DONNELLY, C., and CHANSON, H. (2005). "Environmental Impact of Undular Tidal Bores in Tropical Rivers." *Environmental Fluid Mechanics*, Vol. 5, No. 5, pp. 481-494 (ISSN 1567-7419).

ENVIRONMENTAL IMPACT OF UNDULAR TIDAL BORES IN TROPICAL RIVERS

C. DONNELLY* and H. CHANSON**

* Ph.D. student, University of Lund, Sweden (formerly undergraduate thesis student, Dept of Civil Engineering, The University of Queensland, Brisbane QLD 4072, Australia)
** Reader, Dept of Civil Engineering, The University of Queensland, Brisbane QLD 4072, Australia
Tel: (61 7) 33 65 41 63 - Fax: (61 7) 33 65 45 99 - Email: h.chanson@uq.edu.au

ABSTRACT
A tidal bore impacts significantly on the estuarine ecosystem, although little is known on the flow field, mixing and sediment motion beneath tidal bores. In the absence of detailed systematic field measurements, a quasi-steady flow analogy was applied to investigate undular tidal bores with inflow Froude numbers between 1.25 and 1.6. Experimental results indicated that rapid flow redistributions occur beneath the free-surface undulations, with significant variations in bed shear stress between wave crests and troughs. Dynamic similarity was used to predict detailed flow characteristics of undular tidal bores. The effects of periodic loading on river sediments, scour of river bed and flow mixing behind the bore are discussed. A better understanding of these processes will contribute to better management practices in tidal bore affected rivers, including the Styx and Daly rivers in tropical Australia.

KEYWORDS : Undular tidal bore, undular hydraulic jump, physical modelling, velocity, pressure, boundary shear stress, sediment process, mixing.

1. Introduction

A tidal bore is a wave or a series of waves propagating upstream as the tide turns to rising. Basically a bore is a positive surge of tidal origin that may form with large tidal ranges (more than 6 to 9 m) in a flat converging channel. The front of the surge absorbs random disturbances on both sides and this makes the wave stable and self-perpetuating (e.g. HENDERSON 1966, CHANSON 2004). With appropriate boundary conditions, a tidal bore may travel very long distances upstream. As the surge progresses, the river may flow upstream behind it (e.g. LYNCH 1982). Well-known bores include the Hangzhou (or Hangchow) bore in China, the Amazon river bore (*pororoca*) in Brazil, the tidal bore of the Seine river (*mascaret*) in France and the Hoogly bore on the Ganges (India). There are many tidal bores occurring in tropical regions. In addition to those mentioned above, smaller tidal bores occur on the Styx and Daly rivers (Australia), and at Batang Lupar (Malaysia) (Fig. 1).

A bore impacts on the estuarine eco-system. Effects on sediment transport were studied at Petitcodiac and Shubenacadie rivers (Canada), in the Sée and Sélune rivers (France), in the Hangzhou bay and in the Changjiang Estuary (China) (e.g. CHEN et al. 1990. TESSIER and TERWINDT 1994, CHEN 2003). The impact on the ecology is acknowledged. Tidal bore affected estuarine systems are known feeding and spawning grounds for various species. Examples include the Amazon where piranhas eat matter in suspension after the passage of the bore; at Turnagain Arm where bald eagles fish behind in the bore front and beluga whales were seen swimming and feeding behind the bore; at Broadsound (Australia) where sharks feed behind bores, or the Daly river (Australia) where crocodiles feed behind the bore; in the Severn river (sturgeons in the past, elvers) and in the Bay of Fundy (striped bass spawning) (e.g. COUSTEAU and RICHARDS 1984, MOLCHAN-DOUTHIT 1998, RULIFSON and TULL 1999, WITTS 1999).

Tidal bores have been tourist attractions for decades. The Hangzhou bore (China) attracts more than 300,000 people during the Moon festival each year, and its occurrence has been recorded in Chinese novels as early as the 7th century BC (JONES 2003). It was called then "The Old Faithful" because it kept time better than clocks. Surfing competitions take place regularly on the Dordogne (France) and Severn (UK) rivers, while tidal bore rafting is organised in the Shubenacadie River (Canada). In the 1950s, the 'mascaret' of the Seine river attracted more than 20,000 people each week-end.

BARTSCH-WINKLER and LYNCH (1988) listed over eighty estuaries affected by a tidal bore, but possibly more estuarine systems experience a bore. However little is known on the flow field and basic mixing and sediment motion processes beneath tidal bores, hence on their impact on estuarine processes. Most observations are derived from reports by sailors, fishermen and surfers (e.g. TRICKER 1965), despite a few recent studies (e.g. CHEN 2003, CHANSON 2003, WOLANSKI et al. 2004). It is the purpose of this paper to gain a new understanding of the impact of undular tidal bores on river systems. The study regroups laboratory experiments based upon the quasi-steady flow analogy performed in a large-size facility and a comparison with field observations.

2. Experimental Investigations

2.1 Presentation

Photographs and videos of field occurrences provide unique information on the basic flow features of tidal bores. The second writer studied more than 20 audiovisual documentaries of tidal bore occurrences and written documentations on another two dozen bores. He also observed tidal bore occurrences in four different natural systems.

Initially, most tidal bores develop as undular surges characterised by a train of advancing free-surface undulations, called whelps or "éteules". The waves usually do not break except where affected by proximity to the banks or shoals. Breaking bores are rare, often restricted to spring tide conditions and localised in some estuarine sections. For example, the Dordogne river bore is primarily an undular bore but may break in a few shallow water sections of the river. Secondly, the river flow prior to bore arrival is always quiet and associated with a smooth and glossy free-surface (e.g. Fig. 1). Most occurrences are characterised by very low turbulence inflow conditions.

Herein a quasi-steady flow analogy was applied to investigate an undular tidal bore with the physical model of an undular hydraulic jump. The technique allows detailed flow field observations that are impossible at the same level of details in the field. Two series of field observations were selected and reproduced in the laboratory (Table 1). Dynamic similarity was based upon a Froude similitude, and partially-developed inflow conditions were selected to have smooth inflow conditions.

2.2 Experimental setup

New experiments were performed in stationary undular hydraulic jumps in a rectangular horizontal channel (Table 1). The flume was 0.5-m wide, 3.2-m long. It was made of smooth PVC bed and glass walls (0.3-m high). The upstream supercritical flow was controlled by a vertical gate and the channel ended with an overflow gate.

The water discharge was measured with a Venturi meter, calibrated in-situ with a large V-notch weir. The percentage of error was expected to be less than 2%. The water depths were measured using a rail mounted pointer gauge. Pressure, velocity and bed shear stress distributions were recorded with a Prandtl-Pitot tube (3.35-mm external diameter). The Pitot tube design is based on the Prandtl design (e.g. TROSKOLANSKI 1960), and it was compared with a British Standards design within 1% in wind tunnel tests for Reynolds numbers ranging from 1E+5 to 9E+5. The Prandtl-Pitot tube was further calibrated as a Preston tube based upon in-situ experiments (CHANSON 2000). The calibration curve differed quantitatively from similar calibration curves developed by PRESTON (1954) and PATEL (1965), but experience gained at the University of Queensland suggested that each Preston tube must be calibrated in situ, rather than relying on existing correlations.

In the present study, the data accuracy was expected to be about 2% on dynamic and static pressures, 1% on local velocity and 5% on boundary shear stress. The translation of the gauge and Pitot tube in the vertical direction was controlled by a fine adjustment travelling mechanism (error less than 0.1 mm). The error on the transverse position of the gauge and tube was less than 0.5 mm and the error on their longitudinal position was less than 2 mm.

For each experiment, the supercritical inflow was partially-developed (Table 1, column 6). The upper fluid layer was nearly an ideal flow characterised by low turbulence levels. Pressure, velocity and energy distributions were measured along the jump centreline (CL) at a reference position upstream of the jump, at the 1st, 2nd and 3rd crests, 1st and 2nd troughs, and at the halfway points between 1st trough and 2nd crest and between 2nd crest and 2nd trough (Fig. 2A). Similar sets of distributions were also measured at transverse positions located 8 cm from the centreline (Z2), 16 cm from the centreline (Z3) and 23 cm from the flume centreline (or 2 cm from the flume wall, Z4).

3. Results

For all experiments the free-surface profiles were observed to be basically two-dimensional. Small shock wave effects rendered results close to the sidewalls of the experimental flume somewhat three-dimensional. For each experiment, a recirculation flow region was observed next to the bottom, under the 1st crest, with the recirculation effect diminishing towards the sidewalls. This is illustrated in Figure 2A. The relative height of that recirculation flow region was shown to increase with increasing Froude number. That is, the ratio of recirculation height to water depth at first crest was 0.07 and 0.3 for inflow Froude numbers of 1.25 and 1.6 respectively. The existence of such a recirculation pattern was documented in undular jumps with partially-developed inflow conditions (e.g. MONTES 1986), but it is acknowledged not to occur in undular jumps with fully-developed inflow conditions (CHANSON and MONTES 1995) nor under undular positive surges.

Figure 3 presents dimensionless pressure and velocity distributions on the centreline for the experiment with an inflow Froude number of 1.25. Pressure distributions (Fig. 3 left) are plotted as $P/(\rho.g.d)$ as a function of y/d, where P is the pressure, ρ is the water density, g is the gravity acceleration, d is the local water depth and y is the vertical coordinate measured from the bed. The velocity distributions (Fig. 3 right) are presented as V/V_c as a function of y/d_c, where V is the velocity, V_c is the critical flow velocity and d_c is the critical flow depth. The pressure distributions deviated from hydrostatic (i.e. solid line, Fig. 3 Left) and the trend is qualitatively in agreement with ideal-fluid flow theory (e.g. ROUSE 1938,1959). Present data showed further that the pressure distributions were not symmetrical either side of a crest or a trough. The velocity distributions showed significant flow redistributions between the upstream cross section and the first crest, and between subsequent crests and troughs (e.g. Fig. 3 right). Maximum velocities were observed at troughs and minimum velocities at wave crests. Furthermore the velocity distributions were not symmetrical on either side of a crest or trough.

4. Discussion

4.1 Quasi-steady flow analogy

For an observer travelling on the bank at the same speed at the bore front, the positive surge is seen as a stationary hydraulic jump. This is illustrated in Figure 2B and called the "quasi-steady flow analogy" (e.g. ROUSE 1946 pp. 143-147, HENDERSON 1966 pp. 75-77, CHANSON 2004a pp. 64-68). The quasi-steady flow analogy was developed for one-dimensional flows. Herein it was extended to two-dimensional flows as assuming a vertical distribution of the bore celerity with a power law function (N=10) to achieve zero velocity at the bed : i.e., no slip condition ($V(y=0) = 0$). Measured velocity profiles in the stationary undular flow are summarised in Figure 4(a). For these data, the quasi-steady flow analogy results are presented in Figure 4(b) and correspond to the undular tidal bore flow of the Dordogne river (Table 1).

Overall the quasi-steady flow analogy results (Fig. 4(b)) show negative velocities beneath the undular bore. This is indicative of a flow reversal as a bore propagates upstream, as observed in the field. Small, positive velocities are however noticed next to the free surface at the troughs. Velocities are typically larger at wave crests than at troughs (Fig. 4(b)). This is a distinct contrast with stationary undular hydraulic jump results (Fig. 4(a)). Although velocities are zero at the bed, maximum flow reversal does occur next to the bed indicating a large velocity gradient at the bed (Fig. 4(b))).

Undular tidal bore velocity profiles were compared with typical velocity distributions for a progressive wave using simple linear wave theory. A marked difference is observed as sketched in Figure 5. The effect of the positive upstream velocity profile on the flow field beneath the free-surface undulations can be distinctly observed by comparing Figure 4(b) and Figure 5. (Note that the relative magnitudes are not the same.) Indeed a tidal bore is a positive surge and it is not strictly comparable to a progressive wave.

4.2 Effects on Sediment Erosion

The results presented in Figure 4(b) indicates that, under a tidal bore, the river bed is subjected to an initial reversal of flow, followed by flow accelerations and decelerations associated with the passage of each undulation as the bore propagates upstream. Flow recirculation, observed during experiments on stationary undular jumps (Present study), is analogous to significant flow decelerations observed in a moving bore. In addition the estuary bed is subjected to a cyclic pressure loading exerted by the advancing undulations.

Next to the bed, the large velocity gradients estimated from the quasi-steady flow analogy are associated with large shear stresses. The shear stress at the boundary was estimated roughly from the unsteady surge velocity profiles, using a Prandtl mixing length model assuming that the mixing length l equals the distance y from the bed (SCHLICHTING 1979, CHANSON 2004b). Figure 6 presents estimated bed shear stresses as functions of the longitudinal location for an advancing undular bore. Overall, maximum shear stresses are observed beneath the crests (e.g. 2C, Fig. 6) while minimum shear stresses are observed underneath the troughs (e.g. 1B & 2B, Fig. 6) beneath an advancing bore. This is opposite to the effect observed for the stationary undular hydraulic jump (CHANSON 2000,2001).

Under a tidal bore, the bed is subjected to significant stress reversals as it undergoes cyclic loading and tidal bores usually occur in cohesive sediment river beds. Since the bed is saturated, changes in pore pressures occur during 'fast cycling' : i.e., the rate of cycling is such that changes in pore pressures are not fully dissipated (e.g. O'REILLY et al. 1991, DE WIT 1995). The bed may therefore be subjected to liquefaction (e.g. DORMIEUX et al. 1993), placing bed material into suspension. The material is then advected upstream by the flood tide flow.

4.3 Effect on Flow Mixing

Figure 4(b) illustrates rapid velocity redistributions at all depths of flow associated with flow reversals taking place next to the free-surface between crests and troughs. Other salient field observations include the long-lasting chaotic wave motion following undular bore passage, "*making it difficult for surfers to come back on shore even 20 minutes after the passage of the bore*" (Dordogne river, CHANSON 2001) and the murkiness of the flow after the passage of undular bores. Undular tidal bores have the potential to scour the channel bed (see above). Further, upward flow motion between troughs and subsequent crests advects bed material towards the free-surface. The rapid velocity redistributions, associated with the long-lasting chaotic wave motion, contribute to maintain sediment suspension which is advected upstream with the bore and eventually deposited in intertidal zones.

A tidal bore contributes also to salinity and temperature mixing, although the few field observations are often contradictory. In the Rio Mearim (Brazil) on 30-31 January 1991, KJERFVE and FERREIRA (1993) presented quantitative measurements of salinity and temperature behind a tidal bore, with a sharp jump about 18 minutes after the bore mid-estuary, while, at a more upstream location, the change in salinity took place 42 minutes after the passage of the bore. In the Mersey river (UK), Colin DAVIES obtained salinity data behind the bore with a sharp jump about 10-15 minutes after the bore passage (DAVIES 1988). WOLANSKI et al. (2004) observed an undular bore in the Daly river (Australia) on 2 July 2003. The suspended sediment concentration jumped from 0.2 kg/m^3 to 0.8 to 1.2 kg/m^3 about 2-3 min. after the bore passage, while a strong patch of turbulence was observed about 20 minutes after bore passage for about 3 minutes.

Present results (e.g. Fig. 4(b)) emphasise the complicated flow field beneath undular tidal bores. In particular, the results demonstrated increasing velocity fluctuations with decreasing elevations above the bed that would be consistent with field observations of flow reversal and sudden increase in salinity and suspended sediment concentrations behind bores. The latter were found to be a function of the measurement height. For example, in the Seine river on 25 September 1855 at Vallon de Caudebecquet, PARTIOT conducted some experiments by installing three floats at the surface, at 1.5 m beneath the surface and next to the bottom in the middle of the river. After the undular bore passage, the surface float started to run upstream 135 sec. later, while the mid-depth and bottom floats flowed upstream only 60 sec. after the bore passage (BAZIN 1865, pp. 640-641). In the Daly river on 2 July 2003, the sharp increase in suspended sediment concentration took place respectively 120 and 150 sec. after the bore passage at y = 0.45 and 1.26 m above the bed (WOLANSKI et al. 2004).

5. Conclusion

Tidal bores occur in many tropical regions, including Brazil, India, China, Malaysia and Australia, and most often in the form of undular bores characterised by a train of well-formed free-surface undulations. In the absence of systematic field measurements and since most numerical models based upon Saint-Venant equations cannot handle free-surface undulations, a quasi-steady flow analogy was applied to investigate detailed flow properties in undular tidal bores. Systematic flow measurements were conducted in stationary undular jumps with low inflow turbulence level and inflow Froude numbers between 1.25 and 1.6. Experimental results indicated that rapid flow redistributions occurred beneath the free-surface undulations, with significant variations in velocity field and bed shear stress between successive wave crests and troughs.

These results were combined with salient bore characteristics derived from written, photographic and audio-visual informations of field occurrences, as well as field observations. Dynamic similarity and quasi-steady flow analogy were combined to predict the characteristics of tidal bores with inflow Froude numbers between 1.25 and 1.6. An analysis of velocity profiles within an undular tidal bore indicated that the largest velocity gradients, and therefore shear stresses, exist under the crests of the undulations. It is postulated that the high bed shear stresses would lead to erosion of sediments beneath the bore. The cyclic nature of the loading may further lead to bed liquefaction, while rapid velocity redistributions beneath the free-surface undulations contribute to flow mixing within and behind the bore. Consequently, large amounts of suspended sediment are stirred up with ecological matter. The effect of undular tidal bore is seen on local ecosystems where fish and birds feed in the wake of the bore.

6. Acknowledgments

The writers acknowledge the assistance of K. HICKOX, C. QUINLAN, and Y.H. CHOU (Australia). They thank also Dr J.E. JONES (UK), Dr S. AOKI (Japan), Mr D. THIEDERMANN (USA), the Bore Ryders Club (UK) and many more people for providing them with new material of interest.

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Table 1 - Experimental flow conditions : field observations and corresponding laboratory investigations

Reference (1)	q m^2/s (2)	Fr_1 (3)	x_1 m (4)	d_1 m (5)	δ/d_1 (6)	Remarks (7)
Field observations						
Captain BEECHEY, in TRICKER (1965)	N/A	1.6	N/A	1.5	--	Severn bore, on 1 December 1849. Wave front height: 1.07 m (Centre) to 1.5 m (sides). Wave front celerity: 3.1 to 5.4 m/s (3.6 m/s between Stonebench and Gloucester). River flow velocity before bore: +1.1 m/s (downstream). River flow velocity after bore: -1.68 m/s (upstream).
CHANSON (2001)	N/A	1.3	N/A	1.5 to 2	--	Dordogne river, on 27 September 2000. Wave front height: 1 m. Wave front celerity: 2.5 to 3 m/s. River flow velocity before bore: +0.5 to 1 m/s (downstream).
Laboratory study						B = 0.5 m. Horizontal channel. Quasi-steady flow analogy : undular jump.
Series 1	0.111	1.57	0.45	0.080	0.42	
Series 2	0.0914	1.25	0.35	0.081	0.44	Rounded gate with upstream flow straighteners.

Notes : d_1 : upstream water depth; Fr_1 : inflow Froude number; q : inflow discharge per unit width; x_1 : distance from the upstream gate to the reference cross-section upstream of the jump where d_1 is measured; δ : upstream boundary layer thickness.

Fig. 1 - Tidal bores in tropical rivers

(a) Undular tidal bore on the Daly river, Northern Territory, Australia (Courtesy of Gary & Rhonda HIGGINS)

(b) Tidal bore at Batang Lupar, Malaysia (Courtesy of Mr LIM Hiok Hwa, Department of Irrigation & Drainage, Sarawak)

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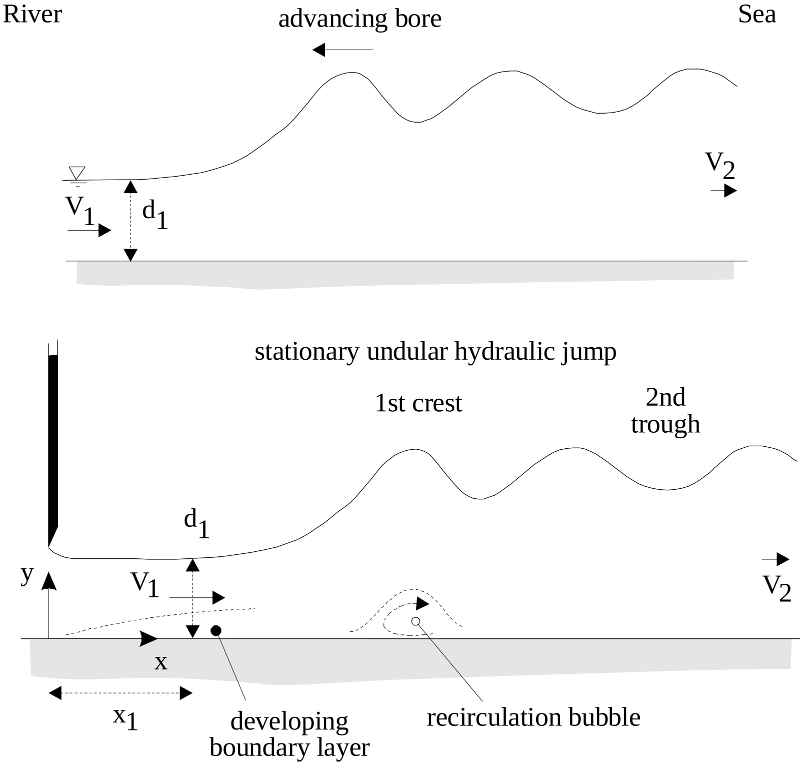
(c) Tidal bore in the Styx river (Australia) on 18 March 2003 (Courtesy of Dr Eric JONES) - Bore propagation from left to right

Fig. 2 - Sketch of stationary hydraulic jump and positive surges

(A) Definition sketch



(B) Quasi-steady flow analogy between hydraulic jump and positive surge

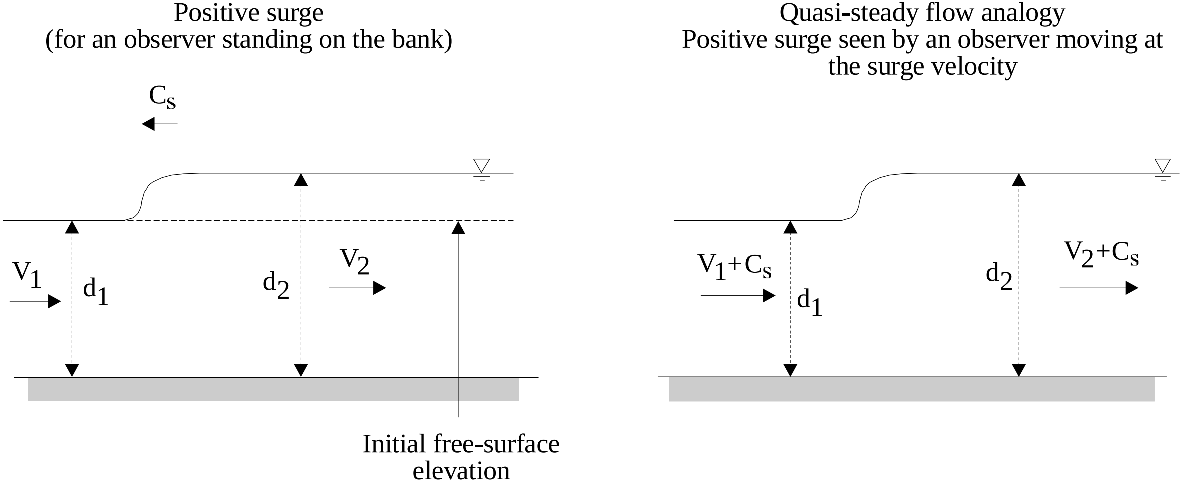


Figure 3 – Dimensionless pressure and velocity profiles along the centreline of the hydraulic jump for Froude Number 1.25

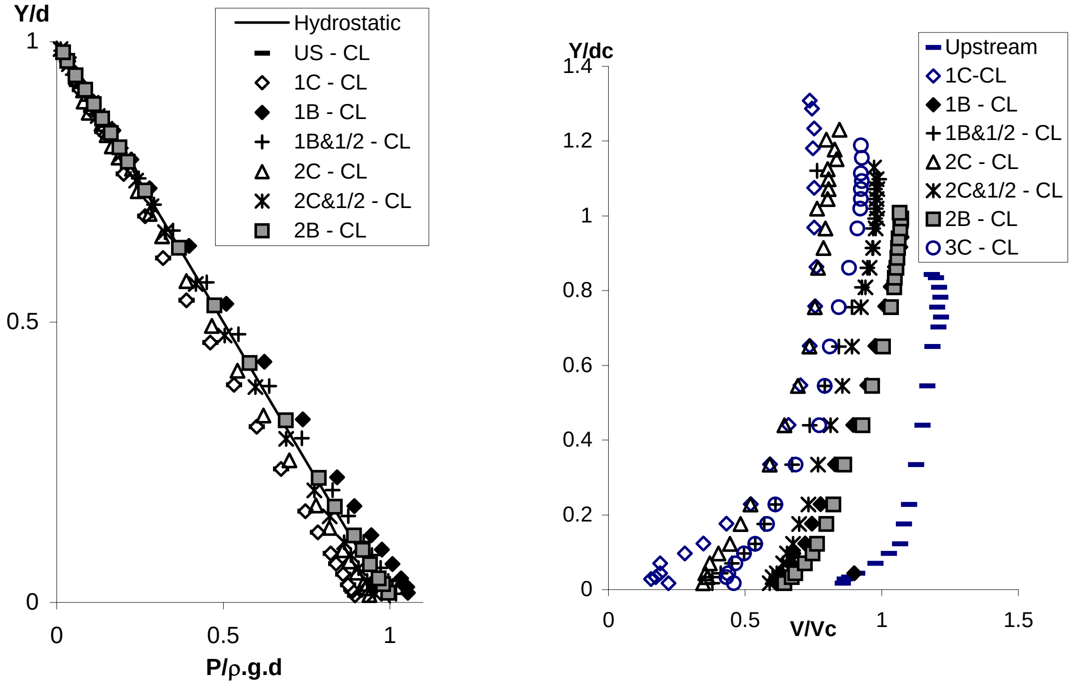


Fig. 4 - Comparison of velocity profiles in undular jump and undular tidal bore

Fig. 4a - Velocity Profiles under an Undular Hydraulic Jump with Partially Developed Inflow Conditions, Fr_1=1.25

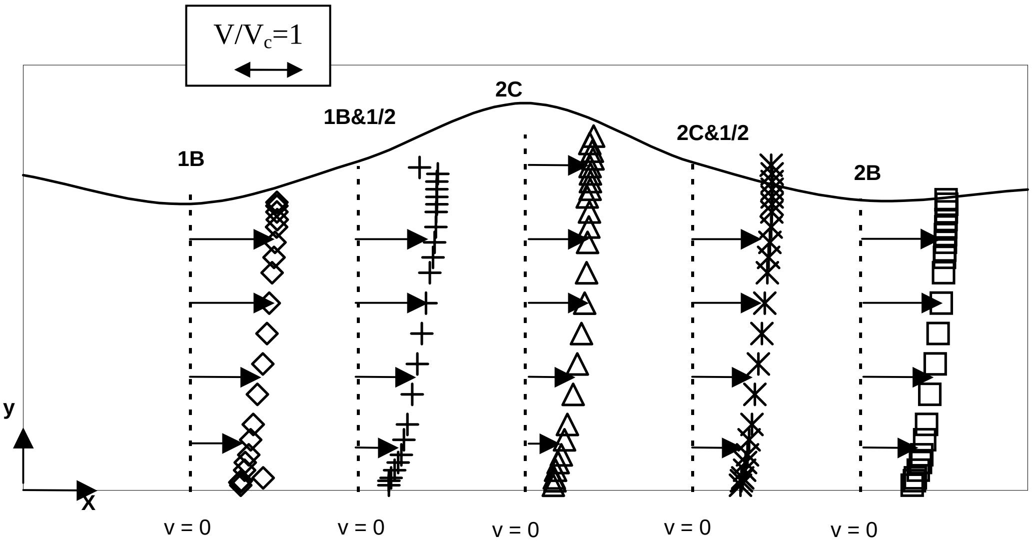


Fig. 4b -Velocity Profiles under an Undular Surge (Fr_1=1.25) estimated using the Quasi-Steady Flow Analogy

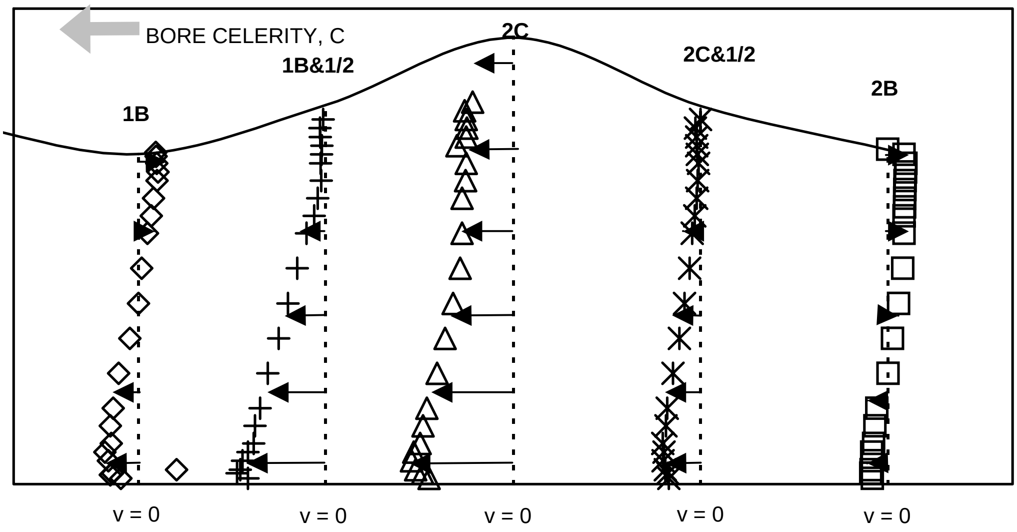


Figure 5 - Velocity Profiles at Crest: Tidal Bore & Progressive Wave

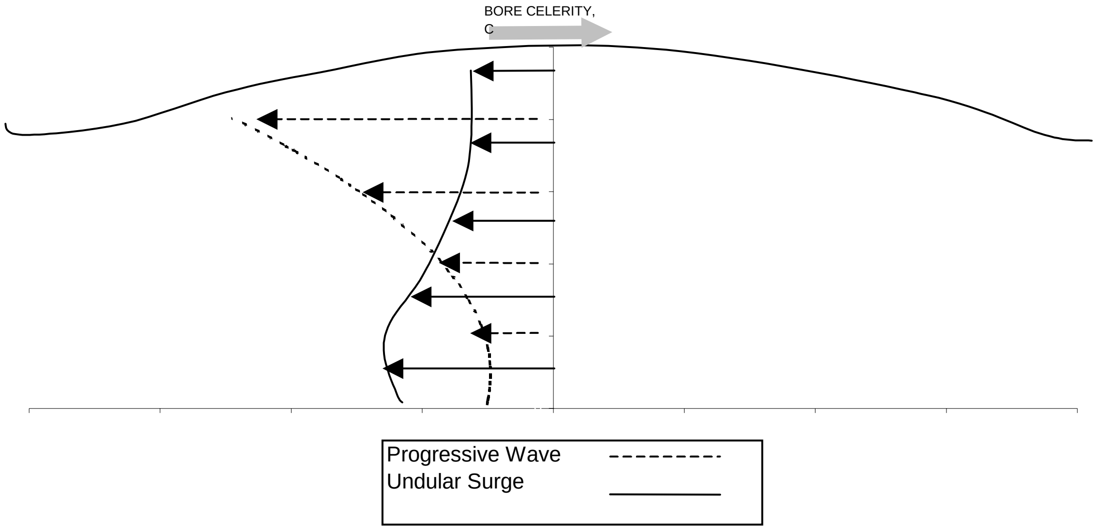


Figure 6 - Estimations of dimensionless boundary shear stress (Prandtl eddy model) under a tidal bore with a surge Froude number $Fr_1 = 1.25$