Hydrodynamics and turbulence in positive surges. A comparative study

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Abstract: *A positive surge results from a sudden change in flow that increases the depth. It is the unsteady flow analogy of the stationary hydraulic jump and a geophysical application is the tidal bore. Positive surges are commonly studied using the method of characteristics and the Saint-Venant equations. The paper presents the results from new experimental investigations conducted in a large rectangular channel. Detailed unsteady velocity measurements were performed with a high temporal resolution using acoustic Doppler velocimetry and non-intrusive free-surface measurement devices. Two series of data were collected with a horizontal bed slope, a constant flow rate (Q=0.060 m³/s) and two different downstream gate openings after closure, which resulted in undular (non-breaking) and in breaking bores, respectively. The analysis of undular free-surface profiles revealed a good agreement with previous both theoretical and experimental studies. Unsteady flow turbulence analysis revealed some significant patterns in streamwise and transverse velocities.*

Keywords: *Environmental hydraulics, turbulence, positive surge, surge front, free surface measurements, instantaneous velocity field, physical modelling.*

1. INTRODUCTION

Positive surges are commonly observed in man-made channels and in natural channels. In water supply canals for irrigation and water power purposes, a positive surge may be induced by a partial or complete closure of a control structure, e.g. a gate, resulting in a sudden change in flow that increases the water depth (Henderson, 1966; Chanson, 2004). In rivers and estuaries, a typical form of positive surge is the tidal bore which is a positive surge of tidal origin. Tsunami-induced bores were also observed (Chanson, 2005). Although a positive surge may be analysed using a quasi-steady flow analogy, its inception and development is commonly predicted using the method of characteristics and Saint-Venant equations. After formation of the surge, the flow properties immediately upstream and downstream of the front must satisfy the continuity and momentum principles (Henderson, 1966; Chanson, 2004). For a fully-developed positive surge, the surge is seen by an observer travelling at the surge speed U as a quasi-steady flow situation called a "hydraulic jump in translation" (Fig. 1). In a rectangular, horizontal channel and neglecting friction loss, the solution of the continuity and momentum equations applied to a control volume across the surge front yields:

$$\frac{d_{conj}}{d_0} = \frac{1}{2}\left(\sqrt{1+8\,Fr^2}-1\right) \tag{1}$$

$$\frac{Fr_{conj}}{Fr} = \frac{2^{3/2}}{\left(\sqrt{1+8\,Fr^2}-1\right)^{3/2}} \tag{2}$$

where d_{conj} and d_0 are respectively the new and initial flow depths (Fig. 1), and the Froude numbers Fr and Fr_{conj} are the bore Froude numbers defined respectively as:

$$Fr = \frac{V_0 + U}{\sqrt{g\, d_0}}$$
$$Fr_{conj} = \frac{V_{conj} + U}{\sqrt{g\, d_{conj}}} \quad (3)$$

where U is the surge velocity as seen by a stationary observer on the channel bank and positive in the upstream direction, V is the flow velocity, the subscript o refers to the initial flow conditions and the subscript conj refers to the new (conjugate) flow conditions (Fig. 1).
The paper presents the results from new experimental investigations conducted in a large rectangular channel to document flow field and turbulence characteristics in positive surges with constant flowrate but different downstream gate openings after closure. The analysis of both free-surfaces and turbulence characteristics provided some significant and novel findings about positive surge hydrodynamics.

2. EXPERIMENTAL SETUP. CHANNEL AND INSTRUMENTATION

The experiments were performed in a large tilting flume at the University of Queensland. The channel was 0.5 m wide 12 m long and it was horizontal. The flume was made of smooth PVC bed and glass walls, and waters were supplied by a constant head tank. A tainter gate was located next to the downstream end. Its controlled and rapid closure induced a positive surge propagating upstream. Two series of data were collected with a constant flow rate (Q=0.060 m³/s) and two different downstream gate openings after closure, i.e. 0.100 m and 0.005 m. They resulted in undular (non-breaking) and in breaking bores, respectively. In steady flows, water depths were measured using rail mounted pointer gauges and acoustic displacement meters. Unsteady water depths are measured with acoustic displacement meters Microsonic™ Mic + 25/IU/TC with an accuracy of 0.18 mm and a response time of 50 ms. Turbulent velocity measurements were conducted with an acoustic Doppler velocimeter (ADV) Sontek™ 16MHz micro-ADV equipped with a two-dimensional side-looking head. For the experiments, the velocity range was 1.0 m/s, the sampling rate was 50 Hz and the data accuracy was 1% of the velocity range. The translation of the ADV probe in the vertical direction was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit. The error on the vertical position of the probe was Δz<0.025 mm. The accuracy on the longitudinal position was Δx<± 2 mm. All measurements were conducted on the channel centreline.

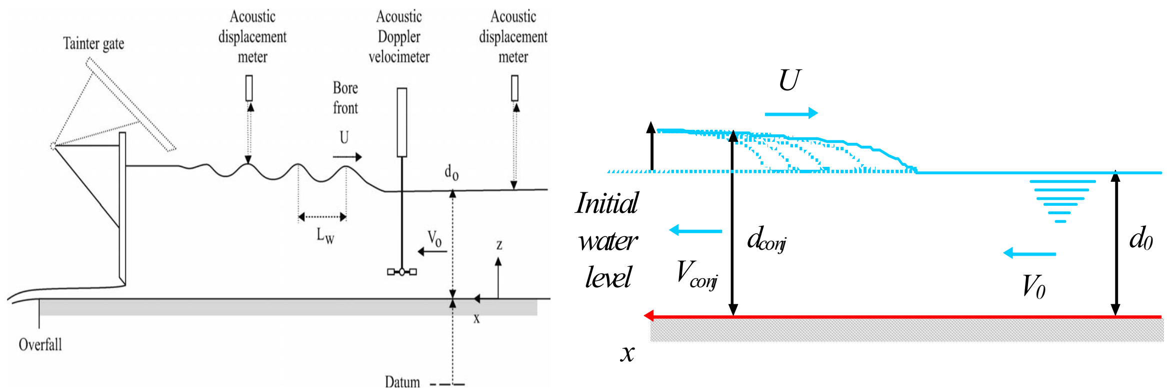

Figure 1 Definition sketch of a positive surge. Positive surge for an observer standing on the bank

ADV measurements are performed by measuring the velocity of particles in a remote sampling volume based upon the Doppler shift effect. An ADV system records simultaneously four values with each component of a sample: the velocity component, the signal strength value, the correlation value and the signal-to-noise ratio. Past and present experiences demonstrated many problems because the signal outputs combine the effects of velocity fluctuations, Doppler noise, signal aliasing, turbulent shear and other disturbances (Goring & Nikora, 2002; Chanson *et al.*, 2008). For all experiments, present experience demonstrated recurrent problems with the velocity data, including low correlations and low signal to noise ratios. The situation improved drastically by mixing some vegetable dye (Dytex Dye™ Ocean Blue) in the entire water recirculation system (Fig. 2).

The study of positive surges was conducted with one set of initial flow conditions (Table 1). The experimental setup was selected to generate both undular bores and breaking surges with the same initial conditions. The only dependant parameter was the downstream gate opening after closure. Steady gradually-varied flow conditions were established for at least 10 min prior to measurements and flow measurements data acquisition were started about 1.5 min prior to gate closure. A positive surge was generated by the rapid partial closure of the downstream gate. After closure the bore propagated upstream and each experiment was stopped when the bore front reached the intake structure. Six gate openings were considered (Table 1). Free-surfaces were studied by using acoustic displacement meters that were located at x=1.985 m, 2.995 m, 4 m, 5 m, 6 m, 9 m and 10.9 m downstream the channel intake. For two cases, detailed velocity measurements were also performed using the ADV at a distance x=5 m downstream of the channel intake and at y/W=0.5 (channel centerline), where W is the channel width. Note that in Table 1 h_g is the gate opening, the surge front celerity U and d_{conj} were calculated using the displacement meter data between x=6 m and 4 m. Also, d_0 was measured at x=5 m. Note that data for Run 60-6 and Run 60-7 refer to the average of 23 surges with the same gate opening but different vertical location of the ADV system.

Table 1 – Experimental flow conditions

Run	Q – m³/s	d_0 – m	h_g – m	Type	U – m/s	d_{conj} – m	Fr	Remarks
60-1	0.060	0.1387	0.050	Undular	0.783	0.216	1.413	No ADV
60-2	0.060	0.1396	0.040	Undular	0.857	0.228	1.466	No ADV
60-3	0.060	0.1396	0.025	Undular	0.875	0.231	1.483	No ADV
60-5	0.060	0.1403	0.010	Weak	0.946	0.242	1.536	No ADV
60-6	0.060	0.1369	0.005	Weak	0.911	0.238	1.543	No ADV
60-6	0.060	0.1429	0.005	Weak	0.918	0.237	1.484	ADV measurements
60-7	0.060	0.1427	0.100	Undular	0.519	0.171	1.149	ADV measurements

3. BASIC FLOW PATTERNS

The analysis of unsteady free-surface measurements revealed that for large gate openings, the surge propagation was relatively slow and the bore front was followed by a train of well-formed undulations, this is typical of an *undular surge*. At the lowest Froude number, i.e. Fr=1.15 (Run 60-7), the free-surface undulations had a ‘‘smooth’’ appearance and no wave breaking and no formed roller was observed (Fig. 2). However some cross-waves, or sidewall shock waves, were seen developing upstream of the first wave crest.

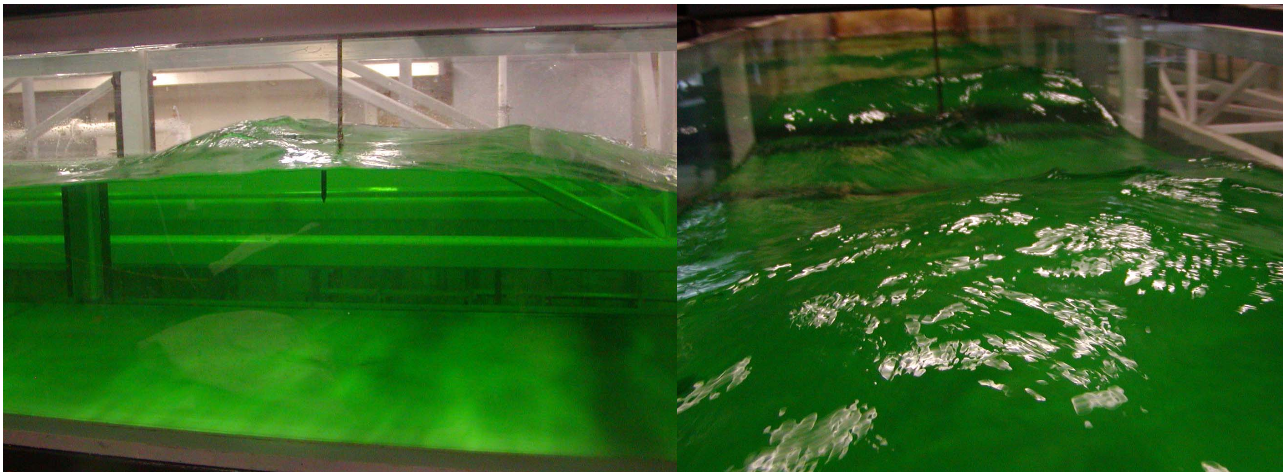

Figure 2 Undular surge, Run 60-7. Lateral view (left) and looking downstream at the incoming first wave crest (right)

For intermediate-surge Froude numbers, in the range from 1.3 to 1.45−1.5, some wave breaking was observed at the bore front and the ensuing free surface undulations were flatter. The surge front celerity was greater than that of non-breaking undular surges (Table 1, column 6). Above Fr=1.5, breaking (weak) surges were observed (Fig. 4). They propagated at a relatively faster speed, and the free-surface appeared to be quasi-two-dimensional, whereas previous studies demonstrated that undular surges have a three-dimensional flow structure (Koch & Chanson, 2009). Also, the bore front was associated with some air entrainment in the roller.

Typical instantaneous free-surface profiles are presented in Figs. 3 and 5. Each curve shows the instantaneous dimensionless flow depth d/d_0 over the dimensionless time from gate closure $t\times(g/d_0)^{0.5}$. Fig. 3 presents data for the undular surge (Run 60-7) at three locations, i.e. x=6 m, x=5 m and x=4 m. The intermediate was the location of the ADV system. The free-surface data showed a slight evolution of the positive surge shape as it propagated upstream. It is conceivable that the bore was not fully developed. However, the data tended to suggest a gentle reduction of the bore height with increasing distance from the downstream gate. This trend was consistent with a fully developed bore propagating against a non uniform gradually varied flow and with previous findings (Koch and Chanson, 2008).

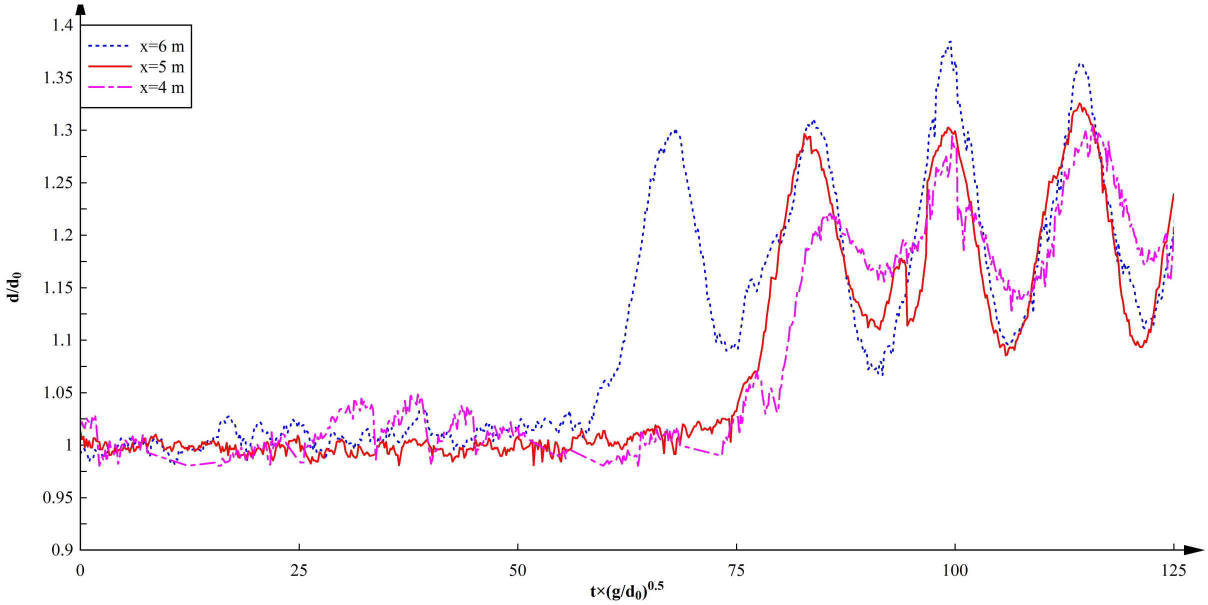

Figure 3 Undular surge, Run 60-7. Dimensionless instantaneous water depth d/d_0

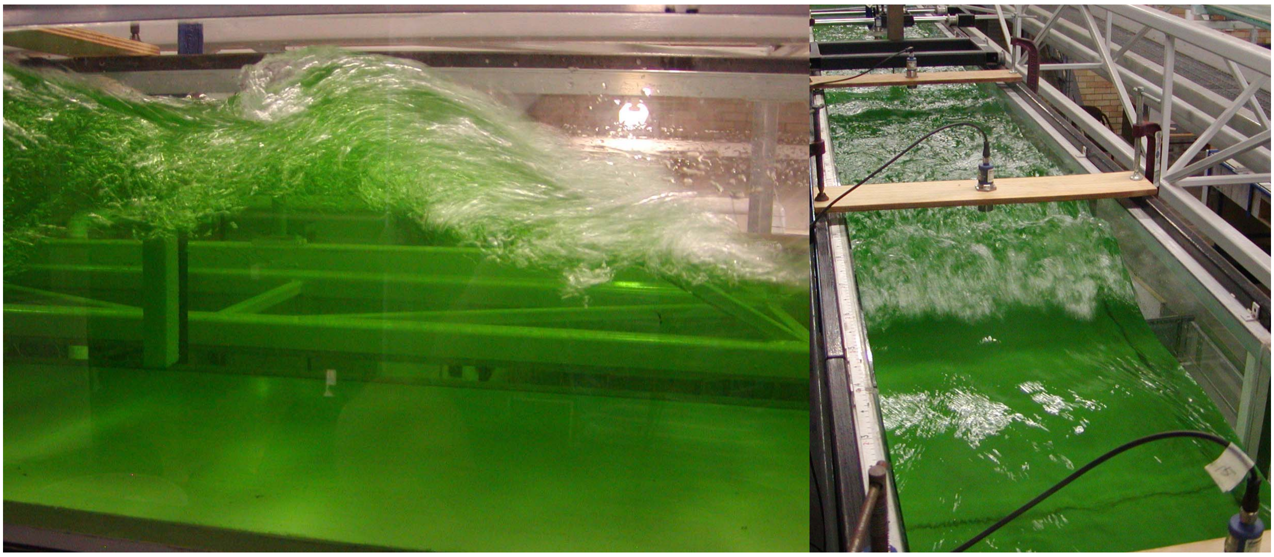

Figure 4 Breaking surge, Run 60-6. Lateral view (left) and looking downstream at the incoming wave crest (right)

Fig. 5 shows data for the weak surge (Run 60-6) at three locations, i.e. x=6 m, x=5 m and x=4 m. It can be observed that the maximum water depth was very similar in the three locations.

Both in Fig. 3 and 5, some spurious points and missing data could be noted. The acoustic displacement meter output was a function of the strength of the acoustic signal reflected by the free-surface. When the free-surface was not horizontal, some erroneous points were recorded. These were relatively isolated and easily ignored.

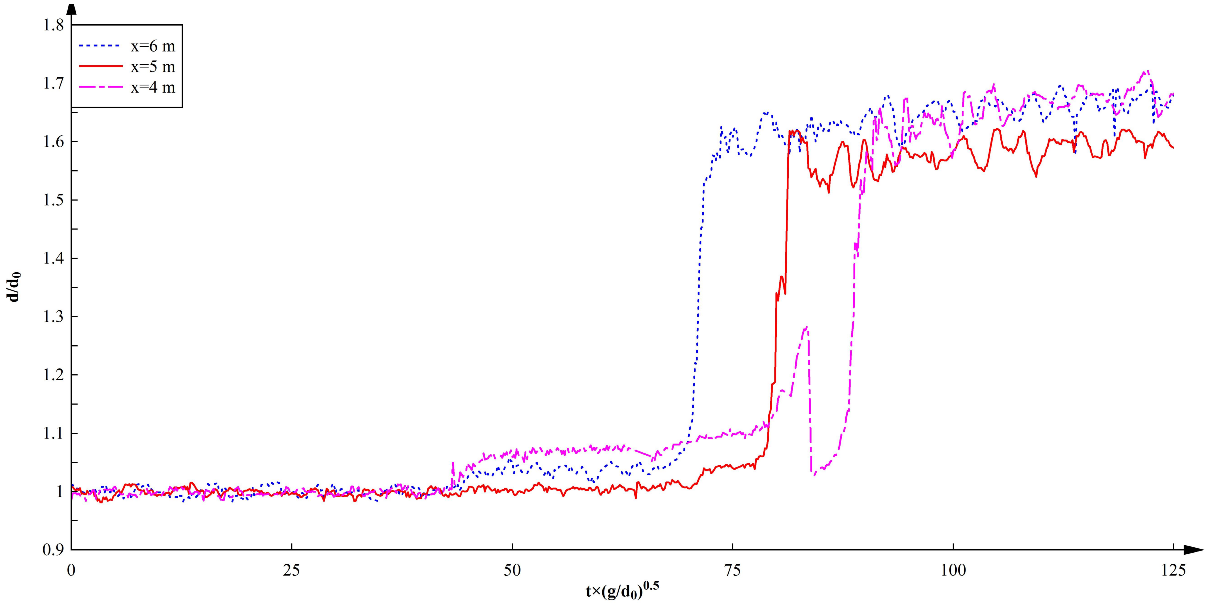

Figure 5 Breaking surge, Run 60-1. Dimensionless instantaneous water depth d/d_0

4. UNDULAR SURGES. COMPARISON WITH LITERATURE THEORIES

Several theoretical estimates of free-surface undulation characteristics were proposed including studies by Keulegan and Patterson (1940), Lemoine (1948), Tursonov (1969) and Andersen (1978). Lemoine (1948) assumed that the energy dissipation takes place by radiation of sinusoidal wave train, while Andersen's (1978) development is based upon a solution of the Boussinesq equation. These theories provide the amplitude a_w and the wave length L_w of the undular surge.

Fig. 6 compares data from Run 60-7 (23 data) with the theories of Keulegan and Patterson (1940), Lemoine (1948) and Andersen (1978) and with previous experimental data, such as those from Favre (1935), from Benet and Cunge (1971) man-made prototype channels, from Treske (1994) and from Koch and Chanson (2008). Some undular tidal bore observations in the river Dee, United Kingdom (Lewis, 1972) are also included. The data are presented as dimensionless quantities a_w/d_0 and L_w/d_0.

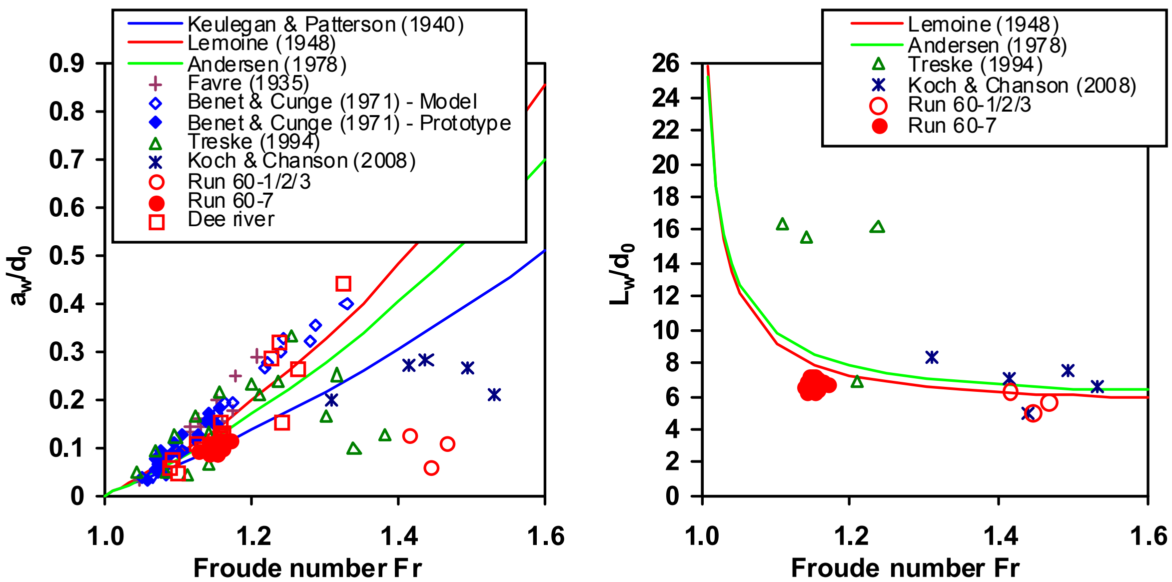

Figure 6 Dimensionless characteristics of undular bores. Wave amplitude (left) and length (right)

Fig.6 shows an excellent agreement between Run 60-7 data and previous both theoretical and experimental studies. Data for dimensionless wave amplitude were in the range from Anderson and Keulegan and Patterson theories. Also, dimensionless wave length L_w/d_0 were close to both Lemoine and Anderson theories. For larger Froude numbers, i.e. Run 60-1, 60-2 and 60-3, dimensionless wave length data were in agreement with both Lemoine and Andersen theories, while dimensionless wave amplitude data were lower than the theoretical. Overall, the entire data set, i.e. Run 60-7, Run 60-1, 60-2 and 60-3, followed the same trend of Treske and Koch and Chanson data, where wave amplitude decreased sharply immediately before the disappearance of free-surface undulations. It is believed that the flow conditions associated with maximum wave amplitude occurred immediately before the appearance of some wave breaking at the first wave crest (Koch and Chanson, 2008), i.e. for Fr in the range from 1.3 to 1.45−1.5 in the present study.

5. UNSTEADY FLOW FIELD IN THE SURGES. RESULTS AND DISCUSSION

In two flow conditions, some detailed velocity measurements were carried out beneath the bore front using the ADV system, which was located at x=5 m (Table 1). Each experiment was repeated to obtain velocity data at several vertical elevations, z.

Figs. 7 & 8 illustrate the effects of an undular and breaking bore, respectively, on the turbulent velocity field at two vertical elevations. Each graph presents the dimensionless velocities V_x/V^* and V_y/V^* and water depth d/d_0, where V^* is the shear velocity measured on the channel centerline in steady flows (V^*=0.0375 m/s). Note that the dimensionless time is zero 10.0 seconds prior to the first wave crest passage at the sampling location.

The analysis of experimental velocity data pointed out some basic flow features. In the undular surge, the streamwise velocity component decreased sharply with the passage of the first wave crest and oscillated with time with the same period as, but out of phase with, the free-surface undulations (Fig. 7). Maximum velocities were observed beneath the wave troughs and minimum velocities below the wave crests. The trend was seen at all vertical locations, and it was consistent with irrotational flow theory although the latter is based upon the assumption of frictionless fluid. It does not account for bed and sidewall friction, nor for the initial flow turbulence Note that the streamwise velocities were always positive. In the upper flow region, above z/d_0=0.50, large fluctuations of transverse, and to some extent longitudinal, velocity components were observed beneath the undulations (Fig. 7). Note that the velocity fluctuation measurements were only an Eulerian characterization of the flow at a fixed position in space. The measured fluctuations included the contributions of the velocity deviation from an ensemble average and the time variation of the ensemble average.

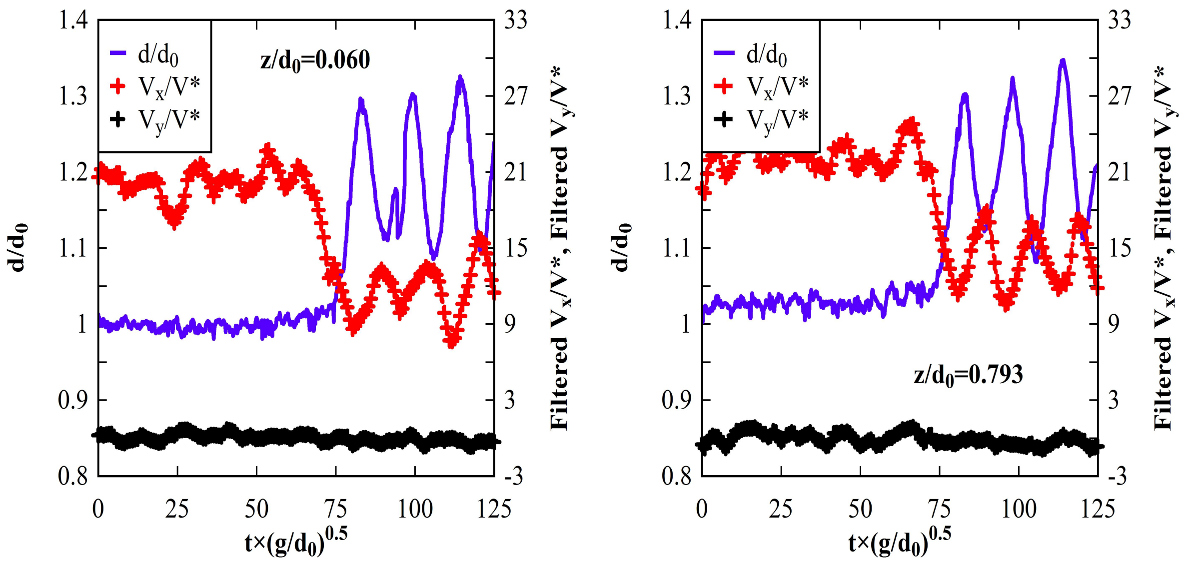

Figure 7 Undular surge, Run 60-7. Dimensionless instantaneous water depth d/d_0 and velocity components V_x/V^* and V_y/V^*. z/d_0=0.060 (left) and z/d_0=0.793 (right)

In the breaking surges, the longitudinal velocity component decreased rapidly with the passage of the surge front. The sudden increase in water depth yielded a slower flow motion to satisfy the conservation of mass (Fig. 8). Second, the velocity records showed some marked difference depending upon the vertical elevation *z* (Fig. 8). At the larger depth, i.e. z/d_0 > 0.3, the streamwise velocity component decreased rapidly at the surge front but remained positive beneath the roller toe. In contrast, for z/d_0 < 0.3, some negative V_x values were observed although for a short duration. The existence a sudden longitudinal flow reversal indicated unsteady flow separation beneath the surge front. Overall, these experimental results confirmed previous observation for both undular and breaking surges at lower flow rates (Koch & Chanson, 2008, 2009).

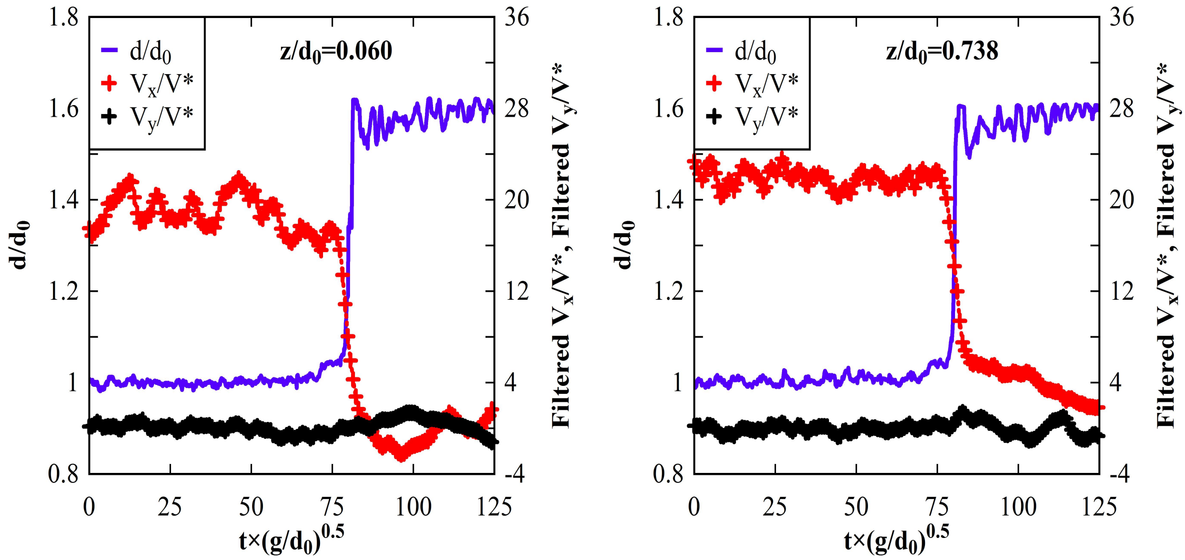

Figure 8 Breaking surge, Run 60-6. Dimensionless instantaneous water depth d/d_0 and velocity components V_x/V^* and V_y/V^*. z/d_0=0.060 (left) and z/d_0=0.738 (right)

6. CONCLUSION

This study presented some results of new experimental investigations conducted under controlled flow conditions in a large channel. Detailed turbulence measurements were performed with a high-temporal resolution (50 Hz) using side looking acoustic Doppler velocimetry and non-intrusive free surface measurement devices. Using one set of initial flow conditions, experiments were performed in positive surges resulting from a rapid gate closure at the downstream end of the flume and propagating upstream against the initial flow. The only dependant variable was the downstream gate opening after closure.

Two main types of positive surge were observed. At the lowest surge Froude numbers, i.e. *Fr*=1.15, the bore was an undular surge. The wave front was followed by a train of well-formed free surface undulations. Some breaking was seen at the first wave crest for *Fr* in the range from 1.4 to 1.5. For larger surge Froude numbers, i.e. *Fr* > 1.7, a weak breaking surge was observed. Analysis of undular free-surface profiles revealed a good agreement with previous both theoretical and experimental studies. Detailed instantaneous velocity measurements showed a marked effect of the surge passage. The longitudinal velocities were characterized by a rapid flow deceleration at all vertical elevations, and some flow reversal were measured next to the bed in the weak surge flow. After all, this study completed and confirmed the main results of previous experimental works carried out with lower flow rate.

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