TURBULENT SHEAR STRESSES IN HYDRAULIC JUMPS AND DECELERATING SURGES

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Abstract: In an open channel, a sudden rise in water level induces a positive surge. Once fully-developed, the surge becomes a hydraulic jump in translation. Herein unsteady turbulent shear stresses were measured during the translation of a fully-developed positive surge. New investigations were conducted in a large rectangular channel (12 m long, 0.5 m wide) and measurements were performed using acoustic Doppler velocimetry with a high temporal and spatial resolution (200 Hz sampling rate). Horizontal and adverse bed slope configurations were tested. In the latter, the surge decelerated until it became a stationary hydraulic jump.

Keywords: Hydraulic jumps, Positive surges, Turbulent shear stress, Sediment processes, Bed scour, Suspension, Decelerating surges.

INTRODUCTION

A hydraulic jump in translation results from a sudden change in flow that increases the depth. Called also a positive surge, it is the quasi-steady flow analogy of the stationary hydraulic jump (HENDERSON 1966). Positive surges were studied by hydraulicians and applied mathematicians for a few centuries. Pertinent reviews comprised BENJAMIN and LIGHTHILL (1954), CUNGE (2003) and CHANSON (2009a).

Although most studies considered horizontal channels, a wide range of practical applications encompasses hydraulic jumps propagating upstream on downward sloping channels: e.g., step pool channels during a flash flood, rejection surges in power canals serving hydro-power stations during sudden decrease in power output, swash runup against rundown on a beach slope. When a positive surge propagates upstream against a supercritical flow on a steep slope, the surge will progressively decelerate and becomes a stationary hydraulic jump. Recent findings hinted a major transformation of the turbulence field during the deceleration phase(s) (KOCH and CHANSON 2009).

In this study, turbulence measurements were performed in decelerating hydraulic jumps. The results are based upon a comparative analysis of the turbulence in fully-developed and decelerating positive surges. It is the aim of this work to gain a better understanding of decelerating surges and their slow transformation process into stationary hydraulic jumps.

EXPERIMENTAL APPARATUS AND INSTRUMENTATION

New experiments were performed in a 12 m long 0.5 m wide tilting flume. The flume had a smooth PVC bottom and glass walls. Comparative experiments were conducted with a horizontal bed (Series 1) and against a bed slope S_o set between 0.009 and 0.027 (Series 2) (Table 1).

In steady flows, the water depths were measured using rail mounted pointer gauges. The unsteady water depths were measured with a series of non-intrusive acoustic displacement meters Microsonic™. Pressure and velocity measurements in steady flows were performed with a Prandtl-Pitot tube (3.3 mm ∅). Instantaneous velocity measurements were conducted with an acoustic Doppler velocimeter Nortek™ Vectrino+ (Serial No. VNO 0436) equipped with a three-dimensional side-looking head. For each experiment, the velocity range was 1.0 m/s, the sampling rate was 200 Hz and the data accuracy was 1%. The translation of the ADV probes in the vertical direction was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit. Further details were reported in CHANSON (2008).

33rd IAHR Congress: Water Engineering for a Sustainable Environment

ISBN: 978-94-90365-01-1

Table 1- Experimental flow conditions

Reference (1)	S_o (2)	Q (m^3/s) (3)	d_o (m) (4)	Surge type at x = 5 m (5)	U (m/s) (6)	Fr (7)	Remarks (8)
Series 1	0	0.058	0.137	Undular to breaking	0.56 to 0.90	1.17 to 1.49	Smooth PVC bed. L = 12 m, B = 0.5 m.
Series 2	0.009 to 0.027	0.035 to 0.06	0.040 to 0.072	Decelerating: undular to breaking	0.002 to 0.22	1.71 to 2.83	Smooth PVC bed. L = 12 m, B = 0.5 m.

Notes: d_o: initial depth measured at x = 5 m; Fr: surge Froude number ($Fr = (V_o + U)/\sqrt{g \times d_o}$); Q: initial steady flow rate; S_o: bed slope; U: surge front celerity measured at x = 5 m.

Surge generation

A positive surge was generated by the sudden 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 to avoid wave reflection interference. For each experiment against an adverse slope, the initially steady flow was supercritical and the gradually-varied flow had a S2 profile (BRESSE 1860, HENDERSON 1966). After gate closure, the travelling jump propagated upstream against the supercritical flow (Fig. 1). For some experiment, the jump travelled the full channel length and the experiment was stopped when the bore reached the channel intake. In other tests, the surge front decelerated and stopped prior to the channel upstream end, and the data acquisition was conducted for up to 14 minutes after gate closure.
Turbulence measurements were conducted with one discharge (Q = 0.058 m^3/s) and two bed slopes (S_o = 0 & 0.0145). The ADV unit was located at x = 5 m, and the initial steady flow was partially-developed with $\delta/d_o = 0.3$ at the sampling location.

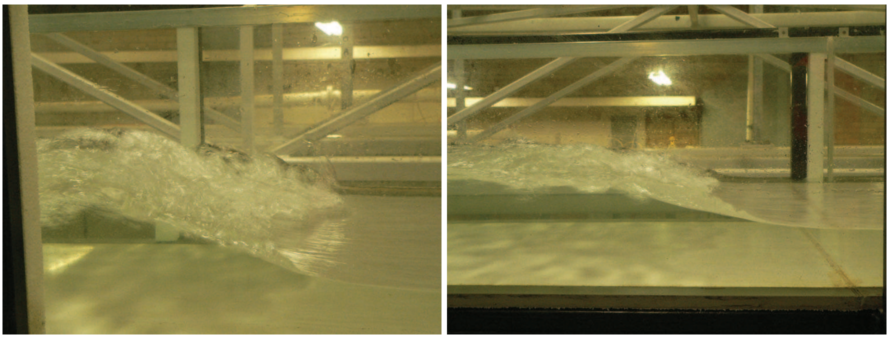
Reynolds stress estimates in rapidly-varied flow motion

The instantaneous turbulent velocity data were decomposed as: $v = V - \overline{V}$, where $\overline{V}$ is a variable-interval time average VITA (PIQUET 1999). A cutoff frequency must be selected such that the averaging time is greater than the characteristic period of fluctuations, and small with respect to the characteristic period for the time-evolution of the mean properties. During the undular surge flows, the Eulerian flow properties showed an oscillating pattern with a period of about 2 s that corresponded to the period of the free-surface undulations. Hence the unsteady data were filtered with a low/high-pass filter threshold greater than 0.5 Hz (i.e. 1/2 s^{-1}) and smaller than the Nyquist frequency (herein 100 Hz). Following KOCH and CHANSON (2008,2009), the cutoff frequency was deduced from a sensitivity analysis: F_{cutoff} = 1 Hz. The same filtering technique was applied to all velocity components for all experiments. Instantaneous Reynolds stresses were calculated from the high-pass filtered signals.

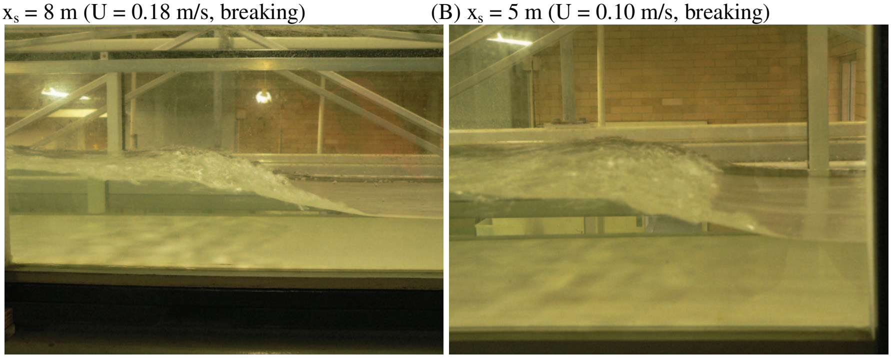
HYDRAULIC JUMP PROPAGATION AND FLOW PATTERNS

On the horizontal slope, the positive surges were fully-developed and visual observations indicated several types of hydraulic jumps in translation: an undular (non-breaking) bore for Froude numbers Fr less than 1.3, an undular surge with some slight breaking for Froude numbers between 1.3 and 1.45, and a breaking jump with a marked roller for Froude number greater than 1.45.
On a steep slope, the positive surge was generated by the rapid closure of the gate at the downstream end of the channel, and the breaking surge propagated against the supercritical flow. Its shape evolved progressively and the surge front speed decreased with increasing time. Figure 1 presents an example with several photographs. The figure caption includes the

location of the jump x_s from the upstream channel end and the surge front celerity U. In some experiments, the surge remained a breaking bore. In others, the surge front transformed progressively into an undular bore. During some experiments, the surge front travelled up to the upstream intake structure. For others, the positive surge became arrested before the channel upstream end and the bore transformed into a stationary hydraulic jump. In some experiments, the shape of the surge changed from a breaking bore into an undular surge, before becoming a stationary undular hydraulic jump. During others, the bore remained a breaking surge until it became a stationary hydraulic jump with a roller.



(A) x_s = 8 m (U = 0.18 m/s, breaking) (B) x_s = 5 m (U = 0.10 m/s, breaking)

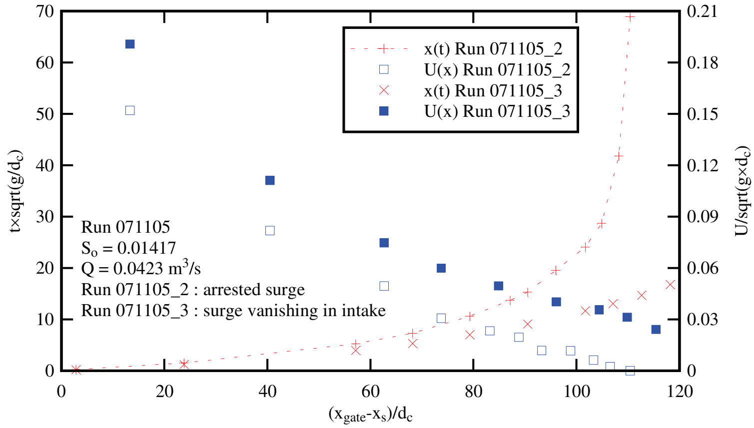


(C) x_s = 3 m (U = 0.075 m/s, breaking) (D) x_s = 1 m (U = 0.05 m/s, breaking)

Fig. 1 - Photographs of a decelerating surge fronts against a steep slope: S_o = 0.00943, Q = 0.0354 m^3/s, d_o = 0.0538m

The observations of the hydraulic jump propagation showed consistently an initial rapid deceleration of the front until the surge leading edge progressed at a very slow pace (1 to 10 mm/s). Ultimately the surge became arrested after a long time. Figure 2 presents some dimensionless graphs with the dimensionless time $t \times \sqrt{g / d_c}$ as a function of the dimensionless distance from the gate $(x_{gate}-x_s)/d_c$ and of the dimensionless surge front celerity $U / \sqrt{g \times d_c}$ as a function of $(x_{gate}-x_s)/d_c$. Herein d_c is the critical flow depth of the initially steady flow: $d_c = \sqrt[3]{Q^2 /(g \times B^2)}$ where Q is the steady flow rate, g is the gravity acceleration and B is the channel width. Figure 2 shows in particular a comparison between an experiment with an arrested surge (run 071105_02) and a non-arrested surge (run 071105_03). (A non-arrested surge propagated all along the channel and entered into the intake structure.) The experimental observations highlighted that the transformation from a positive surge into a stationary hydraulic jump was a very slow process, taking anywhere between 5 to 12 minutes. These observations were consistent with the anecdotal observations of CHANSON (1995) in a 0.25 m wide 20 m long channel.

Importantly, qualitative and quantitative experiments emphasised the complicated transformation of a positive surge into an arrested surge (i.e. stationary hydraulic jump). The process time scale was about 300-600 s (5 to 10 min.). During the decelerating stage, the surge might evolve from a breaking bore to an undular (non-breaking) surge. The change would be very gradual and the evolution time scale was a minute to a few minutes.



Run	S_o	Q (m^3/s)	h (m)	Type
071105_02	0.01417	0.0423	0.065	Arrested
071105_03			0.060	Non-arrested

Fig. 2 - Dimensionless surge front position $(x_{gate}-x_s)/d_c$ and celerity $U/\sqrt{g \times d_c}$ for arrested and non-arrested decelerating surges (Exp. Series 2)

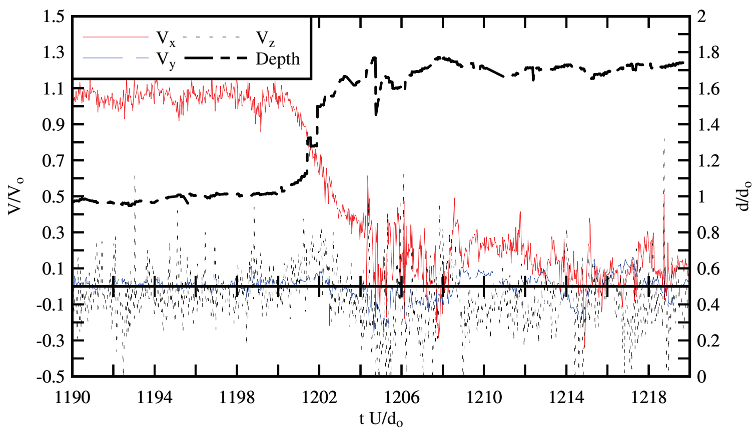


Fig. 3 - Dimensionless instantaneous velocity components beneath a breaking bore on a smooth horizontal invert: d_o = 0.1388 m, V_o = 0.832 m/s, U = 0.903 m/s, Fr = 1.50, S_o = 0, z/d_o = 0.762 (Exp. Series 1)

TURBULENT VELOCITY MEASUREMENTS

On the horizontal slope, the turbulent velocity measurements highlighted a rapid flow deceleration during the jump passage associated with large turbulent fluctuations afterwards. The longitudinal velocity component decreased rapidly when the bore front passed above the sampling volume (Fig. 3). The measurements showed consistently some differences in velocity redistributions between the undular and breaking surges that were consistent with the earlier findings of KOCH and CHANSON (2009). When the undular bore passed above the ADV control volume, a relatively gentle longitudinal flow deceleration was noted at all vertical elevations. V_x was minimum beneath the first wave crest and oscillated afterwards with the same period as the surface undulations and out of phase. The vertical velocity V_z presented a similar oscillating pattern beneath the free-surface undulations with the same periodicity, but out of phase. Such a pattern can be predicted by ideal-fluid flow theory (LIGGETT 1994, CHANSON 2009b).

The breaking surge exhibited in contrast a marked roller and a sharp flow depth discontinuity. The free-surface elevation curved upwards immediately prior to the roller. This is illustrated in Figure 3 for $1199 < t \times U/d_o < 1201$. The velocity data showed some distinct redistribution patterns depending upon the vertical elevation z/d_o. For $z/d_o > 0.5$, V_x decreased rapidly at the surge front although the longitudinal velocity data tended to remain positive beneath the roller. For $z/d_o < 0.2$, the longitudinal velocity became negative although for a short duration. Such flow feature was first reported by KOCH and CHANSON (2009).

Positive surge propagating against an adverse steep slope

The velocity measurements in a positive surge advancing against an adverse sloping surge were conducted for $z/d_o < 0.7$ only because the ADV head could not be placed at higher sampling locations without interfering with the free-surface. Typical measurements are presented in Figure 4. For the experiment shown in Figure 4, the arrested surge became a stationary hydraulic jump at $x_s = 2.65$ m about 330 s (6.5 minutes) after the gate closure. In Figure 4, the data were collected at x = 5 m and spanned between t = 75 s and 115 s after the gate closure. At $t \times U/d_o = 70$ (i.e. t = 115 s), the surge front was located at $x_s = 4.3$ m.

The experimental observations demonstrated that the bore propagation was a slow turbulent process. At x = 5 m, the surge front celerity was 27 times slower than that of the experiment shown in Figure 3. As a result, the velocity data exhibited a gentle deceleration when the bore passed the sampling location. Interestingly the longitudinal velocity component remained positive at all times and at all vertical elevations. In the upper flow region ($z/d_o > 0.3$), the V_x data showed some long-period oscillations with a period of about 2 s. These are seen in Figure 4 for $54 < t \times U/d_o < 60$. The oscillations were caused by the growth, advection, and pairing of large-scale vortices in the developing shear layer of the surge roller. This was also observed in stationary hydraulic jumps. The pulsation frequency F of the longitudinal velocity gave a Strouhal number $F \times d_o/V_o = 0.021$ that was close to classical hydraulic jump data (LONG et al. 1991, MURZYN and CHANSON 2007, CHANSON and GUALTIERI 2008).

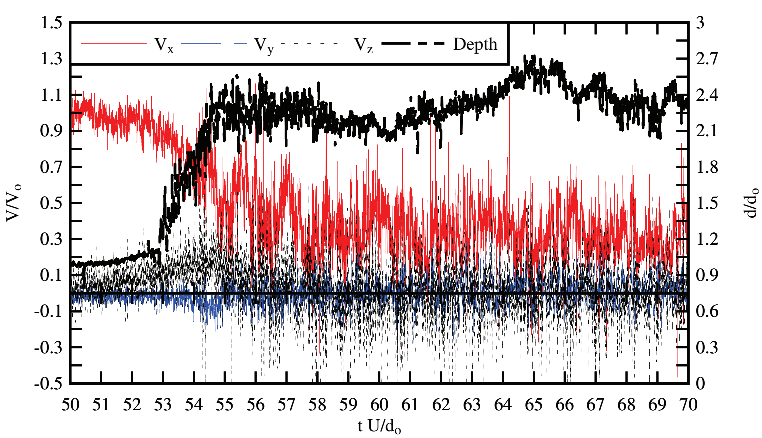


Fig. 4 - Dimensionless instantaneous velocity components beneath a positive surge advancing against a

steep slope: d_o = 0.0701 m, V_o = 1.641 m/s, U = 0.034 m/s, Fr = 2.02, S_o = 0.0145, z/d_o = 0.653 (Exp. Series 2)

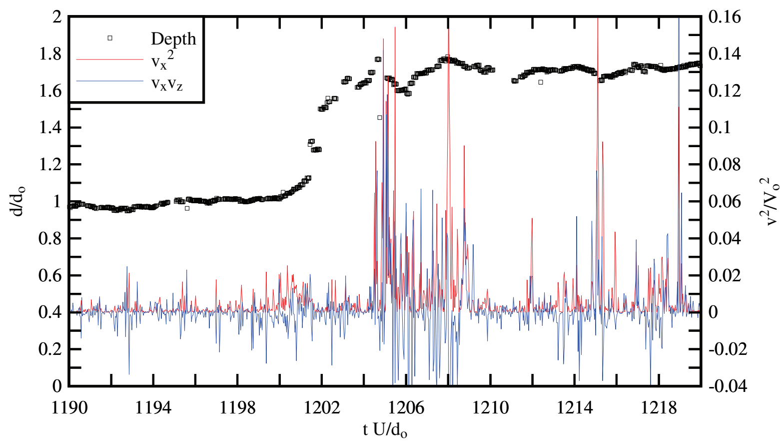
TURBULENT STRESSES IN HYDRAULIC JUMPS IN TRANSLATION

During the surge passage, the unsteady flow field was associated with large fluctuations in Reynolds stresses (Fig. 5). Figures 5A and 5B present some unsteady Reynolds stress data beneath a tidal bore propagating in a horizontal and sloping channel respectively. In each figure, the graph presents the time-variation of the dimensionless Reynolds stresses v_x^2/V_o^2 and $v_x \times v_z/V_o^2$, and water depth d/d_o, where v is the turbulent velocity, the subscripts x and z refer respectively to the longitudinal and vertical velocity components. Table 2 summarises the range of Reynolds stress fluctuations.

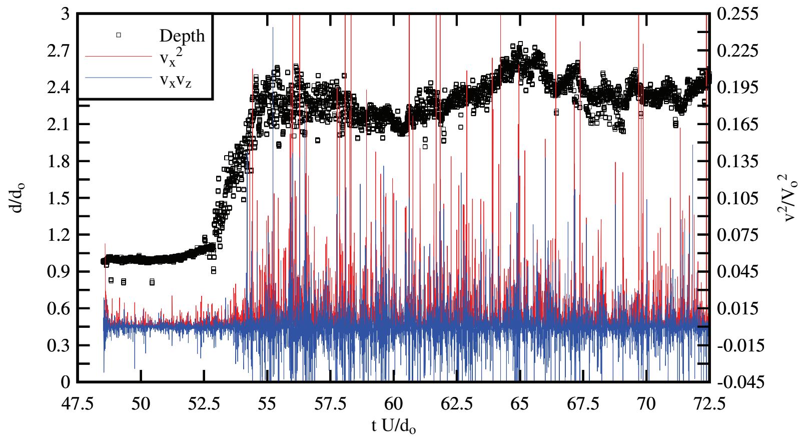
The experimental measurements indicated systematically large, fluctuating turbulent stresses below the bore front and in the flow behind the surge front. The finding was observed for both undular and breaking surges. The Reynolds stress levels were significantly larger than before the surge passage, and substantial normal and tangential stress fluctuations were observed. In the breaking surge, large shear stress levels and fluctuations were observed in particular for $z/d_o > 0.5$. It is believed that these were caused by the proximity of the developing mixing layer of the roller. A comparison between undular and breaking surges showed that (a) the magnitude of the turbulent stresses was comparable for both undular (non-breaking) and breaking bores (Table 2), and (b) the large fluctuations in Reynolds stresses lasted for a significantly longer period beneath the undular bore.

Table 2 - Experimental observations: range of Reynolds stress fluctuations

Slope (1)	Fr (2)	Surge type (3)	z/d_o (4)	v_x^2/V_o^2 (5)	v_y^2/V_o^2 (6)	v_z^2/V_o^2 (7)	v_xv_z/V_o^2 (6)	v_xv_y/V_o^2 (7)	v_yv_z/V_o^2 (8)
0	1,17	Undular	0.15	0-0.04	0-0.015	0-0.05	±0.02	±0.01	±0.015
			0.76	0-0.025	0-0.01	0-0.06	±0.02	±0.008	±0.01
0	1.50	Breaking	0.15	0-0.04	0-0.015	0-0.06	±0.02	±0.015	±0.015
			0.76	0-0.07	0-0.015	0-0.1	±0.03	±0.012	±0.015
0.0145	2.02	Breaking	0.15	0-0.08	0-0.03	0-0.15	±0.04	±0.03	±0.035
			0.65	0-0.07	0-0.03	0-0.2	±0.04	±0.025	±0.025



(A) On a smooth horizontal invert: d_o = 0.1388 m, V_o = 0.832 m/s, U = 0.903 m/s, Fr = 1.50, S_o = 0, z/d_o = 0.762 (Exp. Series 1)



(B) Against a steep slope: d_o = 0.0701 m, V_o = 1.641 m/s, U = 0.034 m/s, Fr = 2.02, S_o = 0.0145, z/d_o = 0.653 (Exp. Series 2)

Fig. 5 - Dimensionless instantaneous turbulent stresses v_x^2/V_o^2 and $v_x \times v_z/V_o^2$ beneath a breaking bore

Turbulent stresses beneath a decelerating surge

In a decelerating surge, the flow field changed very progressively from a positive surge into a stationary hydraulic jump. The turbulent stress data (Fig. 5B) highlighted some large stress levels and fluctuations when the ADV sampling volume was in the "wake" of the roller mixing layer. With increasing time, the levels of shear stresses and shear stress fluctuations tended to decrease slightly.

A comparative analysis between a decelerating surge and a stationary jump highlighted marked differences (Fig. 6). Figure 6 presents the vertical distributions of time-averaged turbulent stresses calculated for the first 2,000 samples beneath the breaking roller (10 s record). The results are compared with the stationary hydraulic jump data of LIU (2004). Both experiments were performed with similar flow conditions: a weak hydraulic jump with roller with similar Froude number and inflow depth. The comparison suggested higher turbulence levels in the decelerating surge, especially in the lower flow region (z/d_o < 0.4 to 0.5) (Fig. 6).

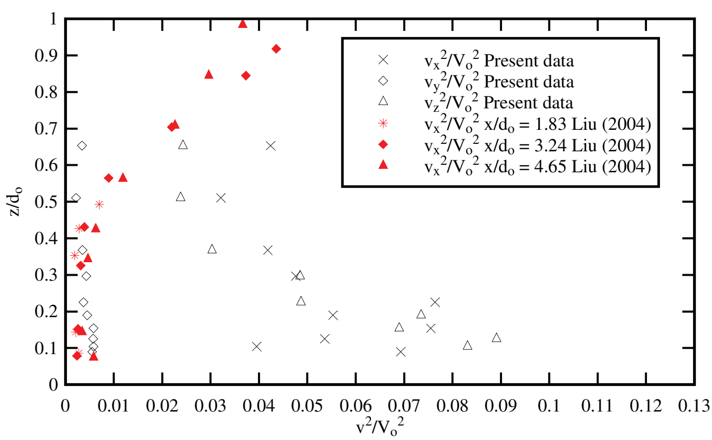


Fig. 6 - Dimensionless time-averaged normal stresses in decelerating jump: Fr = 2.02, d_o = 0.0701 m, x = 5 m, S_o = 0.0145 - Comparison with stationary hydraulic jump data: Fr = 2.0, d_o = 0.071 m, x = 0, 0.13 m, 0.23 m and 0.33 m downstream of toe (LIU 2004)

CONCLUSION

Detailed turbulent measurements wee conducted in hydraulic jumps in translation and decelerating surges. The turbulent Reynolds stresses were deduced from high-pass filtered data using the technique of KOCH and CHANSON (2008,2009). The results highlighted large turbulent stresses and turbulent stress fluctuations beneath the jumps. In a breaking jump, large turbulent stresses were observed next to the shear zone in a region of high velocity gradients. In an undular bore, large velocity fluctuations and Reynolds stresses were recorded beneath the first wave crest and the secondary waves (free-surface undulations).

The present experimental data demonstrated intense turbulent mixing beneath the jump front and the roller for all experiments. Quantitatively, the levels of turbulent stresses were one to two orders of magnitude larger than the critical threshold for sediment motion, in terms of both bed load and suspension. The experiments showed further the complicated transformation of a hydraulic jump in translation into a stationary hydraulic jump on a steep slope. The entire process was very slow and the turbulent velocity field in the decelerating surge presented turbulent characteristics that were closer to those of a stationary hydraulic jump than of a fully-developed surge, despite a few key differences (Fig. 6).

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