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Unsteady turbulence, dynamic similarity and scale effects in bores and positive surges

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HIGHLIGHTS

- Instantaneous free-surface and velocity properties were measured in propagating bores.
- Intense turbulent mixing was observed under breaking and undular tidal bores.
- Unsteady dimensionless properties were compared based upon a Froude and Morton similitude.
- Several parameters were affected by scale effects, including velocity and Reynolds stress fluctuations.
- Results point to the need for detailed field measurements.

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ABSTRACT

A tidal bore is a positive surge or compression wave formed in an estuarine system during the early flood tide under macro-tidal conditions. A series of physical experiments were conducted in a large facility to investigate the unsteady free-surface properties, velocity characteristics and Reynolds shear stresses. Both instantaneous and ensemble-averaged measurements were performed. The results demonstrated the intense turbulence and turbulent mixing under breaking and undular tidal bores. A range of dimensionless unsteady turbulent properties were carefully compared based upon both Froude and Morton similitudes with two different Reynolds number ranges. The data showed that several parameters were affected by scale effects, including velocity and Reynolds stress fluctuations during the bore propagation. The finding implies that laboratory study data might not be up-scaled to prototype conditions without some form of scale effects.

1. Introduction

A positive surge or bore is an unsteady open channel flow motion characterised by a sudden increase in water depth [1]. It is also called a hydraulic jump in translation [2–4]. The bore front constitutes a hydrodynamic shock with a discontinuity in terms of water depth and pressure and velocity fields [5]. A typical geophysical application is a tidal bore propagating upstream in an estuarine zone [6,7] (Fig. 1). Fig. 1 presents two occurrences of tidal bores. A tidal bore is essentially a compression wave formed in an estuary under large tidal range in a narrow funnelled mouth during the early flood tide, under relatively low freshwater flows. For a hydraulic jump in translation, the equations of conservation of mass and momentum in their integral form give a relationship between the Froude number and the ratio of conjugate cross-section areas:

$$Fr_1 = \frac{(V_1+U)}{\sqrt{g \times \frac{A_1}{B_1}}} = \sqrt{\frac{1}{2} \times \frac{A_2}{A_1} \times \frac{B_1}{B^{\#}} \times \left(\left(2 - \frac{B'}{B^{\#}} \right) + \frac{B'}{B^{\#}} \times \frac{A_2}{A_1} \right) + \frac{A_2}{A_2 - A_1} \times \frac{F_{fric} - W \times S_o}{\rho \times g \times \frac{A_1^2}{B^{\#}}}} \qquad (1)$$

where V is the flow velocity, A is the cross-section area, B is the free-surface width, the subscripts 1 and 2 refer to the initial flow conditions and conjugate flow conditions respectively (Fig. 2), U is the celerity positive upstream, ρ is the fluid density, g is the gravity acceleration, F_{fric} is the friction force, W is the control volume weight and S_o is the bed slope, while $B^{\#}$ and B' are characteristic

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(A) Undular tidal bore of the Dordogne River at Port de St Pardon (France) on 24 August 2013—Most surfers and kayakers are surfing ahead of the first wave crest.

(B) Breaking tidal bore in the Qiantang River at Laoyanchang (China) on 6 September 2013.

Fig. 1. Tidal bores in natural environments—Bore propagation from left to right.

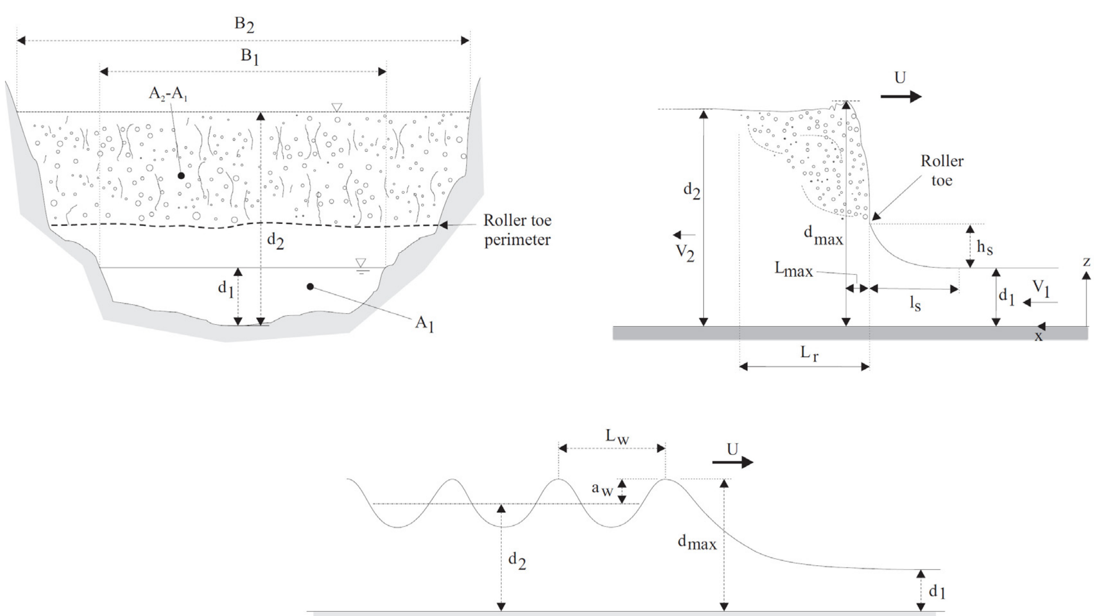

Fig. 2. Definition sketch of breaking and undular bores.

channel widths functions of the cross-sectional shape:

$$B^{\#} = \frac{A_2 - A_1}{d_2 - d_1} \quad (2)$$

$$B' = \frac{\int_{A_1}^{A_2} \int \rho \times g \times (d_2 - z) \times dA}{\frac{1}{2} \times \rho \times g \times (d_2 - d_1)^2} \quad (3)$$

with d the flow depth and z the vertical elevation (Fig. 2). Eq. (1) is a general expression for the bore propagation in an irregular cross-sectional channel [8,9]. For a smooth rectangular horizontal channel, it yields the Bélanger equation:

$$Fr_1 = \sqrt{\frac{1}{2} \times \frac{d_2}{d_1} \times \left(1 + \frac{d_2}{d_1}\right)} \quad (4)$$

where d_1 is the inflow depth and d_2 is the conjugate flow depth [10,6].

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