff, and their body characteristics are listed in Table 2. All three had over 40 years of field work experience in rivers and estuaries. But they were not specifically trained and they did not work previously in floodwaters.

A discussion with all people working in the waters indicated that the hydrodynamic conditions were unsafe to work without handrail and secured ropes, and would be totally inappropriate for any form of evacuation in the floodwaters. The flow conditions were unsafe during the periods T2 and T4 because the intense turbulence and water surges created very hazardous and traitorous conditions (Table 1). These conditions were unstable, with staff loosing footing and balance during water surges. The people who assisted from above mentioned further the risks associated with large debris (trees, logs, plastic containers....) regularly flowing in Gardens Point Road. Works at the twilight and early evening were extremely difficult despite the artificial lighting, because the individuals in the water could be easily disoriented.

Table 1 - Characteristics of the individuals who worked in floodwaters at Gardens Point Road in 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

The present observations are summarised in Figure 6 together with error bars indicating the instantaneous depth and velocity data range. They are compared with the data for stability threshold of adults obtained under controlled conditions (see above). These tests, mostly performed in laboratory, were conducted with constant water velocity and relatively low turbulence. The comparison between present observations, deemed unstable by the authors, and earlier guidelines indicates that these were inappropriate in the context of the inundated Gardens Point Road during the 2011 Brisbane River flood. More generally, the existing guidelines might not be representative of some inundation situations in urban settings with large turbulence levels. Any criterion solely based upon the flow velocity and water depth does not take into account the hazards caused by the water depth and velocity fluctuations, and the flow turbulence. In Gardens Point Road, large and rapid fluctuations in velocity were observed, giving median acceleration amplitude of 0.46 m/s^2 and median jerk amplitude of 19 m/s^3. These guidelines further ignore the risks associated with large debris (logs, trees, bins, containers) entrained in the floodwaters, as experienced in January 2011, nor the sense of insecurity associated with the absence of harness and secured ropes.

Based upon the present observations, new guidelines for human body stability and safety in floodwater may be derived in terms of the instantaneous velocity V_i and depth in floodwaters:

$$d < 0.3 \qquad \text{for } V_i < 1 \text{ m/s} \quad (3a)$$

$$V_i < 4 - 10 \times d \qquad \text{for } d < 0.3 \text{ m} \quad (3b)$$

with d and V_i in m and m/s respectively. Equation (3) is drawn in Figure 6 and applies to the stability of individuals in floodwater in absence of large debris. It is a set of conservative guidelines encompassing natural disaster situations with high turbulence levels.

Note that the scatter bars in Figure 6 represent the full range of the instantaneous depth and velocity data, and these scatter bars significantly increase the difficulty to predict conditions where it is safe/unsafe for evacuation. Preliminary analysis of the phase of the water depth and velocity revealed that the phase was significant and not occurring randomly. If the phase was taken into account, the range of data from the 2011 Brisbane flood shown as cross hatched grey area in Figure 6 would actually have a reduced area because not all combinations of depth and velocity did occur. Nonetheless it is believed that Equation (3) provides some conservative guidelines, more suitable during a natural disaster than previous recommendations.

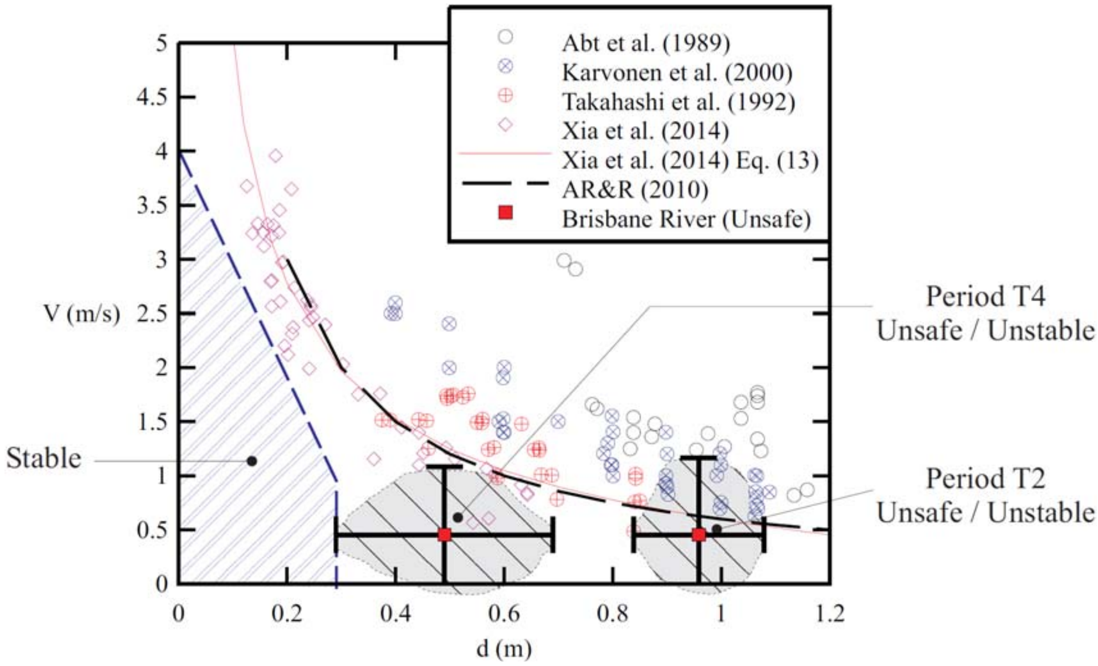


Figure 6 – Relationship between flow velocity and water depth for stability of human body - Comparison between the field observations in the Brisbane River in January 2011 deemed unsafe for evacuation, full-scale tests with adults (Abt et al. 1989, Karvonen et al. 2000, Takahashi et al. 1992), model data of Xia et al. (2014), AR&R (2010) [Low hazard] and correlation by Xia et al. (2014) - Scatter bars details instantaneous data range, data sampled for 3 h 50 min (T2) and 4 h 30 min (T4) respectively

5. CONCLUSION

The flooding of urbanised areas constitutes a hazard to the population and lives were tragically lost in floodwaters during the 2010-2011 Queensland floods (QFCI 2011). Herein the stability of individuals in floodwaters is reviewed based upon field measurements in an inundated section of the central business district of the City of Brisbane (Australia) during the 2011 flood of the Brisbane River. Detailed water elevation and velocity data were recorded with high resolution. A key feature was the high level of turbulence, together with a combination of high-frequency turbulent velocity fluctuations and low frequency water surges. The authors experienced the force of the flood flow in Gardens Point Road during the installation and check of the equipment. In two of the three relevant periods, the flow conditions were unsafe to stand in the floodwaters without handrail and secured ropes.

Flood flow situations in inundated urban environment can be treacherous because of intense turbulence and water surges, as observed in Gardens Point Road in January 2011. Many existing recommendations could lead to hazardous and unsafe situations, when hydrodynamic instabilities develop. A critical review of past data and guidelines suggests that many physical tests were conducted in idealised situations: e.g., with fit individuals, secured conditions, good weather and lighting conditions, absence of large debris. The experience gained by the authors indicates that the real conditions during a natural disaster can be more treacherous and dangerous. New recommendations were derived from the experience in Gardens Point Road in January 2011 (Eq. (3)). The present findings show the critical need to review thoroughly earlier guidelines for human body stability in floodwaters, including AR&R (2010).

Lastly, to the best of the authors' knowledge, no clear guidance/procedure directly relevant to such a floodwater study was published, although swift water flood rescue courses are available. Appropriate selection of equipment can be aided by the requirements of AS4488 Industrial Rope Access, applicable for certain situations of static and dynamic loading including fall arrest, but does not directly apply to moving flood waters. This lack of appropriate guidance for working in floodwaters highlights a need for further studies in this field.

6. ACKNOWLEDGMENTS

This contribution is dedicated to the victims of the 2010-2011 floods in Queensland: Lest we forget. The authors acknowledge all the people who assisted with the field measurements. They thank kindly Professor Junqiang Xia (Wuhan University, China) for providing his experimental data. The financial support of the Australian Research Council (Grant DP120100481) is acknowledged.

7. REFERENCES

Abt, S.R., Wittler, R.J., Taylor, A., Love, D.J. (1989). *Human stability in a high flood hazard*. Water Resour. Bull. 25(4), 881–890.

Agnew P&F Association (2011). *Flood Horror and Tragedy*. Agnew School Parents & Friends Association, Southern Education Managements, Tingalpa QLD, Australia, 344 pages.

AR&R (2010). *Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for People*. Australian Rainfall and Runoff Report No. P10/S1/006, April, 31 pages.

Asai, Y., Ishigaki, T., Baba, Y., and Toda, K. (2010). *Safety Analysis of Evacuation Routes Considering Elderly Persons during Underground Flooding*. Journal of Hydroscience and Hydraulic Engineering, JSCE, 28(2), 15-21.

BOM (2011). *Frequent heavy rain events in late 2010/early 2011 lead to widespread flooding across eastern Australia*. Special Climate Statement 24, National Climate Centre, Bureau of Meteorology, Melbourne VIC, Australia, Revision b, 23 January, 28 pages.

Brown, R, and Chanson, H. (2013). *Turbulence and Suspended Sediment Measurements in an Urban Environment during the Brisbane River Flood of January 2011*. Journal of Hydraulic Engineering, ASCE, 139(2), 244-252 (DOI: 10.1061/(ASCE)HY.1943-7900.0000666).

Chanson, H. (2011). *The 2010-2011 Floods in Queensland (Australia): Observations, First Comments and Personal Experience*. Journal La Houille Blanche, No. 1, pp. 5-11

Cox, R.J., Yee, M., and Ball, J.E. (2004). *Safety of People in Flooded Streets and Floodways*. Proceedings 8th National Conference on Hydraulics in Water Engineering, IEAust., Gold Coast, Australia, H. Chanson and J. Macintosh Editors, 8 pages (CD-ROM).

Foster, D.N., Cox, R.J. (1973). *Stability of children on roads used as floodways*. Technical Report No.73/13, Water Research Laboratory of the University of New South Wales, Manly Vale, Australia.

Karvonen, R.A., Hepojoki, H.K., Huhta, H.K., Louhio, A. (2000). *The use of physical models in dam-break analysis*. RESCDAM Final Report, Helsinki University of Technology, Helsinki, Finland, 56 pages.

Nakagawa, H., and Nezu, I. (1977). *Prediction of the contributions to the Reynolds stress from bursting events in open-channel flows*. Journal of Fluid Mechanics, 80(1), 99-128.

QFCI (2011). *Interim report*. Queensland Flood Commission of Inquiry, Brisbane, Australia, August, 262 pages.

Takahashi, S., Endoh, K., and Muro, Z.I., (1992). *Experimental Study on People's Safety against Overtopping Waves on Breakwaters*, Report on the Port and Harbour Institute, 34(4), 4-31 (in Japanese).

Kundzewicz Z. (2008). *Disaster Aftermath*. In Encyclopedia of Public Health, Springer-Verlag, Heidelberg, Kirch W. Editor (DOI: 10.1007/SpringerReference_82179).

Willmarth, W.W., and Lu, S.S. (1972). *Structure of the Reynolds Stress near the Wall*. Journal of Fluid Mechanics, 55(1), 65-92.

Xia, J., Falconer, R.A., Wang, Y., and Xiao, X. (2014). *New Criterion for the Stability of a Human Body in Floodwaters*. Journal of Hydraulic Research, 52(1), 93-104.