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ENVIRONMENTAL IMPACT OF TIDAL BORES IN TROPICAL RIVERS

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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 field measurements, a quasi steady flow analogy was applied to investigate an undular tidal bore with inflow Froude numbers 1.6 and 1.25. 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 tidal bores with inflow Froude number between 1.3 and 1.6. The effects of periodic loading on river sediments, scour of the riverbed and flow mixing behind the bore were investigated. A better understanding of these processes will contribute to better management practices in tidal bore affected rivers, including the Styx, Daly and Ord rivers in tropical Australia.

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

INTRODUCTION

A tidal bore is a wave or a series of waves propagating upstream as the tidal flow turns to rising. Basically, a bore is a positive surge of tidal origin which may form with large tidal ranges (more than 6 to 9 m) in a flat, converging channel forming a funnel shape. The front of the surge absorbs random disturbances on both sides and this makes the wave stable and self-perpetuating. With appropriate boundary conditions, a tidal bore may travel long distances upstream: e.g., the tidal bore on the Pungue river (Mozambique) is still about 0.7 m high about 50 km upstream of the mouth and it may reach 80 km inland. As the surge progresses, the river may flow upstream behind it (e.g. Lynch, 1982). Famous examples include the Hangzhou (or Hangchow) bore on the Qiantang river (China), the Amazon bore called *pororoca* (Brazil), the tidal bore on the Seine river (*mascaret*) (France) and the Hoogly (or Hooghly) 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 has an effect on the estuarine eco-system. Effects on sediment transport were studied at Petitcodiac and Shubenacadie rivers, on the Sée and Sélune (Tessier and Terwindt, 1994) and on Hangzhou bay (Chen et al., 1990). The impact on the ecology is acknowledged in the Amazon where piranhas eat matter in suspension after the passage of the bore, at Turnagain Arm where bald eagles fish behind the bore, in the Severn river (sturgeons in the past, elvers) and in the Bay of Fundy (striped bass spawning).

Bartsch-Winkler and Lynch (1988) listed over eighty estuaries affected by a tidal bore, but possibly more experience a bore. Despite their impact on estuarine processes, little is known on the flow field, mixing and sediment motion beneath tidal bores. Most observations are derived from reports by sailors, fishermen and surfers (e.g. Tricker, 1965). 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 with two geometric scaling ratios and some field observations.

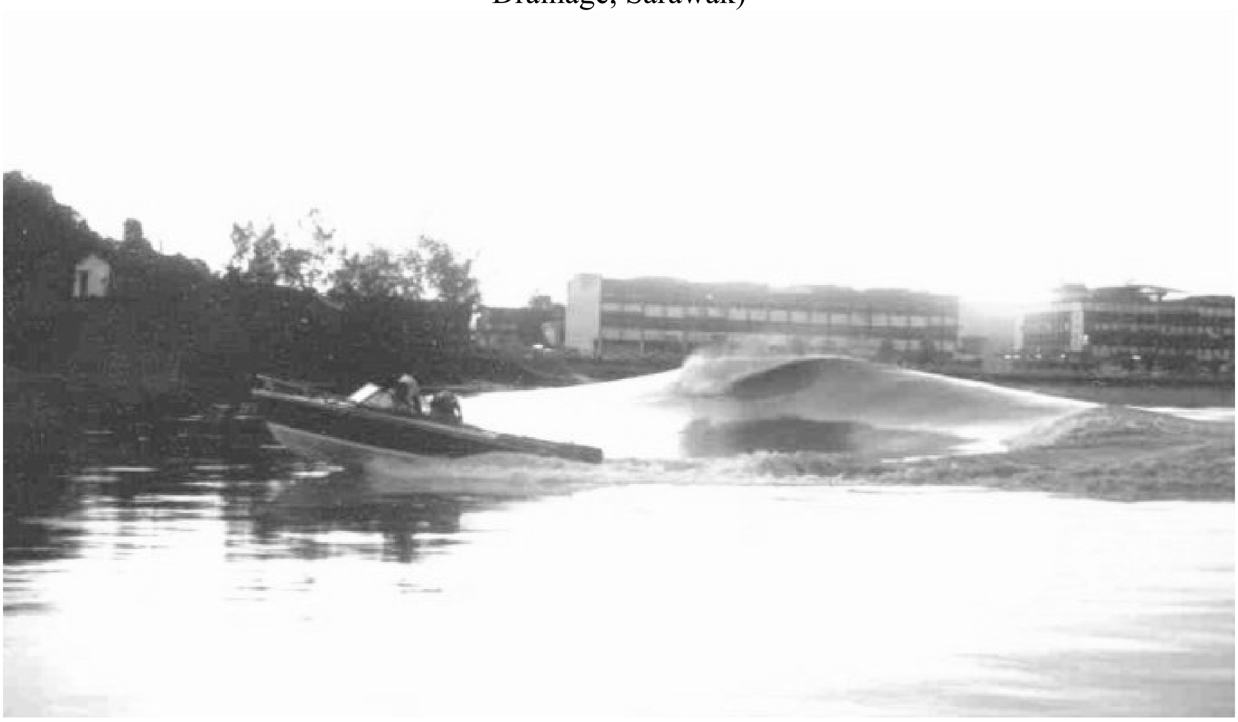
Methodology

Salient characteristics of tidal bores are revealed in photographs and videos of field occurrences. The second writer obtained audiovisual materials on more than 15 tidal bores and received written information on another dozen bores. Initially, most tidal bores develop as undular surges characterised by a train of advancing undulations. The waves usually don't break except where affected by proximity to the banks or shoals. Breaking bores are rare, often restricted to king tide conditions and localised in some estuarine sections. For example, the *pororoca* is primarily an undular bore but may break in some shallow water sections of the river mouth (Murphy, 1983). Secondly, before bore arrival, the river flow appears quiet and the free-surface is often smooth and glossy (e.g. Fig. 1). The inflow conditions are characterised by low turbulence levels.

Fig. 1 - Undular tidal bores in tropical rivers

(A) 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)



In the absence of detailed field measurements and because numerical models based upon the Saint-Venant equations cannot handle free-surface undulations, a quasi-steady flow analogy was applied to investigate an undular tidal bore with the physical model of an undular jump. The flow conditions were chosen for two series of field observations. Firstly the sighting of the Severn bore by Captain Beechey on 1 December 1849 (Tricker, 1965). That is, d_1 = 1.5 m and Fr_1 = 1.6 where d_1 is the upstream water depth and Fr_1 is the bore Froude number. Secondly the observation of the Dordogne river tidal bore on 27 September 2000 with d_1 ~ 1.5 to 2 m and Fr_1 ~ 1.3 (Chanson, 2001).
Dynamic similarity was achieved by selecting a Froude similitude (e.g. Henderson, 1966, Chanson, 1999). Partially-developed inflow conditions were selected to minimise the effects of upstream turbulence: i.e., δ/d_1 ~ 0.4 where δ is the upstream boundary layer thickness. Possible scale effects were investigated with two geometric scales: 18.7 and 32.6 for Fr_1 = 1.6 (i.e. d_1 = 0.080 and 0.046 m respectively). For the second Froude number Fr_1 = 1.3, the geometric scaling ratio was about 22 (i.e. d_1 = 0.081 m).

Table 1 shows the flow conditions for the 3 sets of detailed experimental measurements

Reference (1)	q m^2/s (2)	Fr_1 (3)	x_1 m (4)	d_1 m (5)	δ/d_1 (6)	Remarks (7)
Present study						B = 0.5 m. Horizontal channel.
Exp. No. HQ1	0.0484	1.58	0.3	0.046	0.43	Vertical sluice gate. Opening: 70 mm.
Exp. No. HQ2	0.111	1.57	0.45	0.080	0.42	Vertical sluice gate. Opening: 122.3 mm.
Exp. No. CD1	0.0914	1.25	0.35	0.081	0.44	Round gate with upstream flow straighteners. Gate opening: 80 mm.

EXPERIMENTAL INVESTIGATIONS

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, hemispherical nose). The Pitot tube design is based on the Prandtl design, 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 translation of the gauge and Pitot tube in the direction normal to the channel bottom 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.
The Prandtl-Pitot tube was calibrated as a Preston tube based upon in-situ experiments. The calibration curve was best fitted by:

$$\tau_o = 3.428 * V_b^{1.654} \tag{1}$$

where τ_o is the boundary shear stress and V_b is the velocity measured by the Pitot tube lying on the boundary (Chanson, 2000). Although similar to the calibration curves obtained by Preston (1954), Patel (1965) and Macintosh (1990), Equation (1) differs quantitatively and the difference were discussed specifically by Chanson (2000). The data accuracy was expected to be about 2% on dynamic and static pressures, 1% on local velocity and 5% on boundary shear stress.
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 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 the 1st trough and 2nd crest and between the 2nd crest and 2nd trough. Similar sets of distributions were also measured at a transverse position 8 cm from the centreline (Z2), 16 cm from the centreline (Z3) and 23 cm from the jump centreline (or 2 cm from the flume wall, Z4).

RESULTS

The free-surface profiles for all 3 experiments were observed to be basically two-dimensional for most of the cross section. Small shock wave effects rendered results close to the sidewalls of the experimental flume three-dimensional.
Recirculation bubbles were observed next to the bottom, under the 1st crest with the recirculation effect diminishing towards the sidewalls (Fig.2). Table 2 details the characteristics of the recirculation region beneath the first wave crest for the three experiments. The relative bubble height, h_b/d_c was shown to decrease with decreasing Froude number.

Fig. 2 - Definition sketch

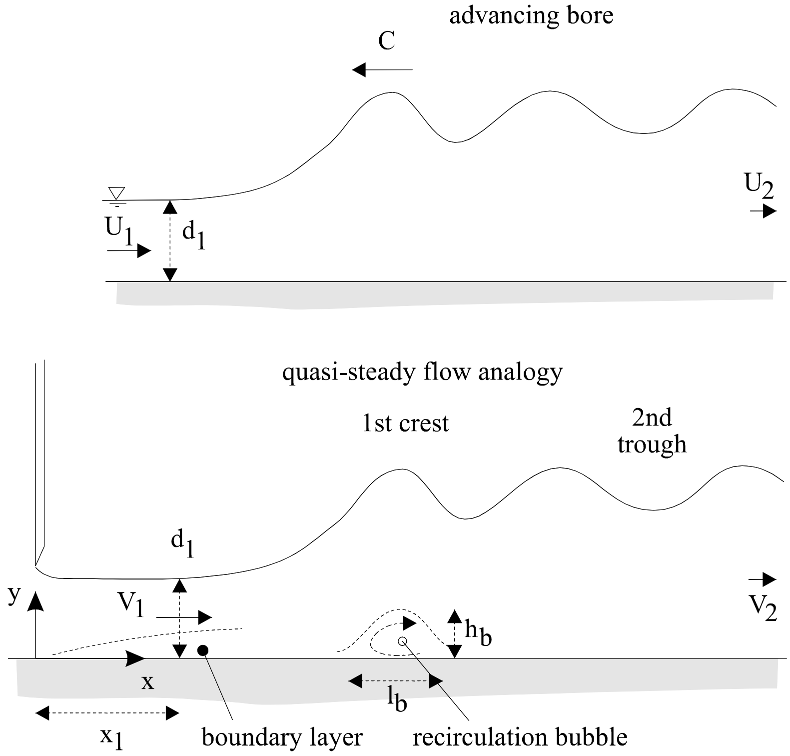


Table 2 - Characteristics of the recirculation region beneath the first wave crest

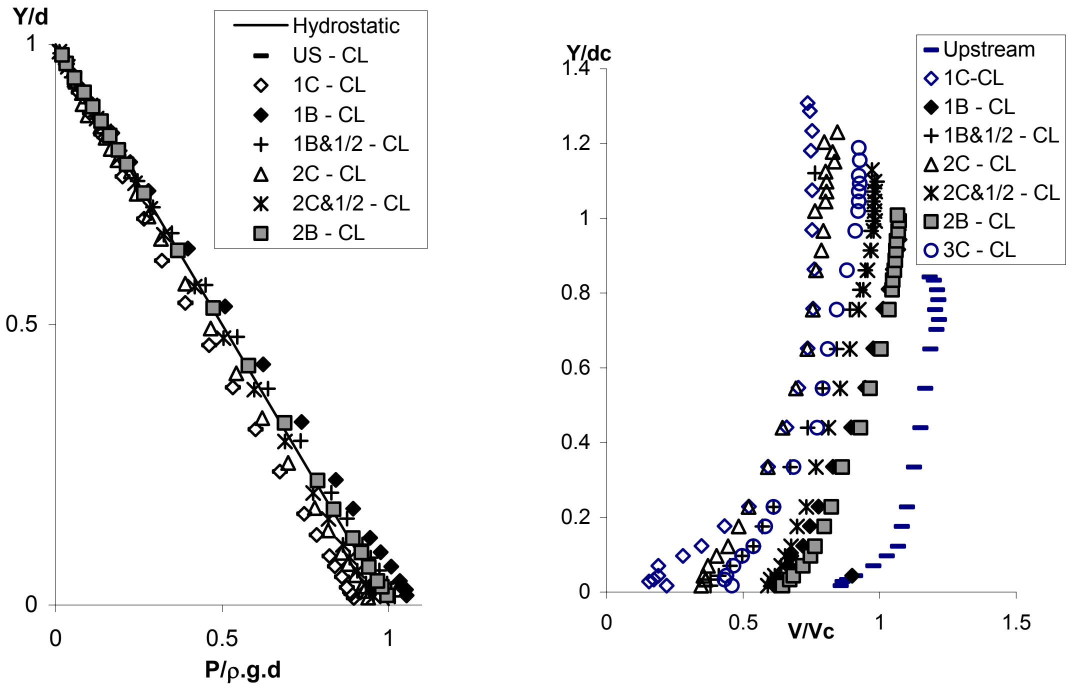
Reference	Fr_1	d_{1C}	h_b	B_b	l_b	Remarks
		m	m	m	m	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Present study						B = 0.5 m. Horizontal channel.
Exp. No. HQ1	1.58	0.095	0.03	0.44	0.05	Vertical sluice gate. Opening : 70 mm.
Exp. No. HQ2	1.57	0.158	0.05	0.40	0.10	Vertical sluice gate. Opening : 122.3 mm.
Exp. No. CD1	1.25	0.1353	0.01	0.40	0.05	Round gate with upstream flow straighteners. Gate opening : 80 mm.

Notes : d_{1C} : centreline water depth at first crest; h_b : recirculation bubble maximum height; B_b : recirculation bubble width; l_b : recirculation bubble maximum length;

Figure 3 presents the dimensionless pressure and velocity distributions along the centreline for the experiment at Froude number 1.25. As predicted by irrotational flow motion theory (e.g. Rouse, 1938, Liggett 1994), the pressure distributions deviate somewhat from hydrostatic. Chanson (2001) compared some experimental data with a solution of the Boussinesq equation. The results showed greater deviations from hydrostatics for the experimental data than for the theoretical approach. Present data show further that the pressure distributions are not symmetrical either side of a crest or trough.

The velocity distributions show significant flow redistributions between the upstream cross section and the first crest, and between subsequent crests and troughs. Maximum velocities are observed at the troughs and minimum velocities at the crests. Furthermore the velocity distributions are not symmetrical on either side of a crest or trough.

Figure 3 – Dimensionless Pressure and Velocity Profiles along the centreline of the hydraulic jump for Froude Number 1.25.



DISCUSSION

Figure 4(a) shows observed velocity profiles in the stationary undular flow. These results were then transformed using the quasi-steady flow analogy for an identical Froude number (Fr_1 = 1.25). The transformation assumed a power law distribution of the bore celerity (N=10) yielding zero velocity at the bed. The results are presented in Figure 4(b) and correspond to the undular tidal bore flow of the Dordogne river

The quasi-steady flow analogy (Fig. 4(b)) shows negative velocities beneath the undular bore. This is indicative of flow reversal observed as a bore propagates upstream. Small, positive velocities are however noticed next to the free surface the troughs. Velocites 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 (Fig. 5). A marked difference is observed. The effect of the positive upstream velocity profile on the flow field beneath the free-surface undulations can be distinctly observed. (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.

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

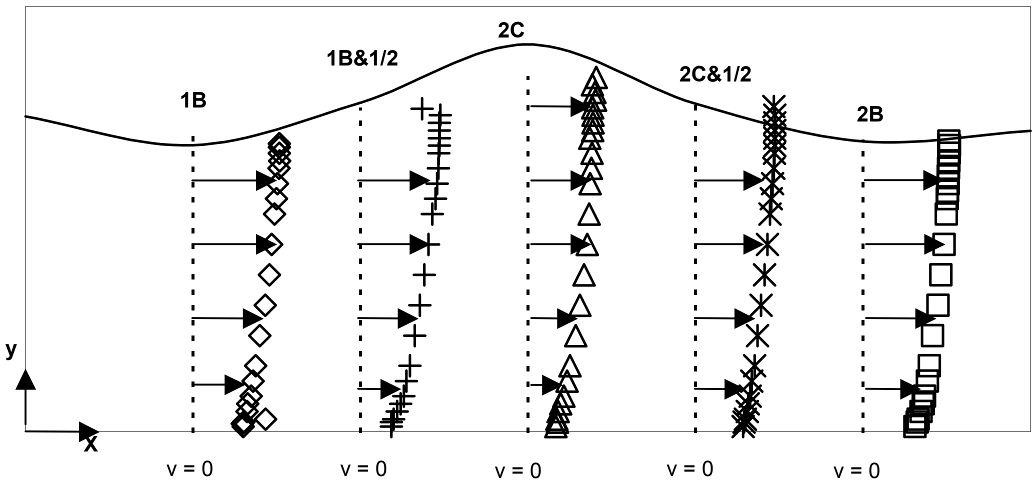
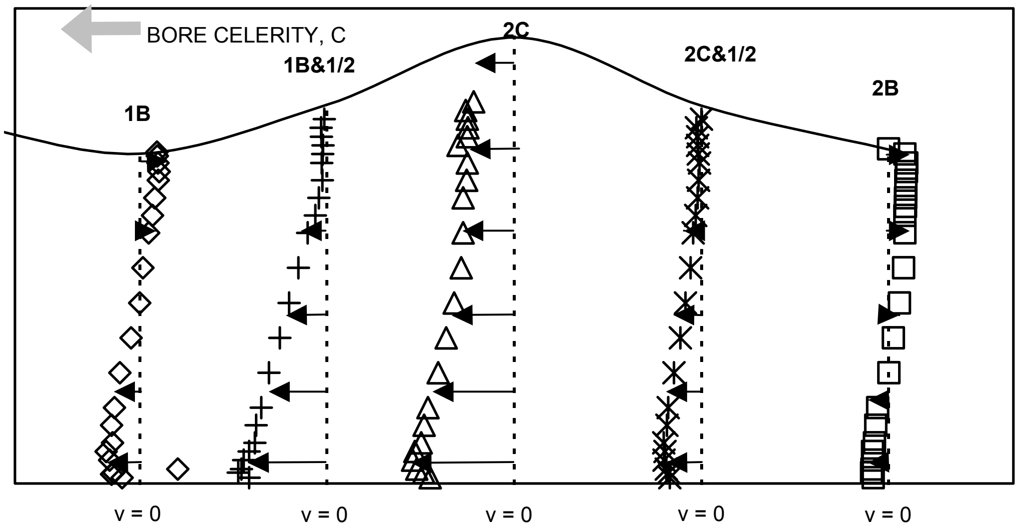


Fig. 4b -Velocity Profiles under an Undular Surge (Fr_1=1.25) estimated using the Quasi-Steady Flow Analogy



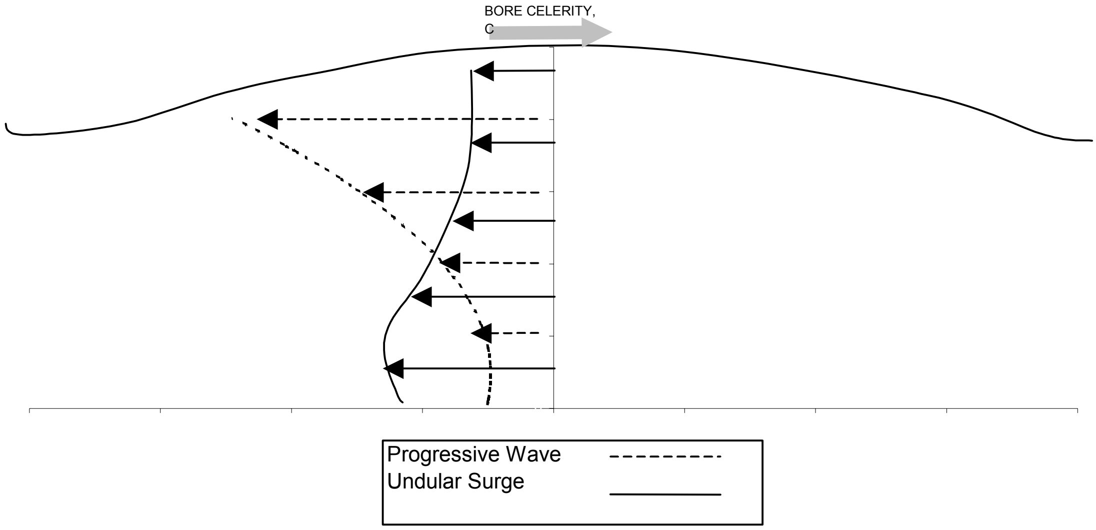
Effects on Sediment Erosion

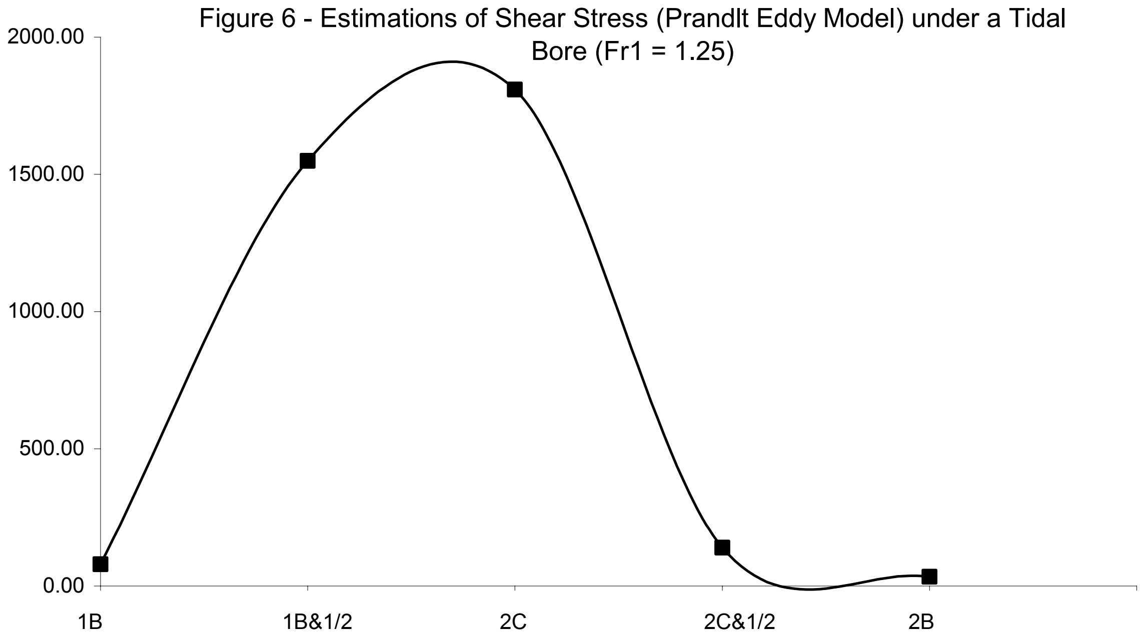
The results presented in Figure 4(b) indicates that the bed under a tidal bore will be subjected to an initial reversal of flow, followed by flow acceleration and deceleration associated withnthe passage of the undulations as the bore propagates upstream. (Flow recirculation observed during the experiments on stationary undular jumps, were analogous to significant flow decelerations observed in a moving bore.) Further the 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. An estimate of shear stress at the phase boundary was calculated using the Prandtl eddy model assuming that the mixing length l equals the distance y from the invert (Streeter &

Wylie 1951, Chanson 1999). Figure 6 presents estimated bed shear stresses as a function of the londitudinal location for an advancing undular bore. Maximum shear stresses are observed beneath the crests while minimum shear stresses are observed underneath the troughs. This is opposite to the effect observed for the stationary undular hydraulic jump (Chanson 2001).

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





O'Reilly and Brown define 'stress reversal' as a change in the sign of the rate of stress increase (O'Reilly & Brown, YEAR). Therefore the bed under an undular tidal bore is subjected to significant stress reversals and hence undergoes cyclic loading. The bed under a tidal bore is saturated and therefore *changes in pore pressures will occur during 'fast cycling', that is where the rate of cycling is such that changes in pore pressures are not fully dissipated* (O'Reilly & Brown, YEAR). The bed may therefore be subjected to liquefaction, placing bed material into suspension (e.g. Dormieux 1993).

Effect on Flow Mixing

Figure 4(b) indicates the rapid velocity redistributions present at all depths of flow and the flow reversals which take place at the surface between crests and troughs. Chanson observed that the passing of the bore was followed by "*chaotic wave motion lasting for some time, making it difficult for surfers to come back on shore even 20 minutes after the passage of the bore*" (Chanson 2001). Another salient field observation was the murkiness of the water after the passage of the bore. Undular tidal bore have the potential to scour the channel bed (see above). Further upward flow motion between trough and subsequent crest advects bed material towards the surface. The rapid velocity redistributions, associated with the long-lasting chaotic wave motion, contribute to maintain sediment suspension which is carried upstream with the bore and eventually deposited in intertidal zones. A transverse mixing coefficient was calculated for the Ord River, Western Australia, of about $\varepsilon_T = 0.71$ m^2/s (Chanson 2002).
A tidal bore contributes to not only sediment mixing but also impacts on the eco-system. Piranhas have been observed in the Amazon basin feeding off material suspended behind the first wave crest of a bore and at Turnagain Arm (Canada), bald eagles dive for fish mixed up in the flow behind bores.

CONCLUSION

In the absence of detailed field measurements and because numerical models based upon the Saint-Venant equations cannot handle free-surface undulations, a quasi steady flow analogy was applied to investigate detailed flow properties of an undular tidal bore. Detailed flow measurements were conducted in stationary undular jumps with inflow Froude numbers of 1.6 and 1.25 and partially developed inflow conditions. 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.
These results were combined with salient bore characteristics derived from written information, photographs, videos of field occurrences and field observations. Dynamic similarity was used to predict the characteristics of tidal bores with inflow Froude number between 1.3 and 1.6. Comparisons of the velocity profiles within a tidal bore indicated that the largest velocity gradients and therefore shear stresses exist under the crests of the undulations. It has been postulated that the high bed shear stresses would lead to erosion of sediments beneath the bore. The cyclic nature of the loading may also lead to liquefaction. Beneath the advancing bore, rapid velocity redistributions 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. Tidal bores occur in many tropical regions including Brazil, India, China, Malaysia and Australia.

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