THE UNIVERSITY OF QUEENSLAND

SCHOOL OF CIVIL ENGINEERING

REPORT CH81/10

FIELD MEASUREMENTS IN THE TIDAL BORE OF THE SÉLUNE RIVER IN THE BAY OF MONT SAINT MICHEL (SEPTEMBER 2010)

AUTHOR: Dominique MOUAZE, Hubert CHANSON and Bruno SIMON

HYDRAULIC MODEL REPORTS

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First published in 2010 by
School of Civil Engineering
The University of Queensland, Brisbane QLD 4072, Australia

ISBN No. 9781742720210

The University of Queensland, St Lucia QLD

Field Measurements in the Tidal Bore of the Sélune River in the Bay of Mont Saint Michel (September 2010)

by

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REPORT No. CH81/10
ISBN 9781742720210
School of Civil Engineering, The University of Queensland
December 2010

Tidal bore of the Sélune River at Pointe du Grouin du Sud on 24 September 2010

ABSTRACT

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. The bore forms during spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide flow is restrained into a narrow funnelled estuary. It is estimated worldwide that over 400 estuaries and shallow-water bays are affected by a tidal bore process. A well preserved macro-tidal environment such shallow-water bay system is the Bay of Mont Saint Michel in France, and some detailed field measurements were conducted in the tidal bore of the Sélune River on 24 and 25 Sept. 2010. The turbulent velocity measurements were performed continuously at high-frequency (64 Hz) in the breaking tidal bore. The passage of the tidal bore was characterised by a strong turbulent mixing in the bore. A key feature was the rapid change in the channel cross-section as the tidal bore expanded over the sand banks over the left channel side. The turbulent velocity data showed the marked impact of the tidal bore roller. The longitudinal velocity component indicated some rapid flow deceleration during the passage of the tidal bore, associated with a sudden rise in the free surface elevation, and a flow reversal after the tidal bore front passage. The observations were consistent with a number of field and laboratory observations. The tidal bore passage was further characterised by some large fluctuations of all three turbulent velocity components. The Reynolds stress data indicated some large and rapid turbulent stress fluctuations during the tidal bore and flood flow. The passage of the bore and the ebb flow was always characterised by large backscatter intensity levels corresponding to large suspended sediment concentrations. The data showed some marked differences between the 24 and 25 Sept. 2010, possibly linked with some different initial flow conditions. On 24 Sept. 2010, the ebb flow was fast flowing and sediment-laden. The tidal bore arrival contributed to further sediment motion, and the BSI levels were significant both before and after the tidal bore. On 25 Sept.2010, the ebb flow was less energetic, and the backscatter data suggested little sediment suspension prior to the tidal bore. But a drastic increase in BSI was observed during with the passage of the bore linked with some sediment re-suspension. A specific particularity of the present field data set was the repeated problems experienced during both days and discussed in the report.

Keywords: Tidal bore, Sélune River, Field measurements, Turbulence, Acoustic Doppler velocimetry, Experimental works, Bay of Mont Saint Michel.

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LIST OF SYMBOLS

The following symbols are used in this report:

A	channel cross-section area (m^2);
A_1	initial channel cross-section area (m^2) immediately prior to the tidal bore passage;
A_2	channel cross-section area (m^2) immediately after to the tidal bore passage;
Ampl	ADV signal amplitude (counts);
B	free-surface width (m);
B_1	initial free-surface width (m) immediately prior to the tidal bore passage;
BSI	backscatter intensity defined as: $\text{BSI} = 10^{-5} \times 10^{0.043 \times \text{Ampl}}$
d	water depth (m);
d_1	initial water depth (m) immediately prior to the tidal bore passage;
Fr	Froude number;
Fr_1	tidal bore Froude number defined as: $Fr_1 = \frac{V_1 + U}{\sqrt{g \times d_1}}$
g	gravity acceleration (m/s^2);
I_b	acoustic backscatter intensity;
N	number of data points;
m	dimensionless exponent;
q_s	instantaneous advective suspended sediment flux per unit area ($kg/m^2/s$) defined as: $q_s = \text{SSC} \times V_x$
SSC	suspended sediment concentration (kg/m^3);
s	relative density of wet sediment;
t	time (s);
T	integration period (s);
U	tidal bore celerity (m/s) for an observer standing on the bank, positive upstream;
V	flow velocity (m/s);
V_1	initial flow velocity (m/s) immediately prior to the tidal bore passage (positive downstream);
V_x	instantaneous longitudinal velocity component (m/s);
V_y	instantaneous transverse velocity component (m/s);
V_z	instantaneous vertical velocity component (m/s);
$\overline{V}$	variable interval time-averaged velocity (m/s)
v	instantaneous velocity fluctuation (m/s) : $v = V - \overline{V}$;
v_x	instantaneous fluctuation (m/s) of V_x;
v_y	instantaneous fluctuation (m/s) of V_y;
v_z	instantaneous fluctuation (m/s) of V_z;
x	longitudinal distance (m) positive downstream;

y	transverse distance (m) positive towards the Tombelaine Island;
z	vertical distance (m) positive upwards;
μ	effective viscosity (Pa.s);
ρ	water density (kg/m^3);
τ	shear stress (N/m^2);
τ_c	apparent yield stress (Pa);
τ_o	boundary shear stress (Pa);
$(\tau_o)_c$	critical boundary shear stress (Pa) for bed load motion;

Subscript

x	longitudinal direction positive downstream;
y	transverse direction positive towards the Tombelaine Island;
z	vertical direction positive upwards;
1	flow property immediately prior to the tidal bore passage;
2	flow property immediately after the tidal bore passage;

Abbreviations

ADV	acoustic Doppler velocimeter;
BSI	acoustic backscatter intensity;
h	hour;
min	minute;
Nb	number;
SSC	suspended sediment concentration;
Std	standard deviation;
s	second
VITA	variable-interval time average.

Note

All times are expressed in local French times (GMT + 1).

1. INTRODUCTION

1.1 PRESENTATION

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising (Fig. 1-1). The bore forms during spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide flow is restrained into a narrow funnelled estuary. The word 'bore' is believed to derive from the Icelandic '*bara*' indicating a potentially dangerous phenomenon such as a breaking tidal bore (COATES 2007). The French name is '*mascaret*' that is said to derive from the Gascony word '*masquaret*' meaning a 'galloping ox' (Petit Robert 1996). In any case, the tidal bore is a positive surge associated with a sudden rise in water depth and a discontinuity of the velocity and pressure fields. The bore front is a flow singularity (LIGHTHILL 1978, LIGGETT 1994). In nature, a tidal bore may have a variety of different shapes, and photographs illustrate in particular that the bore front is not a sharp, vertical discontinuity of the water surface because of the necessary curvature of the streamline and the associated pressure and velocity redistributions (Fig. 1-1). It is estimated worldwide that over 400 estuaries and shallow-water bays are affected by a tidal bore process. A well preserved macro-tidal environment such shallow-water bay system is the Bay of Mont Saint Michel in France (Fig. 1-2).

The Bay of Mont Saint Michel in the Channel (*La Manche*) is renowned for the abbey built on the Mont Saint Michel (granitic mount), its very large tidal range (up to 14 m) and the fast advancing flood tides (up to 3 m/s in the channel and 1 m/s on the tidal flats). The bay is drained by three main rivers: the Couesnon, the Sélune and the Sée. In the past, the hydrodynamics and sedimentology of the bay, including the access to the Mont Saint Michel, were mostly affected by the strong flows of the Couesnon and Sélune Rivers. Since 1879, the Couesnon River has been controlled by man-made river training and works. In 2009, the completion of a new sluice system led to some river bed scour and the tidal bore disappearance. The Sélune River is 70 km long. It was partially controlled around 1860 after the completion of a dyke redirecting the river northwards. The river was further affected by the completion of two dams in 1920 (La Roche Qui Boit) and 1931 (Vezins). Today the Sélune River constitutes the most significant freshwater inflow into the bay. Between Roche Torin and Pointe du Grouin du Sud, the Sélune River is joined by the Sée River, and the river flows past the Tombelaine Island at low tides (Fig. 1-2).

In the Bay of Mont Saint Michel, several tidal bore processes are experienced in creeks and rivers (TESSIER and TERWINDT 1994, CHANSON 2005,2008) (Fig. 1-1). The tidal bore process develops offshore and propagates inland along the channels leading to the main river channels. The entire tidal bore phenomenon lasts several hours and spans over more than 25 km. It further affects numerous small streams, creeks and inlets.

(A) Tidal bore of the Couesnon River on 7 March 2004 about 18:20 (Photograph H. CHANSON) - Looking downstream from Tour Gabriel at the approaching tidal bore

(B) Tidal bore of the Sélune River on 7 March 2008 at Pointe du Grouin du Sud (at sunrise) (Courtesy of Nathanaelle EUDES) - Note the Tombelaine Island in the background

Fig. 1-1 - Tidal bores in the Bay of Mont Saint Michel (France)

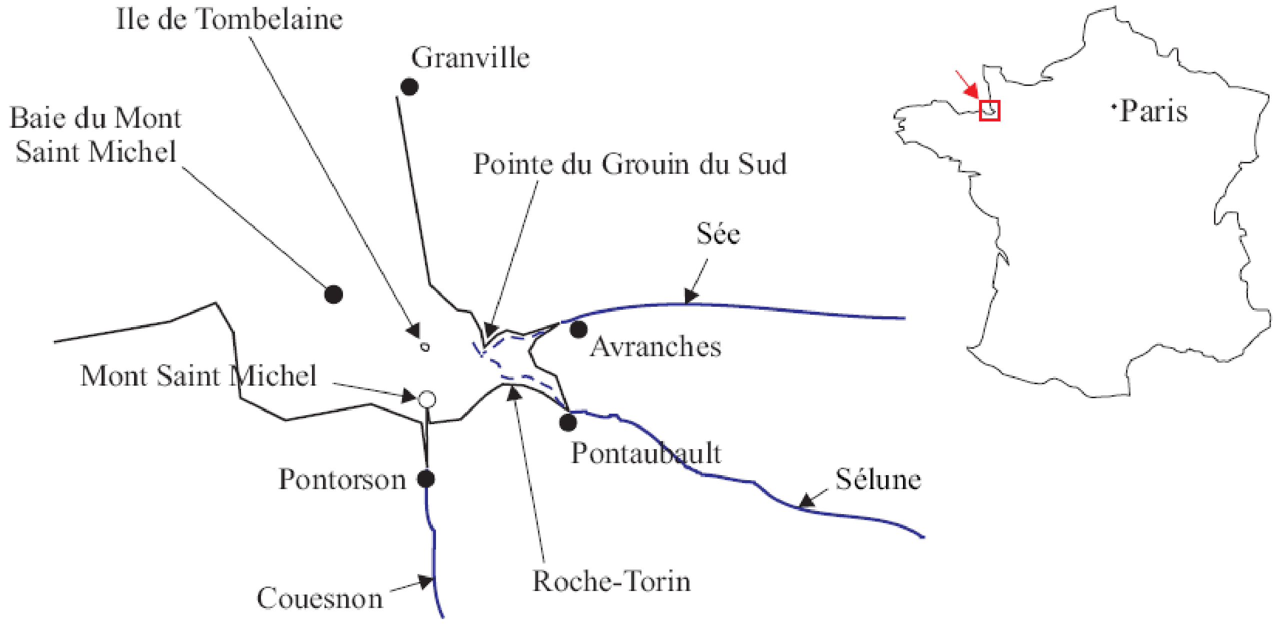

Fig. 1-2 - Map of the Bay of Mont Saint Michel (France)

1.2 STRUCTURE OF THE REPORT

To date, the field measurements in tidal bores are limited despite their importance (Table 1-1). In a number of cases, some damage to the scientific equipments were experienced including in the Rio Mearim (Brazil), in the Daly River (Australia), and in the Dee River (UK) (KJERFVE and FERREIRA 1993, WOLANSKI et al. 2004, SIMPSON et al. 2004). In the present study, some field measurements were conducted in the Bay of Mont Saint Michel (France) on 24 and 25 September 2010. Some turbulent velocity measurements were performed continuously at high-frequency (64 Hz) in the tidal bore of the Sélune River downstream of Pointe du Grouin du Sud. Despite a number of practical issues and problems, the results provided a detailed characterisation of the turbulence features in the breaking tidal bore. The field investigation and instrumentation are described in section 2. The main results are presented in sections 3 to 4, and summarised in section 5. Appendix A lists the field work participants. Appendix B shows a number of photographs of the field study. Appendices C and D present respectively the ADV system configurations and the Reynolds stress tensor results.

Table 1-1 - Field observations of tidal bores

Reference	Initial flow V_1 m/s	d_1 m	Instrument	Channel geometry	Remarks
(1)	(2)	(3)	(4)	(5)	(6)
LEWIS (1972)	0 to +0.2	0.9 to 1.4	Hydro-Products type 451 current meter	Dee River (UK) near Saltney Ferry footbridge. Trapezoidal channel	Field experiments between March and September 1972.
KJERFVE and FERREIRA (1993)			Interocean S4 electro-magnetic current meters (sampling: 1-2 Hz)	Rio Mearim (UK)	Field experiments on 19-22 Aug. 1990 & 28 Jan.-2 Feb. 1991.
NAVARRE (1995)	0.65 to 0.7	1.12 to 1.15	Meerestechnik-Electronik GmbH model SM11J acoustic current meter (sampling 10Hz)	Dordogne River (France) at Port de Saint Pardon. Width ~ 290 m	Field experiments on 25 & 26 April 1990.
WOLANSKI et al. (2001)	--	0.45	Analite nephelometer	Ord River (East Arm) (Australia). Width ~ 380 m	Field experiments in August 1999.
SIMPSON et al. (2004)	0.1	~0.8	ADCP (1.2 0 MHz) (sampling rate:1 Hz)	Dee River (UK) near Saltney Ferry Bridge. Trapezoidal channel (base width ~ 60 m)	Field experiments in May and September 2002.
WOLANSKI et al. (2004)	0.15	1.5 to 4	Nortek Aquadopp ADCP (sampling rate:2 Hz)	Daly River (Australia). Width ~ 140 m	Field experiments in July and September 2002, and on 2 July 2003.
CHANSON et al. (2010)			ADV Nortek Vector (6 MHz) (sampling: 64 Hz)	Arcins channel, Garonne River (France) Width ~ 76 m	Undular tidal bore.
	0.33	1.40			10 Sept. 2010.
	0.30	1.43			11 Sept. 2010.
Present Study			ADV Nortek Vector (6 MHz) (sampling: 64 Hz)	Pointe du Grouin du Sud, Sélune River (France)	Breaking tidal bore.
	0.86	0.15			24 Sept. 2010.
	0.59	0.11			25 Sept. 2010.

Notes: d_1: initial water depth; V_1: initial flow velocity; (--): information not available.

2. FIELD INVESTIGATION AND INSTRUMENTATION

2.1 FIELD INVESTIGATION AND SAMPLING SITE

The field study was conducted in the Sélune River in the Bay of Mont Saint Michel (France). The site (48°39'32.55"N 1°26'52.58"W) was located about 200 m downstream of the Pointe du Grouin du Sud, indicated in Figure 1-2, and 500 m upstream of the Maison de la Baie (Vains). The site was downstream of the confluence of the Sée River with the Sélune River. An unusual feature of the sampling site was the presence of an old WWII German truck (Fig. 2-1A). The main channel of the Sélune River changes constantly and some areas are covered and then exposed over time. For decades, the WWII truck was covered by sediment materials, until the river channel recently scoured the right bank.

On 24 Sept. 2010, the Sélune River channel was about 35 m wide and less than 0.5 m deep at low tide (Fig. 2-1B). The WWII German truck ([1]) was close to the right bank waterline (Fig. 2-1A & 2-1B). At high tide, the flood tide waters submerged all the sand banks and the channel width was about 2 km (Fig. 2-1C). Figure 2-1 shows some photographs of the channel and further photographs are presented in Appendix B. Figure 2-2 presents a cross-sectional survey conducted on 24 Sept. 2010. In Figure 2-2B, the locations of the ADV sampling volume on 24 and 25 Sept. 2010 are shown in the river cross-section.

(A) Sélune River channel on 17 Sept 2010 at 12:52, looking downstream (Photograph: H. CHANSON) - Note the WWII German truck next to the right bank

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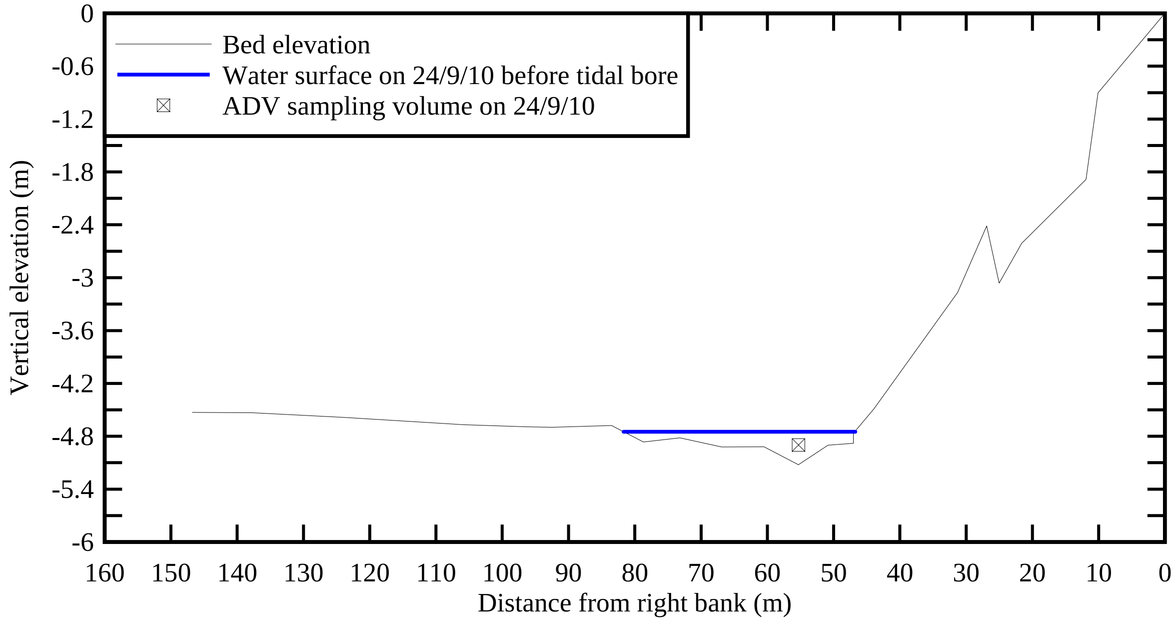
[1] It is believed that the WWII German truck was an Opel KFz 305 Blitz (COCAIGN, J.Y. (2010), *Person. Comm.*).

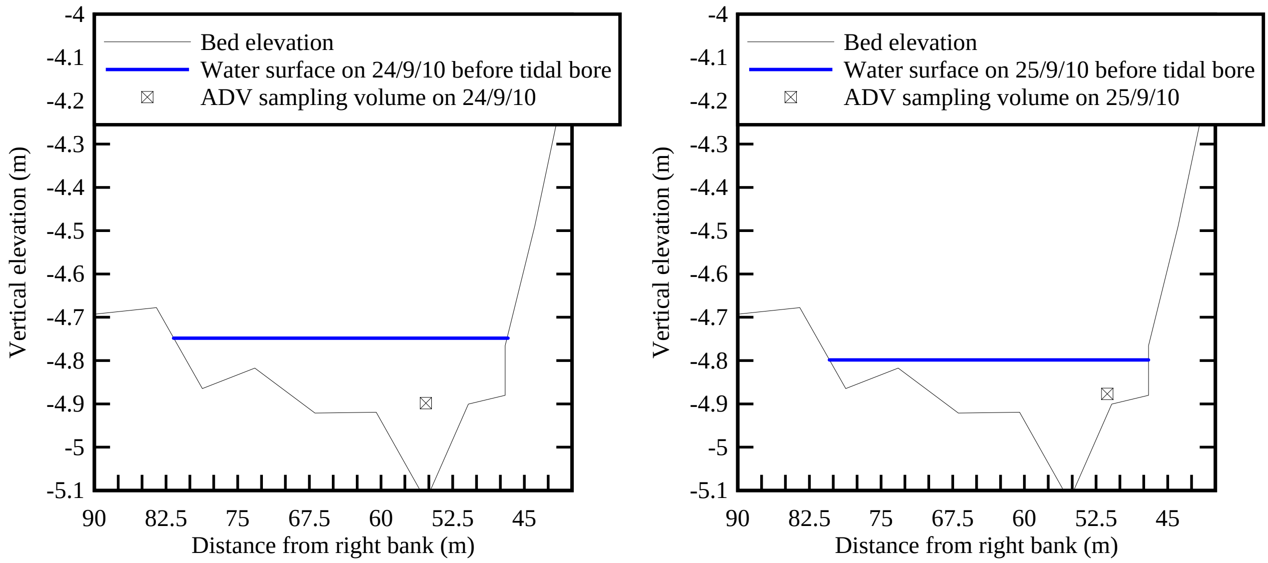
(B) Sélune River channel on 24 Sept 2010 at 19:01 prior to the tidal bore viewed from the right bank (Photograph: H. CHANSON) - The three poles on the right of the WWII German truck supported the ADV system on 24 Sept. 2010 - Note Mont Saint Michel and Tombelaine Island in the left and right background respectively

(C) Sélune River channel on 24 Sept 2010 at 19:51 viewed from the right bank (Photograph: H. CHANSON) - The tip of the survey staff is barely visible while transient front (white foam) is seen behind the survey staff

Fig. 2-1 - Sélune River channel in the Bay of Mont Saint Michel



(A) Surveyed cross-section on 24 Sept. 2010 looking downstream



(B) Surveyed cross-section (looking downstream) with ADV sampling volume and free-surface elevation prior to the tidal bore on 24 and 25 Sept. 2010 respectively

Fig. 2-2 - Surveyed cross-section of the Sélune River channel - Looking downstream

The field measurements were conducted under spring tidal conditions on 24 and 25 September 2010. The tidal range at Saint Malo are summarised in Table 2-1 (column 2). During the study, the water elevations and some continuous high-frequency turbulence data were recorded prior to, during and after the passage of the tidal bore on two days.

Table 2-1 - Tidal bore field measurements in the Sélune River downstream of Pointe du Grouin du Sud (Bay of Mont Saint Michel, France)

Date (1)	Tidal range (m) (2)	High tide time (3)	ADV system (4)	ADV mounting (5)	Sampling volume (8)	Sampling rate (Hz) (6)	Tidal bore time (7)	Tidal bore type (8)
24/10/2010	9.8	19:48	Nortek Vector (6MHz)	Horizontally. Fixed to a tripod.	About 55.1 m from right bank (herbus [salt marches]), 0.225 m above the bed.	64	19:27	Breaking bore
25/09/2010	9.9	08:02	Nortek Vector (6MHz)	Fixed to WWII German truck	About 51.3 m from right bank (herbus [salt marches]), 0.1 m above the bed.	64	07:46	Breaking bore

Notes: Tidal range & high tide time: predicted in Saint Malo; All times are in French local times (GMT+1).

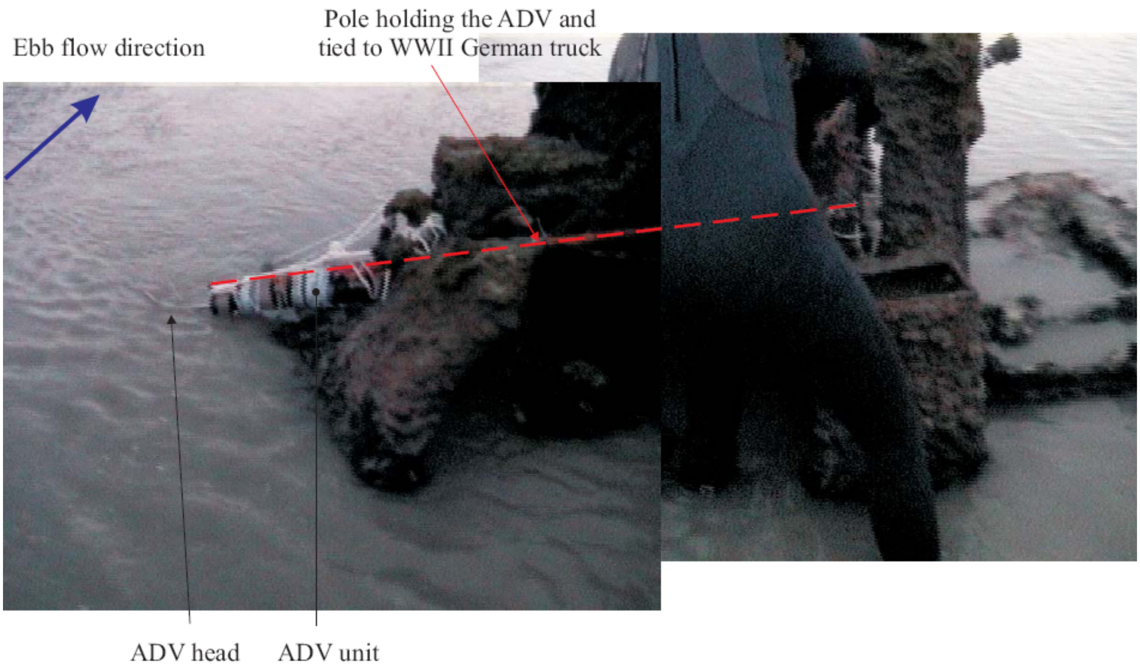
2.2 INSTRUMENTATION

The free surface elevations were measured manually using a survey staff. During the passage of the tidal bore, a video camera recorded the water level and the data were collected frame by frame at 25 fps. The survey staff was mounted on the old WII German truck next to the right bank (Fig. 2-1B). During the field investigation, the turbulent velocities were measured with a Nortek[TM] Vector ADV (6 MHz, serial number VEC3332). The ADV system was equipped with a 3D downlooking head (Head ID VEC4665) and the unit was self-logging (sampling rate: 64 Hz). On 24 Sept. 2010, the ADV system was fixed to a tripod (Fig. 2-3A). The ADV unit was mounted horizontally with the V_x direction pointing upstream, the V_y direction downwards and the V_z direction towards the right bank ([2]). About 40 s after the passage of the bore, the metallic frame started to fail (see section 2.3). On 25 Sept. 2010 early morning, the ADV system was re-positioned in front of the WWII German truck, pointing slightly towards the left bank of the Sélune River channel. The ADV was secured to a pole attached tightly to the WWII German truck structure (Fig. 2-3B). The velocity components were re-constructed from the ADV position ([3]).

[2] That is, the velocity outputs from the ADV.

[3] The velocity re-construction was performed on the post-processed ADV data.

(A) Tripod supporting the ADV system on 24 Sept. 2010 at 16:40 (Photograph F. MURZYN) - From left to right, Frederique LARRARTE, Dominique MOUAZE, Hubert CHANSON and Bruno SIMON - Dominique MOUAZE was preparing the ADV unit with its head pointed towards him



(B) ADV mounted in front of the WWII German truck on 25 Sept. 2010 early morning - Composite photograph made from 2 movie snapshots

Fig. 2-3 - ADV support in the Sélune River channel

The ADV system was sampled continuously at 64 Hz. The settings are reported in Appendix C. All the ADV data underwent a thorough post-processing procedure to eliminate any erroneous or corrupted data from the data sets to be analysed. The post processing was conducted with the software WinADV^{TM} version 2.026, and it included the removal of communication errors, the removal of average signal to noise ratio data less than 15 dB, the removal of average correlation values less than 60%, and some "despiking" using the phase-space thresholding technique developed by GORING and NIKORA (2002).

Further observations were recorded with a digital camera Pentax^{TM} K-7, a digital video camera Canon^{TM} MV500i, a digital camera Nikon^{TM} D700 and a HD digital video camera Canon^{TM} HF10E.

2.3 FIELD EXPERIENCE

On 24 and 25 September 2010, the field study experienced a number of problems and failures especially with the ADV unit and its support. These are summarised below.

On 24 Sept. 2010 afternoon, the ADV system was mounted horizontally and fixed to a tripod (Fig. 2-3A). The tripod consisted of 3 poles driven into the bed sediment materials and tightly fastened down together. The whole setup was further secured to the WWII German truck with a solid rope. This tripod system was used previously in a number of field works in the Bay of Mont Saint Michel. About 40 s after the passage of the bore, the metallic frame started to move. Vibrations were followed by local liquefaction around each pile which then lost their friction stability inside the mobile bed. One pole was lost, and the ADV support failed completely 10 minutes after the tidal bore. The ADV unit pivoted with the head pointing upwards (Fig. 2-4). The entire system remained submerged and the authors did not see any signs of this failure in the darkness.

On 25 Sept. 2010 early morning, the authors found the ADV system (Fig. 2-4) and the last two poles secured by the rope to the WWII German truck. The ADV unit was inspected, and it was re-positioned in front of the WWII German truck (Fig. 2-3B); its installation was completed three minutes prior to the passage of the tidal bore. The remaining poles were digged out of the bed sediments to avoid any damage to the ADV unit during the tidal bore passage. It took three people nearly 25 minutes to remove the poles in the darkness of the early morning.

About 60 s after the tidal bore passage, the ADV signal became very noisy, with a drastic loss in SNR and amplitude. The reason remained unknown, although it might be linked with a low battery level or some debris trapped around the ADV head. About 20 min after the tidal bore, the ADV signal stopped completely because either the ADV memory was full or the battery was dead.

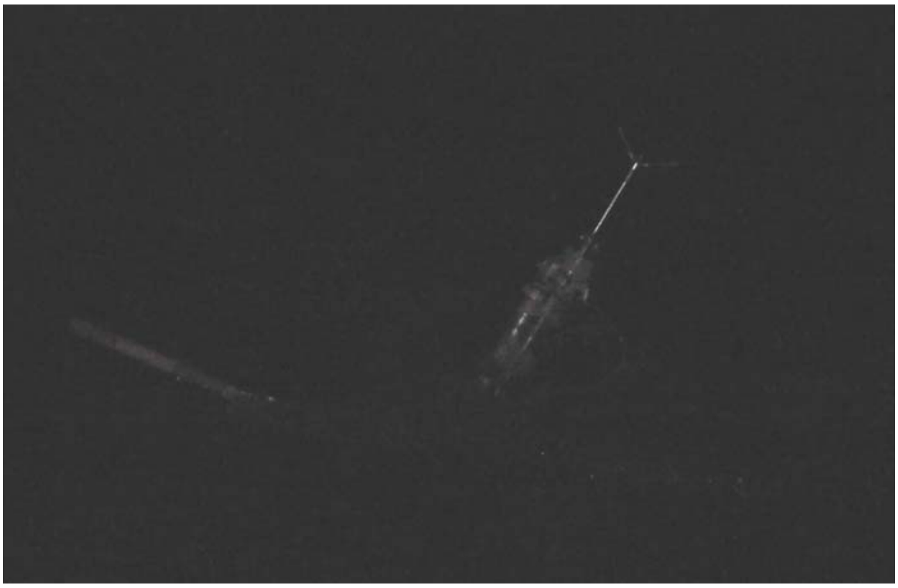


Fig.2-4 - ADV system and damaged support at 07:12 on 25 Sept. 2010, view from the right bank (Photograph F. MURZYN) - Note the ADV head pointing upwards out of the water and one of the poles (initially vertical) on the left

2.4 REMARKS

2.4.1 ADV synchronisation

The water elevation measurements and ADV data were synchronised using the ADV pressure sensor data. These were sampled at 64 Hz together with the velocity data. The cameras and digital video cameras were also synchronised together.

2.4.2 Data accuracy

The accuracy on the ADV velocity measurements was 1% of the velocity range (± 2 m/s) (Nortek 2005). The accuracy of the water elevation was 0.5 cm prior to the tidal bore and 1 cm during the tidal bore passage.

2.4.3 ADV settings

A previous field study with the same equipment reported a number of issues with the ADV settings (CHANSON et al. 2010). The present settings benefited from the previous experience. The ADV settings are documented in Appendix C.

3. GENERAL OBSERVATIONS

3.1 PRESENTATION

The tidal bore propagation in the Sélune River was observed on both 24 and 25 Sept. 2010. On both days, the tidal bore process was relatively similar. The tidal bore was seen (far downstream) first about 12 minutes before it reached the sampling location. The tidal bore expanded across the entire channel width. As the bore advanced upstream, it disappeared in the channel bend in front of Maison de la Baie (Vains), to re-appear as a breaking bore about 200 m downstream to the sampling site. The breaking tidal bore had a marked roller (Fig. 3-1 & 3.2). The roller was about 0.4 m high. The tidal bore front has a curved shape (Fig. 3-1B & 3-1C) in response to the local bathymetry. In region of deeper waters, the surge front accelerated while it decelerated in shallower waters. In the background on the left bank, the bore front advanced on the dry sand bank and the waters were murky (Fig. 3-1D). Some basic properties of the breaking tidal bore are summarised in Table 3-1. The bore continued to propagate upstream past the Pointe du Grouin du Sud where it divided between the Sélune and Sée River channels.

The propagation of the tidal bore was followed by a number of specific features, including standing waves, transient front and the presence of harbour seals looking for food. A number of standing waves formed in front of the sampling site (e.g. Fig. 3-2C). The standing waves evolved with time together with the formation, development and collapse of standing wave and anti-dune bed forms (KENNEDY 1963, CHANSON 2000). These standing waves were active throughout the tide in the Sélune River. For example, on 25 Sept. 2010 early morning, their collapse and formation in the Sélune River channel generated some loud noises that almost masked the rumble noise of the incoming tidal bore.

On both days, some transient fronts were seen at the surface of the flood flow shortly after the tidal bore. For example, the white foam of a front is seen in Figure 3-2C behind the standing waves. The transient fronts were basically a zone of marked local gradients that indicated some form of singularity in terms of one or more parameters (OFFICER 1976, DYER 1997). Secondary flows associated with such fronts led to enhanced surface concentrations of larvae and pollutants, and enhanced sediment transport ([1]). Their presence influenced the horizontal dispersion and residual circulation, with significant impacts on the local chemical and biological processes including fresh and salt water mixing. Transient fronts were seen before behind tidal bores in previous occurrences (CHANSON 2010).

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[1] On 24 Sept. 2010, the harbour seals were swimming upriver beside a transient front, possibly to feed on fish, squid, and crustaceans caught next to the front.

On 24 and 25 Sept. 2010, the authors saw respectively 2 and 3 harbour seals (*Phoca vitulina*) swimming 2 to 3 minutes after the tidal bore. The seals were feeding behind the bore, taking advantages of the fish and crustaceans caught at the end of the Bay by the tidal bore and flood turbulence. On 25 Sept. 2010, the authors saw further the 3 seals swimming back to the Bay with the ebb tide current, about 4 h to 4 h 30 min after the tidal bore (App. B). At that time, the water in the channel was less than 1 m deep and the authors were standing in the water to dismount the equipment. During their stay in the water, all the people felt a lot of fish activities in the Sélune River channel: i.e., numerous fishes touched people's legs and hands Lot of fishes were jumping nearby the ADV.

Figures 3-1 and 3-2 present some photographs of the tidal bore propagation for each tidal bore. Further photographs are presented in Appendix B.

(A) Tidal bore 78 s before it reached the ADV unit (Photograph H. CHANSON)

(B) Tidal bore reaching the ADV unit (Photograph H. CHANSON)

(C) Details of the tidal bore roller, shortly after passing the ADV unit (Photograph D. MOUAZE) - Note the transverse curvature of the bore front

(D) Tidal bore about 5 s after it reached the ADV unit (Photograph H. CHANSON) - Note the curve shape of the bore front and, in the background, the dark colour of the bore front advancing on the sand banks

Fig. 3-1 - Breaking tidal bore of the Sélune River on 24 Sept. 2010 - Views from the right bank

(A) Tidal bore about 50 m downstream of the WWII German truck (Photograph D. MOUAZE)

(B) Tidal bore passing the WWII German truck with Frederique LARRARTE, in the foreground, timing the tidal bore celerity (Photograph D. MOUAZE) - The ADV unit was behind the WWII German truck

(C) Standing waves in the Sélune River channel about 10 minutes after the tidal bore (Photograph D. MOUAZE)

Fig. 3-2 - Breaking tidal bore of the Sélune River on 25 Sept. 2010 - Views from the right bank

Table 3-1 - Tidal bore properties in the Sélune River (Bay of Mont Saint Michel, France) at the sampling location during the field experiments

Date (1)	Tidal range (m) (2)	V_1 channel CL (m/s) (3)	U channel CL (m/s) (4)	d_1 next to ADV (m) (5)	A_1 (m^2) (6)	B_1 (m) (7)	A_1/B_1 (m) (8)	Fr_1 Eq. (3-4) (9)	Remarks (10)
24/10/2010	9.8	0.86	2.0	0.375	5.25	34.7	0.151	2.35	Breaking bore.
25/09/2010	9.9	0.59	1.96	0.325	3.56	33.2	0.107	2.48	Breaking bore.

Notes: Tidal range: predicted in Saint Malo; A_1: channel cross-section area immediately prior to the bore passage; B_1: free-surface width immediately prior to the bore passage; d_1: water depth next to ADV immediately prior to the bore passage; Fr_1: tidal bore Froude number (Eq. (3-4)); U: tidal bore celerity positive upstream on the channel centreline; V_1: downstream surface velocity on the channel centreline prior to the bore passage.

3.2 TIDAL BORE PROPERTIES

The tidal bore front was associated with a marked turbulent roller, some air entrainment and a rapid rise in free-surface elevation (Fig. 3-1 & 3-2). The flow properties before and behind the bore roller must satisfy the continuity and momentum principles (HENDERSON 1966, LIGGETT 1994). In a system of co-ordinates in translation with the tidal bore, the equations of conservation of mass and momentum yield:

$$(V_1 + U) \times A_1 = (V_2 + U) \times A_2 \qquad (3\text{-}1)$$

$$\rho \times (V_1 + U) \times A_1 \times (V_1 + U - (V_2 + U)) = \iint_{A_2} P \times dA - \iint_{A_1} P \times dA \qquad (3\text{-}2)$$

where ρ is the water density, g is the gravity acceleration, U is the tidal bore celerity positive upstream, V is the cross-sectional averaged velocity positive downstream, A is the flow cross-section, P is the pressure, the subscript 1 refers to the initial flow conditions and the subscript 2 refers to the flow conditions behind the tidal bore. Equation (3-2) assumes implicitly a quasi-horizontal channel bed, negligible friction losses and little variation of water density after the bore front passage. Combining Equations (3-1) and (3-2), it yields the classical result:

$$\frac{d_2}{d_1} = \frac{1}{2} \times \left(\sqrt{1 + 8 \times Fr_1^2} - 1 \right) \qquad (3\text{-}3)$$

where d_1 is the initial water depth, d_2 is the downstream conjugate flow depth immediately after the bore passage, and Fr_1 is the tidal bore Froude number. When the channel has an irregular shape, the solution of Equation (3-2) is based upon a tidal bore Froude number defined in terms of the cross-sectional properties (HENDERSON 1966, CHANSON 2004):

$$Fr_1 = \frac{V_1 + U}{\sqrt{g \times \frac{A_1}{B_1}}} \qquad (3\text{-}4)$$

where A_1 is the initial flow cross-section and B_1 is the initial free-surface width. The ratio A_1/B_1 is a cross-sectional averaged water depth.

During the present field experiments, the tidal bore was breaking at the sampling location, and the tidal Froude number was estimated from the surveyed channel cross-section, water level observations and tidal bore celerity observations (Table 3-1, columns 4 to 8). Equation (3-4) yields Fr_1 = 2.35 and 2.48 for the field observations on 24 and 25 Sept. 2010 respectively.

<u>Free-surface properties</u>

The water depth was recorded using a survey staff placed on the WWII German truck (Fig. 2-1B). Figures 3-3 and 3-4 show the time-variations of water depth at the ADV sampling location and the pressure head recorded by the ADV pressure sensor ([2]). Figures 3-3 and 3-4A present the data during the tidal bore passage and the horizontal axis scale corresponds to 300 s. Figure 3-4B show

[2] The pressure head recorded by the ADV pressure sensor is equal to the sampling volume depth assuming a hydrostatic pressure distribution.

the flood and ebb tide data. Note the end of the pressure sensor data on 25 Sept. 2010 when the ADV failed and the absence of water depth data when the survey staff was submerged at high tide. The water depth data showed consistently that the water level was nearly constant for the 60-90 minutes prior to the tidal bore. The arrival of the breaking bore was associated with a very rapid rise of the water elevation. At the sampling location, the free-surface elevation rose very rapidly by 0.4 m with the passage of the roller. For the next 3 minutes, the water elevation rose further by 0.5 m. During the first 45 minutes of the flood tide, the water depth increased altogether by 3 m. In contrast, the water depth dropped at a rate of 1 m in 40 minutes during the ebb tide (Fig. 3-4 B).

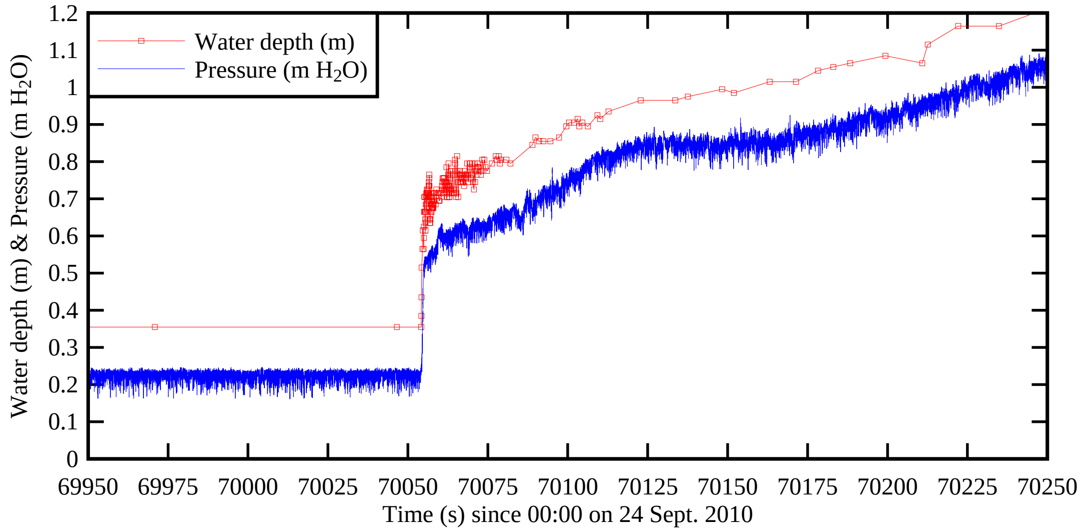
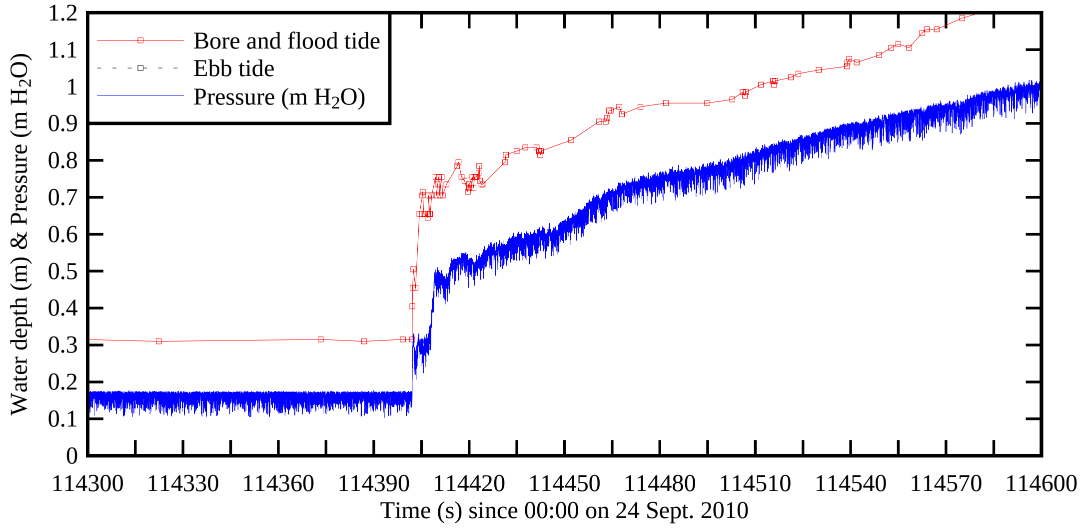
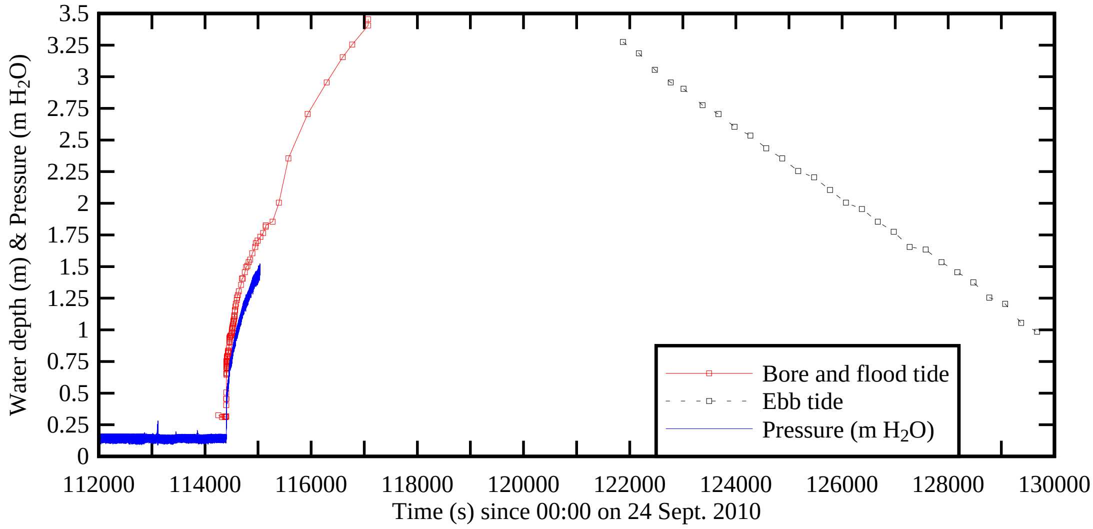


Fig. 3-3 - Time variations of the water depth and ADV pressure sensor on 24 Sept. 2010 during the tidal bore passage



(A) During the tidal bore passage



(B) Entire record during the flood and ebb tides

Fig. 3-4 - Time variations of the water depth and ADV pressure sensor on 25 Sept. 2010

4. TURBULENCE CHARACTERISTICS

4.1 TURBULENT VELOCITY FIELD

The turbulent velocity data indicated the marked impact of the breaking bore propagation on the velocity field (Fig. 4-1 & 4-2). Figures 4-1 and 4-2 show the time-variations of the three velocity components during the breaking tidal bore, where the longitudinal velocity component V_x is positive downstream (down river), the transverse velocity component V_y is positive towards the left bank (towards Mont Saint Michel and Tombelaine Island), and the vertical velocity component V_z is positive upwards. The time-variations of the water depth at the ADV sampling volume location are shown, as well as the backscatter intensity BSI defined as:

$$\mathrm{BSI} = 10^{-5} \times 10^{0.043 \times \mathrm{Ampl}} \qquad (4\text{-}1)$$

where the backscatter intensity BSI is dimensionless and the average amplitude 'Ampl' is in counts. The acoustic backscatter intensity may be related to the instantaneous suspended sediment concentration (SSC) with proper calibration ([1]) (FUGATE and FRIEDRICHS 2002).

The turbulent velocity data showed the drastic effect of the passage of the breaking bore front (Fig. 4-1 & 4-2). The bore passage and a sudden rise in the free surface elevation were associated with a sharp decrease in longitudinal velocity component, and a flow direction reversal (Fig. 4-1 & 4-2). The observations were consistent with the earlier results of SIMPSON et al. (2004) in the field, and HORNUNG et al. (1995), KOCH and CHANSON (2009) and CHANSON (2010b) in laboratory. The tidal bore passage was linked with some large and rapid fluctuations in amplitude of all three turbulent velocity components.

The longitudinal velocity component changed from +0.95 and +0.6 m/s (oriented downriver) in average to -1 and -1.3 m/s (oriented upriver) immediately after the passage of the breaking bore, on the 24 and 25 Sept. 2010 respectively (Fig. 4-1A & 4-2A). Some large velocity fluctuations were observed during the tidal bore. The longitudinal velocity data were consistent with the visual observations by the authors: a relatively strong downstream current was seen prior to the tidal bore, while the surface velocity flowed upstream after the bore. Another key feature was the widening of the channel as the water level rose rapidly above the sand banks. Further on 25 Sept. 2010, the longitudinal velocity data indicated a local minimum (V_x ~ -1.8 m/s) about 2.5 s after the roller toe passage. A similar pattern was seen in laboratory close to the bed (KOCH and CHANSON 2009, CHANSON 2010b). The ADV sampling volume was at an initial relative elevation z/d_1 = 0.3 on 25 Sept. 2010 compared to z/d_1 = 0.6 on 24 Sept. 2010, where z is the vertical elevation and d_1 is the

[1] In Equation (4-1), the coefficient 10^{-5} is a value introduced to avoid large values of backscatter intensity (NIKORA and GORING 2002, CHANSON et al. 2008).

initial water depth at the ADV sampling location (Table 4-1, column 9).

After the passage of the bore, the transverse velocity data fluctuated between -0.4 and +0.3 m/s, and 0 and +0.8 m/s, on 24 and 25 Sept. 2010 respectively. The time-averaged transverse velocity component was +0.05 and +0.4 m/s on 24 and 25 Sept. 2010 (Fig. 4-1B & 4-2B). The finding implied some net transverse circulation towards the left bank, possibly because of the channel widening towards the left bank sand bars The channel bathymetry was asymmetrical implying some transverse currents.

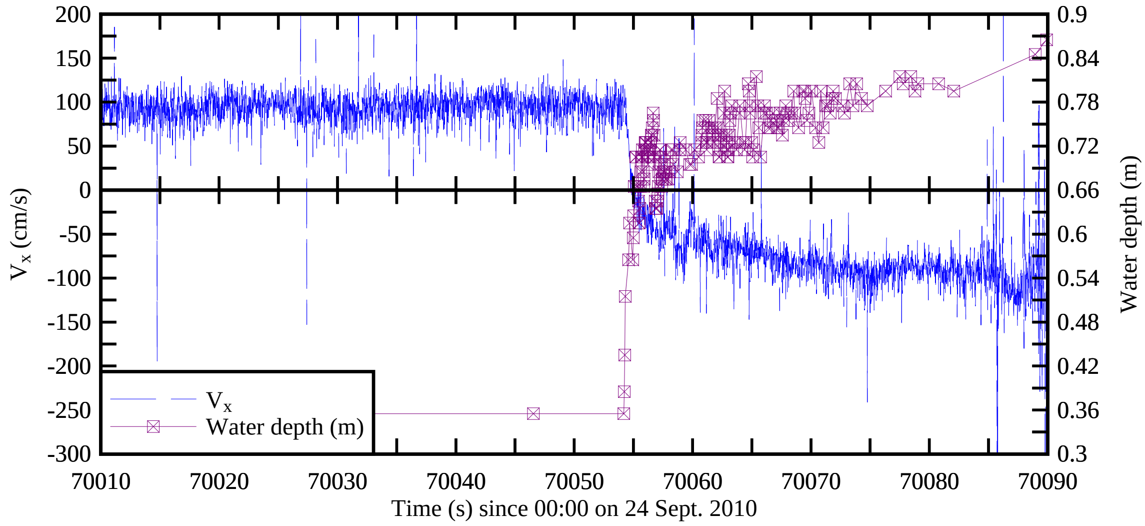
The vertical velocity data highlighted a marked effect of the tidal bore. After the bore passage, the vertical velocity fluctuated between -0.5 and +0.8 m/s, with a time-averaged value of about 0 and +0.24 m/s on 24 and 25 Sept. 2010 (Fig. 4-1B & 4-2B).

Table 4-1 - Turbulent velocity measurements in the tidal bore of the Sélune River downstream of Pointe du Grouin du Sud (Bay of Mont Saint Michel, France)

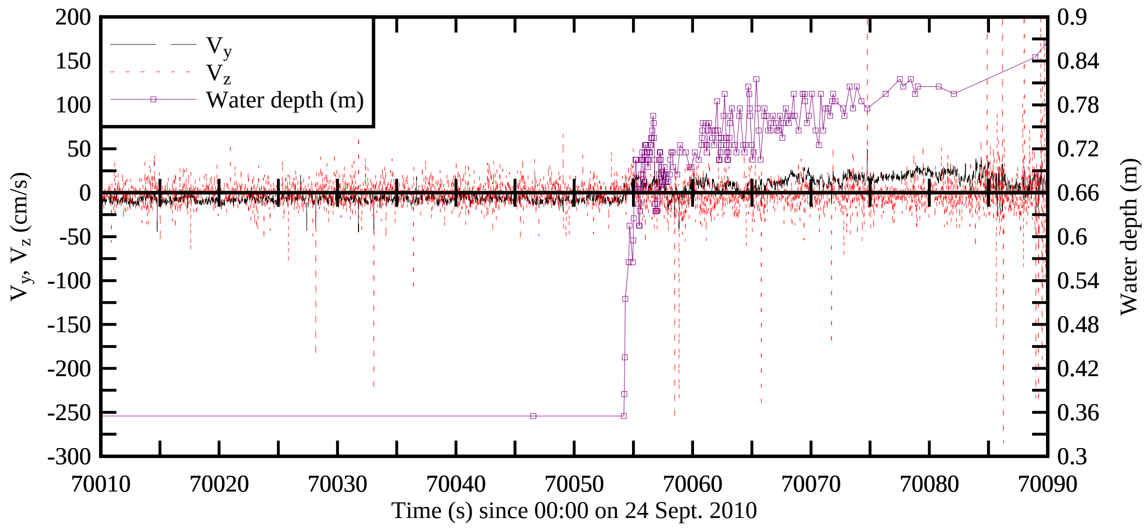
Date (1)	Tidal range (m) (2)	High tide time (3)	Tidal bore type (4)	Tidal bore time (5)	Sampling volume location (6)	z (m) (7)	d_1 (m) (8)	z/d_1 (9)	Tidal bore type (10)
24/10/2010	9.8	19:48	Breaking bore	19:27	About 55.1 m from right bank (herbus [salt marches]), 0.225 m above the bed.	0.225	0.375	0.60	Breaking bore
25/09/2010	9.9	08:02	Breaking bore	07:46	About 51.3 m from right bank (herbus [salt marches]), 0.1 m above the bed.	0.10	0.325	0.31	Breaking bore

Notes: d_1: water depth next to ADV immediately prior to the bore passage; z: sampling elevation above bed

The backscatter intensity data (BSI) showed a number of short transients during and shortly after the tidal bore (Fig. 4-1C and 4-2C) that were likely linked with large suspended sediment concentrations and possibly some re-suspension bursts. Such high levels of particle re-suspension were observed in the tidal bores of the Dee and Garonne Rivers (SIMPSON et al. 2004, CHANSON et al. 2010). The backscatter intensity data showed some marked differences between the 24 and 25 Sept. 2010, possibly linked with some different initial flow conditions (Fig. 4-1C and 4-2C). On 24 Sept. 2010, the ebb flow velocity was significant (V_1 ~ +0.9 m/s), and the ebb flow was sediment-laden ([2]). The tidal bore arrival contributed to further sediment motion, and the BSI levels were significant both before and after the tidal bore. On 25 Sept.2010, the ebb flow velocity was less energetic (V_1 ~ +0.6 m/s). The BSI data suggested little sediment suspension in the water column prior to the tidal bore, although some high concentration of suspended sediment could be present close to the bed, and a drastic increase in BSI with the passage of the bore linked with some sediment re-suspension.

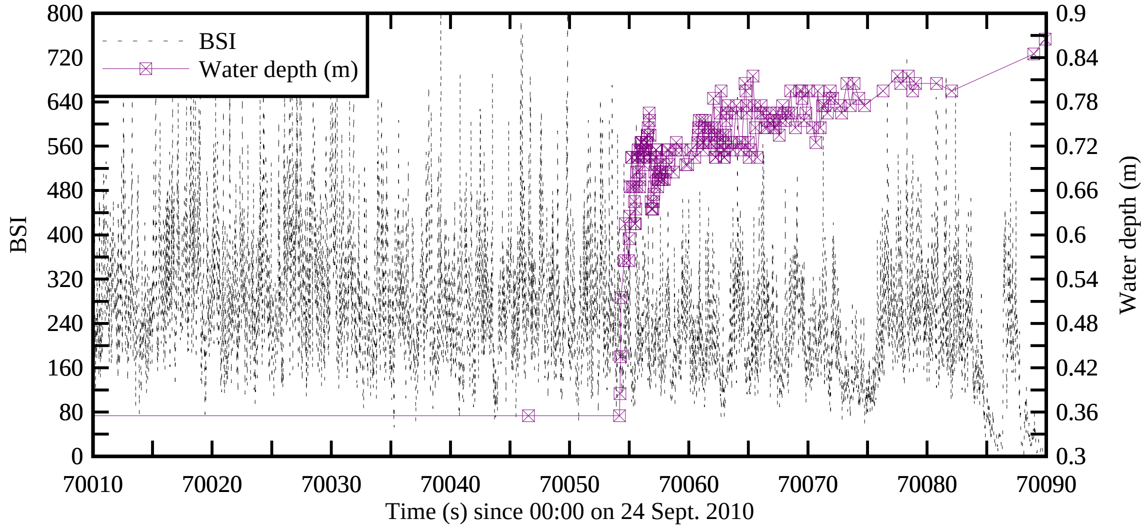


(A) Longitudinal velocity component V_x and water depth



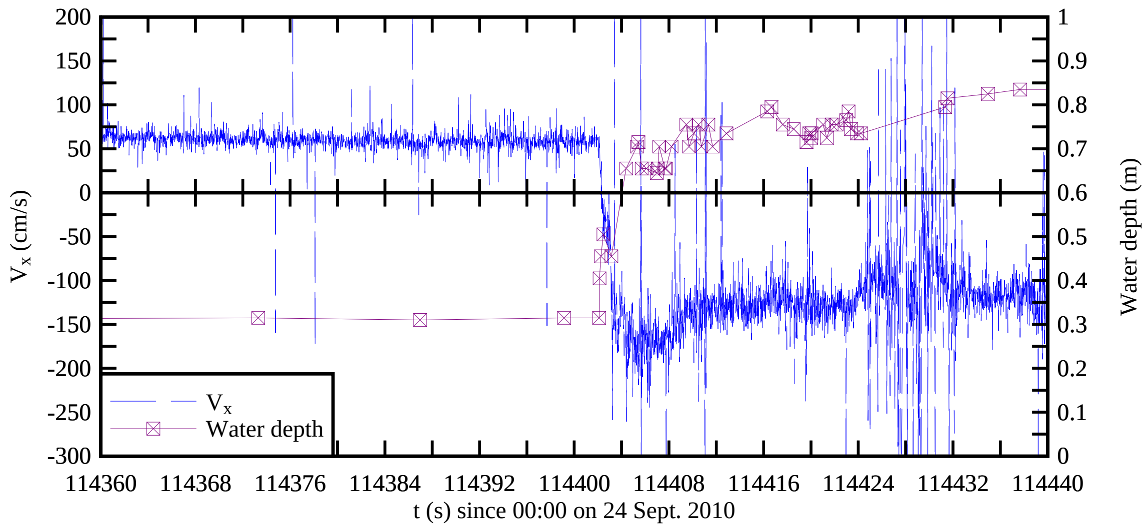
(B) Transverse velocity component V_y, vertical velocity component V_z and water depth

[2] When installing the equipment on 24 Sept. 2010, the authors felt the downstream flux of sediment in suspension with their legs and feet.

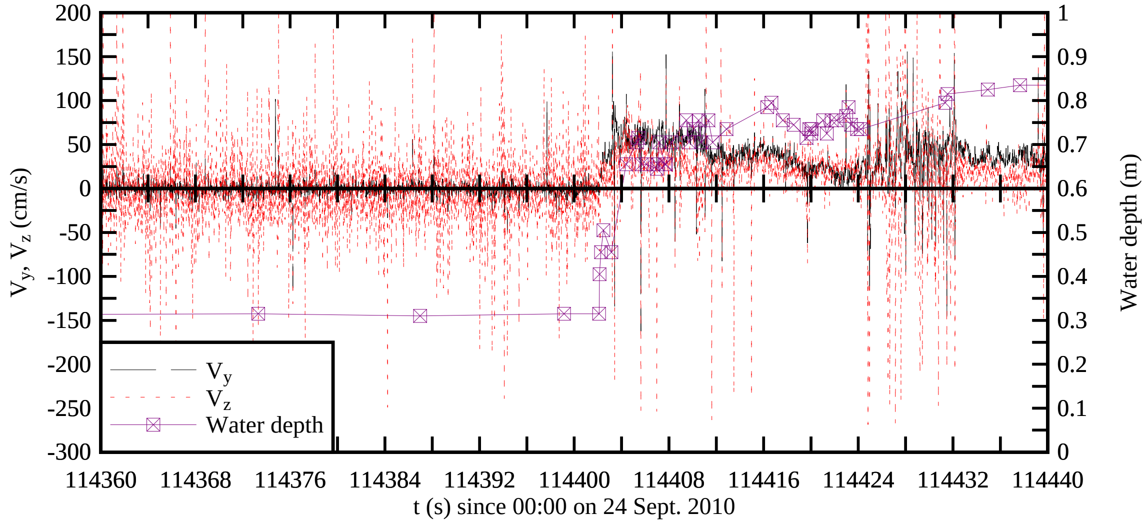


(C) Acoustic backscatter intensity BSI and water depth

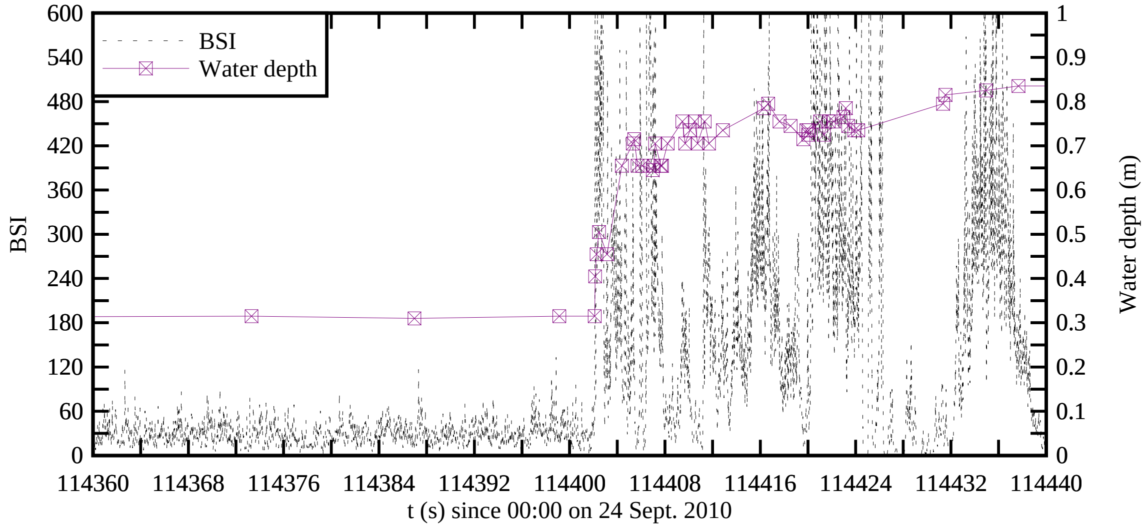
Fig. 4-1 - Time variations of the water depth, turbulent velocity components and acoustic backscatter intensity in the breaking bore of the Sélune River on 24 Sept. 2010 - Post-processed ADV data, sampling rate: 64 Hz - ADV sampling volume elevation: z = 0.225 m above the bed



(A) Longitudinal velocity component V_x and water depth



(B) Transverse velocity component V_y, vertical velocity component V_z and water depth



(C) Acoustic backscatter intensity BSI and water depth

Fig. 4-2 - Time variations of the water depth, turbulent velocity components and acoustic backscatter intensity in the breaking bore of the Sélune River on 25 Sept. 2010 - Post-processed ADV data, sampling rate: 64 Hz - ADV sampling volume elevation: z = 0.1 m above the bed

The ADV sampling volume elevation was z = 0.225 and 0.1 m respectively on 24 and 25 Sept. 2010 (Table 4-1). The velocity data characterised therefore the turbulence relatively close in the mobile bed during the flood flow motion. Lastly note that the ADV records were limited because of a series of problems discussed in section 2.3.

Discussion

Prior to the tidal bore on 24 Sept. 2010, the ADV sampled continuously for nearly 90 minutes in the

Sélune River. The flow was basically steady and the cross-sectional averaged Froude number $V_1 / \sqrt{g \times A_1 / B_1}$ was equal to 0.71. That is, the Sélune River flow was transcritical and some small free-surface standing waves were seen. The ADV system sampled the turbulent velocity at a relative elevation z/d_1 = 0.60. The time-averaged longitudinal velocity $\overline{V_x}$ equalled 0.98 m/s ([3]), and the dimensionless velocity standard deviations were equal to: $v_x'/\overline{V_x}$ = 0.16, $v_y'/\overline{V_x}$ = 0.04, and $v_z'/\overline{V_x}$ = 0.14. The present data indicated altogether some larger turbulent intensities than those recorded in laboratory open channel flows at a comparable relative elevation z/d (NEZU and NAKAGAWA 1993, NEZU 2005). But some key features of the initial flow conditions on 24 Sept. 2010 included the transcritical flow conditions, an active mobile bed and some sediment processes, and a flat, wide and irregular cross-section (Fig. 2-2). Standing wave and dune bed forms could add an extra roughness, enhancing turbulent intensities and resuspension. Figure 4-2C shows some interesting low frequency variations and some questions remain if this could be caused by some burst of suspended sediment being convected with the main flow, or some local modifications of the bathymetry corresponding to bed form migration and/or collapse and reformation.

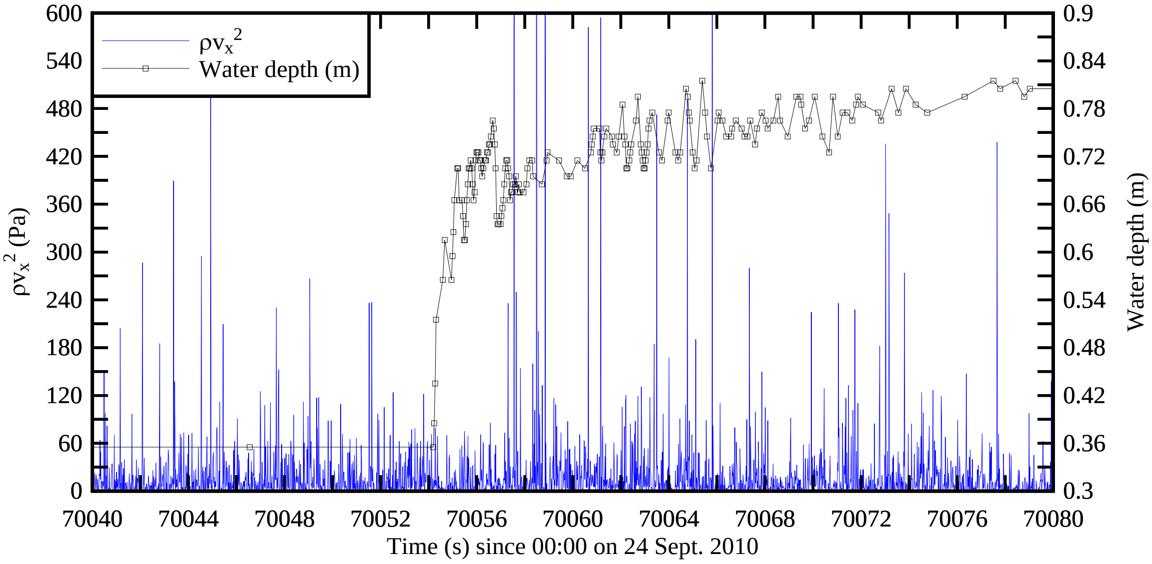
The velocity records showed qualitatively some difference between the 24 and 25 Sept. 2010. The 25 Sept. 2010 data presented a number of "spikes" (Fig. 4-2) on all velocity components. These were linked with trigonometric uncertainties during the velocity re-construction process. Further the velocity data set on 25 Sept. 2010 showed a lot of spikes about 20 s after the tidal bore, associated with some low amplitude (Fig. 4-2). It is unknown if these highlighted a patch or burst of macro-turbulence, as noted by WOLANSKI et al. (2004) in the Daly River, or some problem with the ADV system (see discussion in section 2.3).

4.2 TURBULENT SHEAR STRESSES

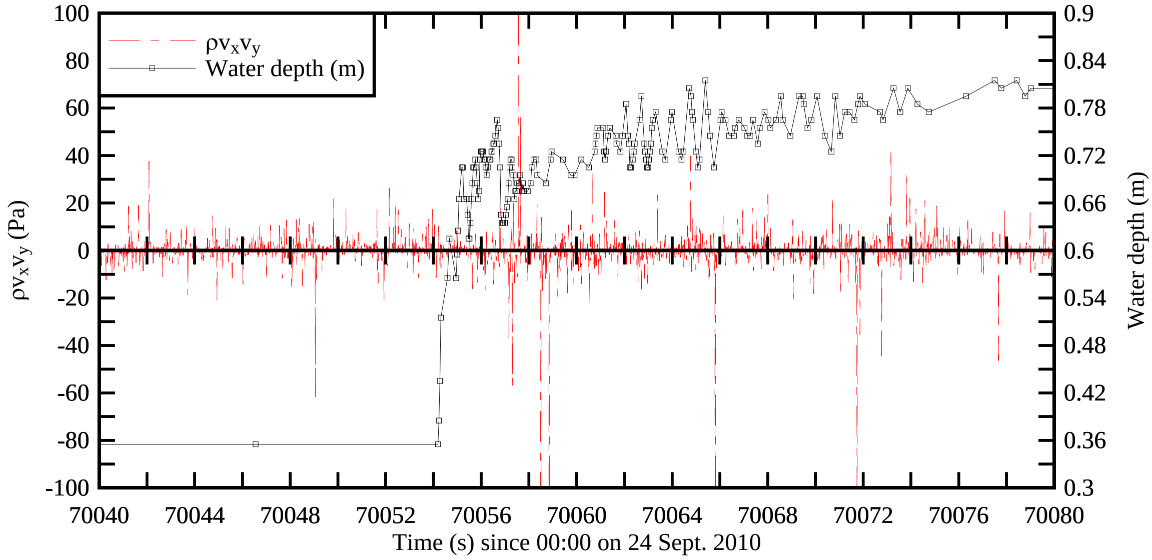
The velocity fluctuation is the deviation of the instantaneous velocity from an "average" velocity component $\overline{V}$. In an unsteady flow, $\overline{V}$ is the variable interval time average VITA (PIQUET 1999). A VITA method was applied using a cut-off frequency derived upon a sensitivity analysis. The results yielded an optimum threshold of F_{cutoff} = 1 Hz, and the filtering was applied to all velocity components. Note that CHANSON et al. (2010) used the same cut-off frequency filter for some field measurements as well as KOCH and CHANSON (2009) in laboratory. The filtering was applied to all velocity components, and the turbulent Reynolds stresses were calculated from the high-pass filtered signals. The turbulent stresses characterise a transport effect resulting from

[3] Between 18:00 and 19:20 on 24 Sept. 2010.

turbulent motion induced by velocity fluctuations with its subsequent increase of momentum exchange and of mixing (BRADSHAW 1971, PIQUET 1999).

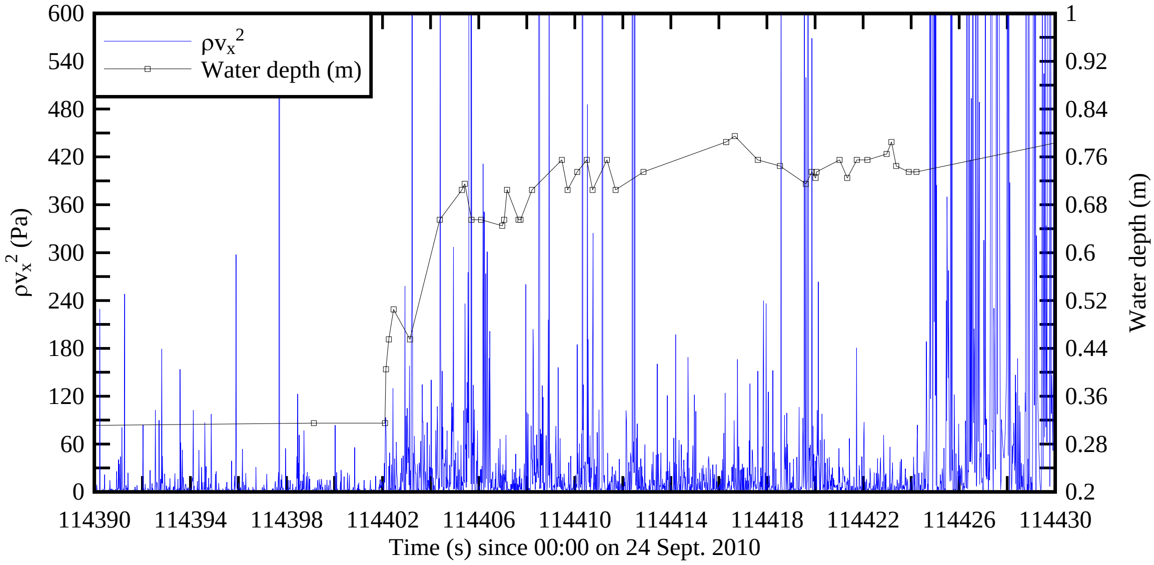


(A) $\rho \times v_x^2$

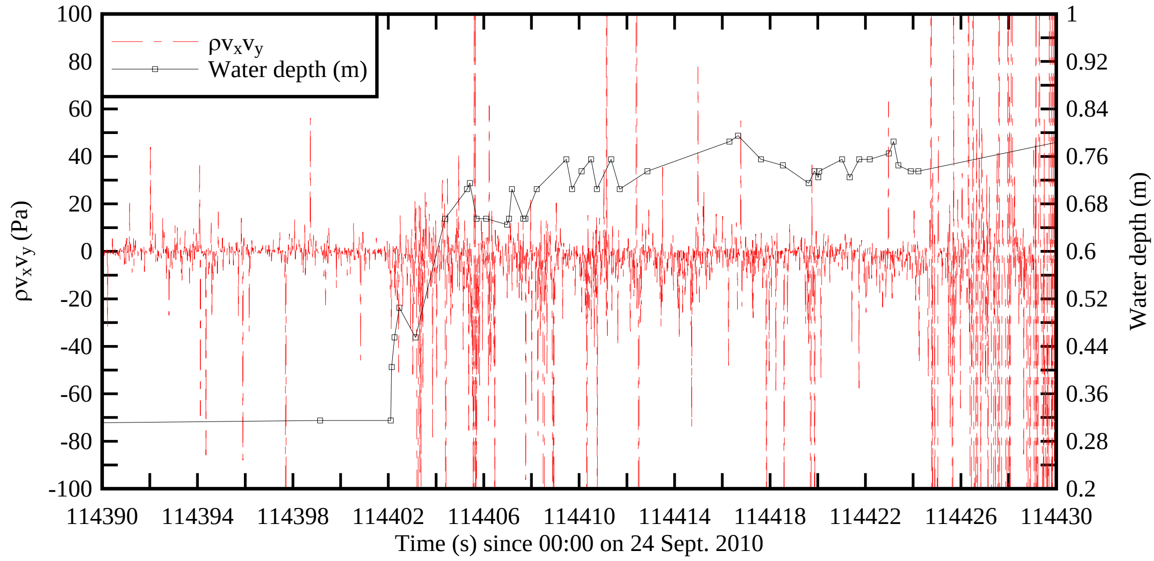


(B) $\rho \times v_x \times v_y$

Fig. 4-3 - Time-variations of Reynolds stresses and water depth during the tidal bore passage on 24 Sept. 2010 - Post-processed ADV data, sampling rate: 64 Hz



(A) $\rho \times v_x^2$



(B) $\rho \times v_x \times v_y$

Fig. 4-4 - Time-variations of Reynolds stresses and water depth during the tidal bore passage on 25 Sept. 2010 - Post-processed ADV data, sampling rate: 64 Hz

Figures 4-3 and 4-4 present some results in terms of normal and tangential Reynolds stresses on 24 and 25 Sept. 2010 respectively, and the full data set is presented in Appendix D. The present data showed large and rapid turbulent Reynolds stress fluctuations below the tidal bore roller and flood flow (Fig. 4-3 & 4-4). The Reynolds stress levels were significantly larger than during the ebb tide, with normal stress magnitudes more than 100 Pa and normal stress magnitudes more than 50 Pa. Such values were significantly larger than previous laboratory data (KOCH and CHANSON 2009, CHANSON 2010b), but less than field observations in the Garonne River (CHANSON et al. 2010).

Discussion

The present field measurements demonstrated the intense turbulent mixing beneath the breaking tidal bore. Some large magnitude and rapid fluctuations of turbulent Reynolds stresses were observed. For a non-cohesive sediment material, the Shields diagram gives a critical shear stress for sediment bed load motion about: $(\tau_o)_c$ = 0.1 to 6 Pa for quartz particles with sizes between 0.1 and 10 mm (JULIEN 1995, CHANSON 2004). Herein the instantaneous turbulent shear stress magnitudes were larger than the critical threshold for sediment motion and transport.

The comparison has some limits. In a breaking tidal bore, the large scale vortices play an important role in terms of sediment material pickup and upward advection. This type of sediment motion occurs by convection since the turbulent mixing length is much larger than the sediment distribution length scale. In such a case, the validity of the Shields diagram application is arguable. Furthermore the high levels of shear stresses revealed during these field measurements occurred during very short transient time (several bursts) and not at a continuous level like in rivers…

5. CONCLUSION

Some field measurements were conducted in the tidal bore of the Sélune River, Bay of Mont Saint Michel (France) on 24 and 25 Sept. 2010. The turbulent velocity measurements were performed continuously at high-frequency (64 Hz) in the breaking tidal bore. The passage of the tidal bore was characterised by a strong turbulent mixing in the bore. A key feature was the rapid change in the channel cross-section as the tidal bore expanded over the sand banks over the left channel side. The tidal bore Froude number was estimated from the channel bathymetry and tidal bore observations. It was equal to 2.35 and 2.48 on 24 and 25 Sept. 2010 respectively.

The turbulent velocity data showed the marked impact of the tidal bore roller. The longitudinal velocity component indicated some rapid flow deceleration during the passage of the tidal bore, associated with a sudden rise in the free surface elevation, and a flow reversal after the tidal bore front passage. The observations were consistent with a number of field and laboratory observations. The tidal bore passage was further characterised by some large fluctuations of all three turbulent velocity components. The Reynolds stress data indicated some large and rapid turbulent stress fluctuations during the tidal bore and flood flow.

The ADV acoustic backscatter intensity (BSI) data provided an indicator of the suspended sediment concentration fluctuations during the tidal bore. The passage of the bore and the ebb flow was always characterised by large backscatter intensity levels corresponding to large suspended sediment concentrations. The data showed some marked differences between the 24 and 25 Sept. 2010, possibly linked with some different initial flow conditions. On 24 Sept. 2010, the ebb flow was fast flowing and sediment-laden. The tidal bore arrival contributed to further sediment motion, and the BSI levels were significant both before and after the tidal bore. On 25 Sept.2010, the ebb flow was less energetic, and the backscatter data suggested little sediment suspension prior to the tidal bore. But a drastic increase in BSI was observed during with the passage of the bore linked with some sediment re-suspension.

A specific particularity of the present field data set was the repeated problems experienced during both days. On 24 and 25 September 2010, the ADV support failed about 40 s after the passage of the bore, and the ADV unit was almost lost. On 25 Sept. 2010 early morning, the ADV system was re-positioned in front of an old WWII German truck. About 60 s after the tidal bore, the ADV signal became very noisy, with a drastic loss in SNR and amplitude, possibly be linked with a low battery level or some debris trapped around the ADV head. Twenty minutes later, the ADV signal stopped completely because either the ADV memory was full or the battery was dead.

This study will be complemented by further field works conducted in the Bay of Mont Saint Michel under different tidal and fluvial conditions during the following years. Some studies should be conducted also in different estuarine systems (e.g. Garonne River). The future studies should include a detailed characterisation of the water physical properties in the tidal bore, including water temperature, conductivity, turbidity, pH, dissolved oxygen...

6. ACKNOWLEDGEMENTS

The authors thank Dr Eric JONES (Proudman Oceanographic Laboratory) for their detailed reviews of the report and valuable comments.

The authors thank in particular Dr Frederique LARRARTE, Dr Bernadette TESSIER and Dr Fredric MURZYN who participated to the field works (Appendix A), without whom the study could not have been conducted. They acknowledge the assistance of the Maison de la Baie (Vains), its personnel and its director Jean-Yves COCAIGN for the tremendous support and friendly help. They acknowledge the support and input of Dr Pierre LUBIN (Université de Bordeaux, France), and the assistance Guillaume SIMON and Monica on Saturday.

Hubert CHANSON received some financial assistance from the Université de Bordeaux and the University of Queensland; Bruno SIMON acknowledges a joint scholarship funded by the TREFLE Laboratory and the Région Aquitaine; the financial assistance of the Agence Nationale de la Recherche (Projet Mascaret) is acknowledged.

APPENDIX A - LIST OF FIELD WORK PARTICIPANTS (24 AND 25 SEPTEMBER 2010)

A.1 LIST OF PARTICIPANTS

Hubert CHANSON (University of Queensland / Université de Bordeaux)

Frédérique LARRARTE (LCPC- Nantes)

Dominique MOUAZE (Université de Caen)

Frédéric MURZYN (ESTACA-Laval)

Bruno SIMON (Université de Bordeaux / University of Queensland)

Bernadette TESSIER (Université de Caen)

A.2 PHOTOGRAPHS OF THE PARTICIPANTS

(A) On 24 Sept. 2010, Frédéric MURZYN and Frédérique LARRARTE (from left to right) preparing the surveying equipment (Photograph H. CHANSON)

(B) On 24 Sept. 2010, Dominique MOUAZE at the theodolite (Photograph H. CHANSON)

(C) On 24 Sept. 2010, Frédéric MURZYN and Hubert CHANSON (from left to right) prior to the tidal bore (Photograph D. MOUAZE) - The survey staff was attached to the WWII German truck

(D) On 24 Sept. 2010, Bruno SIMON, Hubert CHANSON, Frédérique LARRARTE, Frédéric MURZYN from left to right (Photograph D. MOUAZE) - The submerged WWII German truck is barely visible at the bottom right

(E) On 25 Sept. 2010, Dominique MOUAZE, Frédérique LARRARTE, Frédéric MURZYN and Bruno SIMON from foreground to background (Photograph H. CHANSON)

Fig. A-1 - Photographs of the field work participants

APPENDIX B - PHOTOGRAPHS OF THE FIELD STUDY (24 AND 25 SEPTEMBER 2010)

(A) Preparation of the Sélune River channel survey at 16:00 (Photograph F. MURZYN) - From left to right, Bruno SIMON, Frédérique LARRARTE and Dominique MOUAZE with Ile de Tombelaine in the background

(B) Installation of the ADV on the tripod at 16:40 (Photograph F. MURZYN) - From left to right, Frédérique LARRARTE, Dominique MOUAZE, Hubert CHANSON and Bruno SIMON with Ile de Tombelaine in the background

(C) Tidal bore downstream of the sampling site, about 85 s before it reached the ADV unit (Photograph H. CHANSON)

(D) Tidal bore 78 s before it reached the ADV unit (Photograph H. CHANSON)

(E) Tidal bore 17 s before it reached the ADV unit (Photograph H. CHANSON)

(F) Tidal bore 8 s before it reached the ADV unit (Photograph H. CHANSON)

(G) Tidal bore 4 s before it reached the ADV unit (Photograph H. CHANSON)

(H) Tidal bore reaching the ADV unit (Photograph H. CHANSON)

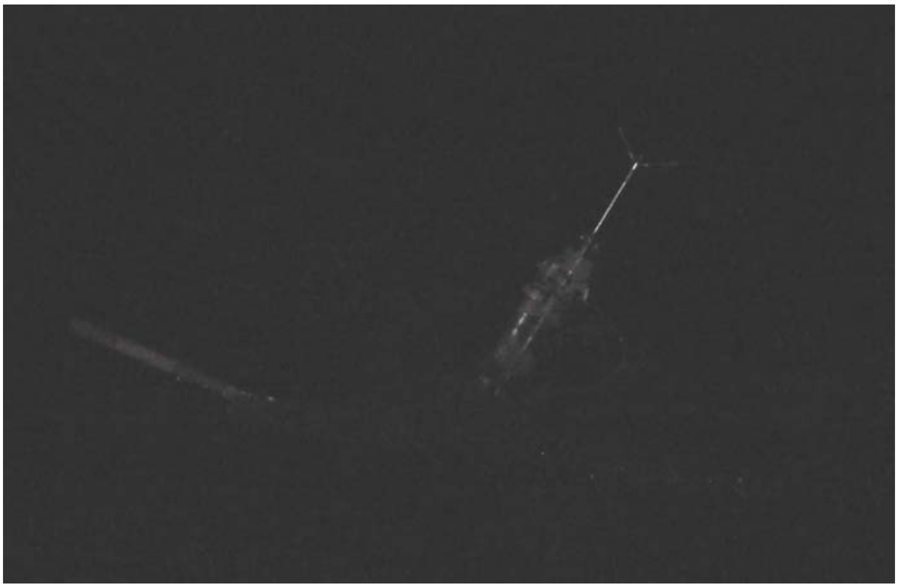
(I) Tidal bore about 2 s after it reached the ADV unit (Photograph H. CHANSON)

(J) Tidal bore 3 s after it reached the ADV unit (Photograph H. CHANSON)

(K) Tidal bore about 5 s after it reached the ADV unit (Photograph H. CHANSON) - Note the curve shape of the bore front and, in the background, the dark colour of the bore front advancing on the sand banks

(L) Tidal bore about 9 s after it reached the ADV unit (Photograph H. CHANSON)

Fig. B-1 - Sélune River and tidal bore on 24 Sept. 2010 - Views from the right bank



(A) ADV system and damaged support at 07:12, view from the right bank (Photograph F. MURZYN) - Note the ADV head pointing upwards and one of the poles on the left

(B) Installation of the ADV system in front of the WWII German truck at 07:40 shortly prior to the tidal bore (Photograph F. MURZYN) - From left to right, Bernadette TESSIER, Bruno SIMON, Hubert CHANSON, Dominique MOUAZE and Frédérique LARRARTE

(C) Tidal bore about 50 m downstream of the WWII German truck (Photograph D. MOUAZE)

(D) Tidal bore about 20 m downstream of the WWII German truck (Photograph D. MOUAZE)

(E) Tidal bore passing the WWII German truck with Frédérique LARRARTE, in the foreground, timing the tidal bore celerity (Photograph D. MOUAZE)

(F) Standing waves in the Sélune River channel about 10 minutes after the tidal bore (Photograph D. MOUAZE)

Fig. B-2 - Sélune River and tidal bore on 25 Sept. 2010 - Views from the right bank

(A) At 19:41 (Photograph D. MOUAZE)

(B) At 19:44 with Ile de Tombelaine in the background (Photograph D. MOUAZE)

Fig. B-3 - Standing waves in the Sélune River flood flow on 24 Sept. 2010 - Views from the right bank

Fig. B-4 - Transient front in Sélune River on 25 Sept. 2010 at 19:36, 6 min after the tidal bore passage (Photograph H. CHANSON) - View from the right bank of the white foam line of the front

Fig. B-5 - Harbour seal in the Sélune River ebb flow on 25 Sept. 2010 at 11:35 (Photograph D. MOUAZE) - View from the right bank

APPENDIX C - ACOUSTIC DOPPLER VELOCIMETER CONFIGURATIONS (24 AND 25 SEPTEMBER 2010)

C.1 PRESENTATION

During the field investigation, a Nortek™ Vector ADV (6 MHz, serial number VEC3332) was deployed. The ADV was equipped with a 3D downlooking head (Head ID VEC4665). The ADV V_x direction (receiver head with red mark) was pointed downstream.

The ADV was fixed on a tripod on 24 Sept. 2010 and it was fixed to the WWII German truck on 25 Sept. 2010. The ADV settings were selected based upon an earlier experience by CHANSON and al. (2010) with the same equipment. They are listed in the next paragraph.

C.2 ADV CONFIGURATION 24-25 SEPT. 2010

Filename:	Selune01.vec
Number of measurements	3215163
Number of velocity checksum errors	0
Number of sensor checksum errors	0
Number of data gaps	0
Time of first measurement	24/09/2010 6:00:00 PM
Time of last measurement	25/09/2010 7:57:18 AM

<u>User setup</u>

Sampling rate	64 Hz
Nominal velocity range	2.00 m/s
Burst interval	CONTINUOUS
Samples per burst	N/A
Sampling volume	6.6 mm
Measurement load	62 %
Transmit length	2.0 mm
Receive length	0.00 m
Output sync	VECTOR
Analog output	DISABLED
Analog input 1	NONE
Analog input 2	NONE
Power output	DISABLED
Output format	VECTOR
Velocity scaling	1 mm
Powerlevel	HIGH
Coordinate system	XYZ
Sound speed	MEASURED
Salinity	0.0 ppt

Distance between pings	1.01 m
Number of beams	3
Software version	1.32
Deployment name	Selune
Wrap mode	OFF
Deployment time	24/09/2010 6:00:00 PM

Comments: Pte Grouin du Sud Camion allemand on 24 Sept. 2010 evening - Tidal bore measurements from tripod

System1	1
System2	16
System3	3
System4	44
System5	512
System9	130
System10	0
System11	0
System12	0
System13	0
System14	1
System16	1
System17	3
System22	10800
System28	1
System29	1
System30	20
System31	15087 15117 15147 15176
System32	2000
System33	32768
System34	16384
System35	32768
System36	16384
System37	8192
System38	30
System39	60
System40	0
System41	1
System42	13422
System43	0
System44	0
System45	2
Start command	Recorder deployment
CRC download	ON

Hardware configuration

Serial number	VEC 3332
Internal code version	13
Revision number	60
Recorder size	154 MByte
Firmware version	1.21

Head configuration

Pressure sensor	YES
Compass	YES
Tilt sensor	YES
System 1	0
Head frequency	6000 kHz
Serial number	VEC 4665
Transformation matrix	2.7312 -1.3479 -1.3835
	0.0217 2.3530 -2.3708
	0.3440 0.3389 0.3479
Pressure sensor calibration	0 0 4472 24558
Number of beams	3
System5	0 0 0 0
System7	-9825 -623 8380 33
	-10357 -282 8699 30
System8	0 0 -1
	0 -1 0
	-1 0 0
System9	0 0 -1
	0 1 0
	1 0 0
System10	0 -1 -1 0
System11	0 -1 1 0
System13	11847 18809 19217 26843
System14	-22839 -1751 12182 110
	-23614 -1245 12444 207
System15	32767 0 811 0
	32368 720 0 0
	32767 64 2 0
	0 0 0 0
System16	0 0 0 0
System17	5279
System18	3600
System19	3600
System20	10000

Data file format

Filename: Selune01.vhd

1 Month (1-12)

2 Day (1-31)

3 Year

4 Hour (0-23)

5 Minute (0-59)

6 Second (0-59)

7 Burst counter

8 No of velocity samples

9 Noise amplitude (Beam1) (counts)

10 Noise amplitude (Beam2) (counts)

11 Noise amplitude (Beam3) (counts)

12 Noise correlation (Beam1) (%)

13 Noise correlation (Beam2) (%)

14 Noise correlation (Beam3) (%)

15 Dist from probe - start (Beam1) (counts)

16 Dist from probe - start (Beam2) (counts)

17 Dist from probe - start (Beam3) (counts)

18 Dist from probe - start (Avg) (mm)

19 Dist from s.vol - start (Avg) (mm)

20 Dist from probe - end (Beam1) (counts)

21 Dist from probe - end (Beam2) (counts)

22 Dist from probe - end (Beam3) (counts)

23 Dist from probe - end (Avg) (mm)

24 Dist from s.vol - end (Avg) (mm)

Filename: Selune01.dat

1 Burst counter

2 Ensemble counter (1-65536)

3 Velocity (Beam1|X|East) (m/s)

4 Velocity (Beam2|Y|North) (m/s)

5 Velocity (Beam3|Z|Up) (m/s)

6 Amplitude (Beam1) (counts)

7 Amplitude (Beam2) (counts)

8 Amplitude (Beam3) (counts)

9 SNR (Beam1) (dB)

10 SNR (Beam2) (dB)

11 SNR (Beam3) (dB)

12 Correlation (Beam1) (%)

13 Correlation (Beam2) (%)

14	Correlation (Beam3)	(%)
15	Pressure	(dbar)
16	Analog input 1	
17	Analog input 2	
18	Checksum	(1=failed)

Filename: Selune01.sen

1	Month	(1-12)
2	Day	(1-31)
3	Year	
4	Hour	(0-23)
5	Minute	(0-59)
6	Second	(0-59)
7	Error code	
8	Status code	
9	Battery voltage	(V)
10	Soundspeed	(m/s)
11	Heading	(degrees)
12	Pitch	(degrees)
13	Roll	(degrees)
14	Temperature	(degrees C)
15	Analog input	
16	Checksum	(1=failed)

Filename: Selune01.pck

1	Sample	
2	Distance	(mm)
3	Amplitude Beam 1	(counts)
4	Amplitude Beam 2	(counts)
5	Amplitude Beam 3	(counts)
6	Amplitude Beam 4	(counts)

APPENDIX D - UNSTEADY TURBULENT REYNOLDS STRESSES DURING THE SÉLUNE RIVER TIDAL BORE ON 24 AND 25 SEPT. 2010

D.1 PRESENTATION

Some detailed turbulence field measurements were conducted continuously at high-frequency (64 Hz) prior to, during and after the tidal bore of the Sélune River on 24 and 25 September 2010 (Table D-1). On 24 Sept. 2010, an acoustic Doppler velocimeter (ADV) system was fixed to a tripod: the unit was mounted horizontally. On 25 Sept. 2010 early morning, the ADV system was re-positioned in front of the WWII German truck, pointing slightly towards the left bank of the Sélune River channel (section 2.3). The velocity components were re-constructed from the ADV position; the velocity re-construction was performed on the post-processed ADV data. The ADV data underwent a thorough post-processing procedure to eliminate any erroneous or corrupted data from the data sets to be analysed. The post processing was conducted with the software WinADV™ version 2.026, and it included the removal of communication errors, the removal of average signal to noise ratio data less than 15 dB and the removal of average correlation values less than 60%. In addition, the phase-space thresholding technique developed by GORING and NIKORA (2002) was applied to remove spurious points.

The turbulent Reynolds stresses characterise a transport effect resulting from turbulent motion induced by velocity fluctuations with its subsequent increase of momentum exchange and of mixing (BRADSHAW 1971, PIQUET 1999). The Reynolds stresses are proportional to the product of two velocity fluctuations, where the turbulent velocity fluctuation is the deviation of the instantaneous velocity from a low-pass filtered velocity component, also called the variable interval time average VITA. A VITA method was applied using a cut-off frequency derived upon a sensitivity analysis. The results yielded an optimum threshold of F_{cutoff} = 1 Hz, and the filtering was applied to all velocity components. Note that CHANSON et al. (2010) used a same cutoff frequency for some field measurements as well as KOCH and CHANSON (2009) in laboratory.. The filtering was applied to all velocity components ([1]), and the turbulent Reynolds stresses were calculated from the high-pass filtered signals.

The experimental results are presented in the next sections.

<u>Remarks</u>

The Reynolds stress data showed qualitatively some difference between the 24 and 25 Sept. 2010

[1] Prior to the filtering, the erroneous data points were replaced by linear interpolation between the end points of the removed data interval.

data sets. The 25 Sept. 2010 data presented a number of "spikes" on all velocity components, associated with trigonometric uncertainties during the velocity re-construction process. Further the velocity data set on 25 Sept. 2010 showed a lot of spikes about 20 s after the tidal bore, associated with some low amplitude. It remains unknown if these spikes highlighted a patch of macro-turbulence, as noted by WOLANSKI et al. (2004) in the Daly River, or some problem with the ADV system (see discussion in section 2.3).

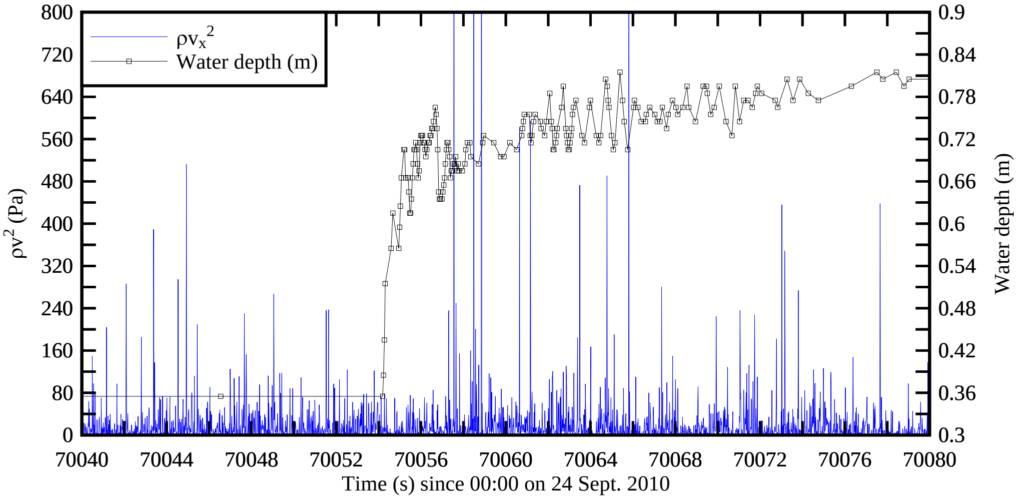
Table D-1 - Turbulent velocity measurements in the tidal bore of the Sélune River downstream of Pointe du Grouin du Sud (Bay of Mont Saint Michel, France)

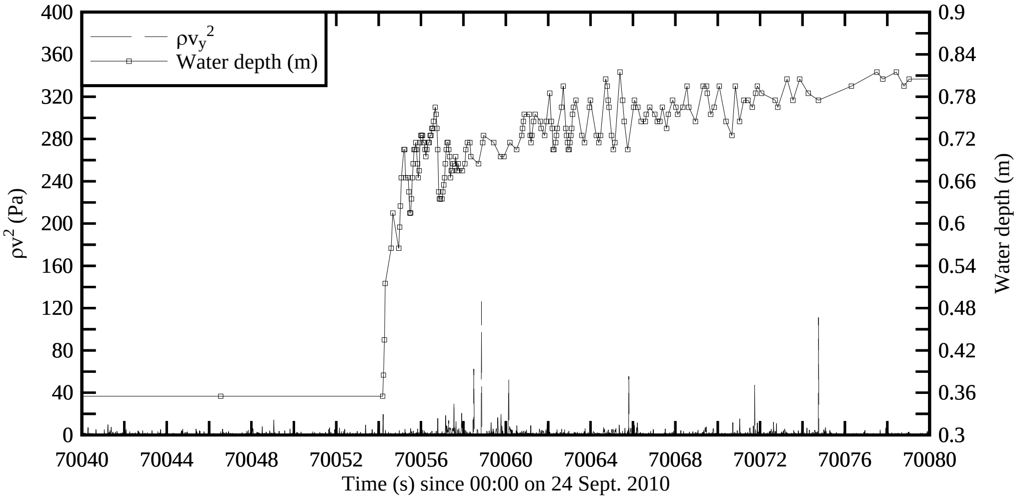
Date (1)	Tidal range (m) (2)	High tide time (3)	Tidal bore type (4)	Tidal bore time (5)	Sampling volume transverse location (6)	z (m) (7)	d_1 (m) (8)	z/d_1 (9)
24/10/2010	9.8	19:48	Breaking bore	19:27	55.1 m from right bank (herbu).	0.225	0.375	0.60
25/09/2010	9.9	08:02	Breaking bore	07:46	51.3 m from right bank (herbu).	0.10	0.325	0.31

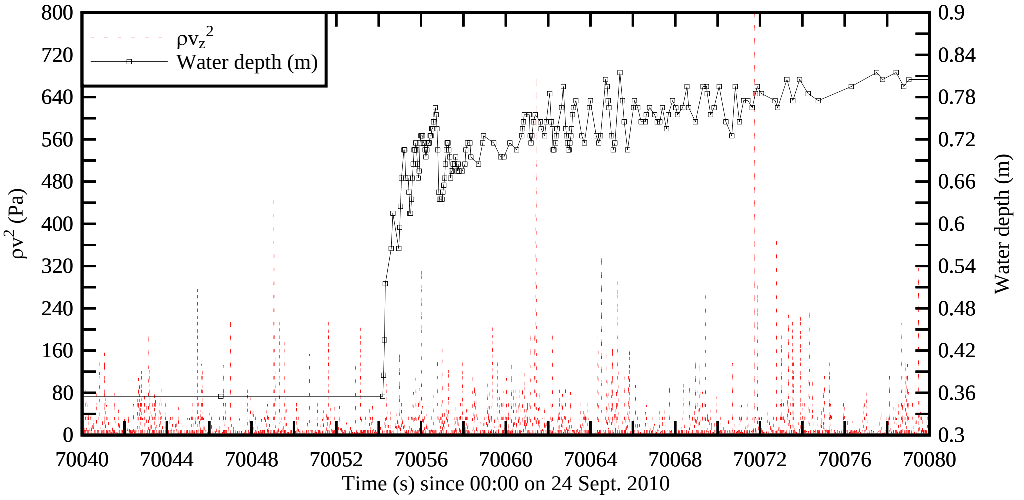
Notes: d_1: water depth next to ADV immediately prior to the bore passage; z: sampling elevation above bed

D.2 EXPERIMENTAL RESULTS ON 24 SEPT. 2010

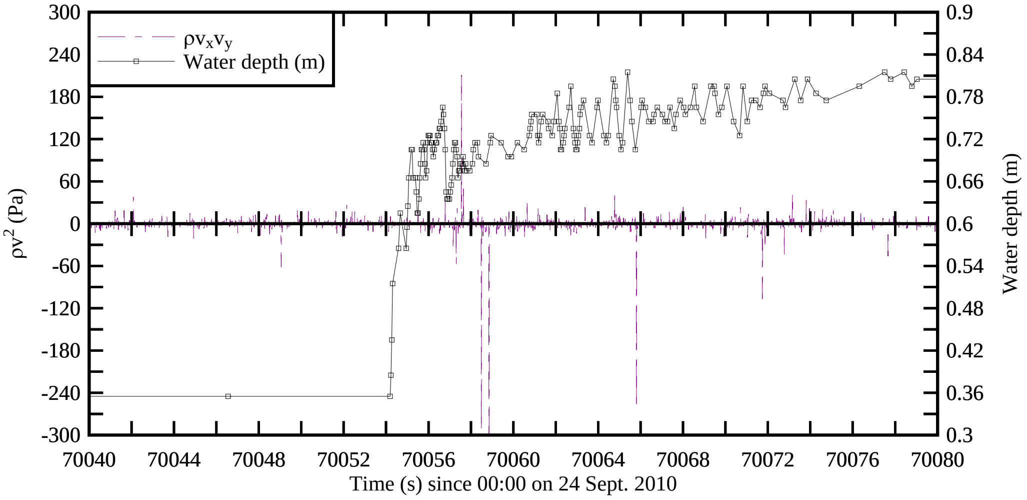
D.2.1 Normal Reynolds stresses

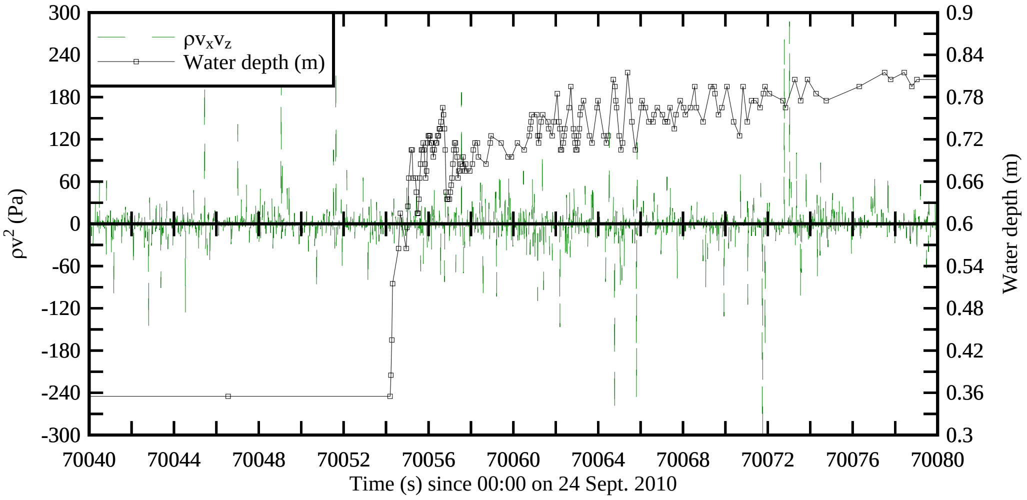


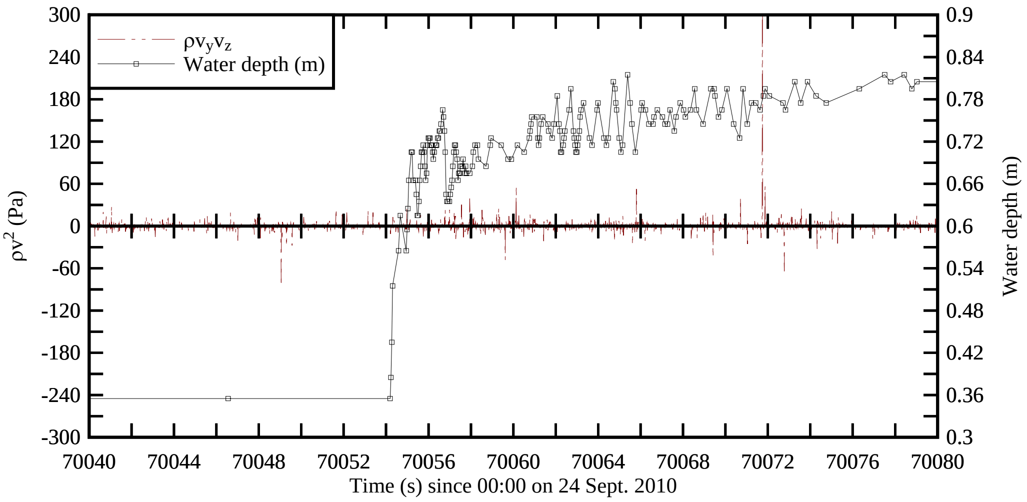




D.2.2 Tangential Reynolds stresses

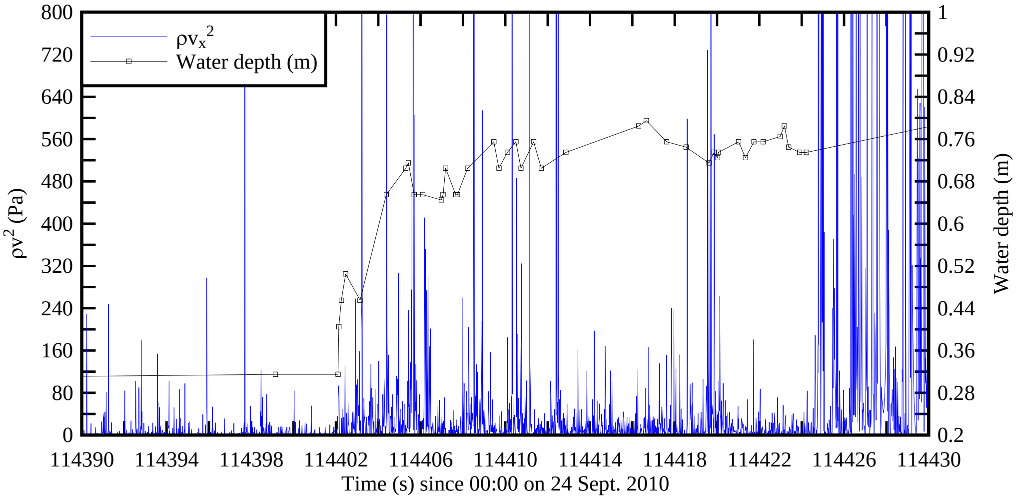


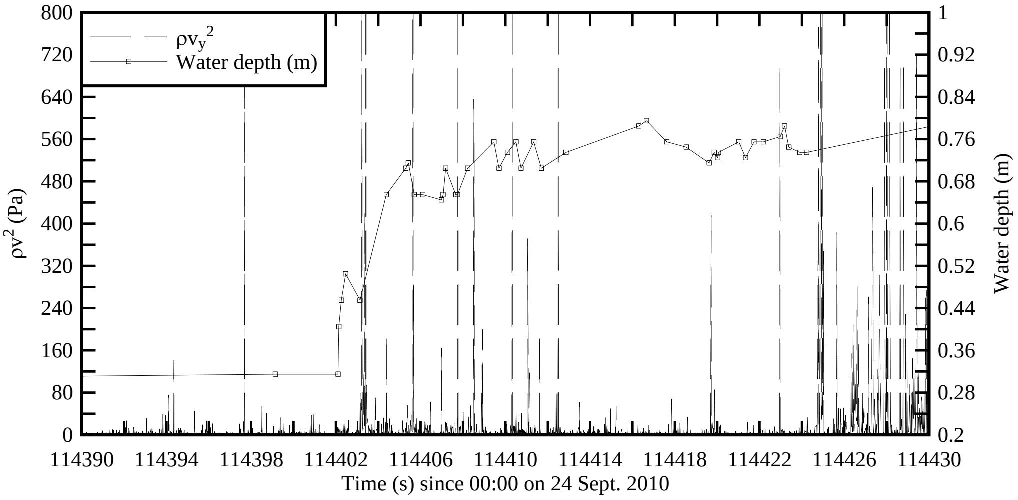


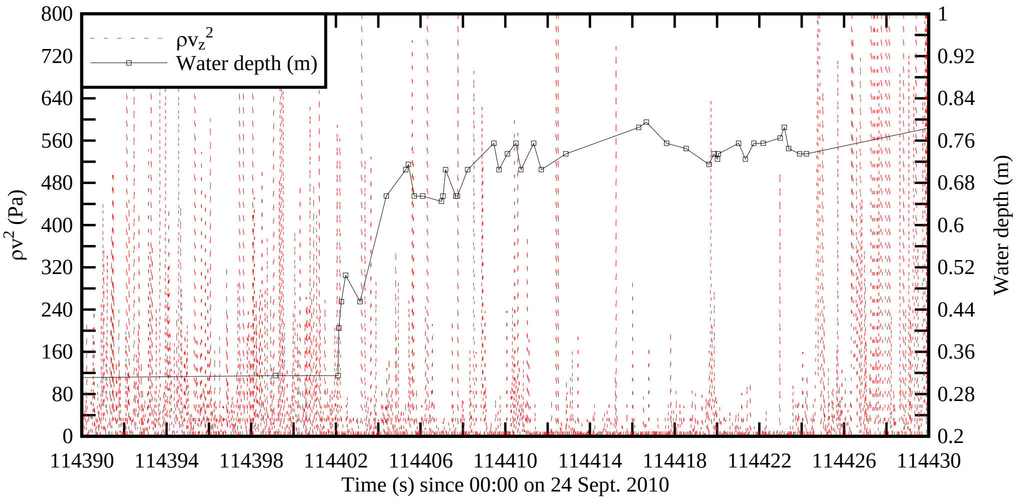


D.3 EXPERIMENTAL RESULTS ON 25 SEPT. 2010

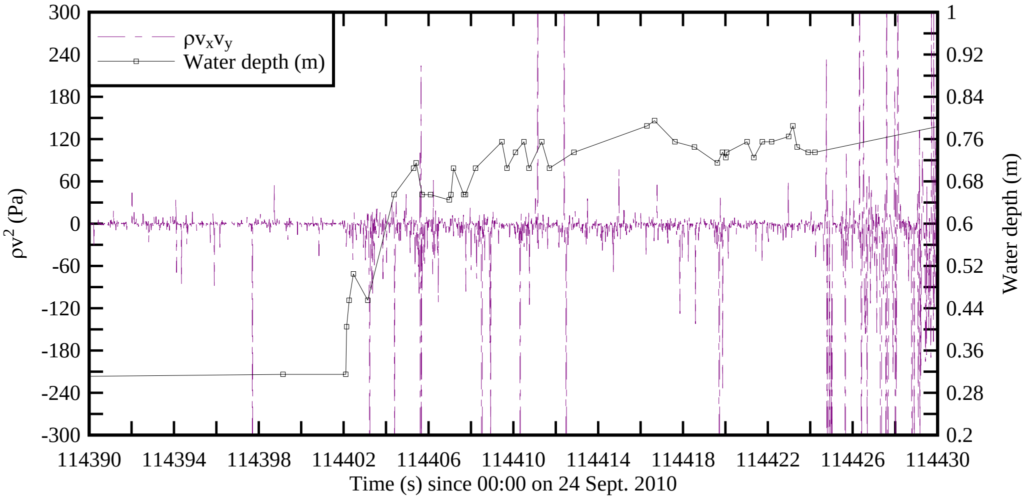
D.3.1 Normal Reynolds stresses

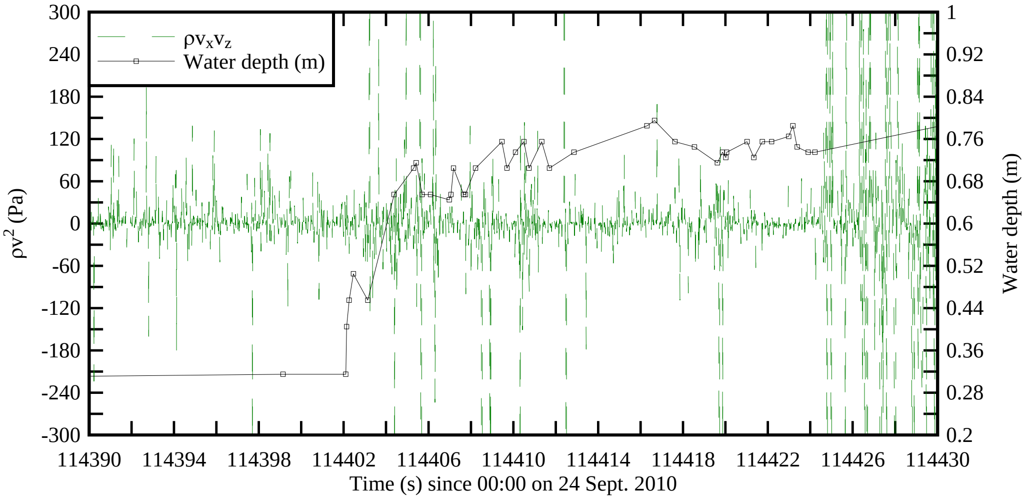


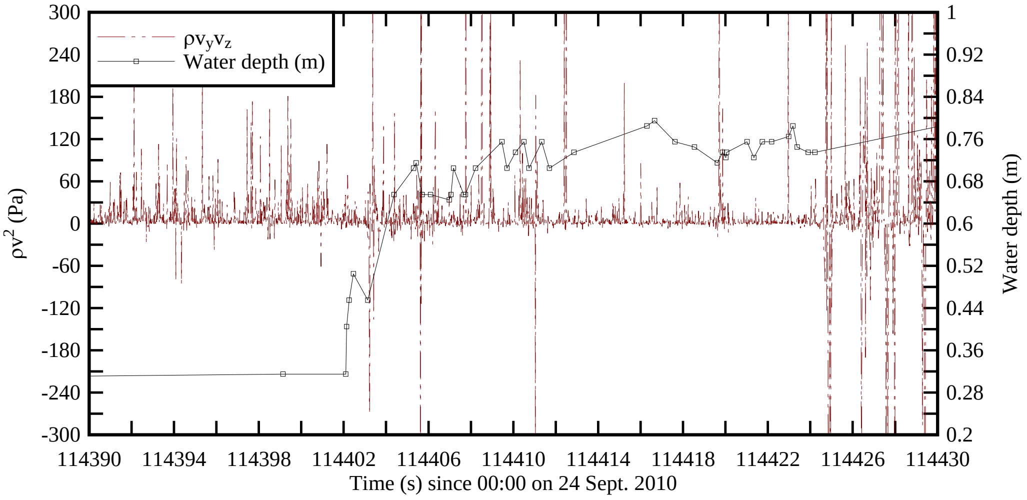




D.3.2 Tangential Reynolds stresses







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The bibliographic reference of the present report is:

MOUAZE, D., CHANSON, H., and SIMON, B. (2010). "Field Measurements in the Tidal Bore of the Sélune River in the Bay of Mont Saint Michel (September 2010)." *Hydraulic Model Report No. CH81/10*, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 72 pages (ISBN 9781742720210).

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