Velocity profile measurements in bore waves

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Hydrodynamic waves are an unsteady flow motion generated by rapid water level rise. In nature, such events can be found in dam-break waves, impulse waves and tsunamis. These phenomena are rare, but highly destructive. The present study is based on an experimental approach and it investigates the hydrodynamic behavior of bores propagating on wet bed in terms of height and velocity profiles. The waves are investigated using Ultrasonic distance Sensors (US) to measure the wave height and average front velocity; the instantaneous velocity profiles were obtained through an Ultrasonic Velocity Profiler (UVP), installed in the bottom of the channel, with an emitting frequency of 2 MHz and inclined with an angle of 20° in the upstream direction. The acoustic scattering was increased using a hydrogen bubble technique with an anode and a cathode installed in the upstream part of the channel. The probe was sampled with a frequency varying from 13.5 to 55 Hz depending on the maximum wave height. A sensitivity analysis of the main influential factors was carried out, pointing out the need for a compromise between quality and quantity for these highly unsteady flows. Results showed some interesting logarithmic profiles typically associated with open channel flows for all wave configurations.

Keywords: Wet bed bores, Tsunami, velocity profiles, Ultrasonic Velocity Profilers (UVP)

1. Introduction

Hydrodynamic waves such as dam-break waves, impulse waves and tsunamis, represent a highly unsteady flow motion resulting into a rapid water level rise. These phenomena are rare, but highly destructive, implying important losses and reconstruction costs. Physically both surges propagating on dry bed and bores propagating on wet bed have a complex behavior and an experimental approach is necessary. After the December 2004 Indian Ocean tsunami, field observations showed velocities between 3 to 4 m/s in Kumala Beach and 6 to 8 m/s in Khao Lak [1]. In Japan in 2011 the tsunami velocity was 10 to 13 m/s near Sendai airport [2]. Nevertheless, recent studies have shown that uncertainties still exist on the evaluation of bore velocities and multiple empirical formula can be found in the existing design codes [3]. This study gives an insight on the hydrodynamic behavior of bores propagating on wet bed, representing successive waves after the first tsunami. It is known that the first wave might not be the highest. The project is based on an experimental approach and the paper focuses on the use of Ultrasonic Doppler methods to measure velocity profiles of highly unsteady flows such as propagating bores. Previous relevant studies were carried out by [4] for similar conditions, proving the effectiveness of such technique for unsteady flows. A sensitivity analysis of the main parameters was carried out, showing the importance of a compromise between high resolution and precision of the results.

2. Experimental Set-up

All experiments were carried out at the Laboratory of Hydraulic Constructions (LCH) of EPFL, Switzerland. Bore formation was achieved through a vertical release of a known water volume from an upper reservoir into a lower reservoir through three identical PVC pipes with external diameter of 311 mm. The opening is obtained through a system of punch and pulley, allowing to activate the system respecting the criteria proposed by [5] for dam-break waves. Similar techniques were previously used by [4], [6] and [7]. The use of 1, 2 or 3 pipes allowed to produce waves with different hydrodynamic properties in terms of velocity and depth. The propagation of the wave took place in a 14 m long and 1.4 m wide smooth horizontal channel, whose roughness corresponded to a Darcy Weisbach friction factor $f = 0.01$ based on measurements. The bore profiles were investigated using 7 Ultrasonic distance Sensors (US), Baumer UNAM 30I6103, sampled with a frequency of 12.5 Hz. The US sensors were located in the centerline of the channel at x = 2, 10.10, 12.10, 13.10, 13.35, 13.60 and 13.85 m from the flume inlet. The facility and the disposition of the US probes are shown in Figure 1.

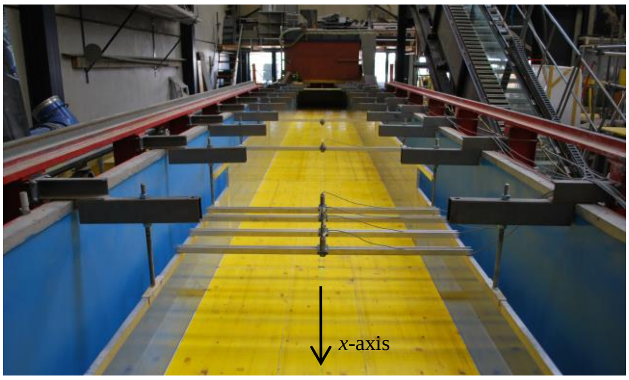

Figure 1: Experimental channel and instrumentation

Flow velocity was investigated using an Ultrasonic Velocity Profile (UVP) produced by the Met-Flow (Switzerland). This instrument provided instantaneous velocity profiles along the axis by detecting the Doppler shift frequency of echoed ultrasound as a function of time. No calibration was needed for these measurements. Only one transducer was used in the cross-section and it was located at a distance of 13.85 m from the channel inlet, where the bore had reached a fully developed condition. Measurements were taken in the transducer axis then projected in the main flow direction (x-axis). Only the component in the x-direction was considered. For the present study, an emitting frequency of 2 MHz was chosen. The transducer had a diameter of 8 mm and it was located 5 mm below the channel bottom with an angle of 20° in the upstream direction. The empty space between the probe and the channel was filled with gel and sealed with plastic tape to assure the transmission of the emitting signal (Figure 2).

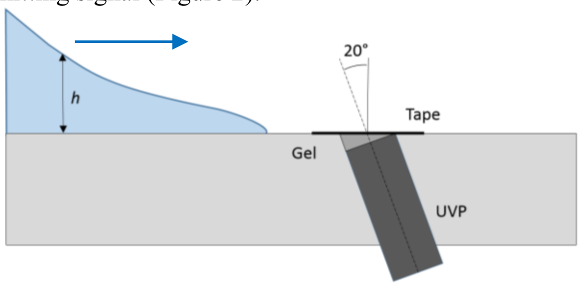

Figure 2: Sketch of the UVP installed in the channel bottom

The acoustic scattering was increased using a hydrogen bubble technique with an anode and a cathode installed in the upstream part of the channel, at x = 1.5 m from the channel inlet (Figure 3). The vertical bars had a diameter of 8 mm and a thin stainless steel wire ($\O$ = 0.0001 m) was wrapped around with a spacing of 5 mm. The bars were covered with waterproof paint to avoid their participation in the reaction. A potential difference of 40 V was applied between the two bars, producing hydrogen bubbles with diameter proportional to $\O$. The ability of this method was previously proved by [8] and [9].

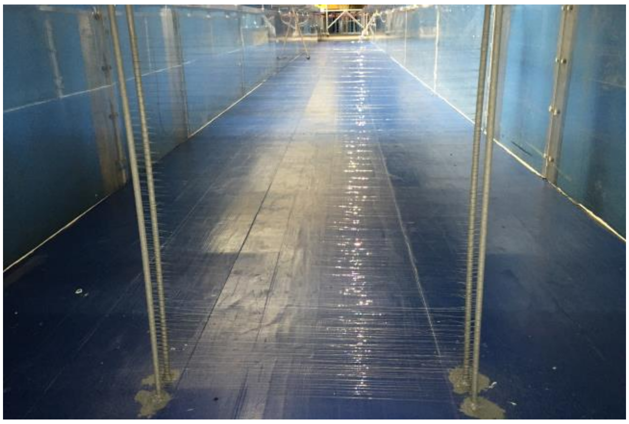

Figure 3 : Hydrogen bubble releasing technique.

The UVP probe was sampled with a frequency varying from 13.5 to 55 Hz depending on the maximum wave height. UVP data was post-processed using a commercial code developed by Met-flow. The use of a trigger function (5V) to start the UVP measurement through a tailor made LabView acquisition system allowed a synchronization of both UVP and US data.

3. Hydraulics of bore waves

In the experimental facility both surges on dry bed and bores on wet bed where produced. However this study only focuses on bores propagating on a wet bed with an initial still water depth of h_0 = 0.05 m. Bores on a wet bed present a highly turbulent and recirculating roller, similar to a translating hydraulic jump, followed by a relatively constant depth. A picture of the produced wet bed bore and its turbulent front is presented in Figure 4.

Figure 4 : Picture of the wet bed bore (h_0 = 0.05 m)

Good agreement was found between the experimental tests and the theoretical solutions of [10] and [11], as shown by [12]. The height profiles obtained at US7 (x = 13.85 m from inlet) for three wet bed bores with identical releasing conditions are presented in Figure 5, where a good repeatability can be observed. The front velocity was measured using the 7 US sensors placed along the channel and the arrival of the bore was identified when a threshold of h = 0.01 m was overpassed; an average value of V_{front} = 2.5 m/s was found for all three bores.

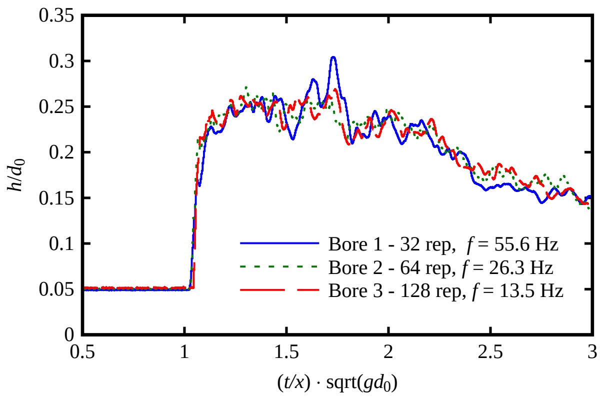

Figure 5 : Profiles of the bores used in the present study: each test was performed with a different UVP acquisition frequency (Table 1)

4. Sensitivity Analysis

Bores are a highly unsteady phenomenon, meaning that its properties rapidly change in space and time, requiring a high frequency for all measurements. For most instruments the quality and the reliability of the measured data is proportional to the number of repetitions used, implying a longer duration and therefore a lower acquisition frequency. A compromise between high frequency and quality of the results was therefore necessary and a sensitivity analysis was carried out on three wet bed surges (h_0 = 0.05 m) to investigate the influence of the main parameters. The main parameters of the study are presented in Table 1.

Table 1. Acquisition parameters used in the sensitivity analysis

	Number of repetitions	Acquisition duration [ms]	Acquisition frequency [Hz]
Bore 1	32	18	55.6
Bore 2	64	38	26.3
Bore 3	128	74	13.5

A depth-averaged velocity (V) was calculated for every profile obtained using Eq.1.

$$V = \frac{1}{N}\sum_{i=0}^{i=N} v_i \qquad (1)$$

in which i varies from 0, the channel bottom, to N (h_{max}). The results obtained for all three bores are presented in Fig 6 as a function of time, where a similar behaviour is observed for all bores. One can notice that a higher frequency (Fig. 6 top, 32 repetitions) corresponded to a greater amount of points, but lower precision and higher scattering were found. With lower frequencies, the number of measurements was reduced, the overall profile behaviour remaining unchanged. It is important to point out that being the first part of the wave highly aerated and turbulent (Figure 4), the transmission of the echo was obstructed by the presence of air bubbles. This resulted into velocity profile measurements characterised by high scattering and low physical meaning. Results also showed some interesting logarithmic profiles typically associated with open channel flows for all scenarios. As an examples the profiles obtained at t = 6.5 s, behind the aerated bore front, are presented in Figure 7. Similarly to the previous case, for higher acquisition times a smoother profile was observed, whereas for higher frequencies more scattering was found. For these reasons in the present study a higher resolution was chosen (128 repetitions) with a corresponding frequency of 13.5 Hz.

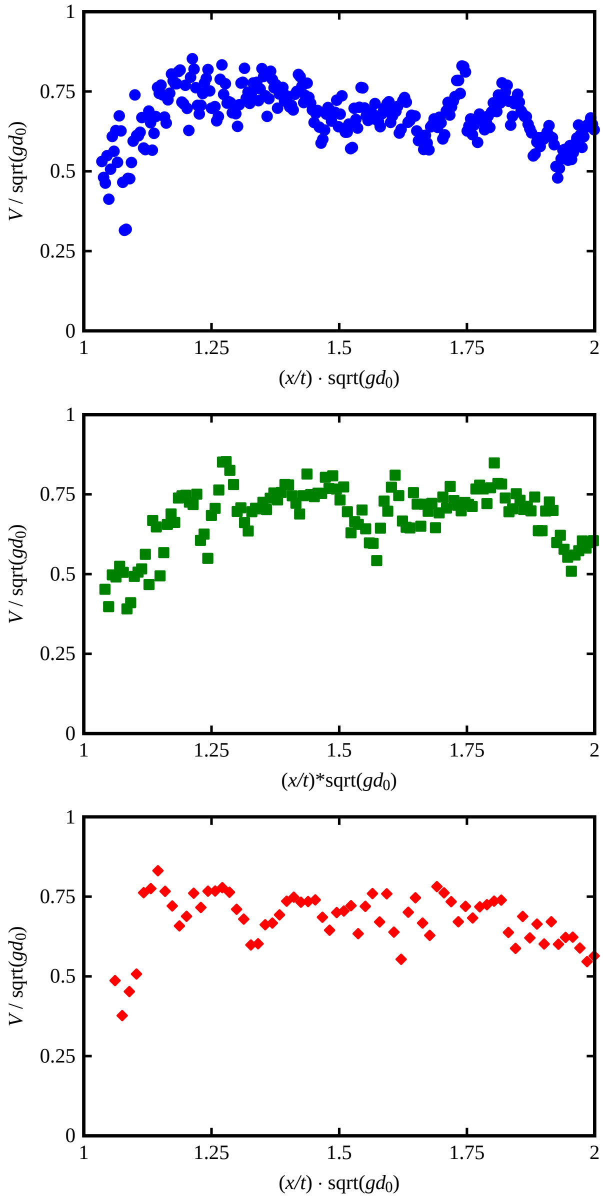

Figure 6 : Time evolution of the depth-averaged velocity : (top) Bore 1, 32 repetitions, (centre) Bore 2, 64 repetitions, (bottom) Bore 3, 128 repetitions

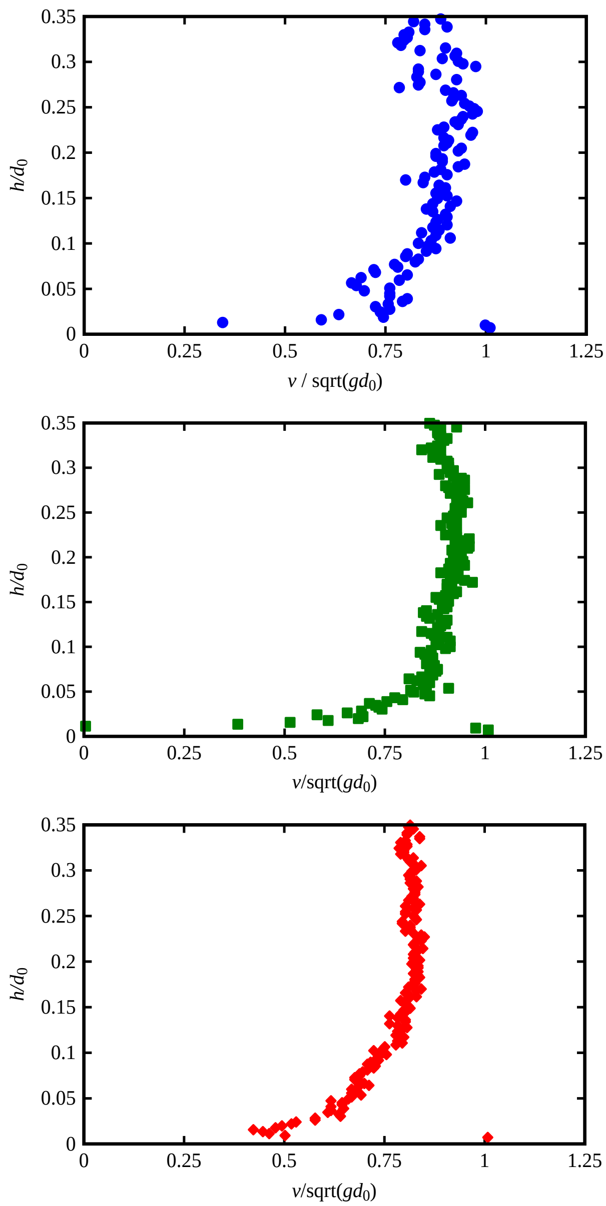

Figure 7 : Examples of profiles obtained for t = 6.5 s, after the turbulent bore front: (top) Bore 1, 32 repetitions, (centre) Bore 2, 64 repetitions, (bottom) Bore 3, 128 repetitions

5. Results

Regardless of the frequency used, a relatively constant and oscillating value of the depth-averaged velocity was observed in the first seconds of the bore, followed by a deceleration far behind the water front. The values obtained were also successfully compared with the wave average velocity derived from the US probes ($V_{\text{front}} \approx 2.5$ m/s), obtaining similar results and therefore proving the consistency of the measurements. All 104 instantaneous velocities profiles between $1 < x/t \cdot \text{sqrt}(gd_0) < 2.5$ were normalized using the depth-averaged velocity (V_i) and the maximum height ($h_{i,\max}$). Results are presented in Figure 8, showing a profile typical of open channel flows. The experimental points were also successfully compared with the Prandtl's power law with an exponent $n = 11.5$, obtained with a friction factor $f = 0.01$ [13]. The scattering in the upper part of the flow is attributed to secondary turbulence in the flow surface.

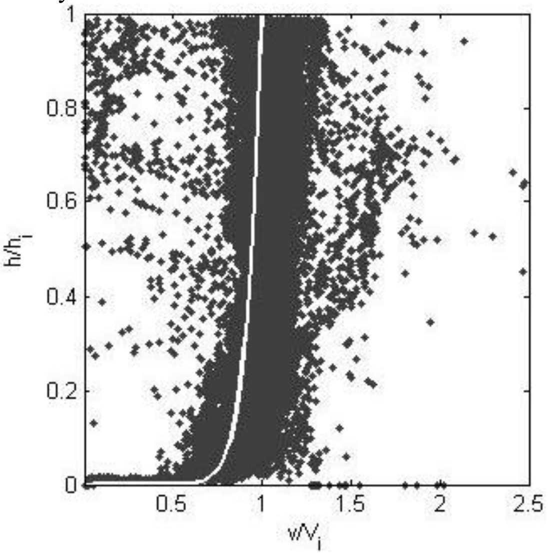

Figure 8 : Dimensionless velocity profiles for a wet bed bore propagating over a $h_0 = 5$ cm still water initial depth

6. Conclusion

Bore waves can be found in nature in dam break waves, impulse waves and tsunamis propagating on a wet bed. This paper is based on an experimental approach and it focuses on the techniques used to measure instantaneous velocity profiles using Ultrasonic Velocity Profilers (UVP). Bore formation is achieved through a vertical release technique and its propagation took place in a 14 m long and 1.4 m wide horizontal channel. A UVP transducer with an emitting frequency of 2 MHz was installed in the channel bottom at an angle of 20° in the upstream direction at a distance of 13.35 m from the channel inlet. Being the flow highly unsteady, the acquisition frequency needed to be sufficiently high to fully capture the properties of the flow and the acquisition time sufficiently long to provide quality results. Thus a compromise needed to be found. To evaluate the influence of these parameters a sensitivity analysis was carried out on three identical bores with different acquisition frequencies. Results showed that for increasing frequencies a higher scattering was observed, nevertheless the overall behaviour remained unchanged. The quality of the instantaneous profiles was higher for longer acquisition times. Furthermore, the velocity profiles showed an excellent agreement with Prandtl's power law, typical of open channel flows.

Acknowledgment

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Notation

f	Darcy-Weisbach friction factor
g	gravity constant
h	Bore height [m]
h_0	Initial still water depth [m]
n	exponent in the Prandtl's power law
N	number of measures in the vertical direction
$Ø$	wire diameter [m]
t	time [s]
v	instantaneous profile velocity [m/s]
V	Depth-averaged Velocity [m/s]
V_{front}	bore front velocity, measured with US [m/s]
x	longitudinal direction along the channel [m]

References

[1] Rossetto T, *et al.*: The Indian Ocean tsunami of December 26, 2004: observations in Sri Lanka and Thailand, Nat. Hazards, 42-1 (2007), 105-124.

[2] Jaffe BE, *et al.*: Flow speed estimated by inverse modelling of sandy tsunami deposits: results from the 11 March 2011 tsunami on the coastal plain near the Sendai Airport, Honshu, Japan, Sedimentary Geology, 282 (2012), 90-109.

[3] Nistor I, *et al.*: Tsunami-induced forces on structures. Handbook of Coastal and Ocean Engineering, Singapore: World Scientific (2009), 261-286.

[4] Meile T: Influence of macro-roughness of walls on steady and unsteady flow in a channel, PhD Thesis No. 3952 and Communication 36 of Laboratory of Hydraulic Constructions, LCH/EPFL (2007), Lausanne, (Ed. A. Schleiss).

[5] Lauber G & Hager W: Experiments to dam-break wave: Horizontal channel, J. Hydraul. Res., 36-3 (1998), 291-307.

[6] Chanson H, *et al*: Unsteady air bubble entrainment and detrainment at a plunging breaker: dominant time scales and similarity of water level variations. Coast. Eng., 46-2 (2002), 139-157.

[7] Rossetto T, *et al*: Physical modelling of tsunami using a new pneumatic wave generator, Coast. Eng., 58-6 (2011), 517–527.

[8] Blanckaert K & Lemmin U: Means of noise reduction in acoustic turbulence measurements, J. Hydraulic Res. 44-1 (2006), 3-17.

[9] Meile T, *et al*: Improvement of Acoustic Doppler Velocimetry in steady and unsteady turbulent open-channel flows by means of seeding with hydrogen bubbles, Flow Meas. Instrum., 19-3 (2008), 215-221.

[10] Ritter A: Die Fortpflanzung der Wasserwellen, Zeitschrift Verein Deutscher Ingenieure, 36-33 (1892), 947-954.

[11] Stoker JJ: Water Waves: The Mathematical Theory with Applications, Intersciences, (1957), 567 pages

[12] Wüthrich D, *et al*: Experimental generation of tsunami-like waves, Proc. of Coastal Structures. Boston, MA, USA. 9-11 September 2015 (under publication).

[13] Chanson H: The hydraulics of Open Channel Flow: an Introduction, Elsevier (2004)