Canadian Journal of Civil Engineering

Physical Modeling of Vanishing Bores in Open-Channel Flows

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2020-0419.R1
Manuscript Type:	Technical Note
Date Submitted by the Author:	15-Feb-2021
Complete List of Authors:	Li, Youkai; The University of Queensland, School of Civil Engineering Chanson, Hubert; The University of Queensland, School of Civil Engineering
Keyword:	tidal bore, open channel flow, vanishing process, physical modeling
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Physical Modeling of Vanishing Bores in Open-Channel Flows

Youkai LI^{a*} and Hubert CHANSON^a

^a*The University of Queensland, School of Civil Engineering, Brisbane, QLD 4072, Australia*

*Corresponding author yukai.li@uqconnect.edu.au

ORCID: Youkai Li 0000-0002-4281-5457

Hubert Chanson 0000-0002-2016-9650

This manuscript is derived from the PhD thesis of Youkai LI.

Li, Youkai (2020). *Hydrodynamics of tidal bores: turbulent propagation and sediment transport*. PhD thesis, School of Civil Engineering, The University of Queensland.
<https://doi.org/10.14264/uql.2020.671>

Draft

Physical Modeling of Vanishing Bores in Open-Channel Flows

Abstract

When an undular bore is propagating upstream against a subcritical flow in a flat channel, its leading front may weaken and vanish. The present study physically investigated the whole decaying process of vanishing bores in a relatively large facility. The invert was made of mobile or fixed natural river gravels. Detailed sampling of water surface elevations and velocities was performed in combination with high-resolution photo and video recordings. Despite some increased turbulence characteristics linked to the bore front arrival, no sediment motion was observed underneath the vanishing bores. The quantitative results provide a unique benchmark data set for further study of the later-stage bore propagations.

Keywords: tidal bore; open channel flow; vanishing process; physical modeling

1. Introduction

A bore or positive surge is a travelling hydraulic jump in an open channel. Relevant natural and artificial processes encompass tsunami-induced bores (St-Germain et al. 2014), storm-surge-induced bores (Murty et al. 1986), wave run-ups in swash zones (Kobayashi and Johnson 2001), positive surges produced by sudden gate operation in open channels like navigation canals and hydro-power canals (Treske 1994), as well as tide-induced processes in natural estuaries - tidal bores [Figure 1 and Chanson (2011a)]. In a rectangular channel, the shape of a bore propagating upstream is intrinsically related to its bore Froude number Fr_1 :

$$Fr_1 = \frac{V_1 + U}{\sqrt{g \times d_1}} = Fr_0 + \frac{U}{\sqrt{g \times d_1}}, \quad (1)$$

where V_1 is the magnitude of bulk velocity of the steady inflow towards downstream and U represents the magnitude of bore travelling speed towards upstream (relative to an observer standing on the riverbank near the bore front), d_1 denotes the initial water depth, g is the gravitational acceleration, and $Fr_0 = V_1/\sqrt{g \times d_1}$ characterises the Froude number of the initially steady inflow.

When a bore propagates upstream against a supercritical inflow in a sloping open channel, it may decelerate and evolve into a stationary hydraulic jump, i.e. an arrested bore (Chanson 2011b; Li and Chanson 2018; Viero et al. 2017). During the whole transforming process, the bore Froude number progressively decreases but remains larger than unity. On the other hand, when a relatively weak bore propagates against a subcritical inflow, the height of the bore front may gradually decrease to zero and the bore vanishes. The vanishing bore processes can commonly be observed at the final stage of decaying tidal bore, e.g. the Qiantang Bore near Wenyan (Zeng et al. 2017). However, the hydrodynamics of vanishing bores still remain rarely studied by physical modeling, because of the challenges to achieve well-controlled and repeatable flow conditions. A few analytical studies proposed models to describe the positive surges propagating in rectangular channels within simplified assumptions (Li et al. 2017; Viero et al. 2017). These models were compared to limited free-surface observations in laboratory flumes, mostly focused on the early stage of bore formation and propagation, and the last phase of bore vanishing was not physically recorded.

The current study investigates the vanishing bore process from the generation to the disappearance, based upon laboratory experiments in a facility of relatively large size. It is the aim of this study to document in details the free-surface and velocity characteristics, under carefully-controlled flow conditions. This study was part of the PhD project of Li (2020).

2. Experimental setup

The physical modeling was performed in a 15 m long and 0.5 m wide rectangular tilting channel with transparent tempered glass sidewalls and a PVC bed (**Figure 2**), previously used by Li and Chanson (2018). Herein, the channel bed was smooth for $x < 1.50$ m and $x > 13.0$ m, where x indicated the longitudinal distance measured from the upstream end of the test section. For $1.50 \text{ m} < x < 13.0 \text{ m}$, the bed consisted of natural river pebbles sieved between 6.7 mm and 9.5 mm, which provided relatively larger flow resistance and maintained the subcritical flow regime through this section to ensure the occurrence of vanishing bores. During the first series of experiments, the pebbles were mobile (i.e. free to move), initially distributed randomly and compacted using a screed (Experiment VB1). In the second series, the same gravel bed was sprayed with some very-thin protective coating (NanoProtect SC-96, < 0.1 mm), which created a fixed gravel invert (Experiment VB2). The channel slope was $S_o = 0.0068$ for both Experiments VB1 and VB2.

The two series of experiments were conducted under similar flow conditions with a discharge $Q = 0.039 \text{ m}^3/\text{s}$, except for different bed gravel configurations (Tables 1 and 2). The discharge was measured by an on-site calibrated Venturi flowmeter with the accuracy of $10^{-4} \text{ m}^3/\text{s}$. In Experiment VB1, the initially steady flow induced some pebble sorting and a limited amount of downstream-moving loose gravels: that is, the bed was slightly water-worked. In Experiment VB2, no pebble motion occurred. The initial inflow was subcritical through the whole mobile/fixed gravel bed section (Table 1). On the mobile gravel bed, the initial flow had a slightly higher Froude number than on the fixed gravel bed at all sampling locations. This should be linked to the slightly organized bed roughness in Experiment VB1 due to water-work. The bores were generated by suddenly closing the Tainter gate in less than 0.2 s with a gap below ($h > 0$ as illustrated in **Figure 2**). The overall unsteady flow conditions are summarised in Table 2.

Twelve acoustic displacement meters (ADMs) Microsonic® Mic+25/IU/TC were installed above the channel centerline at different longitudinal locations, recording the instantaneous free-surface elevations with the error less than 0.1 mm. An acoustic Doppler velocimetry (ADV) Nortek™ Vectrino+ was installed at $x = 7$ m, measuring the instantaneous velocity (**Figure 2**). The accuracy of flow velocity measurements was $\pm 1\%$ of measured value ± 1 mm/s. The measurements of the instantaneous free-surface elevations and flow velocities were performed simultaneously with a sampling rate of 200 Hz. For a given set of flow conditions, the experiment was repeated 25 times to enable some ensemble analysis.

3. Basic flow patterns: bore propagation and transformation

For the two different sets of bore experiments, visual observation and video camera recording showed a comparable bore shape and vanishing process. The bore was slightly breaking after generation and it immediately became an undular bore with a smooth front when it reached the gravel bed section: (**Figure 3a**). The bore Froude number was close to unity ($1 < Fr_1 < 1.1$) when travelling on the gravel bed. The decelerating undular bore was relatively weak and followed by a train of secondary undulations (**Figure 3b**). The passage of the decelerating undular bore did not set any pebbles into upstream motion on the mobile gravel bed (Experiment VB1). Similar to the arrested bore experiments (Li and Chanson 2018), the bore deceleration and weakening were associated with a reduction of front height with further distance travelled upstream. However, the decelerating undular bore did not stop propagating upstream on the gravel bed in the current experiments. Instead, the bore front height gradually reduced towards zero and the secondary waves disappeared as the bore front vanished (**Figure 3c**).

4. Ensemble-statistical measurements

4.1 Free-surface measurements

Some typical dataset of ensemble-median free-surface elevations d_{50} and instantaneous free-surface fluctuations d_{75-25} at different longitudinal locations are presented in **Figure 4**. Herein, d_{75-25} is the difference between the 75th and 25th percentiles of the free-surface elevation ensembles, and characterises the instantaneous free-surface fluctuations. The time $t = 0$ indicates the sudden closure of the Tainter gate, i.e. the time of bore generation.

As the bore propagated upstream from $x = 12$ m to $x = 3$ m, its leading edge gradually lost strength with a reduced front height. Meanwhile, the secondary wave train became barely visible (**Figure 4a**). The bore-induced instantaneous free-surface fluctuations d_{75-25} showed overall smaller peak values at the further upstream locations (**Figure 4b**). Particularly at $x = 3$ m, the bore front was nearly flat and quasi-steady with d_{75-25} less than 1 mm. All data highlighted the decreasing strength of the bore with increasing distance from the gate. When the bore reached $x = 4$ m at the dimensionless time of about 325, there was basically no secondary undulation behind the leading edge. The free-surface downstream of the bore was nearly horizontal, comparable to an M1 backwater surface profile. Such a phenomenon may also be predicted by numerically and analytically (Li et al. 2017; Viero et al. 2017). For $x < 4$ m, the decelerating bore profile became a connection between two nearly-straight free-surface sections downstream and upstream of the “bore front”. This is the vanishing bore illustrated in **Figure 3c**, and its Froude number was close to unity. The shape of the vanishing bore was very similar to the flat gentle surge observed during a 2012 field study of the Garonne River tidal bore (Reungoat et al. 2014).

4.2 Velocity measurements

Typical ensemble-averaged analysis was also conducted, in terms of the median velocity components $(V_i)_{50}$ and the instantaneous velocity fluctuations $(V_i)_{75-25}$ with $i = x, y$ or z . $(V_i)_{75-25}$ is the difference between the 75th and 25th percentiles of the instantaneous velocity ensembles. The presentation of velocity dataset is included in the supplementary material **Digital Appendix A**. The ensemble-median water depth d_{50} is shown to indicate the passage of the bore at the velocity measurement location.

In line with previous bore experiments (Chanson 2011b; Chanson and Docherty 2012; Li and Chanson 2018), the ensemble-median longitudinal velocity component $(V_x)_{50}$ experienced a deceleration at all different vertical elevations when the bore passed the ADV location (**Figure 5**). No flow reversal next to the channel bed was observed during bore passage in the current physical modelling, in contrast to some field work (Reungoat et al. 2014) and numerical simulation (Leng 2018; Lubin et al. 2010; Simon 2014). The instantaneous longitudinal velocity fluctuations $(V_x)_{75-25}$ were slightly affected by the bore arrival and the near-bottom region experienced a rapid response, reaching a peak immediately after the bore front. The near-surface region presented some enlarged $(V_x)_{75-25}$ values with some slight delay. In the 2012 field study in the Garonne River (Reungoat et al. 2014), the flat undular bore ($Fr_1 = 1.02$) induced a different change in streamwise velocity: the surface velocity experienced a delayed reversal about 50 s after the bore front.

The transverse velocity data $(V_y)_{50}$ was basically not affected by the bore arrival and oscillated about zero with the passage of the bore. The instantaneous transverse velocity fluctuations $(V_y)_{75-25}$ showed some slightly increased disturbance from bottom to surface. The vertical velocity component did not experience any evident change with the bore arrival. Compared to the flat undular bore ($Fr_1 = 1.02$) documented by Reungoat et al. (2014), the current vanishing

bore experiments did not show any major changes to the transverse and vertical velocity components¹.

4.3 Reynolds stress data

In turbulent flows, the Reynolds stress tensor $\tau_{ij} = -\rho \overline{v_i v_j}$ ($i, j = x, y, z$) characterises the shear stress on the surface area $dx \times dy$, $dy \times dz$ or $dz \times dx$ of a basic control volume $dx \times dy \times dz$, where ρ indicates the fluid density and v is the turbulent velocity fluctuation (Chanson and Docherty 2012; Piquet 1999). For a rapidly-varied flow, its instantaneous velocity fluctuation can be calculated as $v = V - V_{50}$, where V is the instantaneous velocity and V_{50} is the ensemble-median of V (Bradshaw 1971; Chanson and Docherty 2012). Based on the ensemble turbulent velocity measurements, the normal Reynolds stresses $v_x \times v_x$, $v_y \times v_y$, $v_z \times v_z$ and tangential Reynolds stresses $v_x \times v_y$, $v_y \times v_z$, $v_z \times v_x$ were derived. The data of dimensionless ensemble-median Reynolds stresses and their quartile analysis results in terms of $v_x \times v_x$, $v_z \times v_z$ and $v_z \times v_x$ are illustrated in the supplementary material **Digital Appendix A**.

The normal stress $v_x \times v_x$ experienced some weak peak values with the bore arrival at all three vertical elevations (**Figure 6**), and the third quartile data represented some characteristic larger values. In the near-bottom region, $(v_x \times v_x)_{50}$ and $(v_x \times v_x)_{75}$ were relatively smaller after the bore front passage, in comparison to those in the initially steady flow. In the near-surface area, some large values of $(v_x \times v_x)_{50}$ and $(v_x \times v_x)_{75}$ were also seen during the secondary undulations after the bore front passage.

The data of $v_z \times v_z$ and $v_z \times v_x$ exhibited similar patterns in the near-surface and near-bottom elevations, although the magnitudes of the data might be unreliable because of the noise of instantaneous vertical velocity data².

¹ See **Figure A-1** in **Digital Appendix A**.

² See **Figures A-2** and **A-3** in **Digital Appendix A**.

5. Conclusion and future work

The vanishing process of bores and positive surges in subcritical open-channel flows were modeled by laboratory experiments in a facility of relatively large size. Visual observations of the bore shape transformation were recorded and quantitative measurements were performed in terms of free-surface elevations and unsteady velocities, under well-controlled flow conditions.

During the upstream propagation of a weak undular bore against a subcritical inflow, the height of the leading front decreased with time until it vanished. At the late stage, the bore Froude number was close to unity and the bore profile was nearly flat. Despite the weak strength, some increase of turbulence characteristics was still linked to the passage of bore front, i.e. free-surface fluctuations, velocity fluctuations and Reynolds stresses.

The current study provides a benchmark dataset for theoretical and numerical models of bores and surges at the decaying stage. Further research may be extended to the whole flow field variations underneath vanishing bores, as well as different boundary conditions, although great care is required to reproduce the vanishing bores systematically.

Acknowledgement

The authors acknowledge the technical assistance of Jason Van Der Gevel and Matthews Stewart (The University of Queensland). The helpful discussions with Dr Xinqian (Sophia) Leng are acknowledged. The first author is grateful to China Scholarship Council for the financial support during his PhD study at The University of Queensland, Australia.

Disclosure statement

No potential conflict of interest is reported by the authors.

Funding

This work was supported by the Australian Research Council (DP120100481).

References

- Bradshaw, P. 1971. An introduction to turbulence and its measurement. Pergamon, Oxford, UK. doi:10.1016/C2013-0-02451-6.
- Chanson, H. 2011a. Tidal bores, aegir, eagre, mascaret, pororoca: Theory and observations. World Scientific, Singapore. doi: 10.1142/8035.
- Chanson, H. 2011b. Turbulent shear stresses in hydraulic jumps, bores and decelerating surges. Earth Surface Processes and Landforms, **36**(2): 180-189. doi:10.1002/esp.2031.
- Chanson, H., and Docherty, N.J. 2012. Turbulent velocity measurements in open channel bores. European Journal of Mechanics - B/Fluids, **32**: 52-58. doi:10.1016/j.euromechflu.2011.10.001.
- Kobayashi, N., and Johnson, B.D. 2001. Sand suspension, storage, advection, and settling in surf and swash zones. Journal of Geophysical Research: Oceans, **106**(C5): 9363-9376. doi:10.1029/2000jc000557.
- Leng, X. 2018. A study of turbulence: the unsteady propagation of bores and surges. Ph.D thesis, School of Civil Engineering, The University of Queensland, Brisbane, Australia. doi:10.14264/uql.2018.501.
- Li, Y. 2020. Hydrodynamics of tidal bores: turbulent propagation and sediment transport. Ph.D thesis, School of Civil Engineering, The University of Queensland, Brisbane, Australia. doi:10.14264/uql.2020.671.
- Li, Y., and Chanson, H. 2018. Decelerating bores in channels and estuaries. Coastal Engineering Journal, **60**(4): 449-465. doi:10.1080/21664250.2018.1529261.

- Li, Y., Pan, D., Chanson, H., and Pan, C. 2017. Tidal bore progressing on a small slope. *Experimental Thermal and Fluid Science*, **88**: 513-518. doi:10.1016/j.expthermflusci.2017.07.004.
- Lubin, P., Chanson, H., and Glockner, S. 2010. Large Eddy Simulation of turbulence generated by a weak breaking tidal bore. *Environmental Fluid Mechanics*, **10**(5): 587-602. doi:10.1007/s10652-009-9165-0.
- Murty, T.S., Flather, R.A., and Henry, R.F. 1986. The storm surge problem in the bay of Bengal. *Progress in Oceanography*, **16**(4): 195-233. doi:10.1016/0079-6611(86)90039-X.
- Piquet, J. 1999. *Turbulent flows: models and physics*. Springer, Berlin, Heidelberg. doi:10.1007/978-3-662-03559-7.
- Reungoat, D., Chanson, H., and Caplain, B. 2014. Sediment processes and flow reversal in the undular tidal bore of the Garonne River (France) [Article]. *Environmental Fluid Mechanics*, **14**(3): 591-616. doi:10.1007/s10652-013-9319-y.
- Simon, B. 2014. Effects of tidal bores on turbulent mixing: a numerical and physical study in positive surges. Ph.D thesis, School of Civil Engineering, The University of Queensland, Brisbane, Australia. doi:10.14264/uql.2014.19.
- St-Germain, P., Nistor, I., Townsend, R., and Shibayama, T. 2014. Smoothed-particle hydrodynamics numerical modeling of structures impacted by tsunami bores. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **140**(1): 66-81. doi:10.1061/(ASCE)WW.1943-5460.0000225.
- Treske, A. 1994. Undular bores (Favre-waves) in open channels - Experimental studies. *Journal of Hydraulic Research*, **32**(3): 355-370. doi:10.1080/00221689409498738.
- Viero, D.P., Peruzzo, P., and Defina, A. 2017. Positive surge propagation in sloping channels. *Water*, **9**(7): 518. doi:10.3390/w9070518.

Zeng, J., Chen, G., Pan, C., and Zhang, Z. 2017. Effect of dike line adjustment on the tidal bore in the Qiantang Estuary, China. *Journal of Hydrodynamics, Ser. B*, **29**(3): 452-459. doi:10.1016/S1001-6058(16)60756-4.

Draft

Table 1. Initial flow conditions prior to tidal bore passage on the mobile/fixed gravel section in the sloping channel during vanishing bore experiments. – Fr_o : inflow Froude number; x : longitudinal location measured from upstream end of flume.

Table 2. Unsteady flow conditions during the vanishing bore experiments. – Q : flow rate; S_o : channel slope ($S_o = \sin \theta$); h : Tainter gate opening after closure; Fr_1 : bore Froude number; d_1 : initial water depth of inflow; U : bore celerity; B : channel width; d_c : critical water depth, $d_c = [Q^2/(g \times B^2)]^{1/3}$; V_c : critical flow velocity, $V_c = Q/(d_c \times B)$.

Figure 1. A gentle undular bore with some smooth surface undulations and a surfer in the Garonne River (France) on the afternoon of 3 June 2012. The red arrows indicate the leading bore front.

Figure 2. Experimental flume configuration for the vanishing bore experiments – The vertical coordinate z was measured from the top of the pebble layer. – θ : channel tilting angle; V_1 : bulk velocity of initial inflow; d_1 : initial water depth of inflow; U : bore celerity; V_2 : bulk velocity of conjugate flow; d_2 : water depth of conjugate flow; h : Tainter gate opening after closure.

Figure 3. Photographs of propagating and vanishing undular bores: (a) An undular bore (red arrow) shortly after generation propagating from right to left near $x = 13$ m in Experiment VB1; (b) A decelerating undular bore (red arrow) propagating from right to left near $x = 11$ m on the sloping mobile gravel bed before vanishing in Experiment VB1; (c) A vanishing bore (red

arrow) propagating from right to left near $x = 5.5$ m on the sloping fixed gravel bed in Experiment VB2. – Flow conditions: $Q = 0.039$ m³/s, $S_o = 0.0068$, $h = 63$ mm.

Figure 4. Time evolution of ensemble-median free-surface elevations d_{50} (a) and instantaneous free-surface fluctuations d_{75-25} (b) at different longitudinal locations in Experiment VB1 (mobile bed). – Flow conditions: $Q = 0.039$ m³/s, $S_o = 0.0068$, $h = 63$ mm, $Fr_1 = 1.06$ at $x = 7$ m, $d_c = 0.085$ m.

Figure 5. Time evolution of ensemble-median flow velocity $(V_x)_{50}$ and instantaneous velocity fluctuations $(V_x)_{75-25}$ at different vertical elevations in Experiment VB1 (mobile bed). – Some curves were offset vertically for better reading as indicated in the legends. – Flow conditions: $Q = 0.039$ m³/s, $S_o = 0.0068$, $h = 63$ mm, $Fr_1 = 1.06$ at $x = 7$ m.

Figure 6. Time evolution for the ensemble-median normal Reynolds stresses $(v_x \times v_x)_{50}$ (a) and the third quartile of normal Reynolds stresses $(v_x \times v_x)_{75}$ (b) at different vertical elevations in Experiment VB1 (mobile bed). – Some curves were offset vertically for better reading as indicated in the legends. – Flow conditions: $Q = 0.039$ m³/s, $S_o = 0.0068$, $h = 63$ mm, $Fr_1 = 1.06$ at $x = 7$ m, $d_c = 0.085$ m, $V_c = 0.914$ m/s.

Experiment	Bed Type	Fr _o (--) at different longitudinal locations <i>x</i> (m)									
		12	11	10	9	8	7	6	5	4	3
VB1	Mobile gravel	0.85	0.84	0.79	0.81	0.79	0.72	0.69	0.76	0.80	0.84
VB2	Fixed gravel	0.79	0.75	0.77	0.77	0.74	0.69	0.67	0.73	0.76	0.82

Draft

Experiment	Bed Type	Q (m ³ /s)	S_o (--)	h (mm)	Fr_1^* (--)	d_1^* (m)	U^* (m/s)	d_c (m)	V_c (m/s)
VB1	Mobile gravel	0.039	0.0068	63	1.06	0.106	0.34	0.085	0.914
VB2	Fixed gravel	0.039	0.0068	63	1.03	0.108	0.34	0.085	0.914

* These parameters were measured/calculated at $x = 7$ m of the test section.

Draft

Figure 1. A gentle undular bore with some smooth surface undulations and a surfer in the Garonne River (France) on the afternoon of 3 June 2012. The red arrows indicate the leading bore front.

395x140mm (300 x 300 DPI)

Figure 2. Experimental flume configuration for the vanishing bore experiments – The vertical coordinate z was measured from the top of the pebble layer. – θ : channel tilting angle; V_1 : bulk velocity of initial inflow; d_1 : initial water depth of inflow; U : bore celerity; V_2 : bulk velocity of conjugate flow; d_2 : water depth of conjugate flow; h : Tainter gate opening after closure.

Figure 3. Photographs of propagating and vanishing undular bores: (a) An undular bore (red arrow) shortly after generation propagating from right to left near $x = 13$ m in Experiment VB1; (b) A decelerating undular bore (red arrow) propagating from right to left near $x = 11$ m on the sloping mobile gravel bed before vanishing in Experiment VB1; (c) A vanishing bore (red arrow) propagating from right to left near $x = 5.5$ m on the sloping fixed gravel bed in Experiment VB2. – Flow conditions: $Q = 0.039 \text{ m}^3/\text{s}$, $S_o = 0.0068$, $h = 63$ mm.

899x635mm (96 x 96 DPI)

Figure 4. Time evolution of ensemble-median free-surface elevations d_{50} (a) and instantaneous free-surface fluctuations d_{75-25} (b) at different longitudinal locations in Experiment VB1 (mobile bed). – Flow conditions: $Q = 0.039 \text{ m}^3/\text{s}$, $S_o = 0.0068$, $h = 63 \text{ mm}$, $Fr_1 = 1.06$ at $x = 7 \text{ m}$, $d_c = 0.085 \text{ m}$.

1084x635mm (96 x 96 DPI)

Figure 5. Time evolution of ensemble-median flow velocity $(V_x)_{50}$ and instantaneous velocity fluctuations $(V_x)_{75-25}$ at different vertical elevations in Experiment VB1 (mobile bed). – Some curves were offset vertically for better reading as indicated in the legends. – Flow conditions: $Q = 0.039 \text{ m}^3/\text{s}$, $S_o = 0.0068$, $h = 63 \text{ mm}$, $Fr_1 = 1.06$ at $x = 7 \text{ m}$.

480x180mm (300 x 300 DPI)

Figure 6. Time evolution for the ensemble-median normal Reynolds stresses $(v_x \times v_x)_{50}$ (a) and the third quartile of normal Reynolds stresses $(v_x \times v_x)_{75}$ (b) at different vertical elevations in Experiment VB1 (mobile bed). – Some curves were offset vertically for better reading as indicated in the legends. – Flow conditions: $Q = 0.039 \text{ m}^3/\text{s}$, $S_0 = 0.0068$, $h = 63 \text{ mm}$, $Fr_1 = 1.06$ at $x = 7 \text{ m}$, $d_c = 0.085 \text{ m}$, $V_c = 0.914 \text{ m/s}$.

258x190mm (300 x 300 DPI)