PHYSICAL MODELLING OF TIDAL BORE DYKE OVERTOPPING: IMPLICATION ON INDIVIDUALS' SAFETY

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ABSTRACT

A tidal bore is a surge of waters propagating upstream as the tidal flow turns to rising and the flood tide rushes into a funnel-shaped river mouth. The bore forms during the spring tides when the tidal range exceeds 4–6m and the rising tidewaters are confined to the narrow funnelled estuary. The tidal bore can be a major tourism attraction. In China, the Qiantang River bore attracts more than 300,000 people each year for the Moon festival while the bore propagation is seen live on television by over 15 millions of television spectators. All the year around, tens of thousands of tourists come to see the tidal bore during spring tide conditions. In Europe, the Dordogne and Severn Rivers are the sites of well-known tidal bore surfing competitions that many individuals come to watch. In the early 1960s, the *mascaret* of the Seine River attracted more than 20,000 people during the weekends. When the river banks are protected by dykes, these become attractive view points, despite the hazards caused by the risks of bore overtopping. For the last 20 years in China, over 80 people are drowned in the Qiantang River bore flood tide motion. Herein a physical study was conducted in a relatively large size facility. The upstream propagation of a tidal bore in a compound channel was investigated based upon a Froude similitude. The data highlighted the occurrence of transient secondary currents in the wake of the bore front. The results demonstrated that these currents constituted major hazards for individuals standing on the dyke.

Keywords: *Tidal bores, Individuals' safety, Dyke overtopping, Physical modelling*

1. INTRODUCTION

A tidal bore is a positive surge of tidal origin that may occur in an estuary when the tidal flow turns to rising. The bore is an unsteady rapidly varied flow motion generated by the rapid water level rise at a river mouth during the early flood tide when the flood tide waters rush into a funnel-shaped river mouth that amplifies the tidal range. The leading edge of the tidal bore is a discontinuity in water depth with a sharp water elevation rise, as illustrated in Figure 1. Figure 1 shows tidal bores in China and France. Figure 1 (Top) presents the bore of the Qiantang River in Hangzhou. The tidal bore advances in the river channel past the city with a groyne structure in the foreground. Figure 1 (Bottom) presents the tidal bore of the Dordogne River (France). The surfers give the scale of the bore front. Worldwide it is estimated that over 400 estuaries are affected by a tidal bore process, on all continents but Antarctica (Chanson 2011). The tidal bores can be dangerous and some have had a sinister reputation. For example, in the Seine River estuary (France), more than 220 ships were lost between 1789 and 1840 in the Quilleboeuf–Villequier section (Malandain 1988). Similarly, the bores of the Petitcodiac River (Bay of Fundy, Canada) and Colorado River (Mexico) were feared. In China, some tidal bore warning signs are erected along the Qiantang River banks and yet a number of tragic accidents happen every year (Fig. 2). For the last 20 years, over 80 people are drowned in the Qiantang River bore flood tide motion. The tidal bores affect the shipping and navigation in the estuarine zone as in Papua New Guinea (Fly and Bamu Rivers), Malaysia (Benak at Batang Lupar), and India (Hoogly bore).

Herein a physical investigation was conducted under controlled flow conditions in a relatively large size facility. The upstream propagation of a tidal bore in a compound channel was investigated based upon a Froude similitude to test the hazards for individuals standing on a river dyke. Based upon physical tests with human body scale models, new design guidelines are proposed for the safety of individuals and compared with field tests conducted on the Qiantang River dykes.

Figure 1. Tidal bores. (Top) Qiantang River bore (China) on 12 October 2014 at Meilvba, South bank about 14:30-14:40; (Bottom) Dordogne River bore (France) on 24 August 2013 at St Pardon

Figure 2. Tidal bore warnings along the Qiantang River (China) in October 2014. (Left) at Meilvba; (MIddle) at Xiasha; (Right) Police car patrolling the river bank at Xiasha, warning the populace of the tidal bore arrival

2. THEORETICAL CONSIDERATIONS

Considering a human body standing on a river dyke that becomes submerged, there are two main mechanisms of instability: namely sliding and tumbling (Fig. 3). Past studies showed that sliding is common in high-velocity shallow waters, and tumbling is more common in deep waters (Cox et al. 2004, Xia et al. 2014). During a dyke overtopping event, an individual is subjected to several forces including its weight, a buoyancy force, the resultant of the pressure forces, a normal reaction force, and the surface friction on the floor (Abt et al. 1989, Takahashi et al. 1992). The sliding resistance of a human 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 sloping. Its rotational stability is the resultant of the forces acting at the downstream lower edge of the body (Point O, Fig. 3 Right). Toppling, tilting or tumbling may occur when the moment of the hydrodynamic force resultant exceeds the moment due to the resultant weight of the body.

Basic dimensional considerations show that the stability of a human body in water 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 possibly the type of gait (Chanson et al. 2014):

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

where d and V are respectively the water depth and velocity, and d' and V' are some water depth fluctuation and velocity fluctuation respectively characterising the flow turbulence (Fig. 3). A number of experimental studies were conducted with adults, children and scale models. The results yielded some threshold for the stability of adults and children in floodwaters in the form of a relationship between velocity V and water depth d. Typical results are presented in Figure 4 for adults. The data showed a trend independent of the type of failure (sliding, toppling), with decreasing threshold velocity with increasing water depth. However the data presented a broad scatter: a study used a stuntman, another used emergency personnel, student athletes… Basically most full-scale data were obtained in idealised situations, under controlled conditions (e.g. low turbulence), using fit individuals, in secured conditions (harness & ropes), during daytime, with clearwater, flat floor, and in absence of (large) debris. Chanson et al. (2014) conducted field observations during a major flood of the Brisbane River (Australia). Their results demonstrated that the real conditions during a natural disaster could be more treacherous and dangerous. Their observations are also reported in Figure 4. In turn they proposed new recommendations derived from their observations, which are shown in Figure 4 (Dashed area on left).

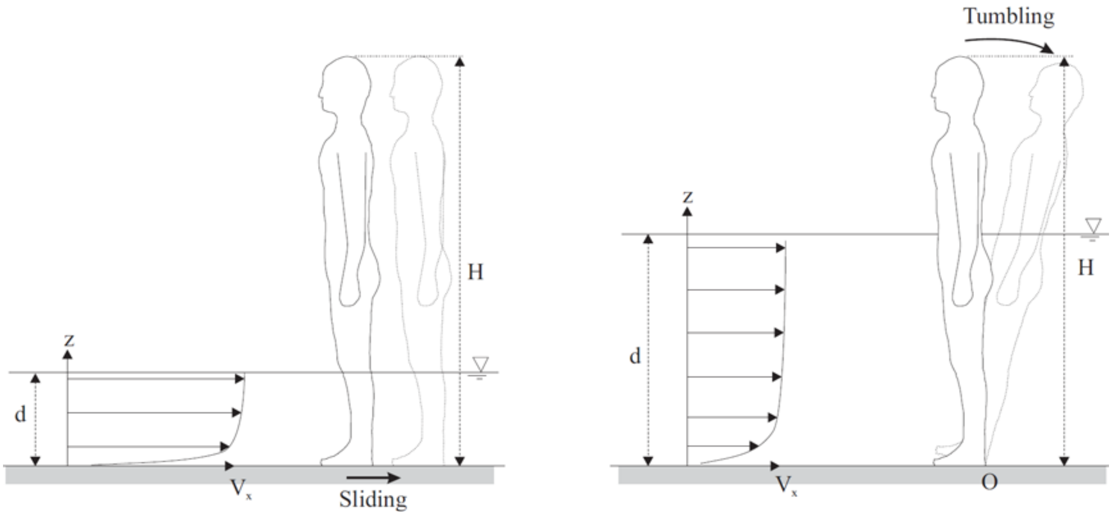


Figure 3. Forces acting on a human body in floodwaters (After Chanson et al. 2014)

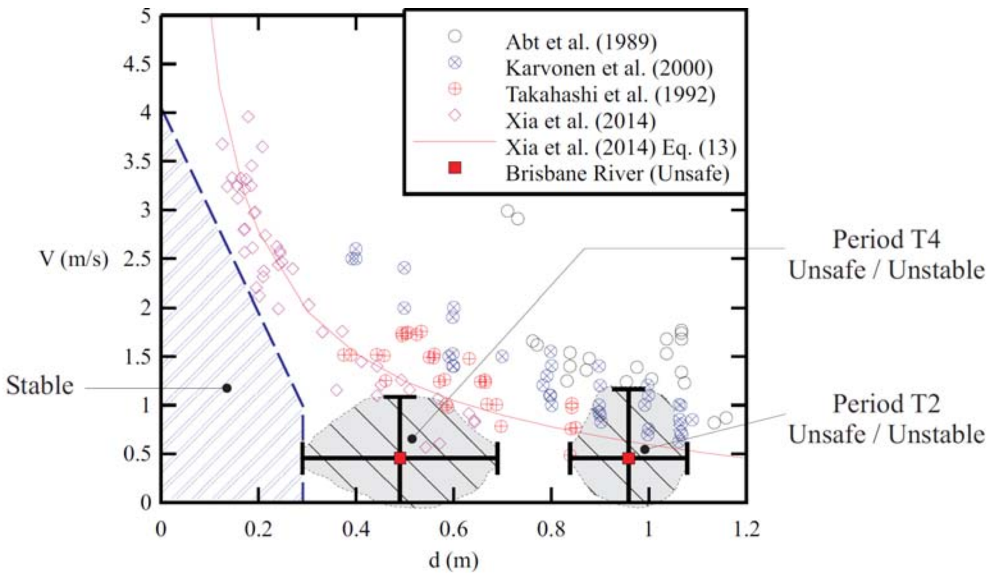


Figure 4. Relationship between flow velocity and water depth for stability of human body - Full-scale tests with adults (Abt et al. 1989, Karvonen et al. 2000, Takahashi et al. 1992), model data of Xia et al. (2014), correlation by Xia et al. (2014) - Comparison with field observations in the Brisbane River in January 2011 deemed unsafe for evacuation (Chanson et al. 2014), scatter bars showing instantaneous data range for data sampled for 3 h 50 min (T2) and 4 h 30 min (T4)

3. PHYSICAL MODELLING AND INSTRUMENTATION

3.1 Presentation

True dynamic similarity is achieved in a geometrically similar model if and only if each Π-term has the same value in the field and laboratory. Scale effects might occur when one or more Π-terms have different values between model and prototype. In a tidal bore, the gravity effects are important and a Froude similitude is commonly used (Tricker 1965, Chanson and Toi 2015). The turbulent processes involve some viscous dissipation, thus implying a Reynolds similitude. It is however impossible to satisfy simultaneously a true similarity in geometrically similar models with the same fluids in model and prototype. In the present study, both Froude and Morton similitudes were adopted following Hornung et al. (1995), Koch and Chanson (2009) and Chanson and Toi (2015).

The laboratory experiments were performed in a 12 m long 0.5 m wide tilting flume previously used by Koch and Chanson (2009) and Chanson and Toi (2015), but with different flow conditions. The channel bed was made of smooth PVC and the sidewalls were glass panels. A river dyke was added along the right sidewall for the full length (12 m) of the test section (Fig. 5). The dyke was made of smooth plywood and it was 0.150 m high and 0.200 m wide.

The water discharge was measured using an orifice installed in the supply line and calibrated on-site. The unsteady water depth was measured with an array acoustic displacement meters Microsonic™ Mic+25/IU/TC located along the channel, at x = 4, 5 and 6m where x is the distance from the test section's upstream end. At each cross-section, a sensor was mounted at y = 0.150m and y = 0.400m, where y is the transverse distance from the left sidewall.

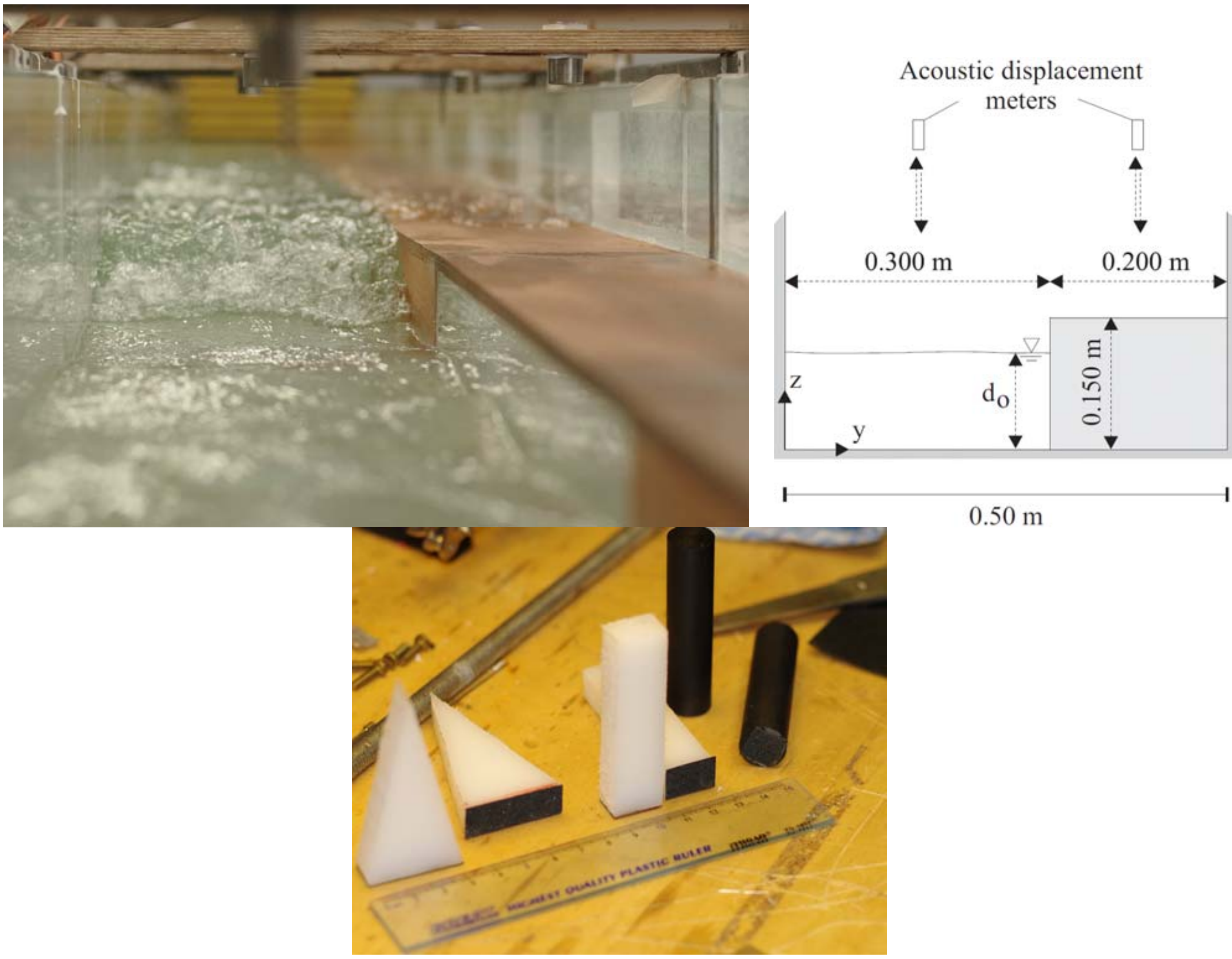


Figure 5. Experimental compound channel at the University of Queensland. (Top left) Looking downstream at the incoming breaking bore: Q = 0.0188 m^3/s, d_o = 0.0765 m (x = 5.5 m), Fr = 1.5; (Top right) Dimensioned cross-section; (Bottom) Human body models

3.2 Human body models

The stability of human body standing on the river dyke was tested with an initially dry dyke (i.e. initial flow depths d_o < 0.150 m). Three types of models were made out of PVC with a density of 0.95, the same volume of 1.5×10^5 m^3 and the same height (H = 70 mm). Model M1 was a 70 mm high cylinder (Ø = 17 mm); model M2 was rectangular, 70 mm high, 18 mm long and 12 mm wide; model M3 has a triangular A-frame shape, 70 mm high, 12 mm thick, 35mm wide at the base. All models had sand paper glued to their base. Figure 5 (Bottom) shows the human body models.

3.3 Experimental investigations

A fast-closing Tainter gate located at x = 11.15 m was used to generate a tidal bore propagating upstream against the initially steady flow. The gate closure time was less than 0.2 s and such a closure time was small enough to have little effect on the surge propagation. The experimental flow conditions encompassed both breaking and undular bores.

4. Preliminary results

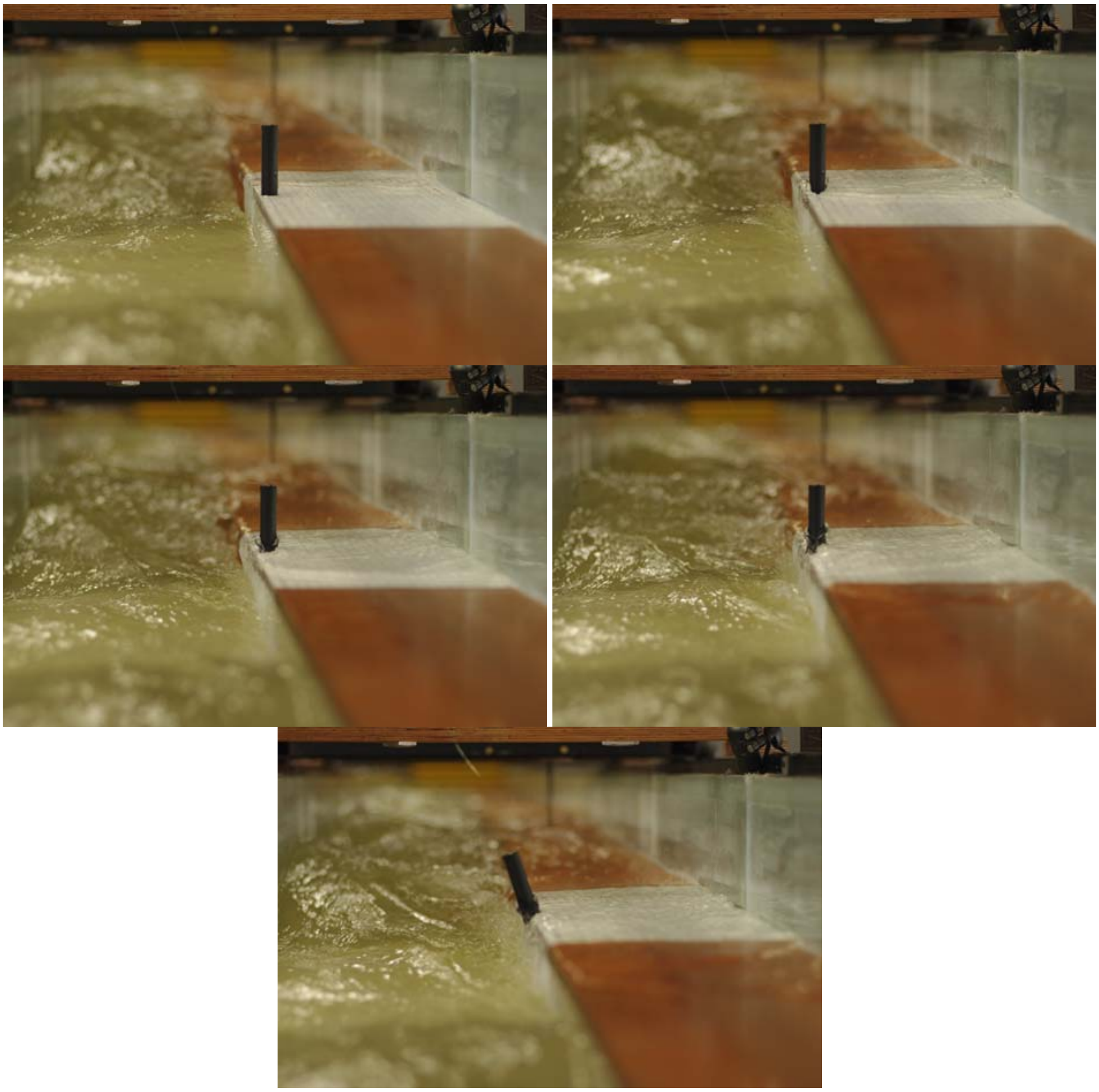
Visual observations were conducted for a broad range of initial flow conditions, with the initial depth d_o ranging from less than 0.1 m to more than 0.2 m. For each set of initial flow conditions, a range of tidal bore Froude numbers were tested. Three major flow patterns were observed: (a) d_o < 0.15 m and d_{conj} < 0.15 m, (b) d_o < 0.15 m and d_{conj} > 0.15 m, and (c) d_o > 0.15 m.

For d_o < 0.15 m and d_{conj} < 0.15 m, both the initial flow and tidal bore were constrained in the 0.3 m wide low flow channel. The bore and flood tide free-surface elevation was below the dyke level. Altogether the bore flow pattern was identical to that in a rectangular channel.

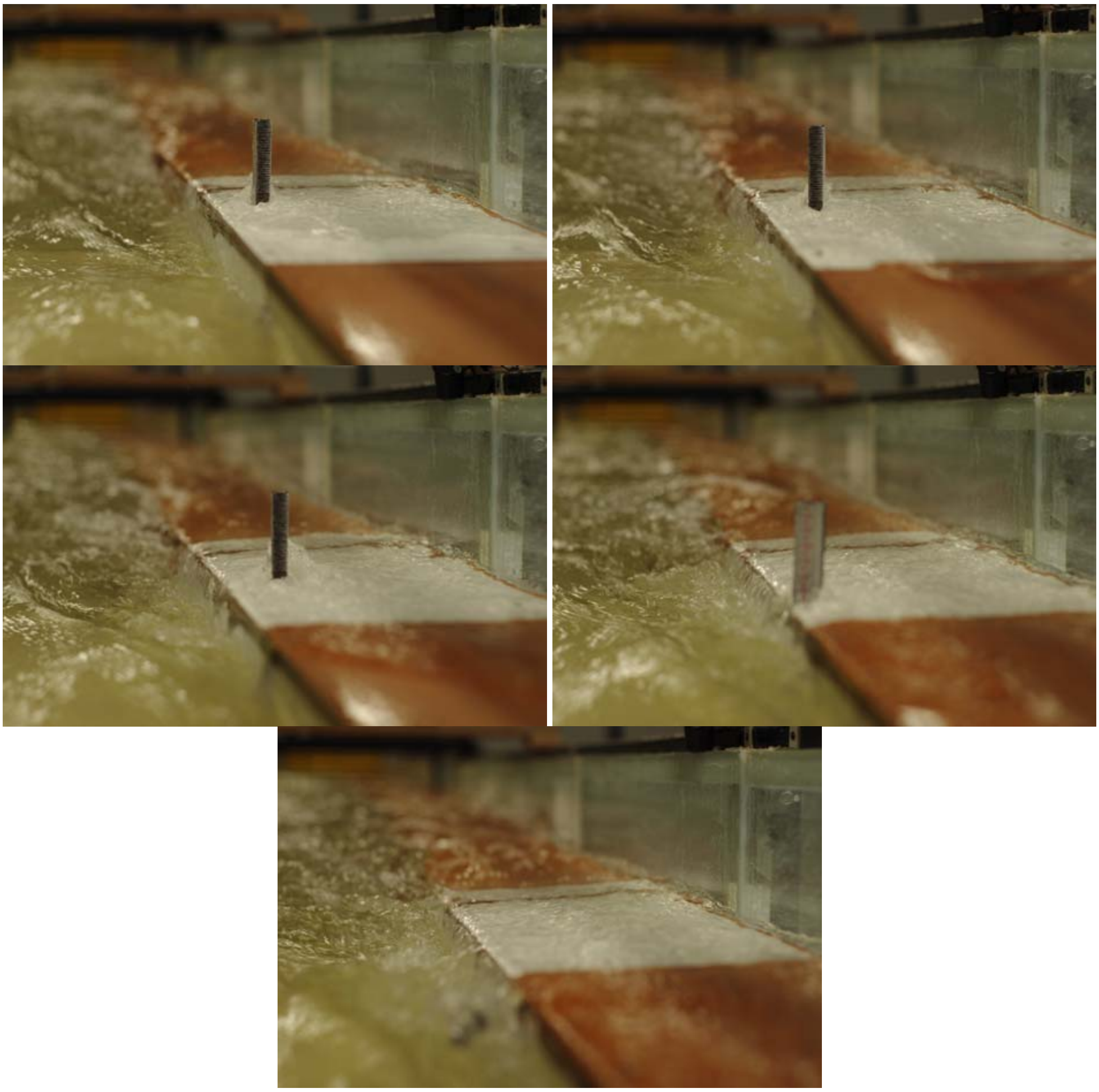
For d_o < 0.15 m and d_{conj} > 0.15 m, the initial flow was contained in the 0.3 m wide low flow channel. The bore rose past the dyke level and expanded above the embankment. Figure 6 shows two experiments. Visual observations showed strong interactions between the main channel flow and the dyke overflow. This is illustrated in Figure 6 by the failure of human body models which are down in the main channel.

For d_o > 0.15 m, the initial water level was above the dyke and the initial flow corresponded to a flow in a compound channel. The tidal bore propagated upstream above the compound channel. The bore advancing on the dyke had a breaking front, while the bore in the main channel exhibited typically an undular front (Fig. 7).

In the last two cases (i.e. d_{conj} > 0.15 m), photographic and video observations indicated the occurrence of transient secondary currents in the wake of the bore front. Figure 7 illustrates such a wake motion.



(A) Cylindrical model M1 falling into the deep channel, with 0.19 s between two successive photograph



(B) Rectangular model M2 sliding, tilting and then falling into the deep channel (last photograph), with 0.19 s between two successive photograph

Figure 6. Dyke overtopping by an advancing bore and human body stability failure tests

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.

Chanson, H. (2011). Tidal Bores, Aegir, Eagre, Mascaret, Pororoca: Theory and Observations. *World Scientific*, Singapore, 220 pages.

Chanson, H., Brown, R., and McIntosh, D. (2014). Human body stability in floodwaters: the 2011 flood in Brisbane CBD. in *Hydraulic Structures and Society – Engineering Challenges and Extremes*, The University of Queensland, Brisbane, Australia, Proceedings of the 5th IAHR International Symposium on Hydraulic Structures (ISHS2014), 25-27 June 2014, Brisbane, Australia, H. Chanson and L. Toombes Editors, 9 pages (DOI: 10.14264/uql.2014.48).

Chanson, H., and Toi, Y.H. (2015). Physical Modelling of Breaking Tidal Bores: Comparison with Prototype Data. *Journal of Hydraulic Research*, IAHR, Vol. 53 (DOI: 10.1080/00221686.2014.989458). (In Print)

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).

Hornung, H.G., Willert, C., and Turner, S. (1995). The Flow Field Downstream of a Hydraulic Jump. *Journal of Fluid Mechanics*, 287:299-316.

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.

Koch, C., and Chanson, H. (2009). Turbulence Measurements in Positive Surges and Bores. *Journal of Hydraulic Research*, IAHR, 47(1):29-40 (DOI: 10.3826/jhr.2009.2954).

Liggett, J.A. (1994). Fluid Mechanics. *McGraw-Hill*, New York, USA.

Malandain, J.J. (1988). La Seine au Temps du Mascaret. ('The Seine River at the Time of the Mascaret.') *Le Chasse-Marée*, No. 34, pp. 30-45 (in French).

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).

Tricker, R.A.R. (1965). Bores, Breakers, Waves and Wakes. *American Elsevier Publ. Co.*, New York, USA.

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.

Figure 7. Dyke overtopping by an advancing bore and wake motion (Arrow) behind the bore front at the edge of the dyke - Bore motion from background to foreground

