MAST III – SASME Project

Surf and Swash Zone Mechanics

SASME Report FIUD-03-00

Swash zone hydrodynamics on a 1:15 bottom slope: laboratory data

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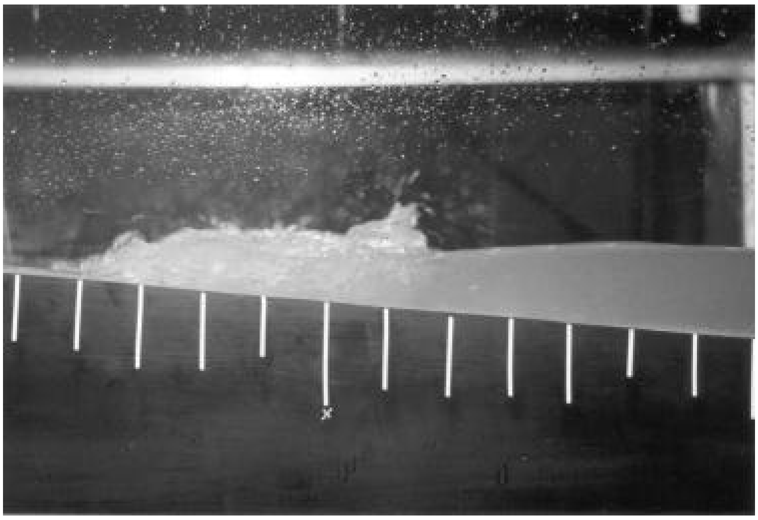

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Swash zone hydrodynamics on a 1:15 bottom slope: laboratory data

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1. Introduction

This report refers on the 3rd year in SASME Project activity. The experiments, focussed on the surf and swash zone, were carried out on a 1:15 fixed impermeable sloping beach and took place in the flume of the Department of Civil Engineering, University of Florence.

The generated wave motion in the tank consisted of a set of regular and irregular waves (the same used in the two previous series of experiments performed on a 1:10 sloping beach (Petti et al., 1998) and on a 1:5 sloping beach (Petti et al., 1999)), three monochromatic wave trains and three bichromatic wave trains, with different periods. The experimental equipment were a series of twin wire wave gauges (water level gauges and run up meter), an image acquisition system and Laser Doppler Velocimetry. The measurements were concentrated in the surf and swash zone and referred to free surface elevation along the flume, set up profiles and swash zone amplitude, water level and fluid velocities at several points along three sections in the swash zone. The collected velocity data were elaborated to obtain phase averaged velocity profiles and mass flux, turbulence fluctuations and phase averaged turbulent energy.

The Wave Flume was operated by Mauro Gioli, Muzio Mascherini; Stefano Sadun and Matteo Tirindelli participated in executing the experiments; data analysis and the drawing up of the present report were conducted by the following research team:

Marco Petti, University of Udine, Italy, principal investigator;
Sandro Longo, University of Parma, Italy;
Nicoletta Pasotti, University of Udine, Italy.

2. Experimental facilities

The wave flume adopted for the experiments is located in the Hydraulic Laboratory of the Department of Civil Engineering in Florence. It is 48 m long, 0.8 m wide, 0.8 m high and the maximum water depth is 0.6 m. For a detailed description of the experimental equipment and set-up, the wave maker and the electronic acquisition system see “SASME Report FIUD-01-98” (§2 – “Experimental Facilities”).

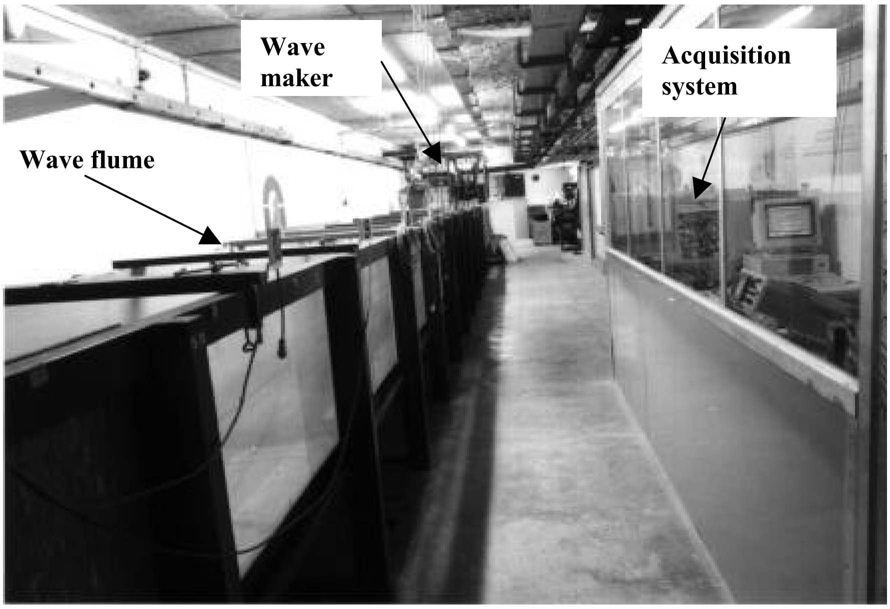


Fig.2.1- *Location of the wave flume, the wave maker and the acquisition system.*

2.1 Wave gauges and run up meter

A series of resistive wave gauges were used to measure the free surface water level, movable gauges along the plane bottom of the flume (fixed to an insulating movable support) and fixed gauges in the surf and swash zone (with two ends fixed with brass screws directly onto the sloping bottom). They consist of twin parallel wire (Ø=0.3 mm) meters and they measure the resistance between the wires, which is converted into output voltage in the range of 0÷10 Volt. The relation between the characteristic

Voltage and the water level, if the electrical field around the wires is homogeneous and symmetrical, is linear and it can be expressed by the following relation:

$$\eta = aV + b \tag{2.1}$$

Calibration of the resistive gauges was carried out by setting the water level at different static levels, fixed with an overall accuracy of 0.1 mm. The maximum error in the water level measurement, due to electric noise level (evaluated as the standard deviation of the output signal in still water condition) and to meniscus disturbances, has been estimated to be equal to:

$$\Delta\eta = \pm 1 \text{ mm.}$$

During the experiments we periodically checked both the linearity and the stability of the wave gauges, by repeating the calibration steps. Particular attention was given to the calibration of wave gauges in the swash zone, characterised by a periodical absence of water. In Fig. 2.2 a typical calibration output for a vertical gauge is shown. The entire set of gauge calibrations is presented in Annex 1.

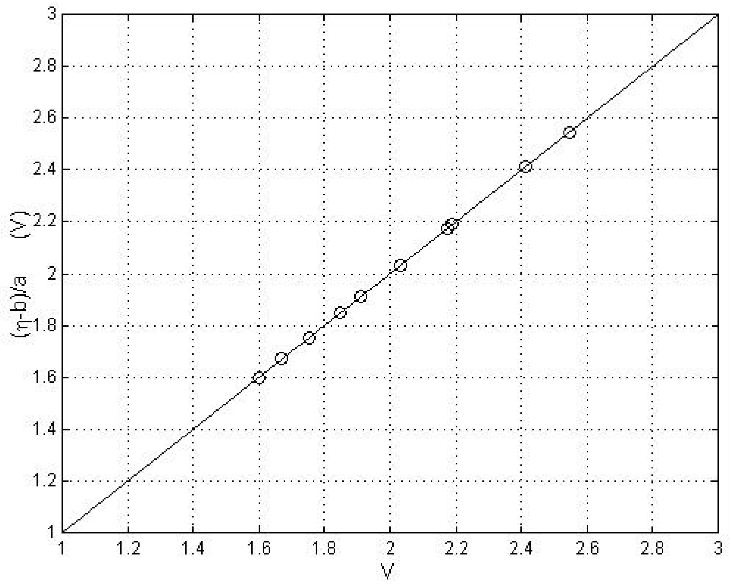


Fig. 2.2 - *Typical calibration of a vertical wave gauge.*

A run up meter was used to measure the run up and run down level in the swash zone: it consists of a resistive gauge placed parallel to the sloping bottom, at 5 mm from the surface. This type of configuration, sketched in Fig. 2.3, introduces a systematic geometrical error.

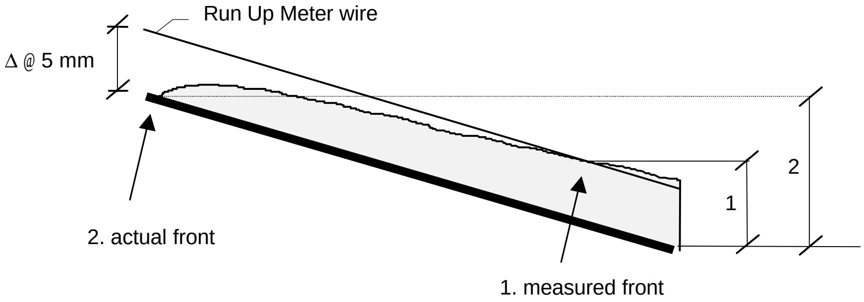


Fig. 2.3 – *Systematic geometrical error in run up meter measures*.

To correct the geometrical error of the run up meter measurement a video image analyses has been used: the position measured by the run up meter has been compared to the position of the bore front detected by video images. The video image acquisition system has been very useful also for a qualitative preliminary analysis of the breaking process and field of motion.

The calibration of the run up meter has been carried out observing that the electromagnetic field around the wire, in this bottom configuration, is quite symmetrical and homogeneous: for this reason it is well represented by a linear function. The linear fitting of calibration points of the run up meter is presented in Fig. 2.4.

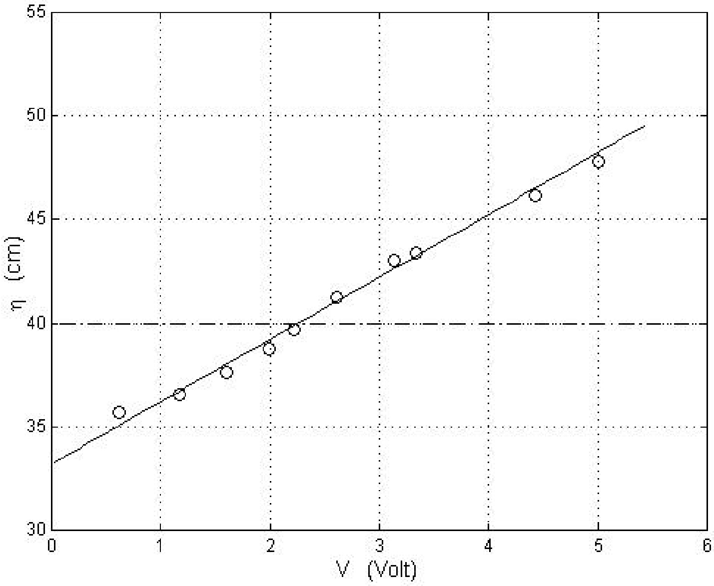


Fig. 2.4 - C*alibration of the run up meter*.

2.2 Laser Doppler Velocimeter

The local velocity was measured through a Laser Doppler He-Ne 30 mW system, characterised by an ellipsoidal measurement volume with axes of the order of 1 mm. A photomultiplier (PM) was used to collect the Doppler frequency information, while a frequency shifter device introduces an adjustable frequency (f_S) in order to distinguish the velocity orientation.

The conversion of the voltage signal output (V_{out}), as elaborated by frequency tracker (FT), into velocity measured orthogonal to the fringe pattern (u) is expressed through the following linear function:

$$u = 3.18 f_D = 3.18\left(\frac{RV_{OUT}}{10} \mp f_S\right) \qquad (2.2)$$

where:

- u [m/s] is the instantaneous velocity;

- f_D [MHz] is the Doppler frequency;
- V_{out} [V] is the output tension;
- R [MHz] is the upper limit of the chosen frequency range;
- f_s [MHz] is the shift frequency.

The coefficient 3.18 is dependent upon the optical set-up and laser radiation wavelength.

Aluminium powder (∅=10 μm) is used as a tracer in order to increase light scattering and consequently the S/N ratio. The error in velocity measurements declared by DISA-DANTEC is 1% of the selected frequency range.

The LDV signal in the swash zone is characterised by a periodic unlocking interval, caused by the absence of water (backwash phase and air bubbles crossing the measurement volume) and even in presence of regular wave trains it is impossible to predict the locking-unlocking sequence. A computational method has been developed to select and extract the valid signal, defining a Boolean function *f (t)* used in further elaboration of water level and velocity and checking the overall accuracy by visual observation of the raw series.

3. Experiments

This chapter describes the experiments performed on a 1:15 sloping beach. Comparisons of experimental results for the whole set of experiments during the SASME project activity (bottom slope conditions: 1st year 1:10; 2nd year 1:5 and 3rd year 1:15) are also presented.

3.1 Water Level and Set-up

A concrete bottom 1:15 sloping beach was built up starting 34.3 m from the paddle correspondent to the location of gauge 4.

In order to measure the surface roughness of the bottom, three specimens were collected and analysed; the surface roughness profiles are presented in Annex 1.

The resistive gauge series collecting the water level measurements are shown in Fig. 3.1. As for the first two bottom configurations, the movable gauges (1-4 and 4b) are placed along the flume and the fixed ones (5-12) are located in the surf and swash zone.

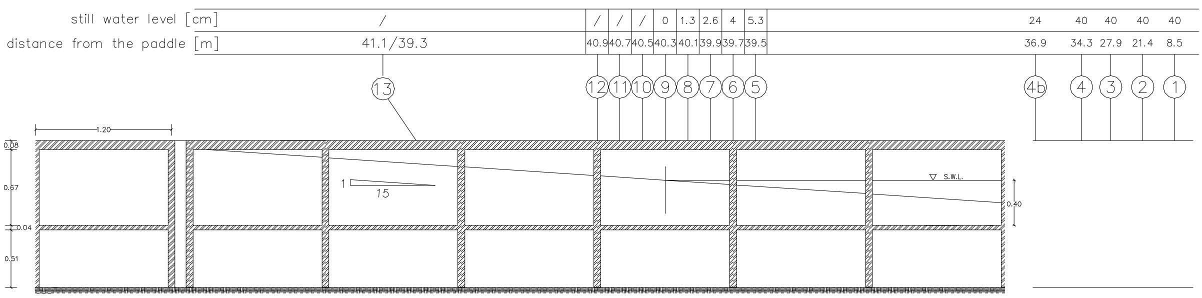


Fig. 3.1 – *Experimental set-up and location of wave gauges*.

The location of the first gauge (8.5 m from the paddle) has been left unchanged for the whole set of bottom slope conditions and its output was used to check the generated waveform. Other two movable gauges (gauges 2 and 3) were placed on the flat portion of the flume, at distances of 21.4 m and 27.9 m from the paddle; gauge 4 was positioned at 34.3 meters from the wave paddle, where the sloping beach starts. A fifth gauges was placed at the mid-point between gauges 4 and 5, at 36.9 m from the paddle.

The set-up of the fixed gauges (5-12) has been kept (for the whole series of experiments) with a spatial step of 20 cm, which assured an adequate resolution of the investigated zone avoiding reciprocal interference between gauges. The run up meter wire (gauge 13) was placed parallel to the bottom, at a distance of 5 mm from the concrete surface to avoid meniscus effect and consequent output distortion, and it was insulated in order to prevent the resistance short-circuiting.

The positions of the wave gauges for the three series of experiments (bottom 1:10 – 1:5 – 1:15) carried out during the SASME Project Activity are summarised in Tab. I. The underlined values represent the three vertical sections where the velocity laser measurements have been performed; the correspondent gauges are No *S7-S8-S9* for the 1st year configuration (1:10) and No *S8-S9-S10* for the 2nd and 3rd year configurations (1:5 and 1:15).

Tab. I – Distances from the paddle (m) of wave gauges for 1:10 – 1:5 – 1:15 bottom slope configurations (underline distances correspond to vertical section of velocity laser measurements).

	Fixed gauges and run up meter (#13)									**Movable gauges**				
gauge ⇒ slope ⇓	***13*** [m]	***12*** [m]	***11*** [m]	***10*** [m]	***9*** [m]	***8*** [m]	***7*** [m]	***6*** [m]	***5*** [m]	***4b*** [m]	***4*** [m]	***3*** [m]	***2*** [m]	***1*** [m]
1:10	40.4 43.7	42.3	42.1	41.9	***<u>41.7</u>***	***<u>41.5</u>***	***<u>41.3</u>***	41.1	40.9	/	39.2	37.5	23.0	8.5
1:5	40.7 42.6	42.1	41.9	***<u>41.7</u>***	***<u>41.5</u>***	***<u>41.3</u>***	41.1	40.9	40.7	40.1	39.5	31.8	24.0	8.5
1:15	41.1 39.3	40.9	40.7	***<u>40.5</u>***	***<u>40.3</u>***	***<u>40.1</u>***	39.9	39.7	39.5	36.9	34.3	27.9	21.4	8.5

The location of the three sections where velocity measurements were carried out on 1:15 sloping beach is shown in Fig. 3.2. The *upper section* was placed 20 cm shoreward, the *mid-section* at the intersection between the still water level and the bottom slope and the *lower section* 20 cm seaward. For wave period of 2.0 s the upper section was placed 5 cm shoreward, in order to compare the results with the first two bottom configurations.

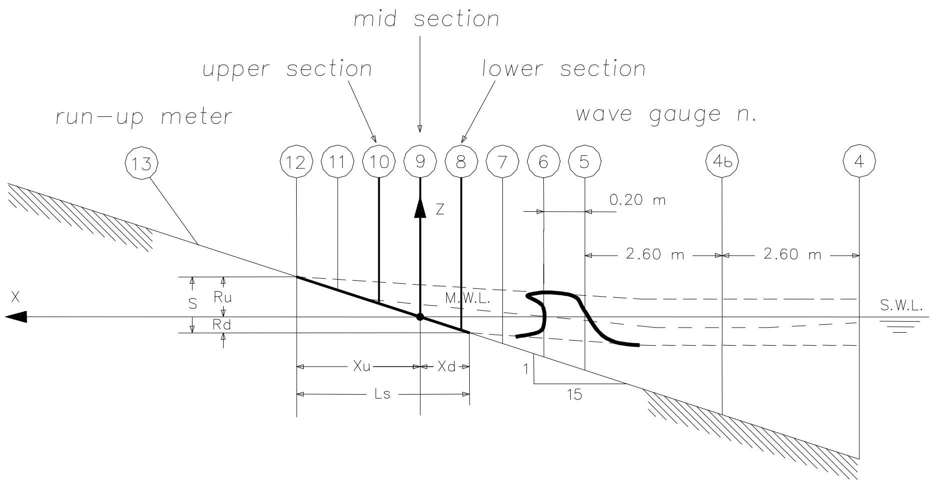


Fig. 3.2 – *Location of the wave gauges in the surf and swash-zone.*

Instantaneous local velocities were measured in the swash zone along the vertical of the three sections (upper, mid-, lower) through a LDV system in forward scatter. Measurements started at 0.5 mm from the bottom with a spatial step of 1 mm, reaching different maximum levels.

A summary of maximum levels (mm) of velocity measurements for the three series of experiments is reported in Tab.II.

*Tab. II – Maximum heights (*mm*) of LDV measurement along the vertical sections for 1:10 – 1:5 – 1:15 bottom slope configurations.*

	UPPER SECTION (x = +20 cm or +5 cm)			**MID-SECTION** (x = 0 cm)			**LOWER SECTION** (x = -20 cm)		
Wave period ⇒ Slope ⇓	**2.0** s [mm]	**2.5** s [mm]	**3.0** s [mm]	**2.0** s [mm]	**2.5** s [mm]	**3.0** s [mm]	**2.0** s [mm]	**2.5** s [mm]	**3.0** s [mm]
1:10	5.5	5.5	9.5	8.5	11.5	18.5	13.5	16.5	22.5
1:5	14.5	9.5	16.5	15.5	28.5	28.5	41.5	51.5	51.5
1:15	4.5	2.5	4.5	6.5	9.5	12.5	16.5	20.5	22.5

3.2 Tests

In order to compare the experiments referred to different bottom configurations, we generated the same set of regular and irregular wave trains:

- 3 monochromatic wave trains with a period of 2.0 s, 2.5 s and 3.0 s, with an acquisition time equal to 300 s (acquisition time of 600 s only for 1:10 bottom slope experiments);
- 9 sets of bichromatic wave trains, in group of 3 with a mean period equal to 2.0 s, 2.5 s and 3.0 s, with an acquisition time equal to 180 s. The amplitude of the two summed components had different values in order to obtain 1) the same amplitude of the regular waves (e.g. file name IH040*T20*, for T=2.0 s); 2) a significant wave equal to $H_{1/3}$ of the regular wave tests (e.g. file name I4*T25*H13, for T=2.5 s); 3) a significant wave equal to H_{rms} of the regular wave tests (e.g. file name I4*T30*HRM for T=3.0 s).

Each test was performed maintaining the still water level in the flume at 40 cm. Before starting each run we waited enough time in order to get actual still water conditions. The gauge measurements were checked for the entire length of each test.

In Tab. III the sets of **regular wave** tests performed during the project are summarised. H_1 refers to wave height collected at gauge *S1*; H_0 and L_0 represent respectively the wave height and the wave length in deep water conditions, evaluated by linear wave theory assuming *S1* as control gauge; H_0/L_0 is the wave steepness. In Tab. IV detailed information of the nine tests on **irregular waves** are presented. A_1 and T_1 (or f_1) represent the amplitude and period (or frequency) of the first component of the bichromatic wave train; A_2 and T_2 (or f_2) represent the amplitude and period (or frequency) of the second component of the same wave train. In Tab. V the analysed irregular waves are summarised, where the subscript "$_s$" means significant value.

Tab. III – *Regular waves for the three bottom slope conditions (**1:10 – 1:5 – 1:15**).*

Test	H_0 [cm]	H_1 [cm]	T [s]	L_0 [m]	H_0 / L_0	*Sampling rate* [Hz]	*Acquisition time* [s]
RH04T20	3.6	3.5	2.0	6.24	0.0057	100	300 (600)
RH04T25	3.2	3.4	2.5	9.75	0.0033	100	300 (600)
RH04T30	3.3	3.8	3.0	14.05	0.0024	100	300 (600)

Tab. IV – *Irregular waves for the three bottom slope conditions (**1:10 – 1:5 – 1:15**).*

Test	A_1 [cm]	T_1 [s]	f_1 [Hz]	A_2 [s]	T_2 [s]	f_2 [Hz]	*Sampling rate* [Hz]	*Acquisition time* [s]
IH040T20	1	1.9	0.52	1	2.1	0.47	100	180
IH040T25	1	2.3	0.43	1	2.7	0.37	100	180
IH040T30	1	2.8	0.35	1	3.2	0.31	100	180
I4T20HRM	1.63	1.9	0.52	1.63	2.1	0.47	100	180
I4T25HRM	1.45	2.3	0.43	1.45	2.7	0.37	100	180
I4T30HRM	1.61	2.8	0.35	1.61	3.2	0.31	100	180
I4T20H13	1.1	1.9	0.52	1.1	2.1	0.47	100	180
I4T25H13	1.1	2.3	0.43	1.1	2.7	0.37	100	180

I4T25H13	1.2	2.8	0.35	1.2	3.2	0.31	100	180

Tab. V – *Irregular waves summary.*

Test	H_{S1} [cm]	T_{S1} [s]	T_1 [s]	T_2 [s]	*Sampling rate* [Hz]	*Acquisition time* [s]
I4T20H13	3.5	2.0	1.9	2.1	100	180
I4T25H13	3.4	2.5	2.3	2.7	100	180
I4T25H13	3.8	3.0	2.8	3.2	100	180

The breaking characteristics were determined taking into account the linear shoaling effect, using gauge *S1* as a control gauge. Surf similarity parameters ξ_b and I_b were estimated for each wave train as (Gourlay, 1992):

$$\xi_b = \frac{1.45 \cdot \tan(\vartheta)}{\left(H_0 / L_0 \right)^{0.36}} \qquad I_b = \frac{1}{2.5 \cdot \xi_b}$$

The results of the breaking analyses are reported in Tab. VI, where $\boldsymbol{K_S}$ and $\boldsymbol{K_R}$ represent respectively the linear shoaling and the reflection coefficients. In Fig. 3.4 the summary of the breaking process is reported.

Tab. VI – *Breaking parameters summary.*

slope	***Test***	$H_1 = H_i$ **[cm]**	ξ_b	I_b	***Breaking type***	K_S	K_R
1:10	***RH04T20***	3.5	0.99	0.40	Plunging	0.98	0.16
	RH04T25	3.4	1.30	0.31	Collapsing	1.06	0.27
	RH04T30	3.8	0.85	0.47	Collapsing	1.14	0.34
1:5	***RH04T20***	3.5	1.86	0.22	Collapsing-Surging	0.98	0.57
	RH04T25	3.4	2.27	0.18	Surging	1.06	0.69
	RH04T30	3.7	2.57	0.16	Surging	1.14	0.74
1:15	***RH04T20***	3.5	0.62	0.65	Plunging + bore	0.98	0.085
	RH04T25	3.4	0.76	0.53	Plunging + bore	1.06	0.12
	RH04T30	3.8	0.85	0.47	Plunging	1.14	0.17

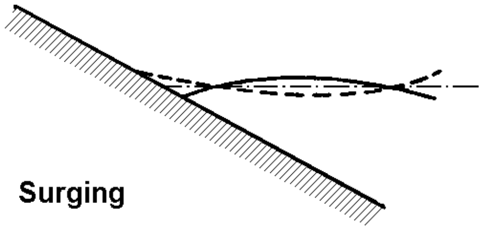
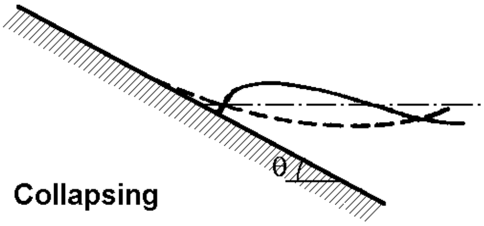
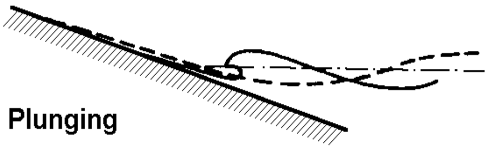
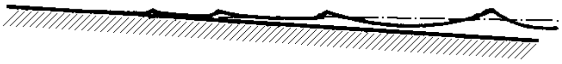
 Surging	***RH040T30 (1: 5)*** ***RH040T25 (1: 5)***	$\xi_b > 2$
 Collapsing	***RH040T20 (1: 5)*** ***RH040T30 (1:10)*** ***RH040T25 (1:10)***	$1.14<\xi_b<2$
 Plunging	***RH040T20 (1:10)*** ***RH040T30 (1:15)***	$0.80<\xi_b<1.14$
 Plunging plus bore	***RH040T25 (1:15)*** ***RH040T20 (1:15)***	$0.40<\xi_b<0.80$
 Spilling plus bore		$\xi_b < 0.2$

Fig. 3.4 – *Breaking range covered with tests performed during the SASME experimental activity. Bottom slope 1:10, 1:5 and 1:15.*

4. Measurements

Simulation in the flume of the open-sea conditions in front of a beach involves the reflection of the beach, which occurs even in natural conditions, and re-reflection of the paddle. In order to avoid this problem, analysis was extended to interval times when there was no re-reflection. Different time intervals were chosen for the data analysis of each gauge, as shown in Tab. VII.

Tab. VII – *Time intervals for data analysis.*

wave period	***S1***	***S2***	***S3-S13***
T = 2.0 s	10.9÷30.9 s	34.5÷54.5 s	31.3÷51.3 s
T = 2.5 s	10.9÷35.9 s	34.5÷59.5 s	31.3÷56.3 s
T = 3.0 s	10.9÷40.9 s	34.5÷64.5 s	31.3÷61.3 s

4.1 Water levels

For each time intervals and for each gauge a phase analysis was carried out. The phase averaged water level $\tilde{\eta}(t)$ was calculated for each gauge as:

$$\tilde{\eta}(t) = \frac{1}{N}\sum_{k=0}^{N-1}\eta(t+kT) \qquad 0 \le t < T \qquad (3.1)$$

where $\eta(t)$ represents instantaneous oscillation from SWL, N is the number of waves in the chosen time interval and T is wave period. A small fluctuation ($\approx$ 1%) of wave period in the generated wave motion has been found. The Phase Average operator given by eq. (3.1) is highly sensitive even to these small fluctuations. For this reason a conditional average operator has been used, the so called Variable Interval Time Average, defined as below:

$$\widetilde{\eta(t)} = \frac{1}{N}\sum_{k=0}^{N-1}\eta(t+t_k) \qquad 0 \text{ £ } t < \min(T) \tag{3.2}$$

The condition is represented, for the *k*-cycle, by the instant of trigger t_k (a starting point in the averaging operation), min (T) is the minimum time period in the series of N cycles (or N waves). For these analyses we have chosen the local minimum water level as instant of trigger. Before averaging, the data in each cycle have been "stretched" in order to extend each period all over the mean period.

Another operator used in further analysis is the moving average:

$$<\eta(t)>= \frac{1}{T_m}\int_{t}^{T_m}\eta(\tau)\, d\tau \qquad t \text{ £ } t < T_m \tag{3.3}$$

where T_m is the averaging period.

The signal analysis in the presence/absence of water can be carried out using a phasic average operator, represented by the following expression:

$$\hat{\eta} = \frac{\sum_i \int_{\Delta T_i}\eta(t)\,dt}{\sum_i \Delta T_i} \tag{3.4}$$

where ΔT_i are the time intervals during water presence.

All the above mentioned operators are linear and can be applied in sequence without rank.

In Fig. 4.1(a) and (b) an example of phase averaged analysis is shown for each gauge, referring to test RH040T30.

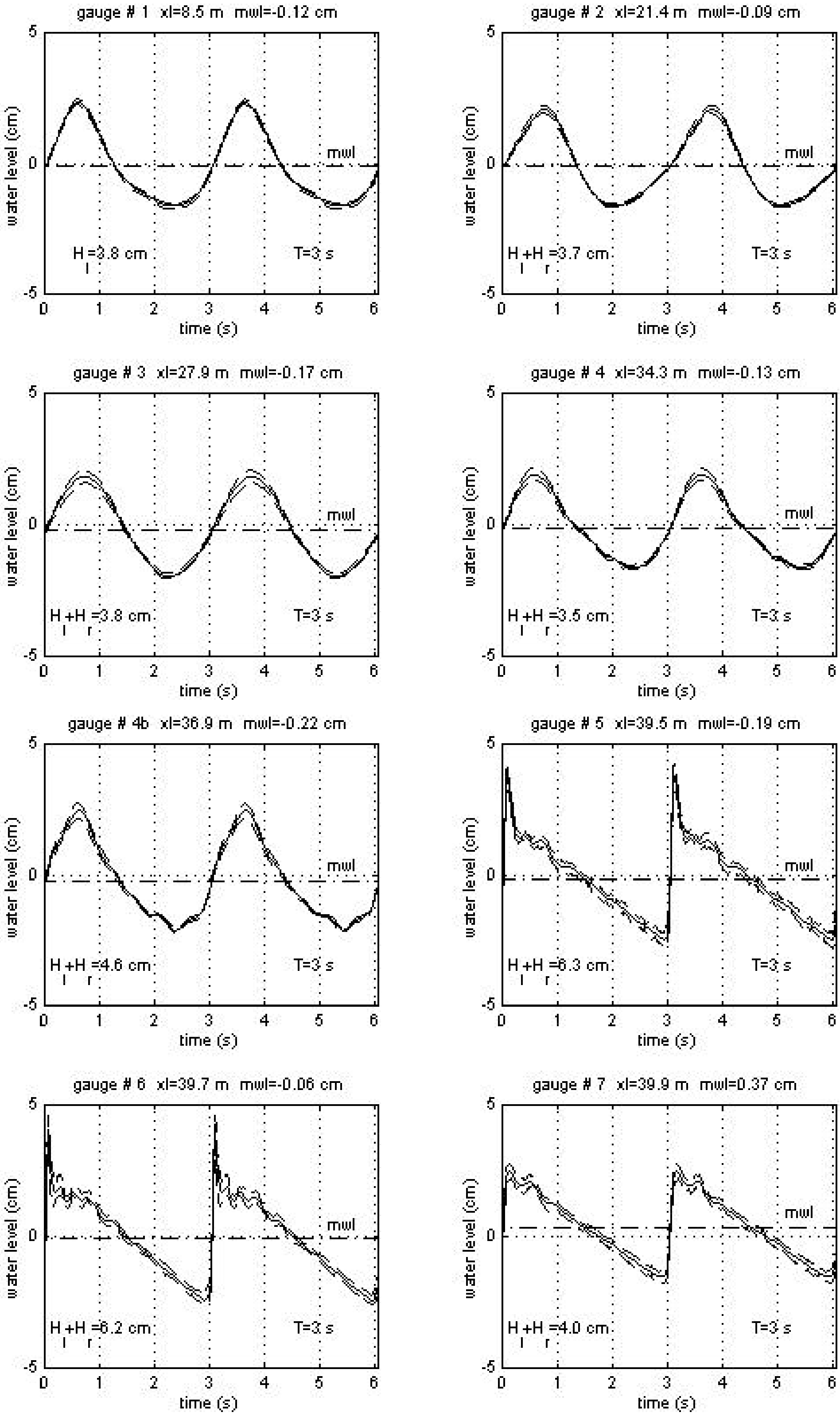


Fig. 4.1(a) - Test RH040T30*: Phase analysis for gauges 1-7. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

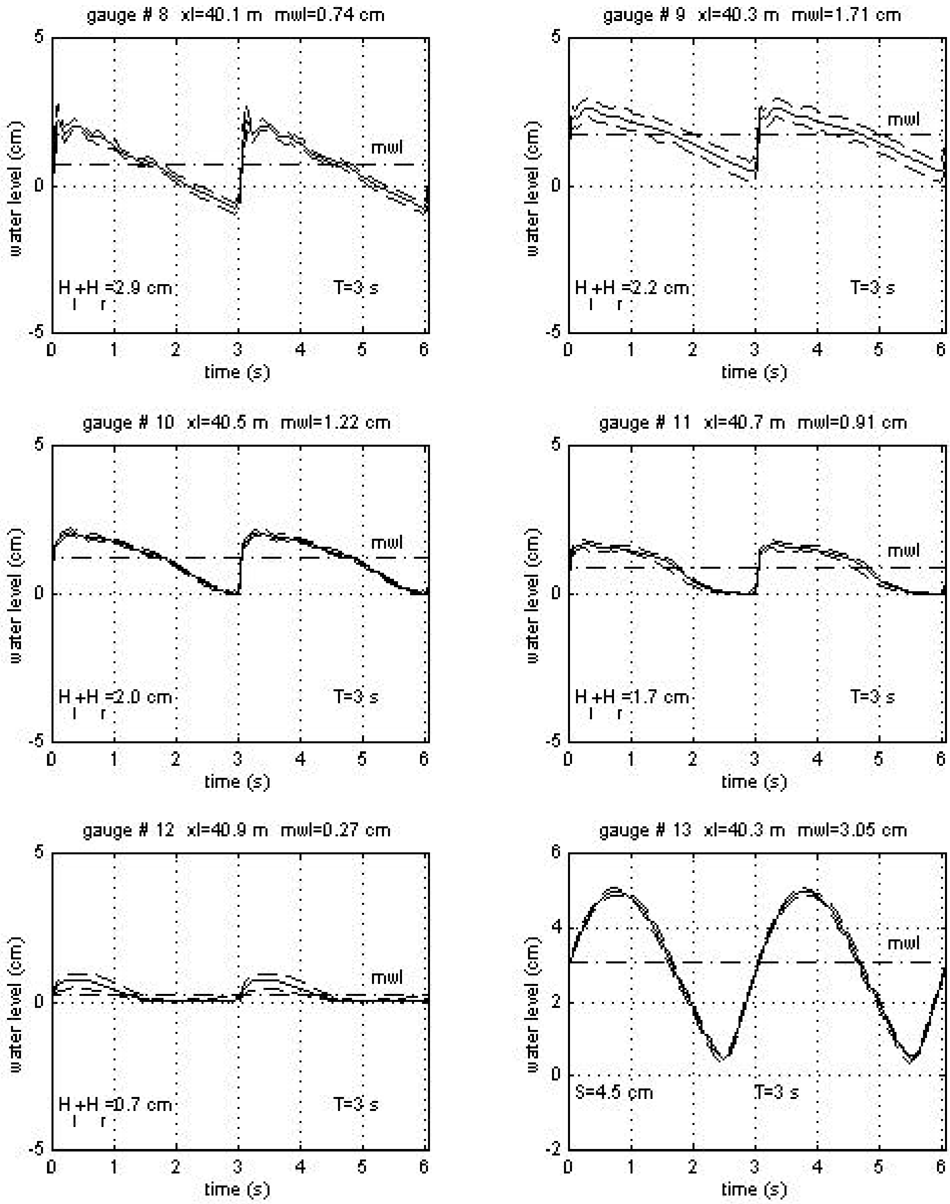


Fig. 4.1(b) - Test RH040T30*: Phase analysis for gauges 8-12 and the run up meter (gauge 13). Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

Breaking process for the wave period of 3.0 s takes place at gauge *S5*, as observed by the videocamera frames. The analysis results for the whole set of tests are reported in Annex 2.

Numerical values of time averages $\langle\eta\rangle$, phasic averages $\hat{\eta}$, maximum and minimum values of the local water level and wave heights estimated for each gauge are reported in Tab. VIII, for the 3.0 s period.

Tab.VIII*: water levels evaluated referred to S.W.L. (*η_{max} *= max values,* $\hat{\eta}$ *= phasic average values,* $\langle\eta\rangle$ *= time average values,* η_{min} *= min values, H = wave height). Wave period 3.0 s.*

Gauge #	η_{max} [cm]	$\hat{\eta}$ [cm]	$\langle\eta\rangle$ [cm]	η_{min} [cm]	*H* [cm]
1	2.3	-0.1	-0.1	-1.5	3.8
2	2.1	-0.1	-0.1	-1.6	3.7
3	1.8	-0.2	-0.2	-2.0	3.8
4	1.9	-0.1	-0.1	-1.6	3.5
4b	2.5	-0.2	-0.2	-2.1	4.6
5	3.8	-0.2	-0.2	-2.5	6.3
6	3.8	-0.1	-0.1	-2.4	6.2
7	2.5	0.4	0.4	-1.5	4.0
8	2.2	0.7	0.7	-0.7	2.9
9	2.7	1.7	1.7	0.5	2.2
10	3.4	2.6	2.5	1.4	2.0
11	4.4	3.8	3.6	2.7	1.7
12	4.7	4.5	4.3	4.0	0.7

All tests are characterised by the surf similarity parameter ξ_b varying from 0.6 to 0.9, corresponding to the range of “plunging” and “plunging plus bore” breaking type. The crest and through spatial envelopes of water level oscillations are shown in Fig. 4.2 for wave period equal to 3.0 s (see Annex 2 for 2.0 s and 2.5 s waves).

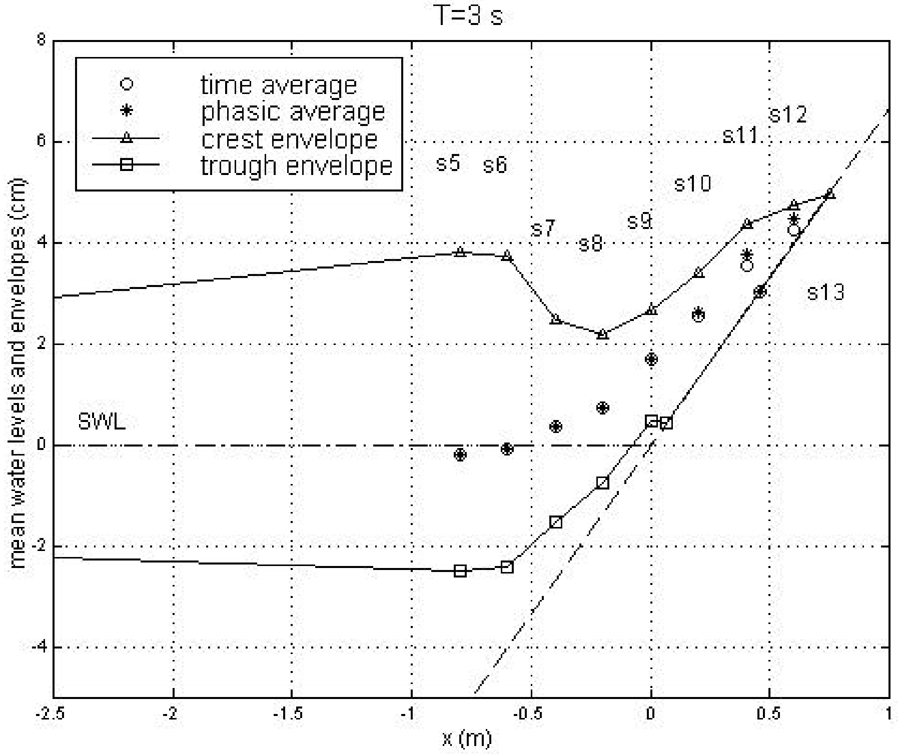


Fig. 4.2 - Test RH040T30: *Set up profiles, crest and trough envelopes.*

Data collected by the run up meter (gauge *S13)* and corrected by the video support, allow the evaluation of the run-up (R_u) and run-down (R_d) levels, the amplitude of swash zone (S) and the time averaged level $\langle\eta\rangle$. The results for the three bottom slope conditions are summarised in Tab. IX, while the results of the irregular wave tests are summarised in Tab. X.

Tab. IX - *Regular waves for bottom slope 1:10, 1:5 and 1:15. Water levels evaluated at the run up meter referring to S.W.L. (R_u = run up, $\hat{\eta}$ = phasic averaged values, $\langle\eta\rangle$ = time averaged values, R_d = run down, S = swash amplitude)*

slope	Test #	R_u [cm]	$\langle\eta\rangle = \hat{\eta}$ [cm]	R_d [cm]	S [cm]
1:10	***RH040T20***	4.2	2.8	0.6	3.6
	RH040T25	5.5	3.5	0.2	5.3
	RH040T30	7.5	4.7	0.1	7.5
1:5	***RH040T20***	9.7	4.5	-4.0	13.7
	RH040T25	8.2	2.9	-4.8	13.0
	RH040T30	11.2	3.5	-5.6	16.8
1:15	***RH040T20***	2.7	1.9	0.8	1.9
	RH040T25	3.4	2.2	0.6	2.8
	RH040T30	5.0	3.0	0.5	4.5

Tab. X - *Irregular waves for bottom slope 1:10, 1:5 and 1:15. Water levels evaluated at the run up meter referring to S.W.L. (Ru_{max} = max run up, $\langle\eta\rangle$ = time averaged values, Rd_{min} = min run down, S = swash amplitude)*

slope	Test #	Ru_{max} [cm]	$\langle\eta\rangle$ [cm]	Rd_{min} [cm]	S [cm]
1:10	***IH040T20***	4.2	2.2	-0.2	4.4
	IH040T25	5.1	1.9	-1.4	6.5
	IH040T30	6.9	2.7	-2.5	9.4
1:5	***I4T20H13***	10.2	2.9	-4.0	14.2
	I4T25H13	8.8	1.6	-5.1	13.9
	I4T30H13	11.0	2.3	-6.3	17.3
1:15	***IH040T20***	3.0	1.6	0.1	2.9
	IH040T25	3.6	1.6	-0.4	4.0
	IH040T30	5.1	2.1	-0.8	5.9

4.2 Mass fluxes

Phase averaged surface oscillations $\tilde{\eta}(t)$ collected at gauges located in the surf zone allow the estimation of the mass flux through the mid-section (gauge *S9*), placed at the intersection between the bottom slope and the still water level. The continuity equation is the following:

$$uh\Big|_{x=0} = \frac{\partial V}{\partial t} \tag{3.5}$$

where *uh* is the mass flux through the mid-section placed at *x=0*, *h* is the sum of water level ***h*** referred to SWL and still water depth *d*; *V* is the volume included between the section under evaluation and the instantaneous coastal line. The volume *V* has been estimated using the phase-phasic averaged levels recorded by gauges *S9-S12* in the swash zone assuming a plane surface between two successive gauges:

$$V(t) = \frac{\Delta x}{2}\left[\left(\sum_{i=9}^{12} 2h_i(t)\right) - h_9(t) - h_{12}(t)\right] \qquad 0 \le t < T \tag{3.6}$$

where the space interval is Δx, equal to 20 cm, is the constant horizontal distance between two successive gauges (Fig. 4.3).

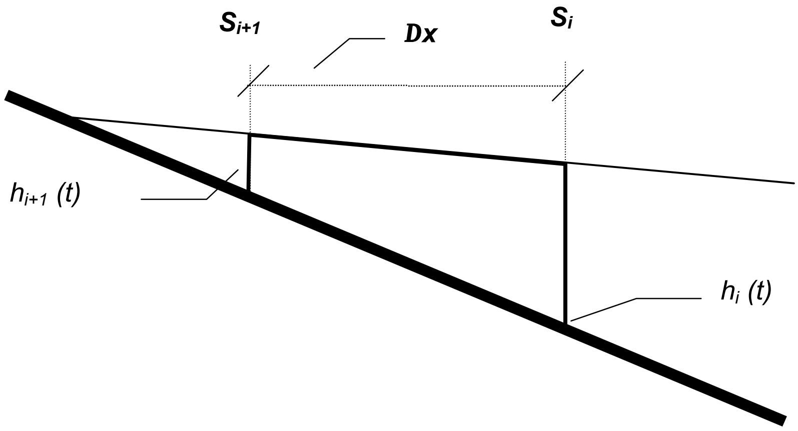


Fig. 4.3 - *Sketch for flux evaluation.*

The time series *V (t)* were filtered eliminating frequency oscillation $f > 2$ Hz.

Fig. 4.4 shows flux analyses for the regular test RH040T20; analyses for all tests are reported in Annex 4.

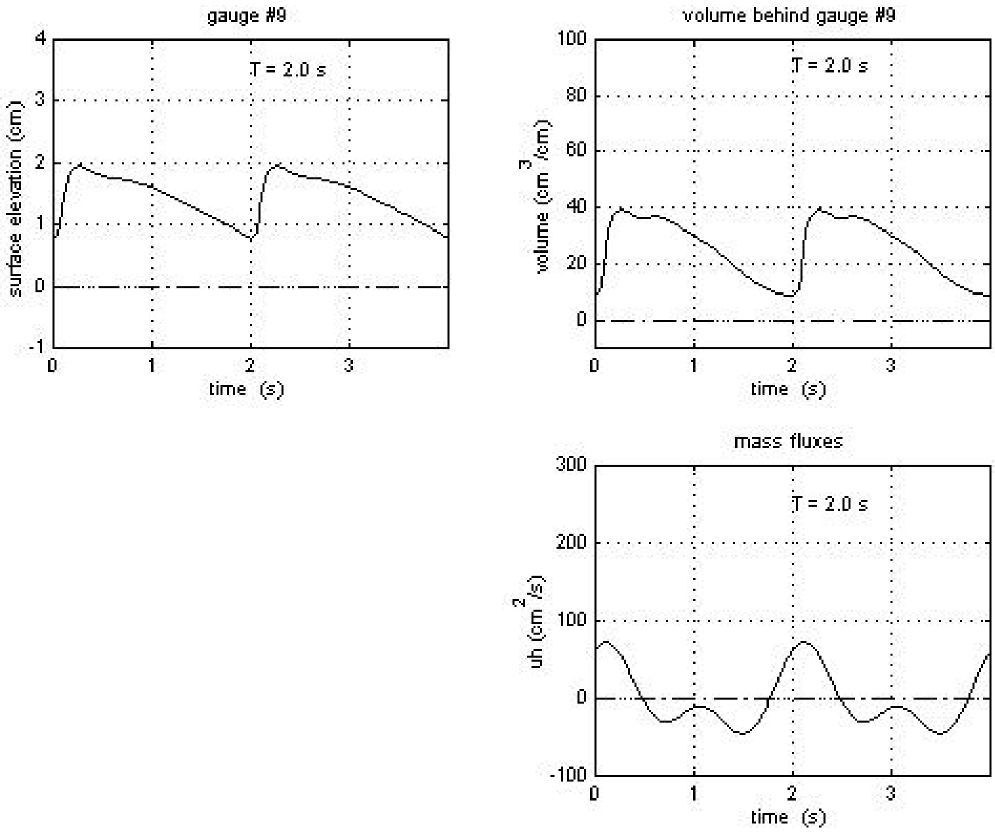


Fig. 4.4 - *Test RH040T20: flux analysis in the mid-section (gauge S9)*.

4.3 Fluid velocities

Velocity measurements were collected in the swash zone along three vertical sections the *lower*, *mid-* and *upper* section (Fig. 4.5). Measurements start at 0.5 mm from the bottom for successive steps of 1 mm. The upper section in the test RH040T20 was fixed at x = +5 cm rather than x = +20 cm, to be able to compare the results with the first and second year experiments (1:10 and 1:5 bottom slope).

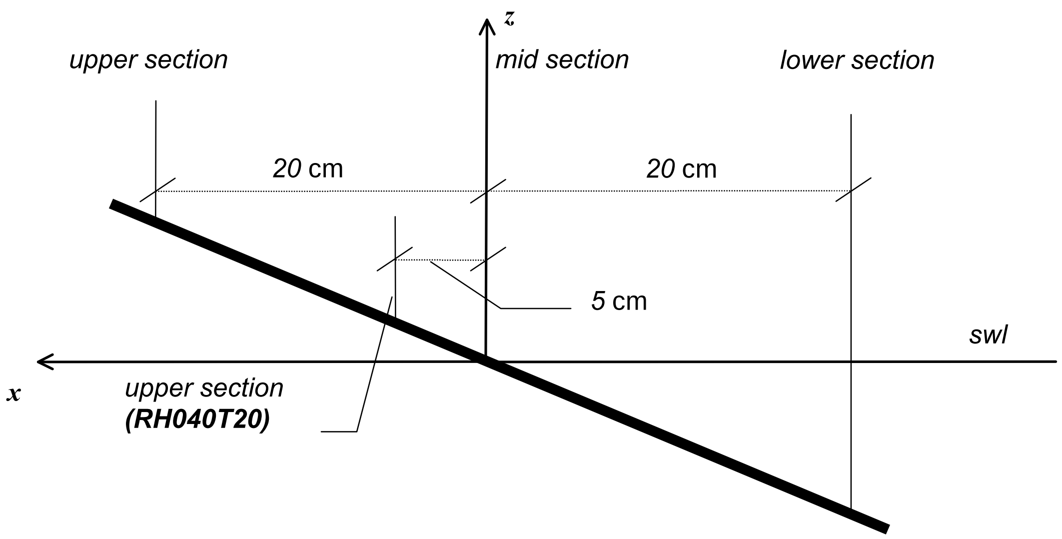


Fig. 4.5 - *Measurement sections for LDV.*

Phase velocity analyses were performed using the Variable Interval Time Average, triggering on the local minimum water depth and taking into account the locked/unlocked laser signal (Fig. 4.6):

$$\widetilde{u(t)} = \frac{\sum_{k=0}^{N-1} u\left(t+t_k\right) \cdot f\left(t+t_k\right)}{\sum_{k=0}^{N-1} f\left(t+t_k\right)} \qquad 0 \le t \le \min\left\{T_k\right\}_{k=0,\dots,N-1} \qquad (3.7)$$

where f is the Boolean signal validity (or mass presence). The phase velocity profiles were calculated considering the first ten waves, to avoid re-reflection effects caused by the paddle.

Small differences of 1% in the time period (equal to t_k- t_{k-1}) were observed in each cycle and before averaging, a time span was adopted on the data of each cycle over the mean period, as was performed for the water level phase analysis.

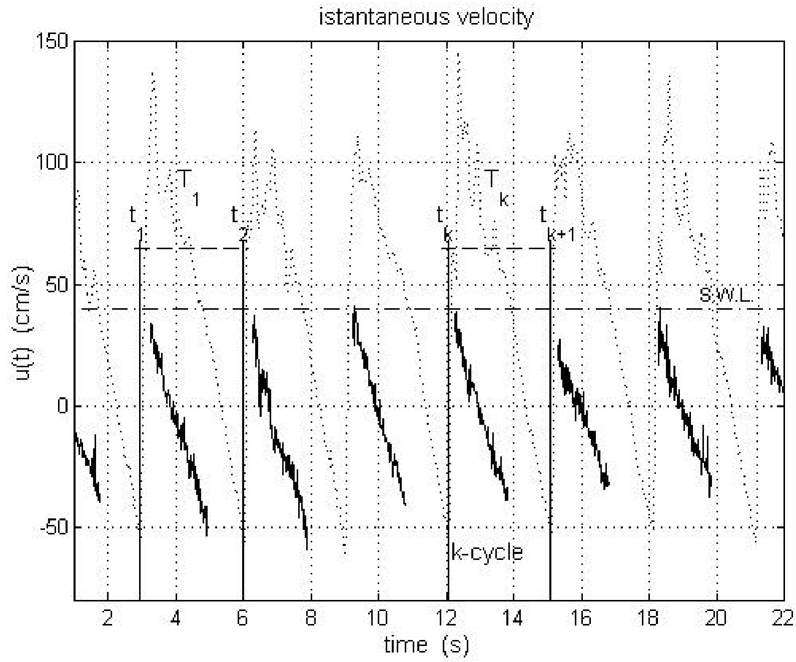


Fig. 4.6 – *Example of the phase average using the minimum local water level as trigger event.*

In Fig. 4.7, 4.8, and 4.9 phase velocity profiles each 30° and the maximum water depth δ are reported, calculated as:

$$\delta = \tilde{\eta}_{max} + d \qquad (3.8)$$

where $\tilde{\eta}_{max}$ is the maximum value of $\tilde{\eta}(t)$ and d is the still water depth, for the three sections (test RH040T20). The entire set of analyses is reported in Annex 6. δ was assumed as the significant length vertical scale.

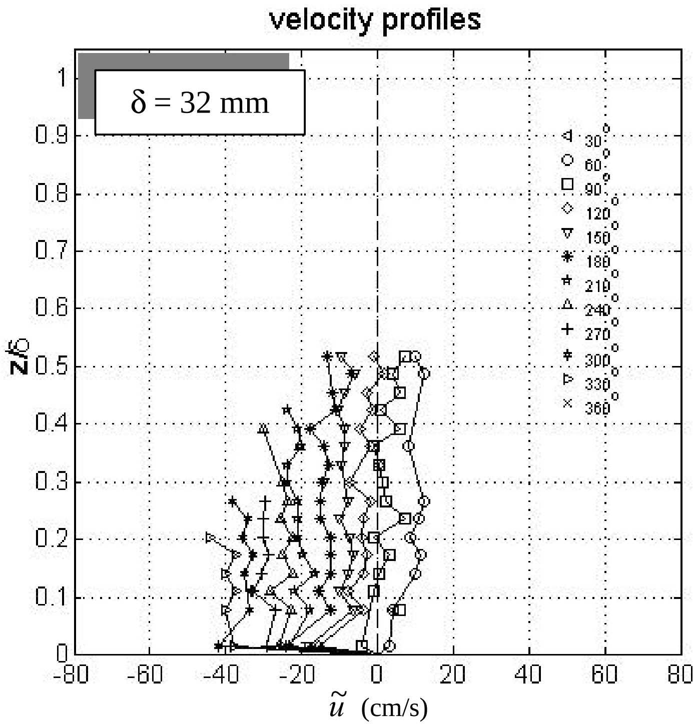


Fig. 4.7 - *RH040T20: velocity profiles in the lower section.*

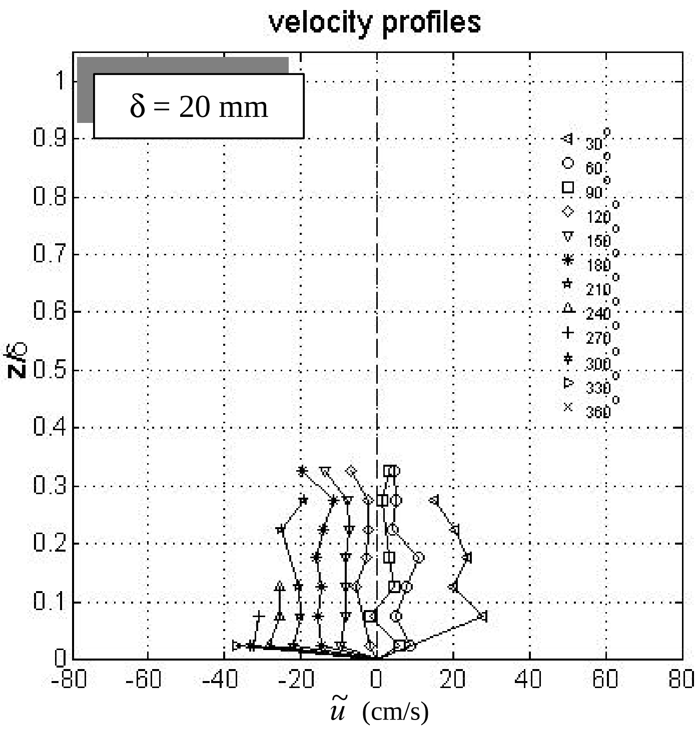


Fig. 4.8 - *RH040T20: velocity profiles in the mid-section.*

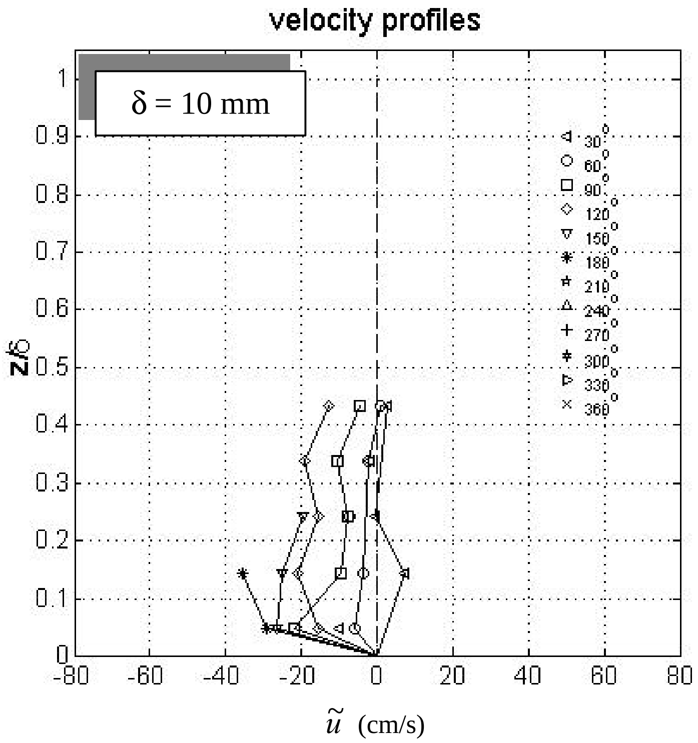


Fig. 4.9 - *RH040T20: velocity profiles in the upper section*.

4.4 Turbulence

The horizontal turbulence component $u'(t)$ was evaluated by subtracting the phase average (conditional) $\widetilde{u(t)}$ from the raw signal $u(t)$:

$$u'(t) = u(t) - \widetilde{u(t)} \tag{3.9}$$

The horizontal turbulent energy, proportional to the square of the instantaneous velocity fluctuation, is expressed by the following expression:

$$u'^2(t) = \left[u(t) - \widetilde{u(t)}\right]^2 \tag{3.10}$$

The phase-phasic average of the turbulent fluctuations at different levels over the bottom is:

$$\widetilde{u'^2(t)} = \frac{\sum_{k=0}^{N-1} u'^2(t+kT)\cdot f(t+kT)}{\sum_{k=0}^{N-1} f(t+kT)} \qquad 0\ £\ t < T \qquad (3.11)$$

where f is again the Boolean function of mass presence (or signal validity).

Fig. 4.10 shows the averaged horizontal turbulent energy, at phase intervals of 30°, and the correspondent water level. Uprush and backwash phases are plotted separately.

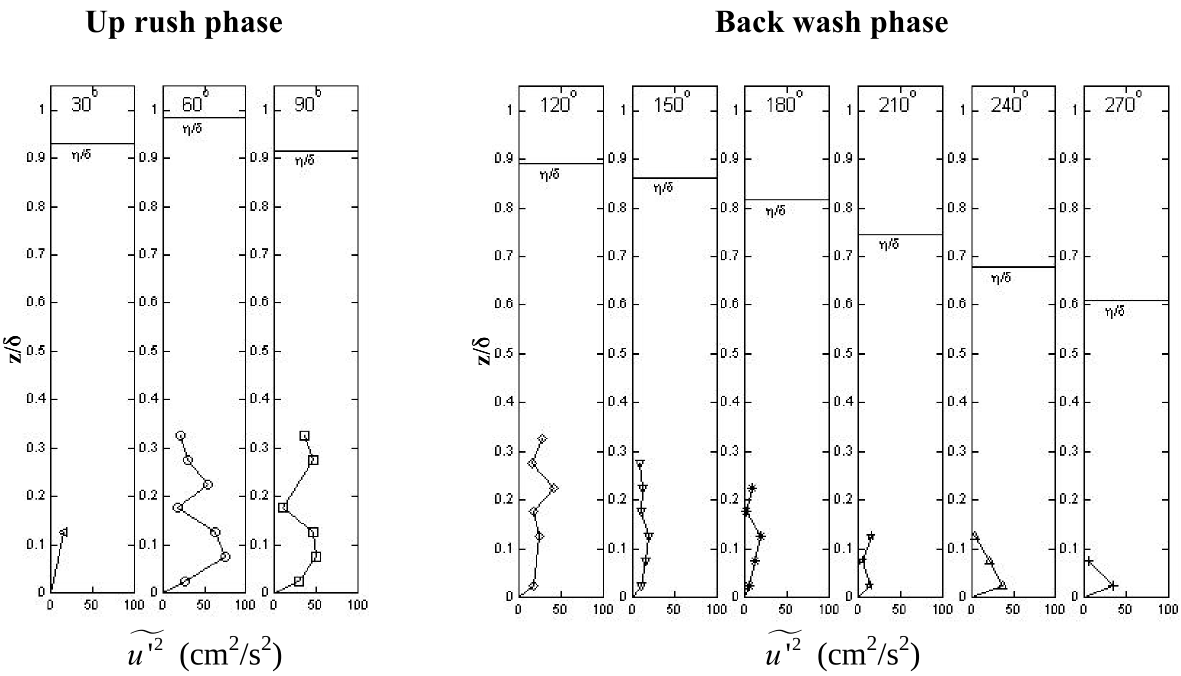


Fig. 4.10 - *Test RH040T20: Non-dimensional phase averaged horizontal turbulent energy and non-dimensional free surface level (h/δ) during the uprush phase and backwash phase. Mid-section.*

5. Summary and conclusions.

Experimental investigations on the surf and swash zone of a 1:15 impermeable smooth bottom were performed. The same series of regular and irregular waves tested during first and second year SASME experiments (performed on a 1:10 and 1:5 sloping beach, Petti et al., 1998; Petti et al. 1999) were generated.

Free surface level data were collected along the flume by resistive gauges and fluid velocity data were collected along three vertical sections in the swash zone through LDV. Data elaboration allowed the evaluation of the free surface oscillations along the flume, set up profiles, run up and rundown oscillations in the surf and swash zone; the mass flux through a reference section (mid-section); the phase averaged velocity profiles; the turbulence fluctuations along three sections (lower, mid, upper section) and a turbulent energy estimator.

6. Acknowledgements

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Annex 1

- Reference system
- Calibration of wave gauges
- Surface bottom profiles

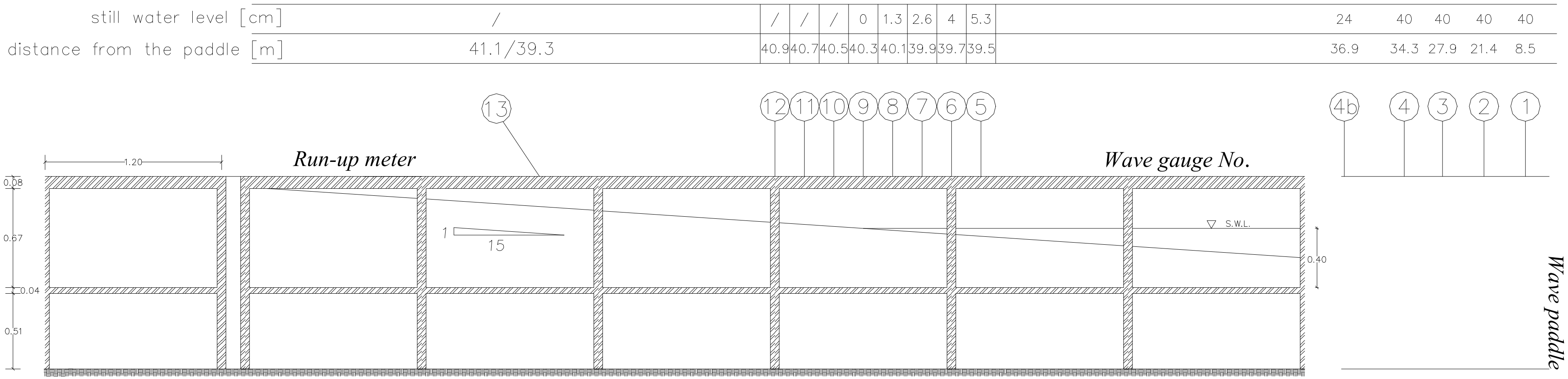

Fig.A1-1 *Experimental set-up and location of the wave gauges.*

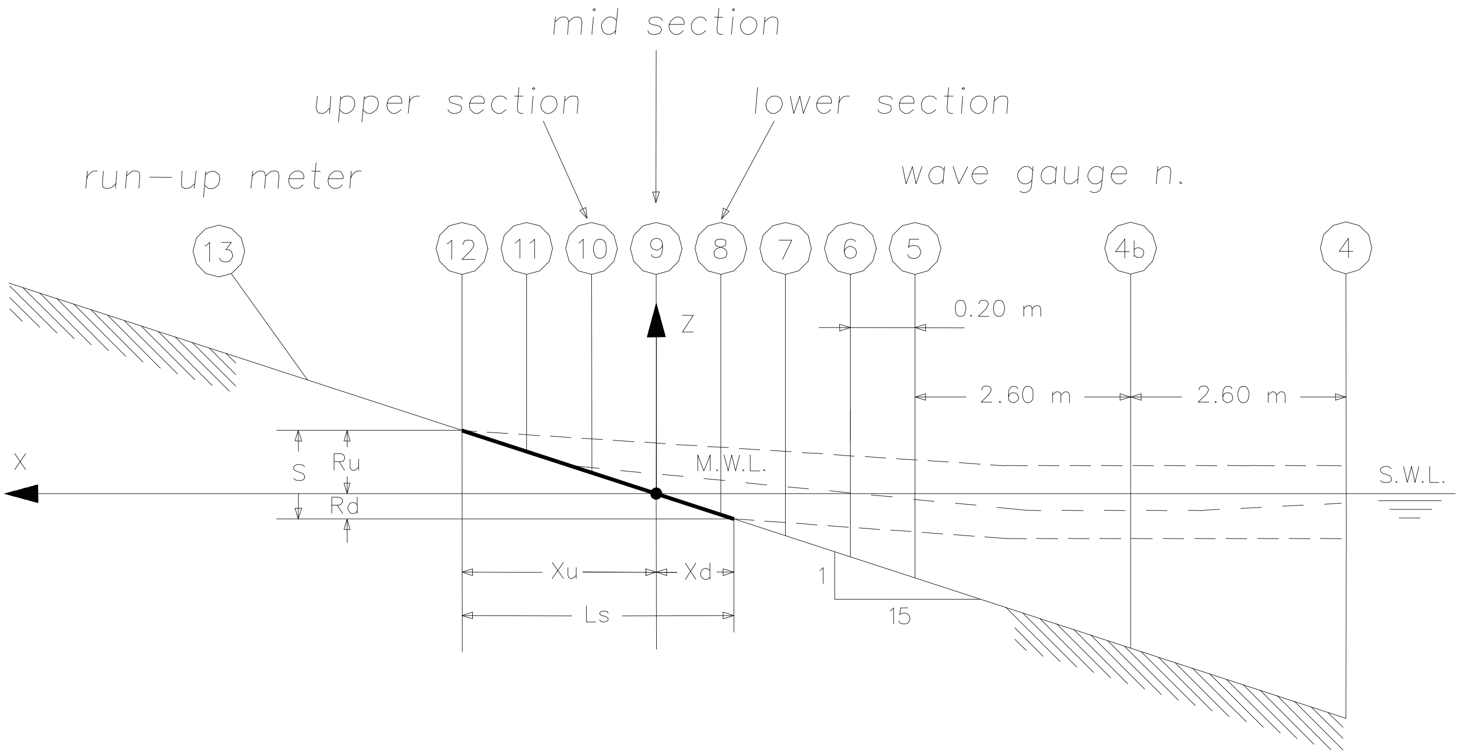

Fig.A1-2 *Reference system and location of the wave gauges in the surf and swash zone.*

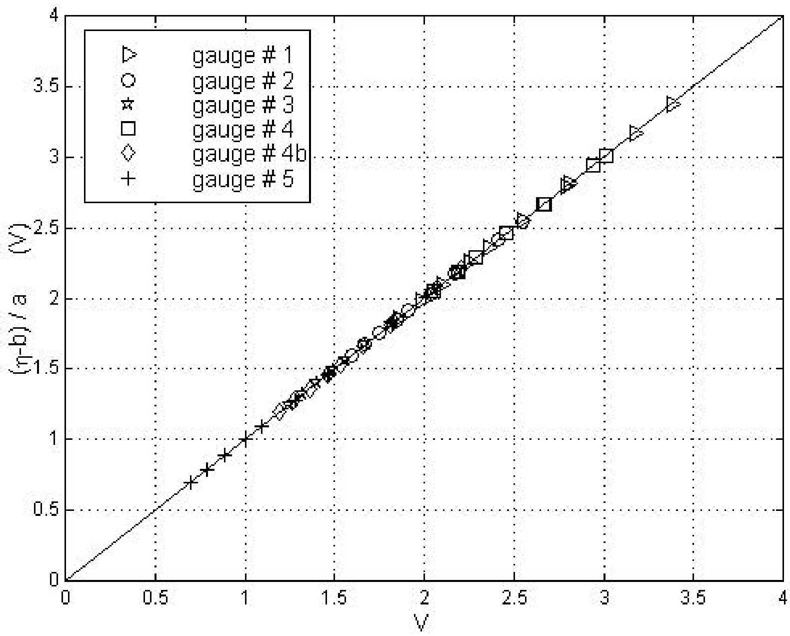

Fig.A1-3 *Calibration of gauges 1-4 and 4b-5.*

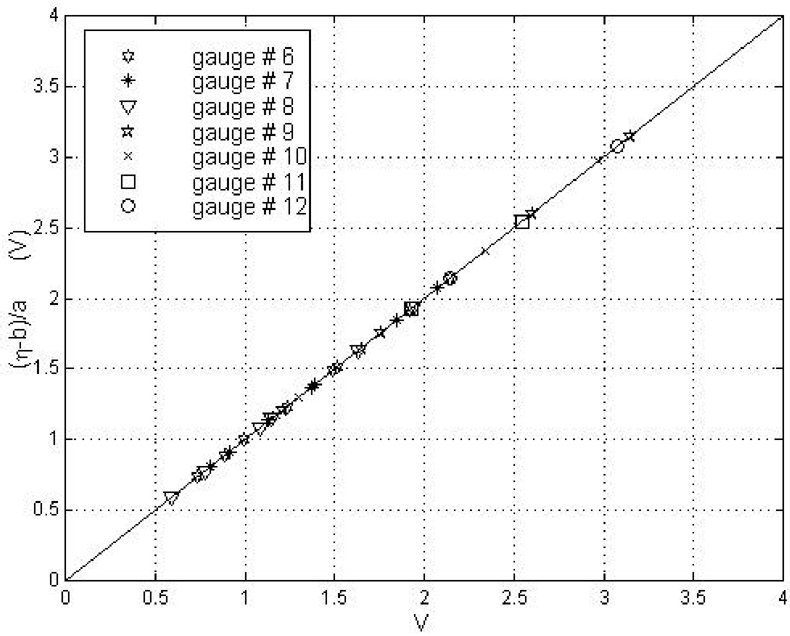

Fig.A1-4 *Calibration of gauges 6-12.*

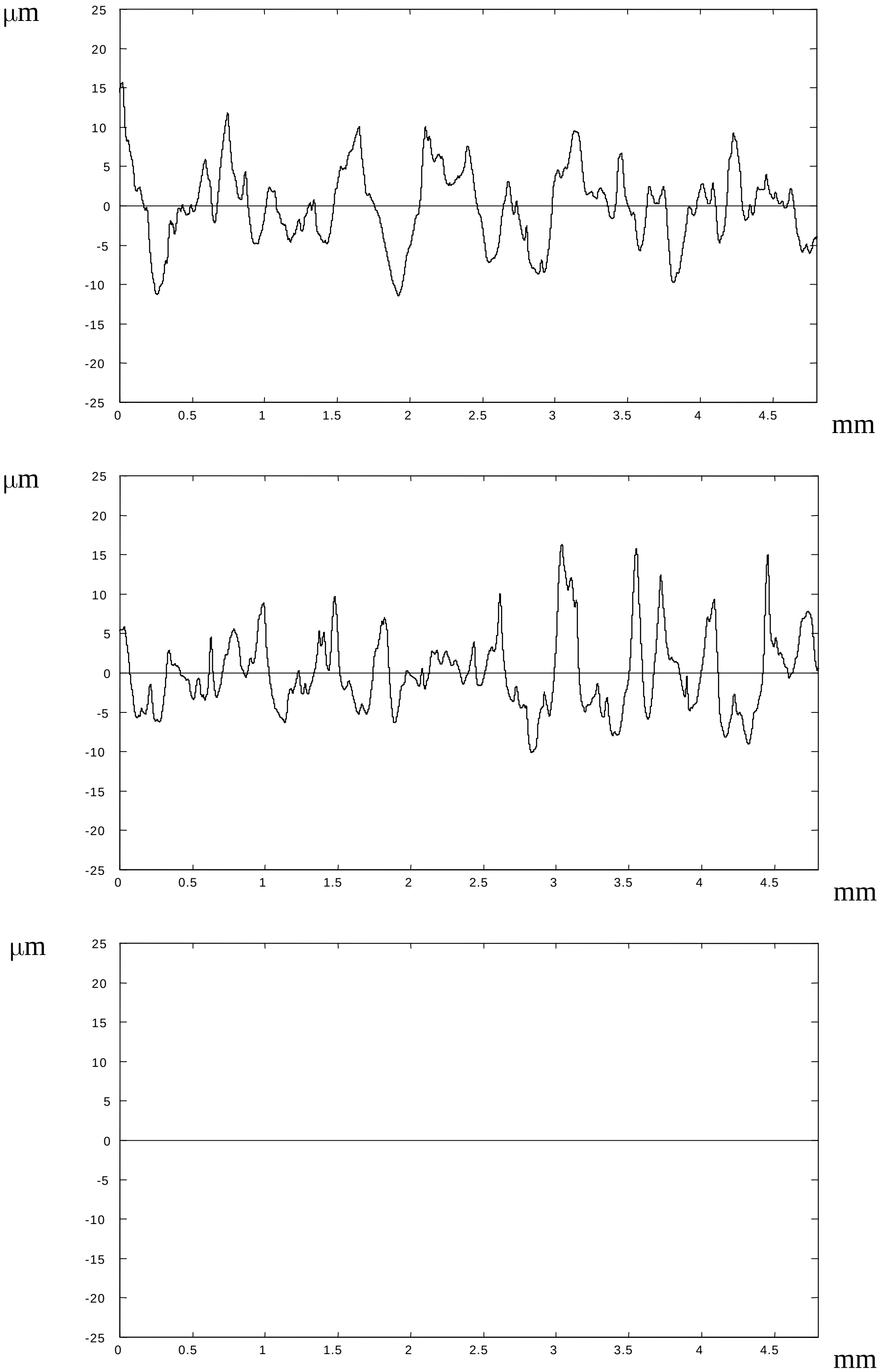

Fig.A1-5 *Concrete bottom surface profile. Specimen X.*

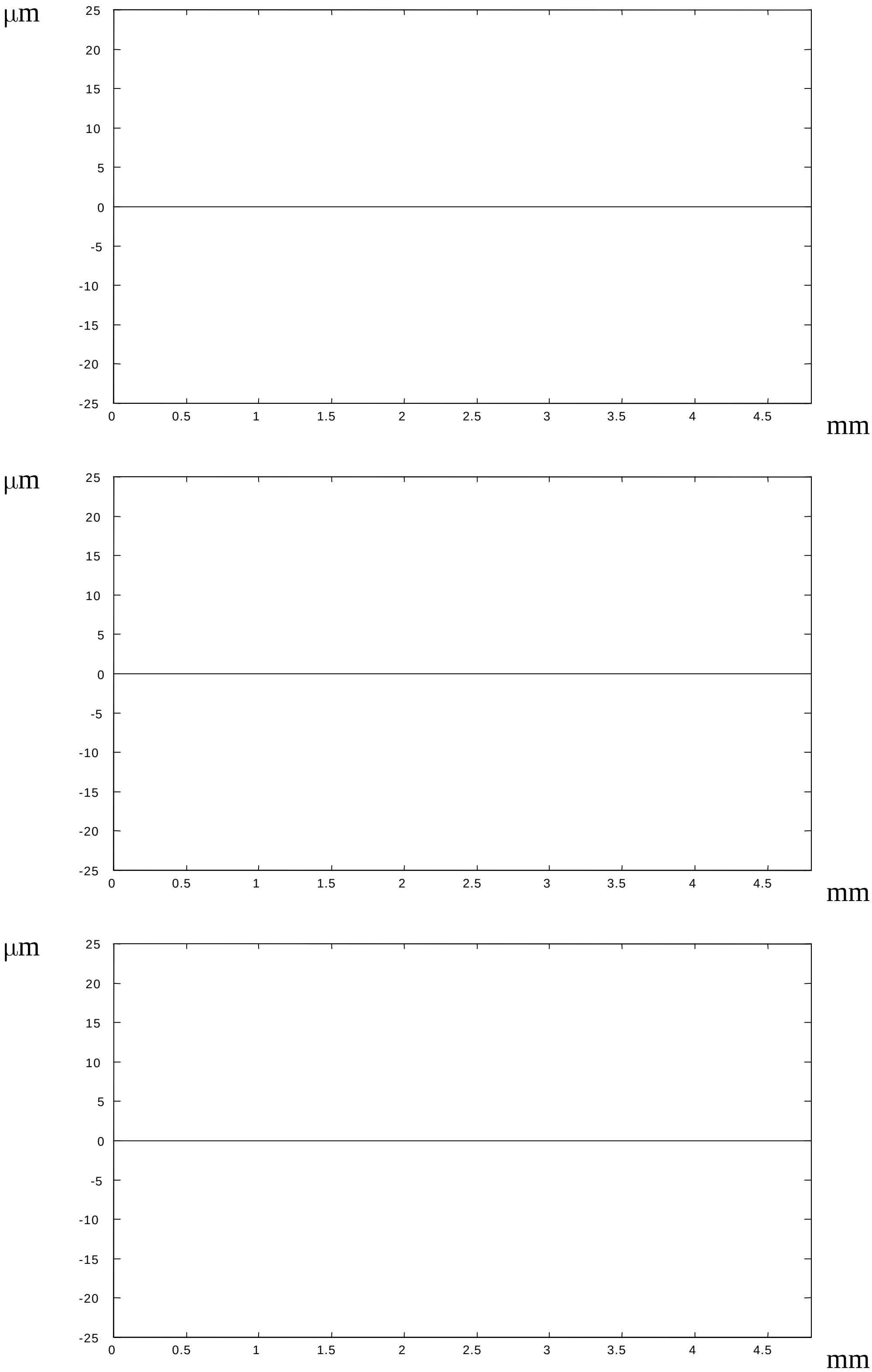

Fig.A1-6 *Concrete bottom surface profile. Specimen Y.*

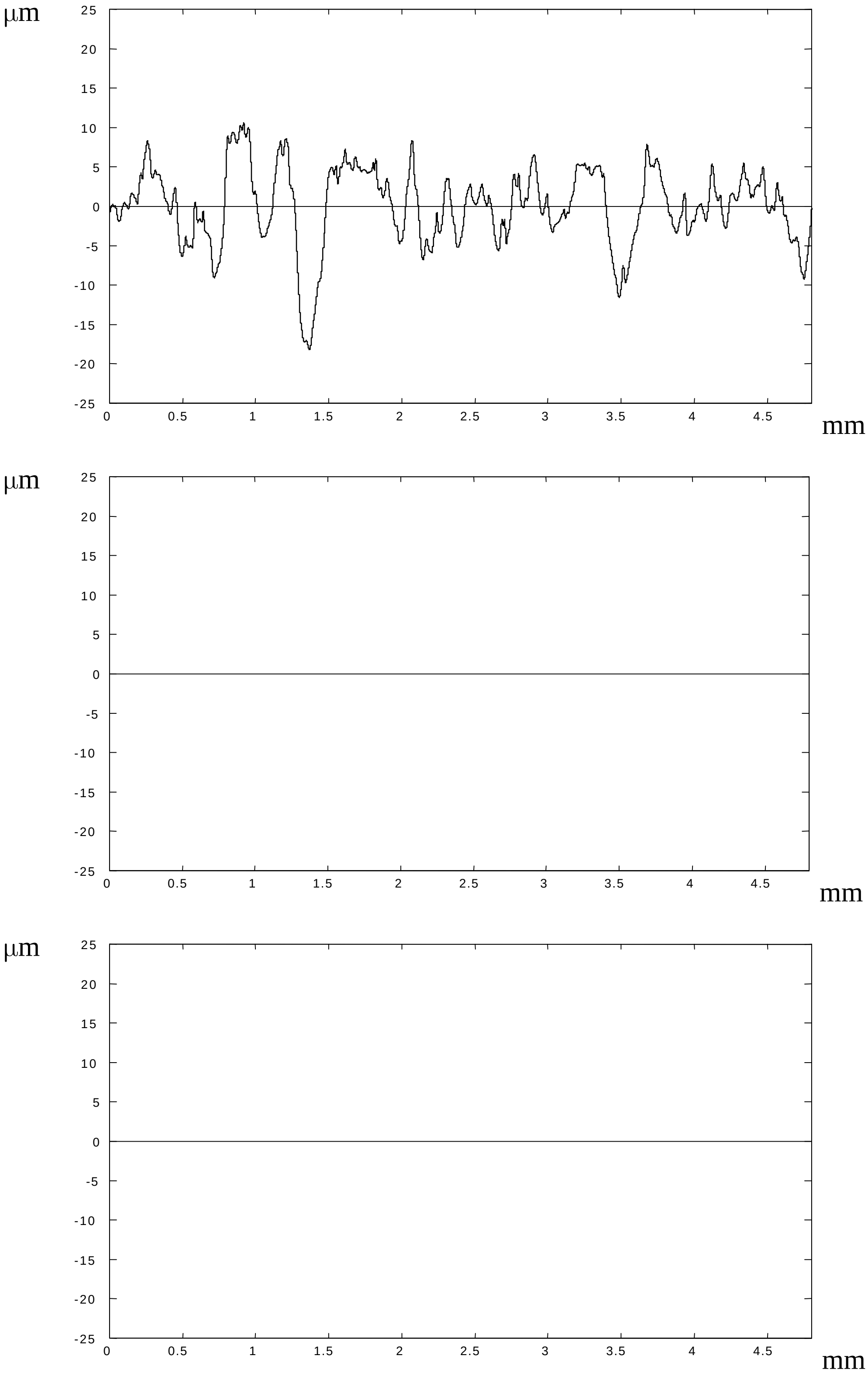

Fig.A1-7 *Concrete bottom surface profile. Specimen Z.*

Annex 2

Phase analysis of regular wave tests:

- RH040T20
- RH040T25
- RH040T30

Tab.A2-I ***Test RH040T20:*** *water levels evaluated referring to S.W.L. (*h_{max} *= max values,* $\hat{\eta}$*= phasic average values,* $\langle\eta\rangle$*= time average values,* h_{min} *= min values, H = wave height)*

Gauge #	η_{max} [cm]	$\hat{\eta}$ [cm]	$\langle\eta\rangle$ [cm]	η_{min} [cm]	*H* [cm]
1	1.9	-0.1	-0.1	-1.6	3.5
2	1.7	-0.1	-0.1	-1.6	3.3
3	1.7	-0.1	-0.1	-1.7	3.4
4	1.4	-0.1	-0.1	-1.4	2.8
4b	1.9	-0.1	-0.1	-1.8	3.7
5	3.6	-0.1	-0.1	-1.7	5.3
6	1.7	0.0	0.0	-1.5	3.2
7	1.8	0.4	0.4	-0.9	2.7
8	1.7	0.7	0.7	-0.2	1.9
9	1.9	1.5	1.5	0.7	1.2
10	2.3	2.0	1.9	1.3	1.0
11	2.69	2.7	2.7	2.67	0.02
12	/	/	/	/	/

Tab.A2-II ***Test RH040T25:*** *water levels evaluated referring to S.W.L.*

Gauge #	η_{max} [cm]	$\hat{\eta}$ [cm]	$\langle\eta\rangle$ [cm]	η_{min} [cm]	*H* [cm]
1	2.0	-0.1	-0.1	-1.4	3.4
2	2.0	-0.1	-0.1	-1.4	3.4
3	1.6	-0.1	-0.1	-1.6	3.2
4	1.5	-0.1	-0.1	-1.2	2.7
4b	1.6	-0.2	-0.2	-1.6	3.2
5	3.9	-0.1	-0.1	-2.1	6.0
6	2.2	-0.1	-0.1	-1.9	4.1
7	2.0	0.3	0.3	-1.2	3.2
8	2.0	0.7	0.7	-0.5	2.5
9	2.2	1.5	1.5	0.5	1.7
10	3.2	2.5	2.4	1.3	1.9
11	3.4	3.1	2.9	2.7	0.7
12	/	/	/	/	/

Tab.A2-III ***Test RH040T30:*** *water levels evaluated referring to S.W.L.*

Gauge #	η_{max} [cm]	$\hat{\eta}$ [cm]	$\langle\eta\rangle$ [cm]	η_{min} [cm]	H [cm]
1	2.3	-0.1	-0.1	-1.5	3.8
2	2.1	-0.1	-0.1	-1.6	3.7
3	1.8	-0.2	-0.2	-2.0	3.8
4	1.9	-0.1	-0.1	-1.6	3.5
4b	2.5	-0.2	-0.2	-2.1	4.6
5	3.8	-0.2	-0.2	-2.5	6.3
6	3.8	-0.1	-0.1	-2.4	6.2
7	2.5	0.4	0.4	-1.5	4.0
8	2.2	0.7	0.7	-0.7	2.9
9	2.7	1.7	1.7	0.5	2.2
10	3.4	2.6	2.5	1.4	2.0
11	4.4	3.8	3.6	2.7	1.7
12	4.7	4.5	4.3	4.0	0.7

Tab.A2-IV- *Regular waves: water levels evaluated at the run up meter referring to S.W.L. (R_u = run up, $\hat{\eta}$ = phasic averaged values, $\langle\eta\rangle$ = time averaged values, R_d = run down, S = swash amplitude)*

Test #	R_u [cm]	$\hat{\eta}=\langle\eta\rangle$ [cm]	R_d [cm]	S [cm]
RH040T20	2.7	1.9	0.8	1.9
RH040T25	3.4	2.2	0.6	2.8
RH040T30	5.0	3.0	0.5	4.5

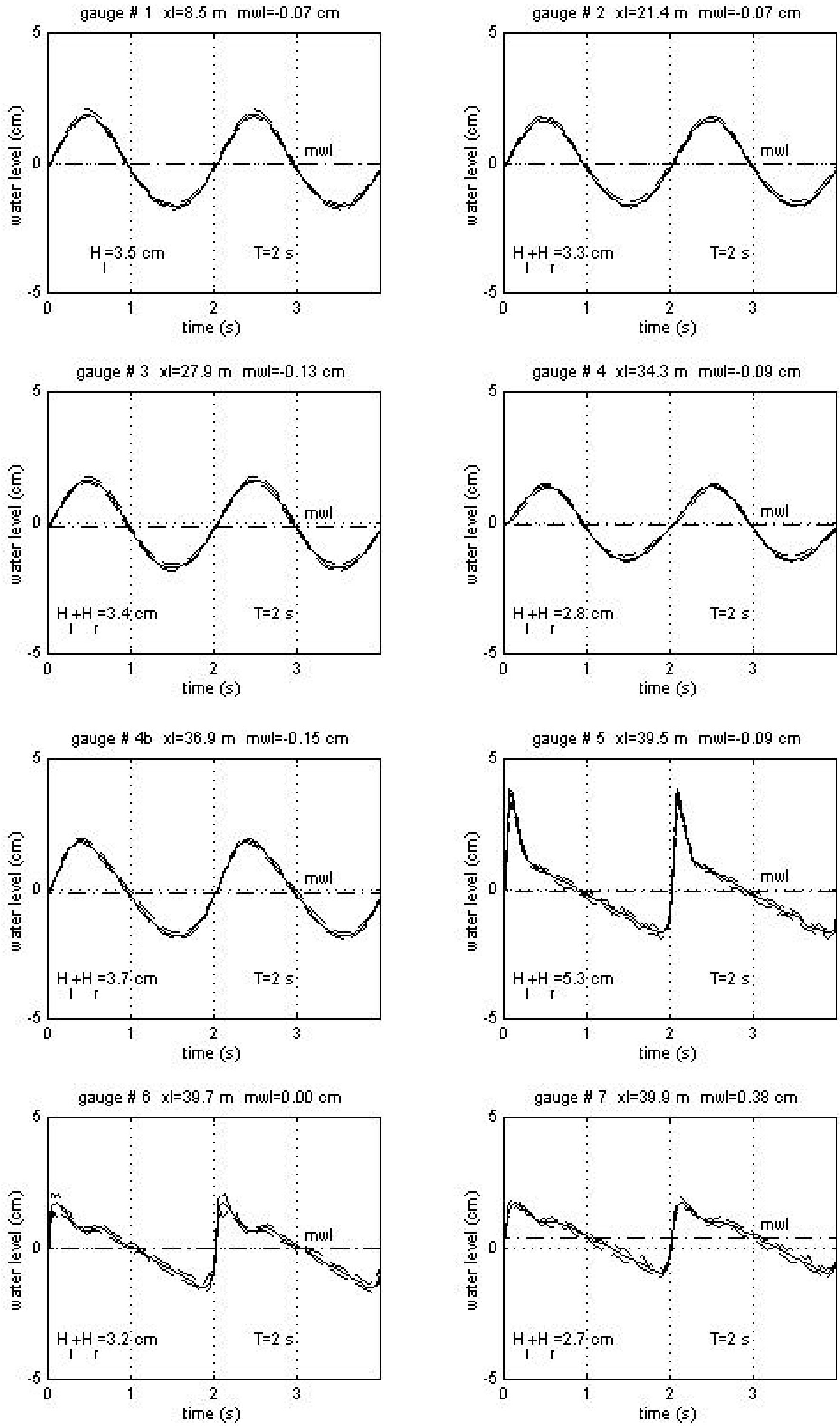

Fig.A2-1. Test RH040T20: *phase analysis of gauges 1-4 and 4b-7. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

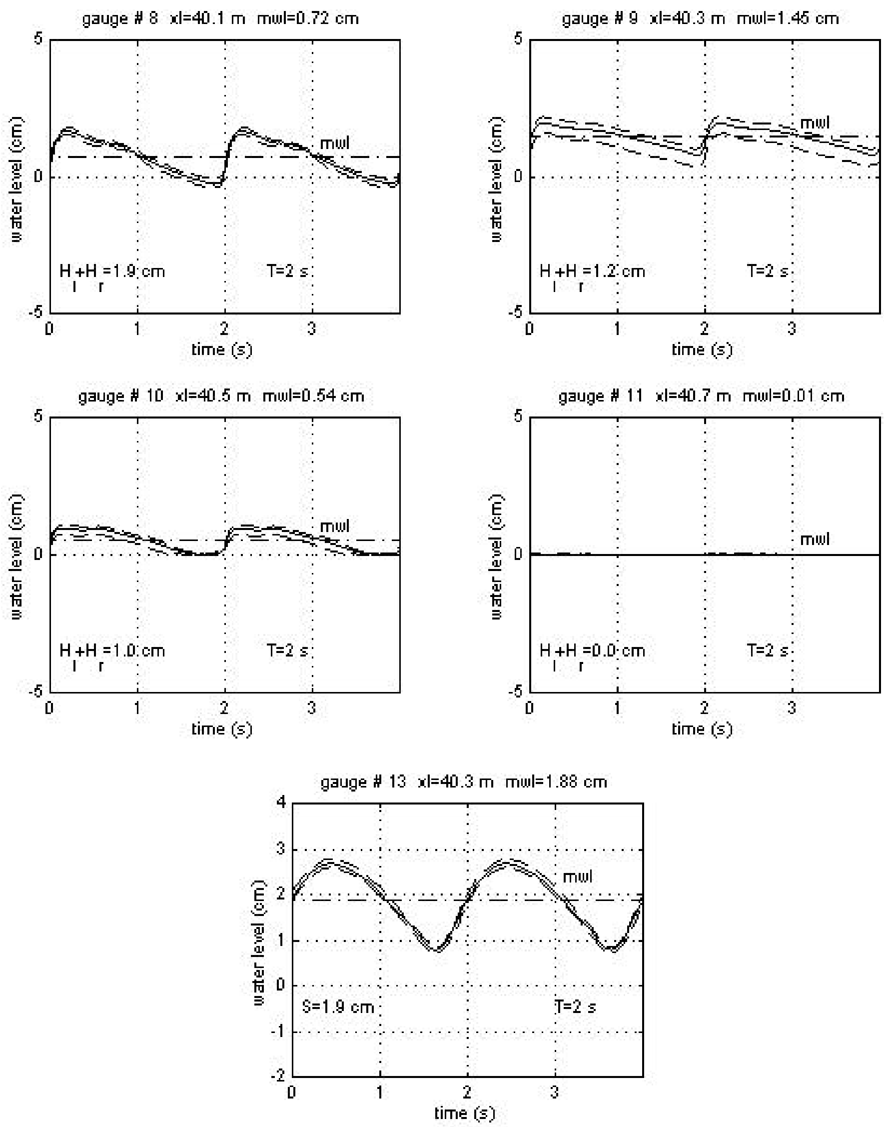

Fig.A2-2. Test RH040T20: *phase analysis of gauges 8-11 and 13. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

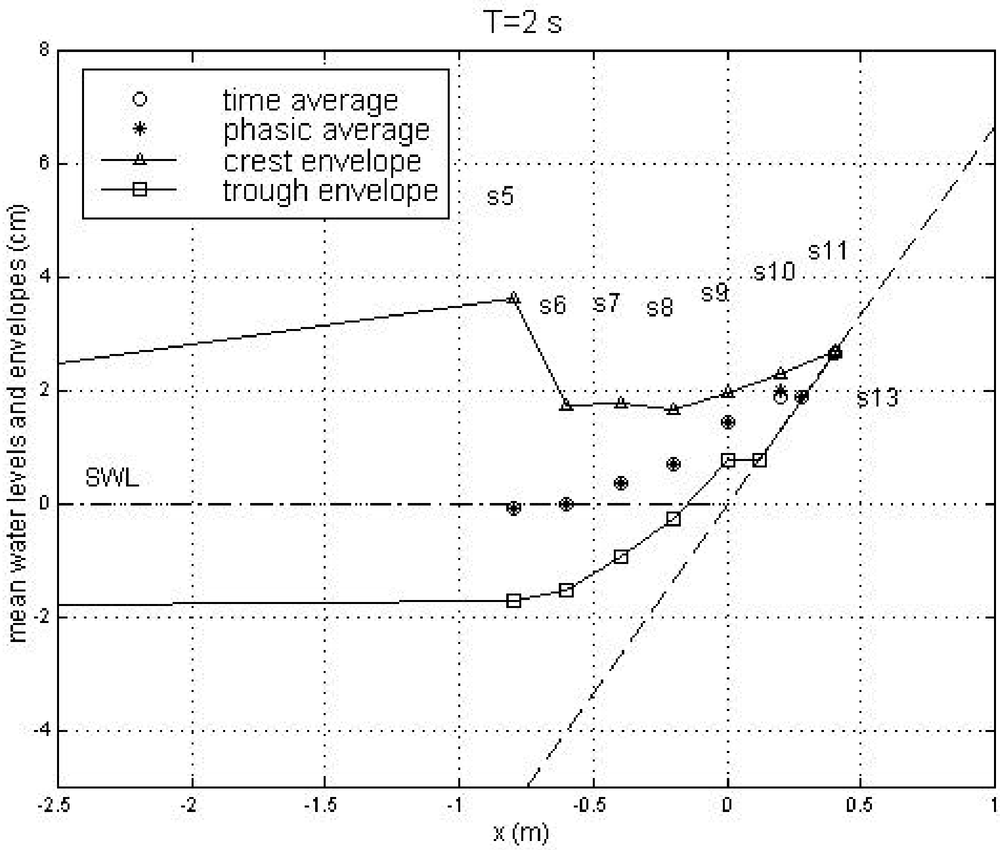

Fig.A2-3. Test RH040T20: *Set up profiles, crest and trough envelopes.*

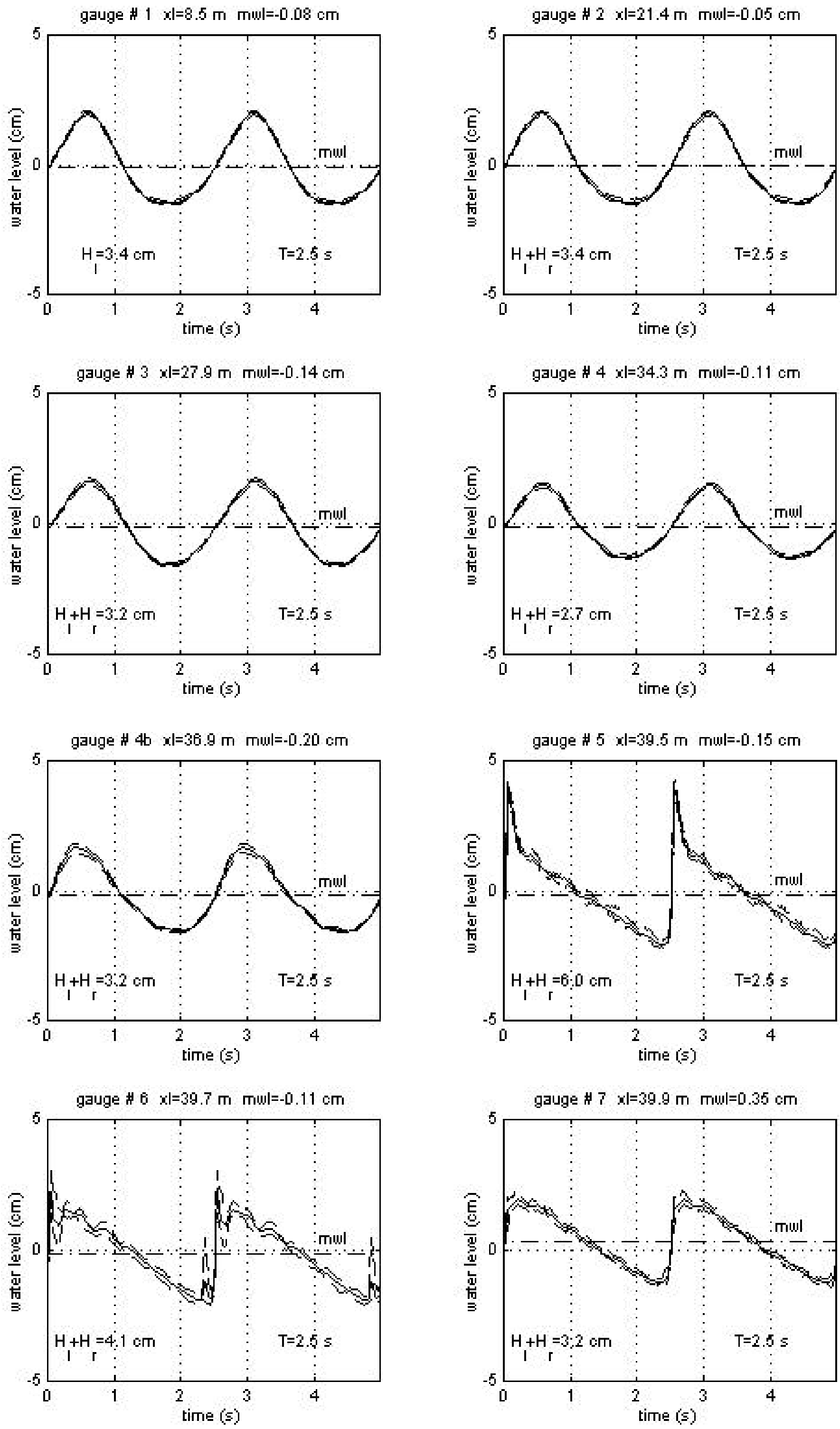

Fig.A2-4. Test RH040T25: *phase analysis of gauges 1-4 and 4b-7. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

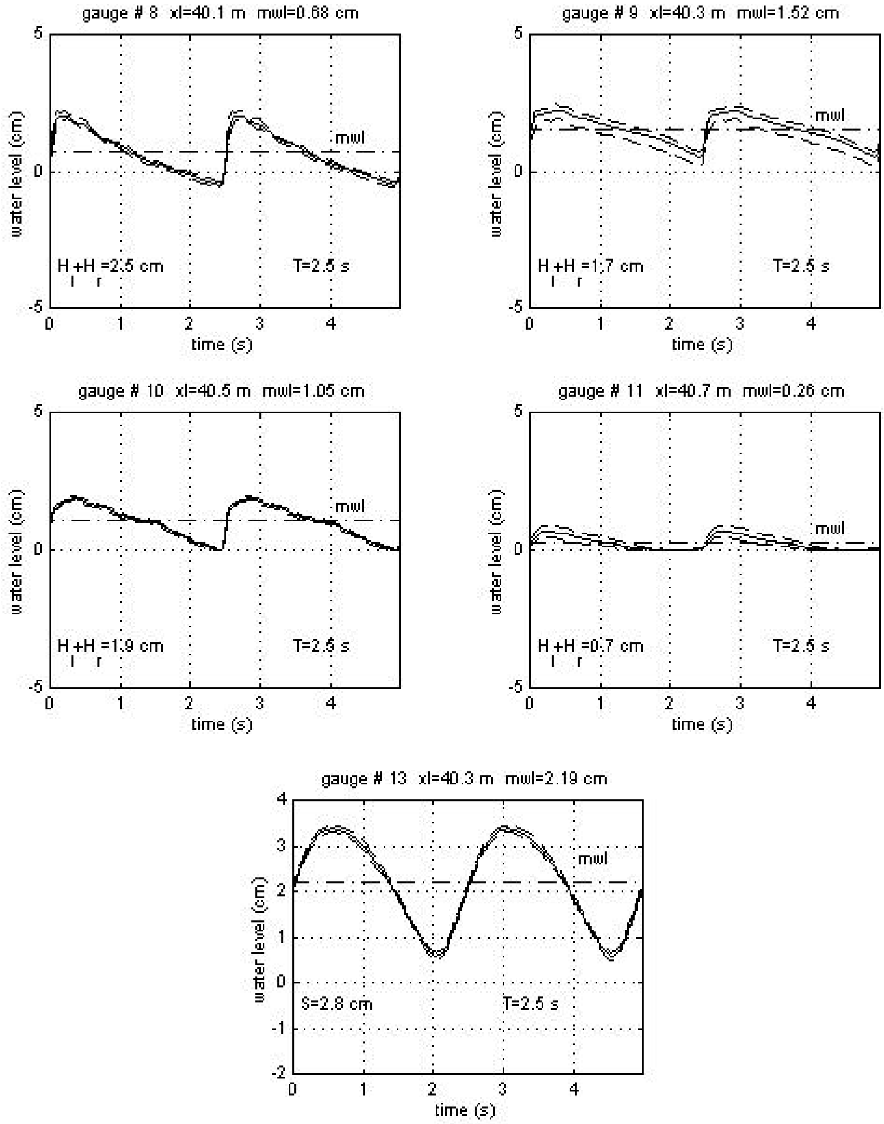

Fig.A2-5. Test RH040T25: *phase analysis of gauges 8-11 and 13. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

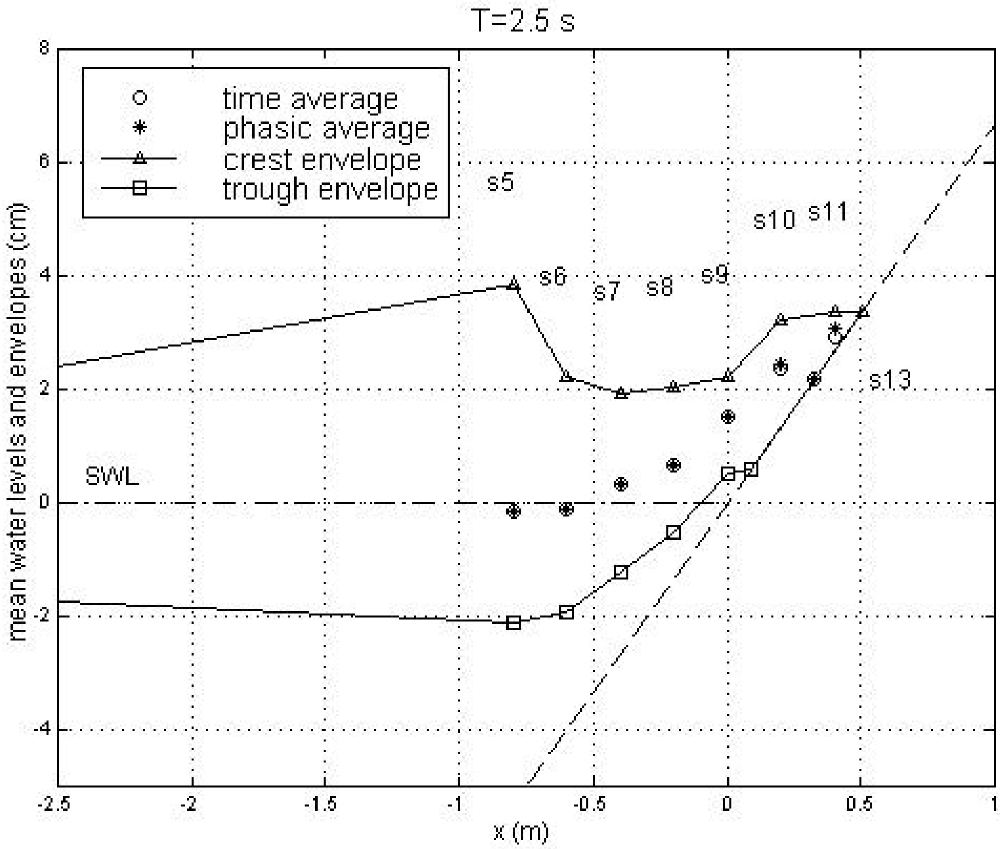

Fig.A2-6. Test RH040T25: *Set up profiles, crest and trough envelopes.*

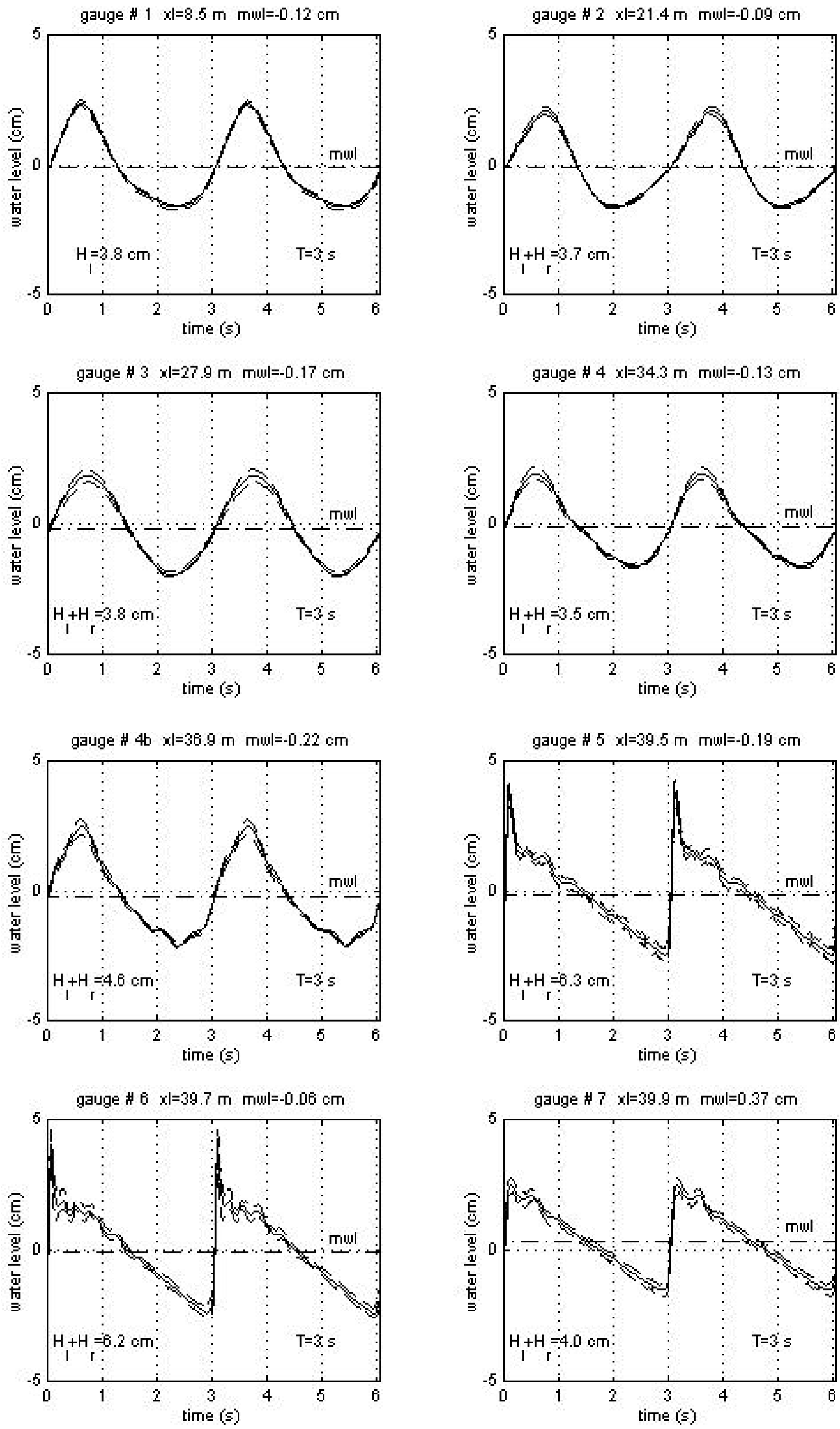

Fig.A2-7. Test RH040T30: *phase analysis of gauges 1-4 and 4b-7. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

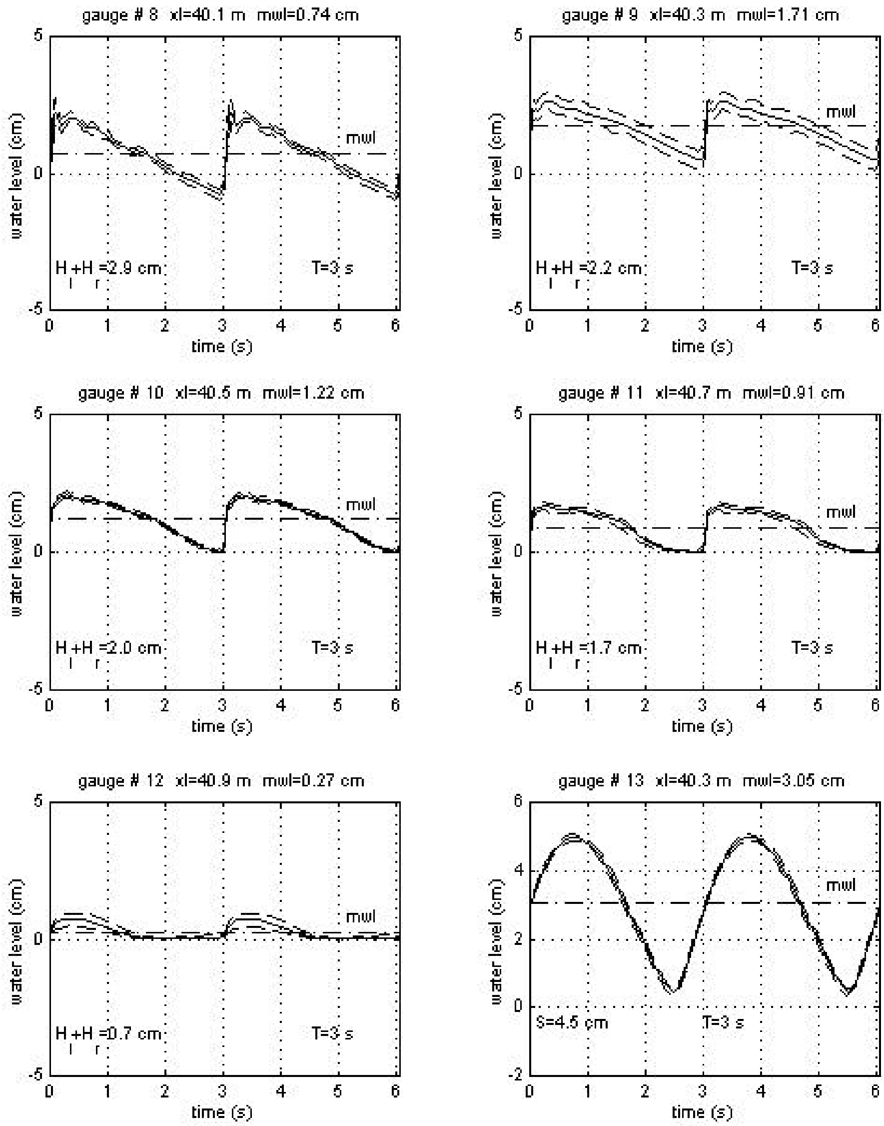

Fig.A2-8. Test RH040T30: *phase analysis of gauges 8-13. Dashed lines are the envelopes of maximum and minimum levels recorded in all sets of measurements.*

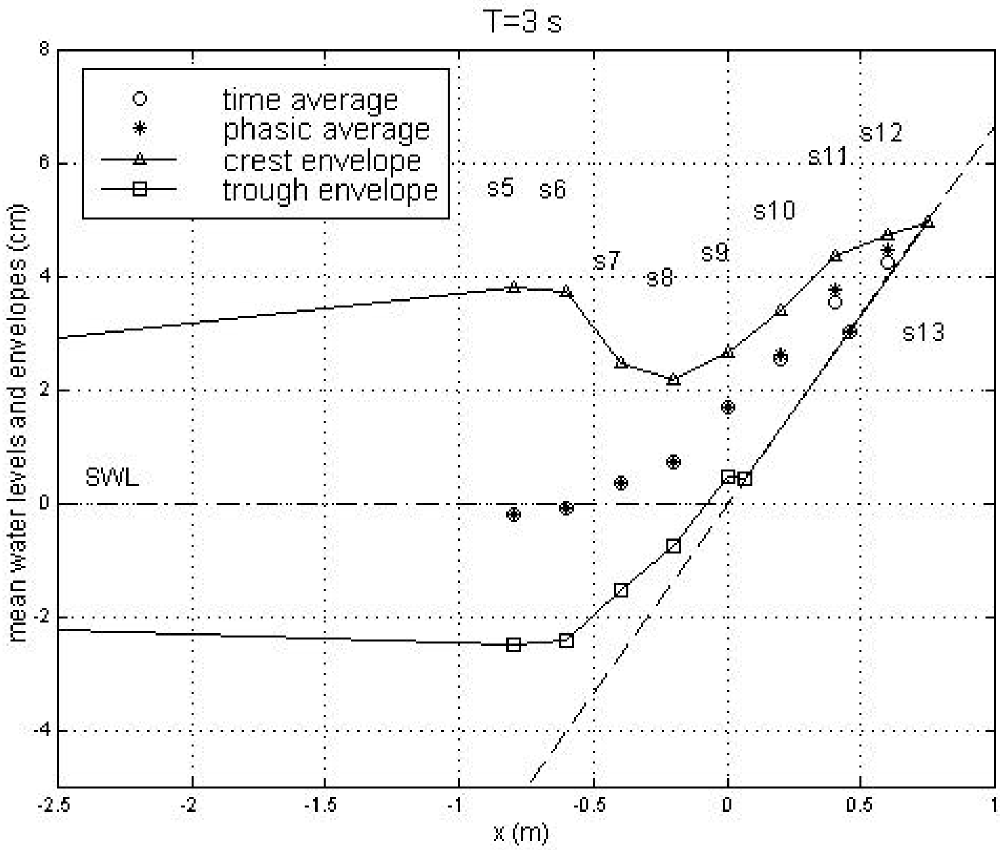

Fig.A2-9. Test RH040T30: *Set up profiles, crest and trough envelopes.*

Annex 3

Analysis of irregular wave tests:

- IH040T20
- IH04T025
- IH040T30

Tab. A3-1. *- Irregular waves: water levels evaluated at the run up meter referring to S.W.L. (Ru_{max} = max run up, $\langle\eta\rangle$ = time averaged values, Rd_{min} = min run down, S = swash amplitude)*

Test #	Ru_{max} [cm]0	$\langle\eta\rangle$ [cm]	Rd_{min} [cm]	S [cm]
IH040T20	3.0	1.6	0.1	2.9
IH040T25	3.6	1.6	-0.4	4.0
IH040T30	5.1	2.1	-0.8	5.9

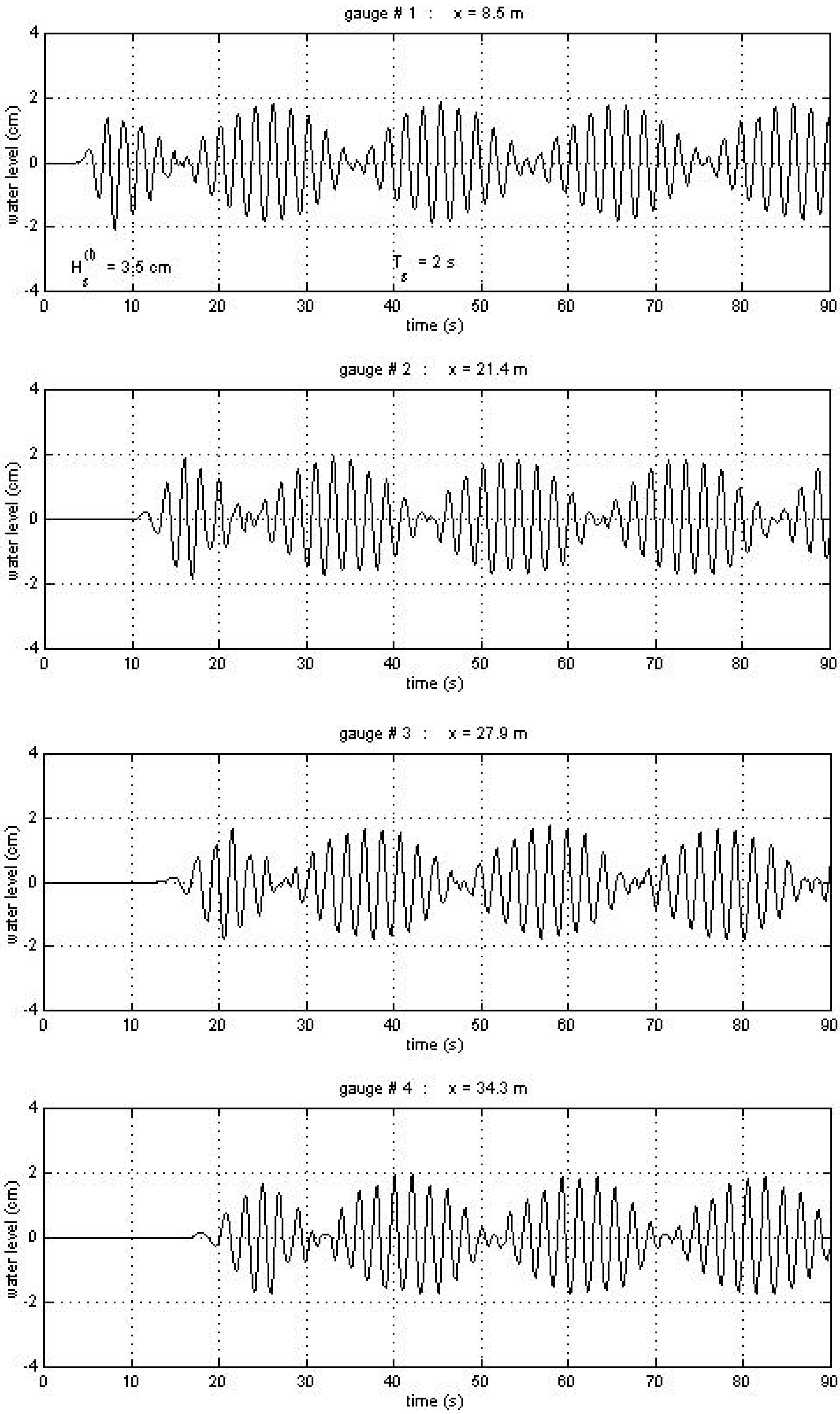

Fig.A3-1. Test IH040T20*: time recording of gauges 1-4*.

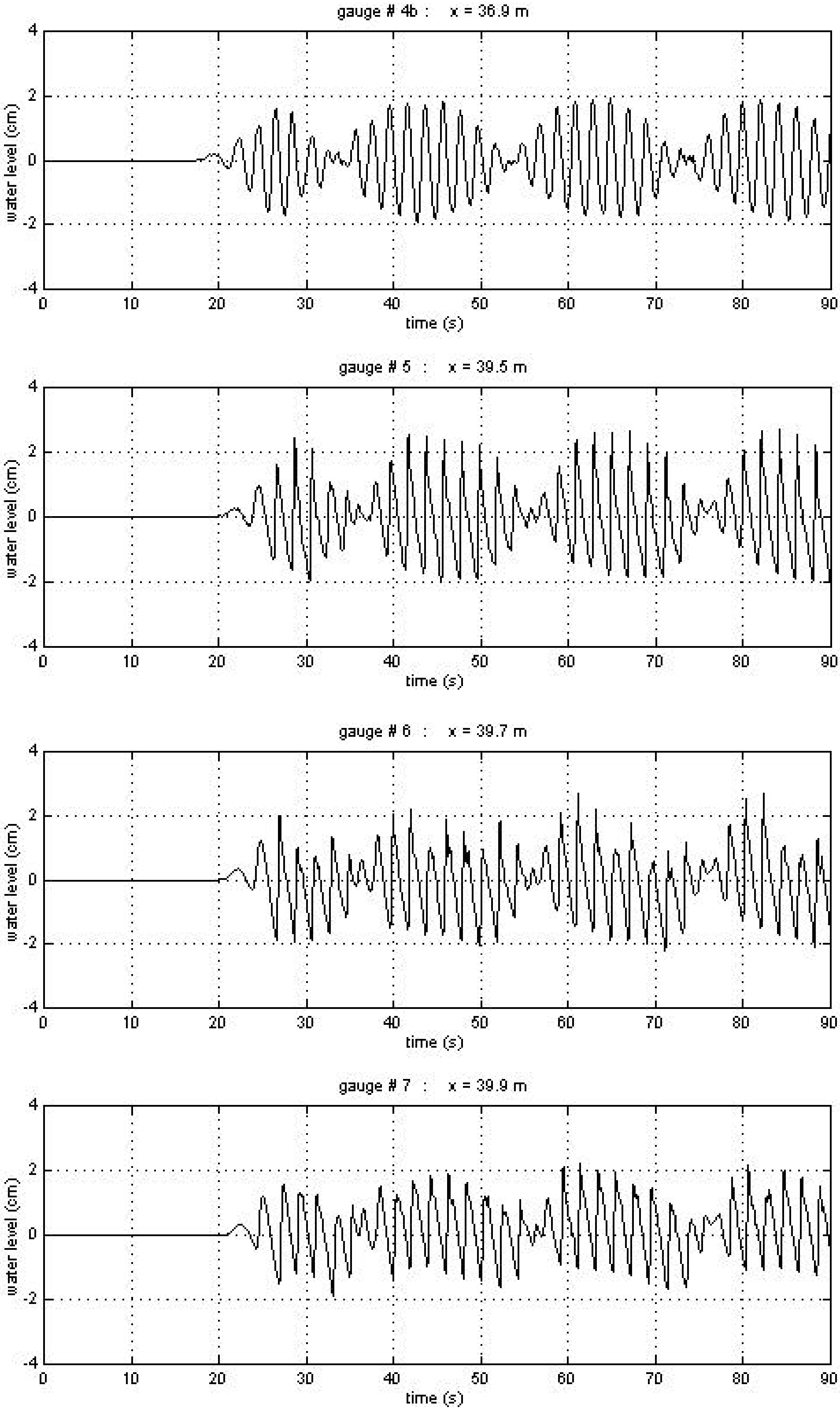

Fig.A3-2. Test IH040T20: *time recording of gauges 4b-7.*

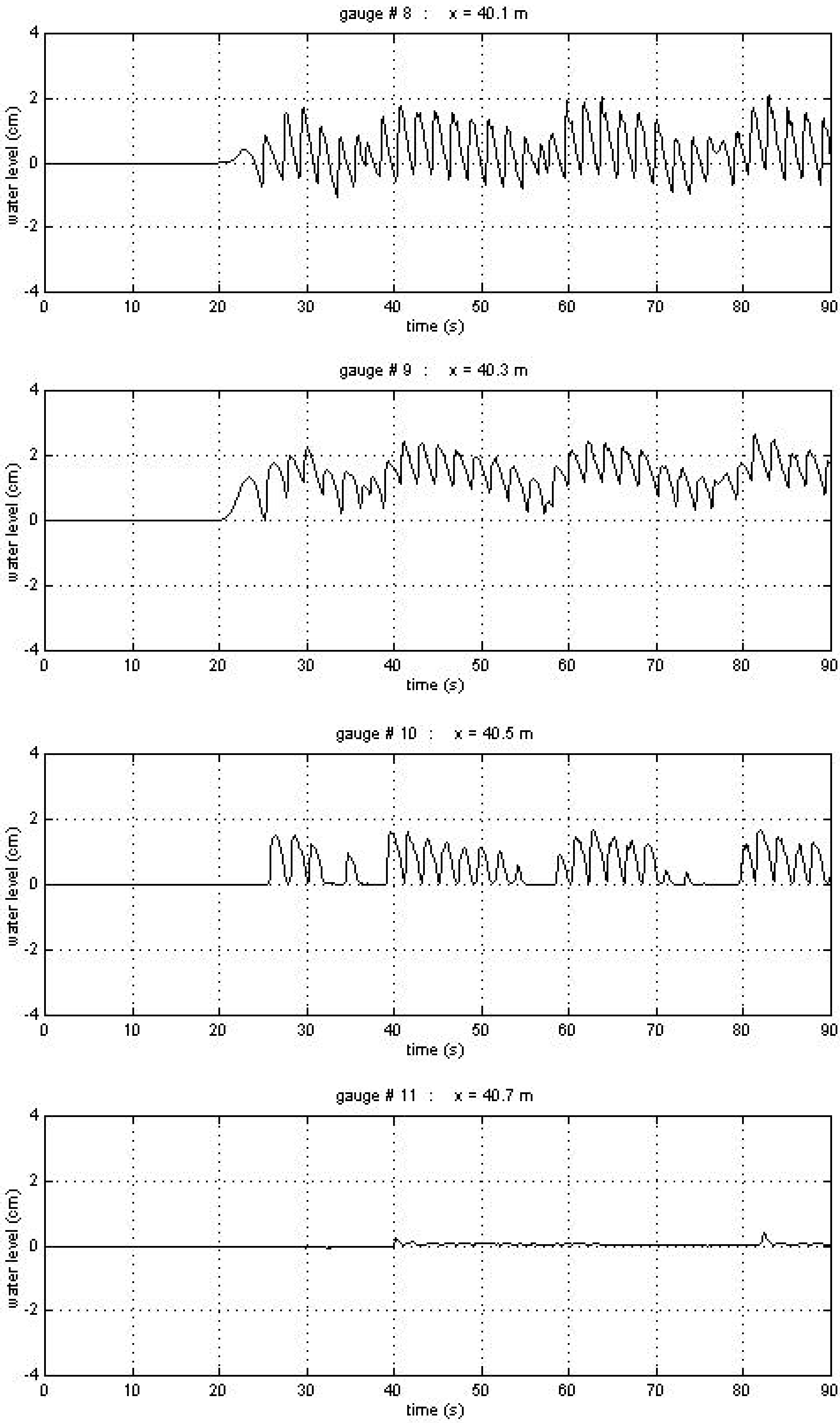

Fig.A3-3. Test IH040T20: *time recording of gauges 8-11.*

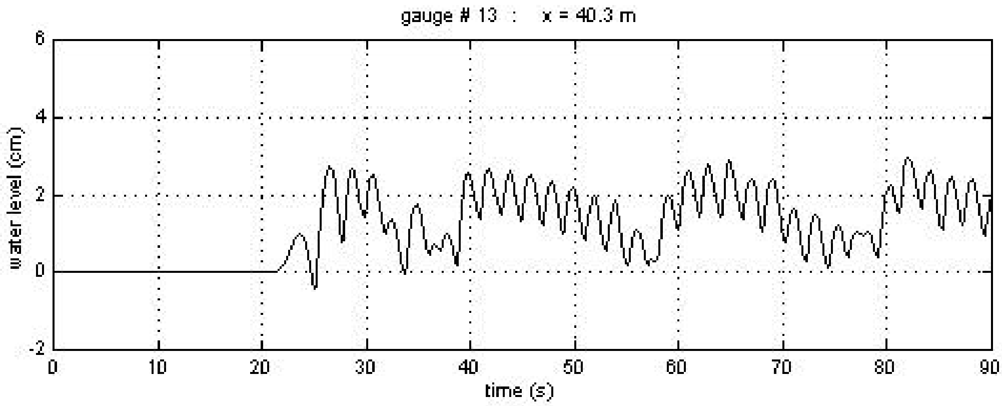

Fig.A3-4. Test IH040T20*: time recording of gauge 13*.

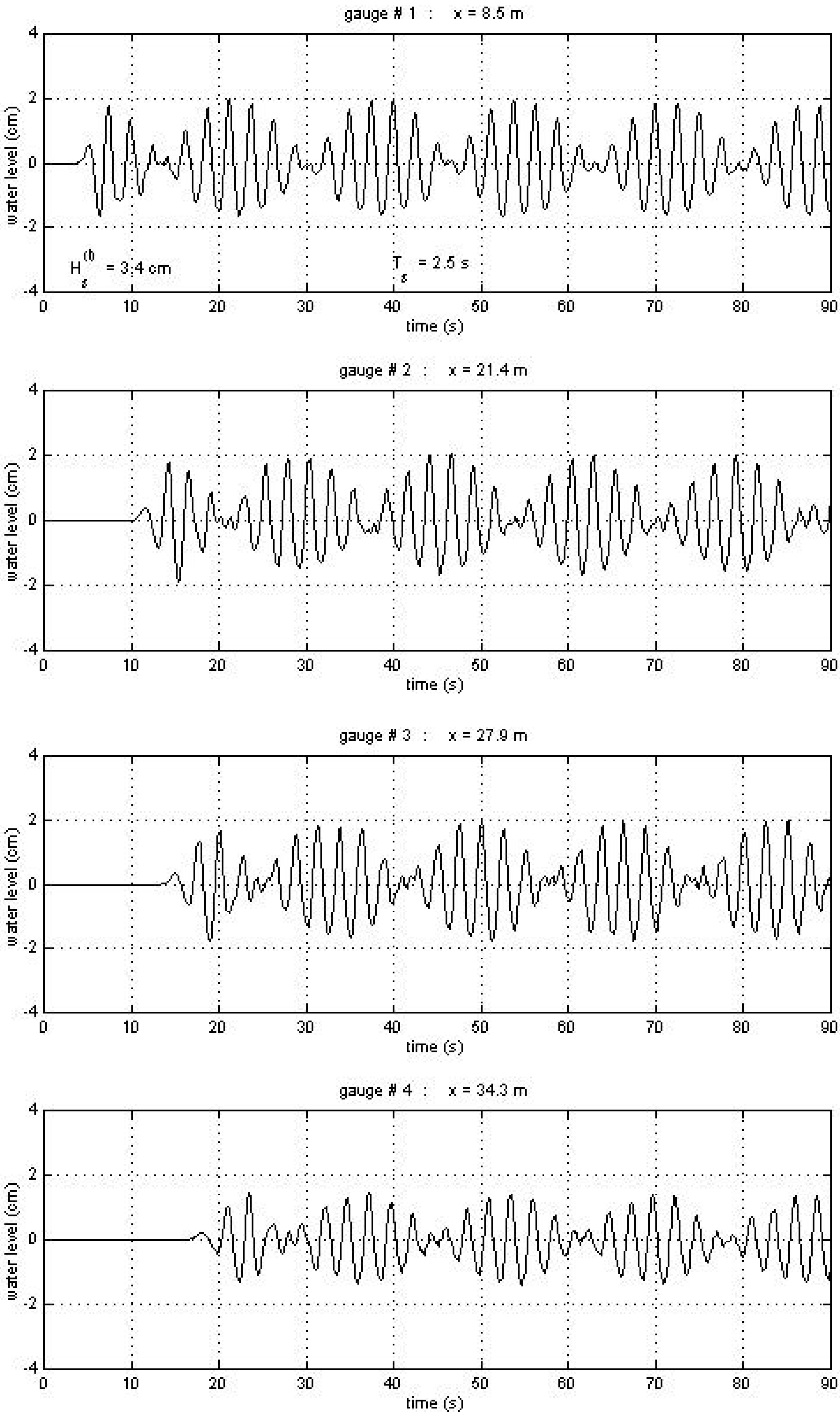

Fig.A3-5. Test IH040T25*: time recording of gauges 1-4*.

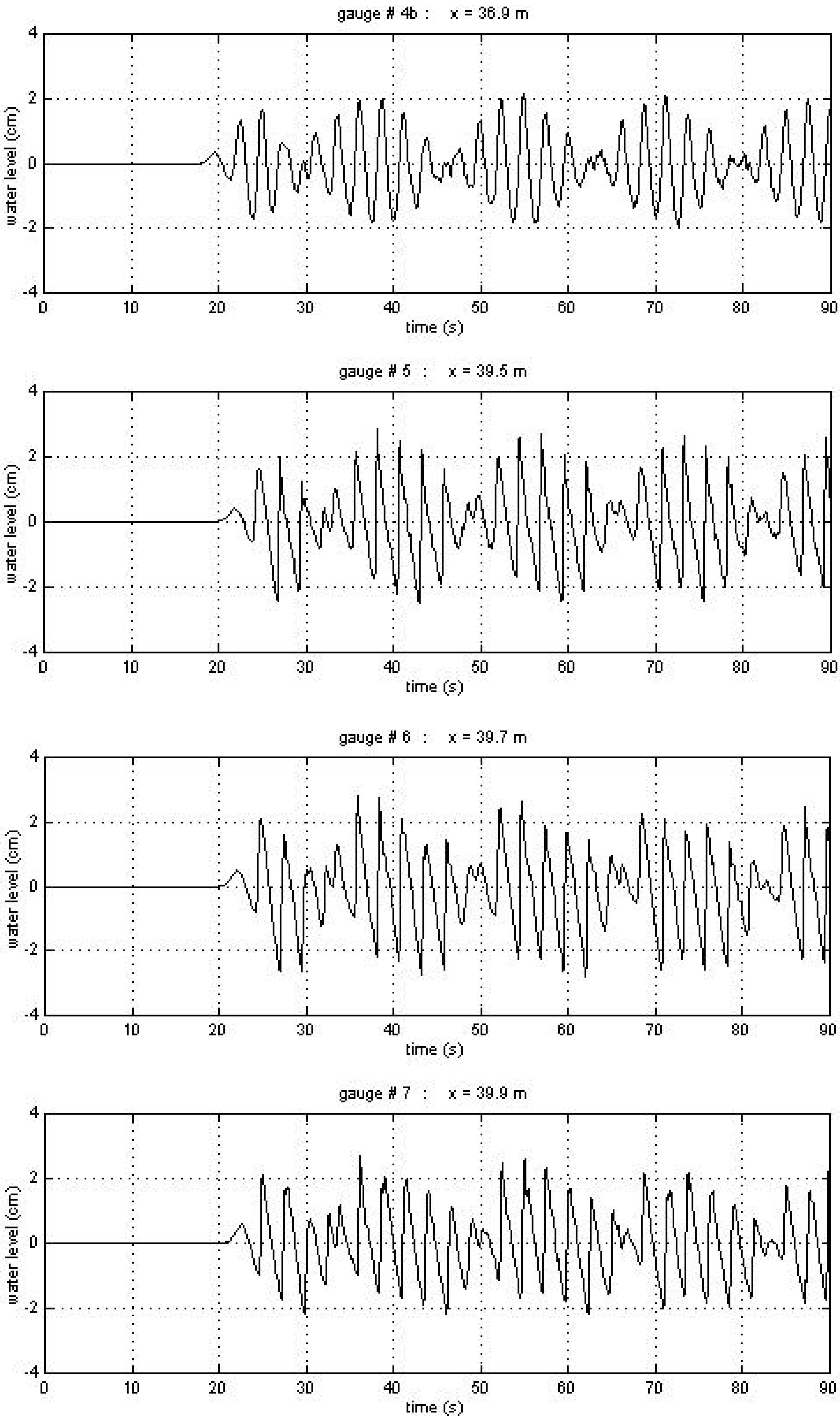

Fig.A3-6. Test IH040T25: *time recording of gauges 4b-7.*

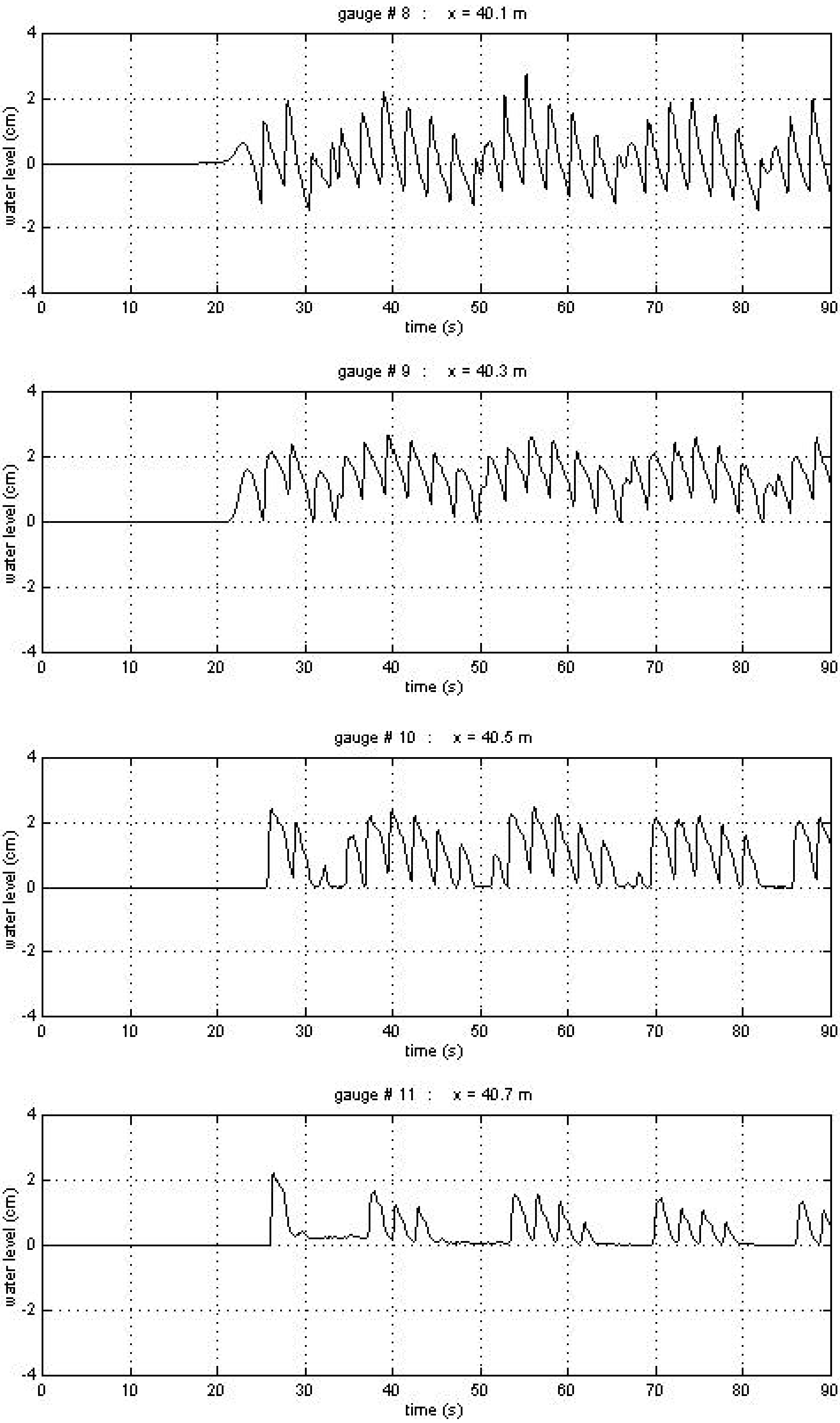

Fig.A3-7. Test IH040T25: *time recording of gauges 8-11*.

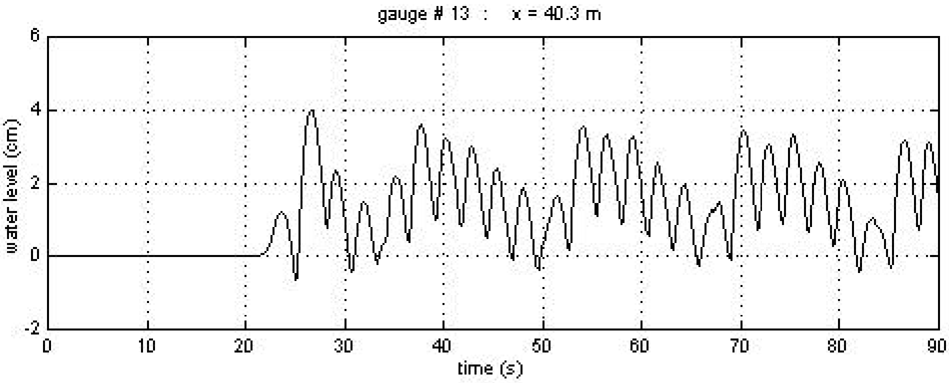

Fig.A3-8. Test IH040T25*: time recording of gauge 13*.

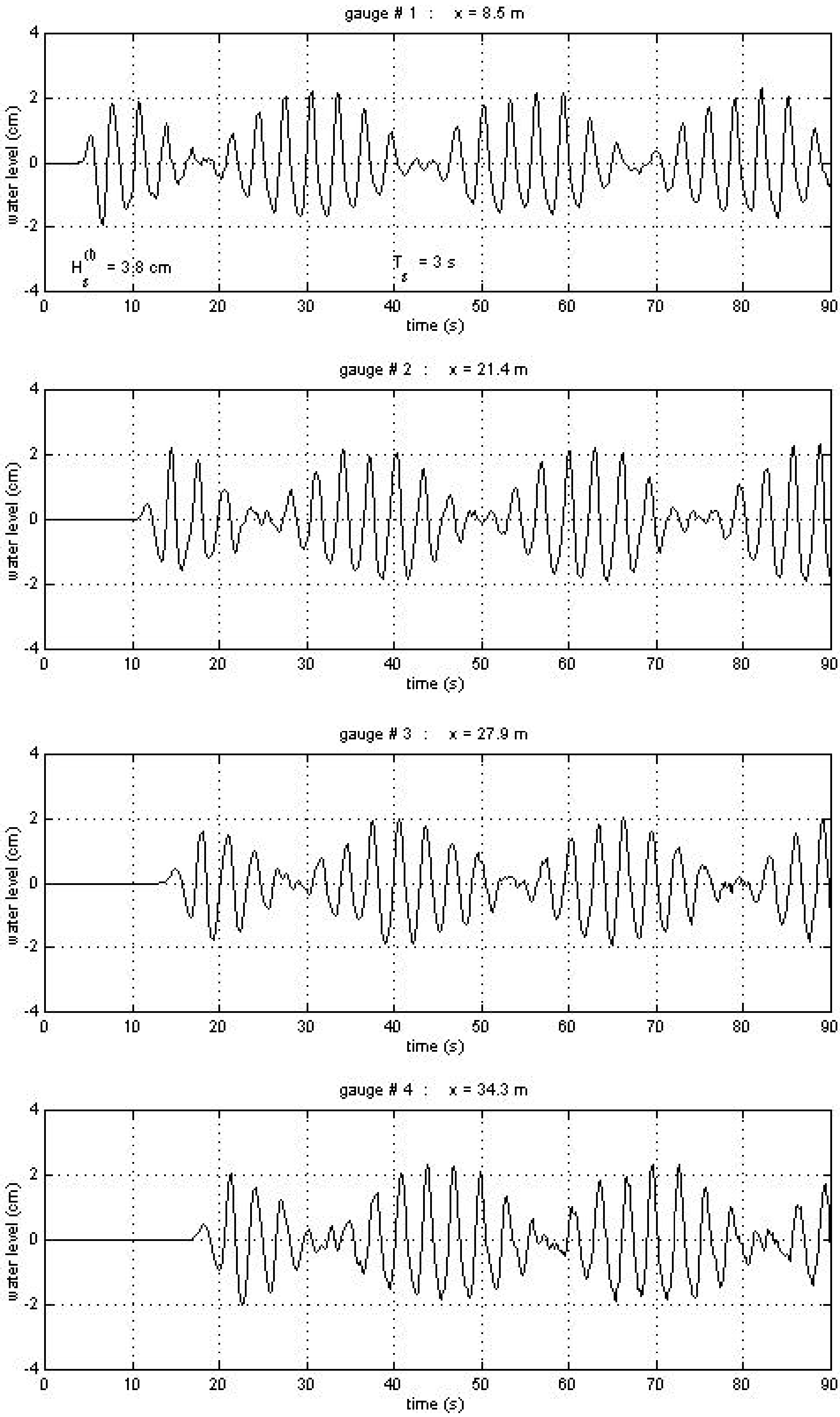

Fig.A3-9. Test IH040T30*: time recording of gauges 1-4*.

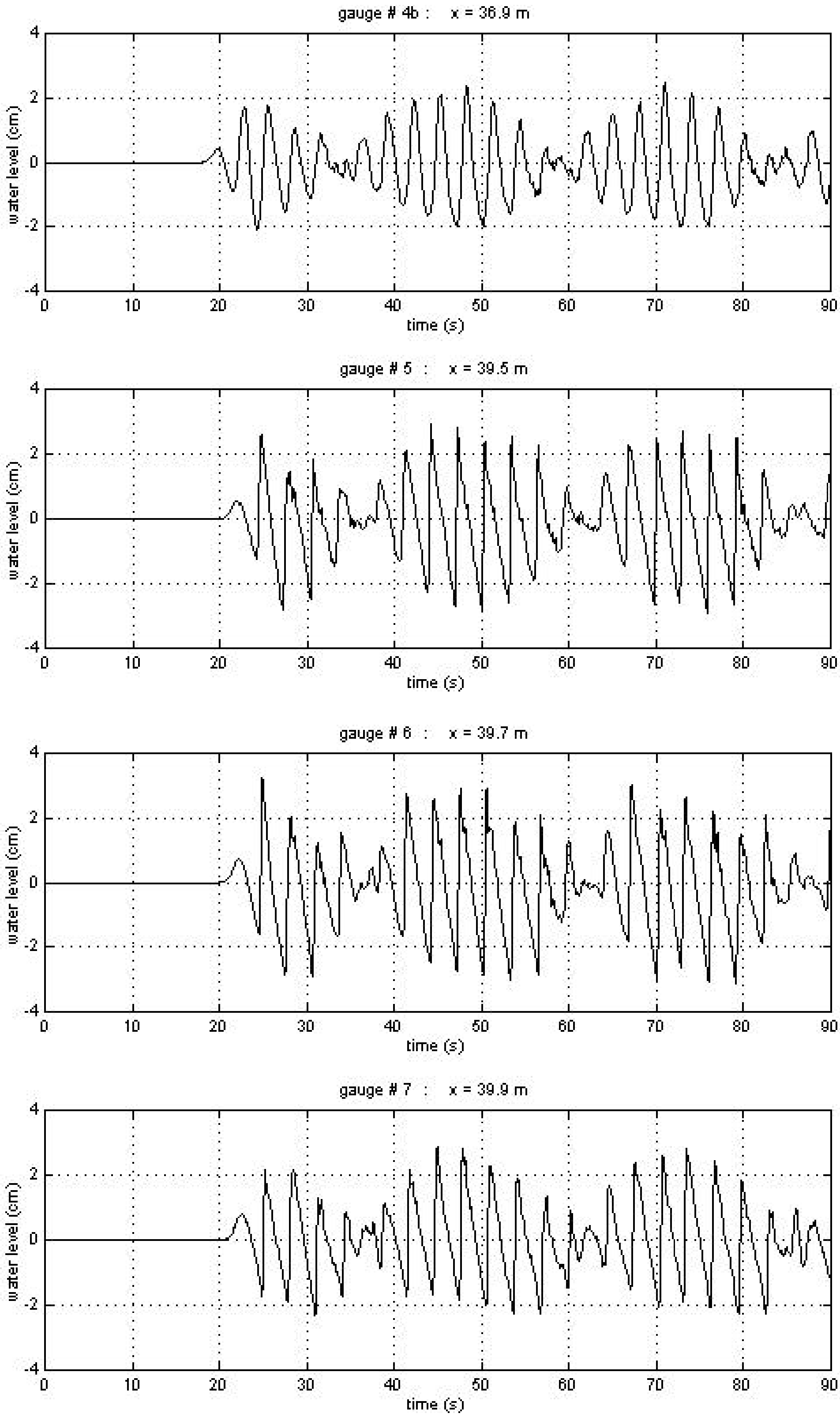

Fig.A3-10. Test IH040T30*: time recording of gauges 4b-7*.

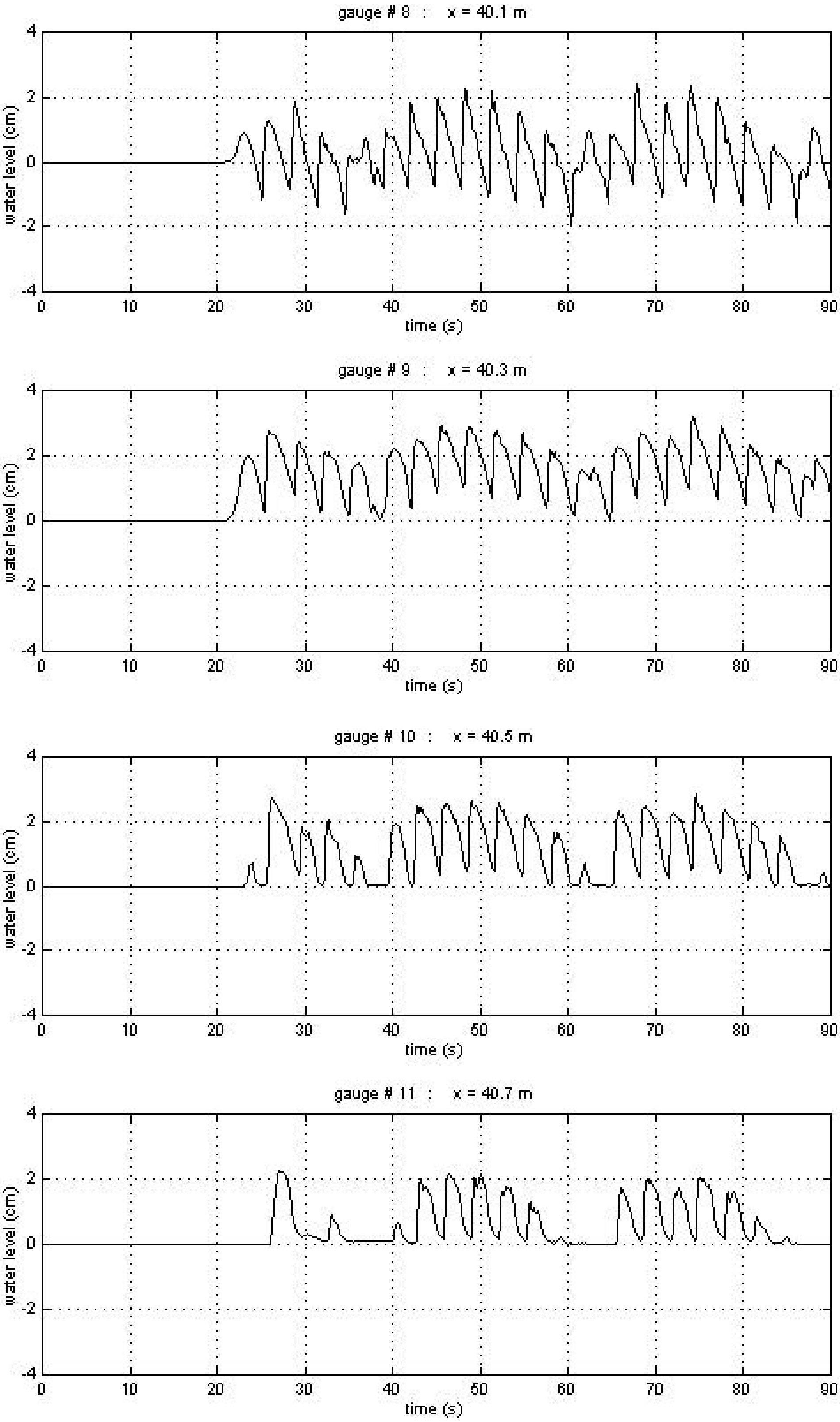

Fig.A3-11. Test IH040T30*: time recording of gauges 8-11*.

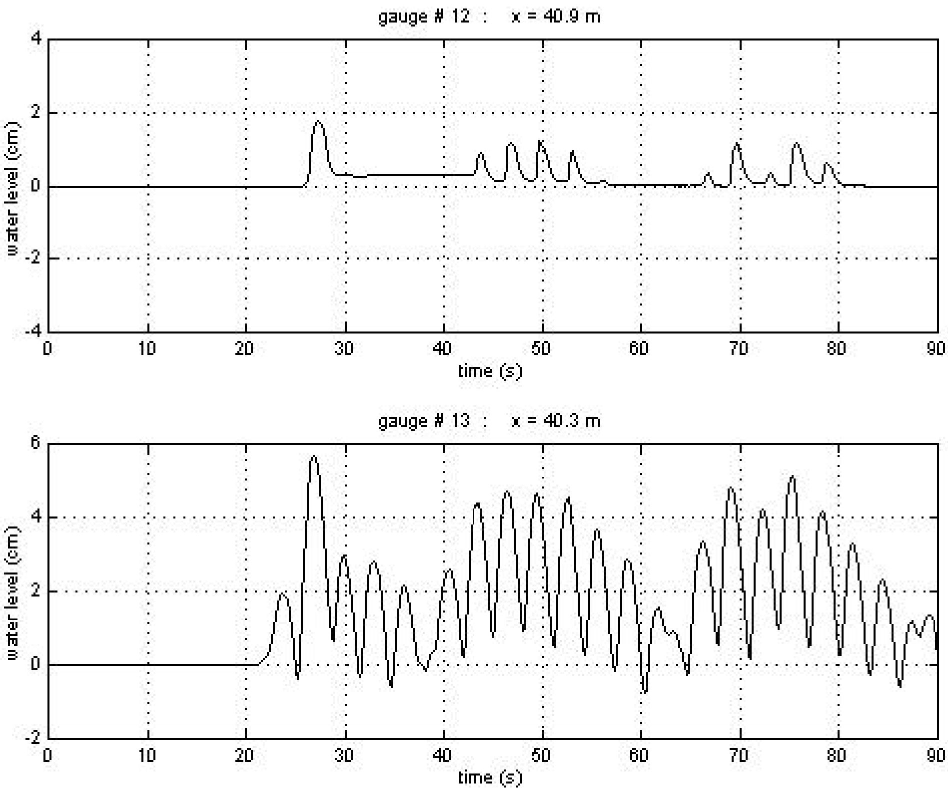

Fig.A3-12. Test IH040T30*: time recording of gauges 12 and 13*.

Annex 4

Flux analyses of regular wave tests:

- RH040T20
- RH040T25
- RH040T30

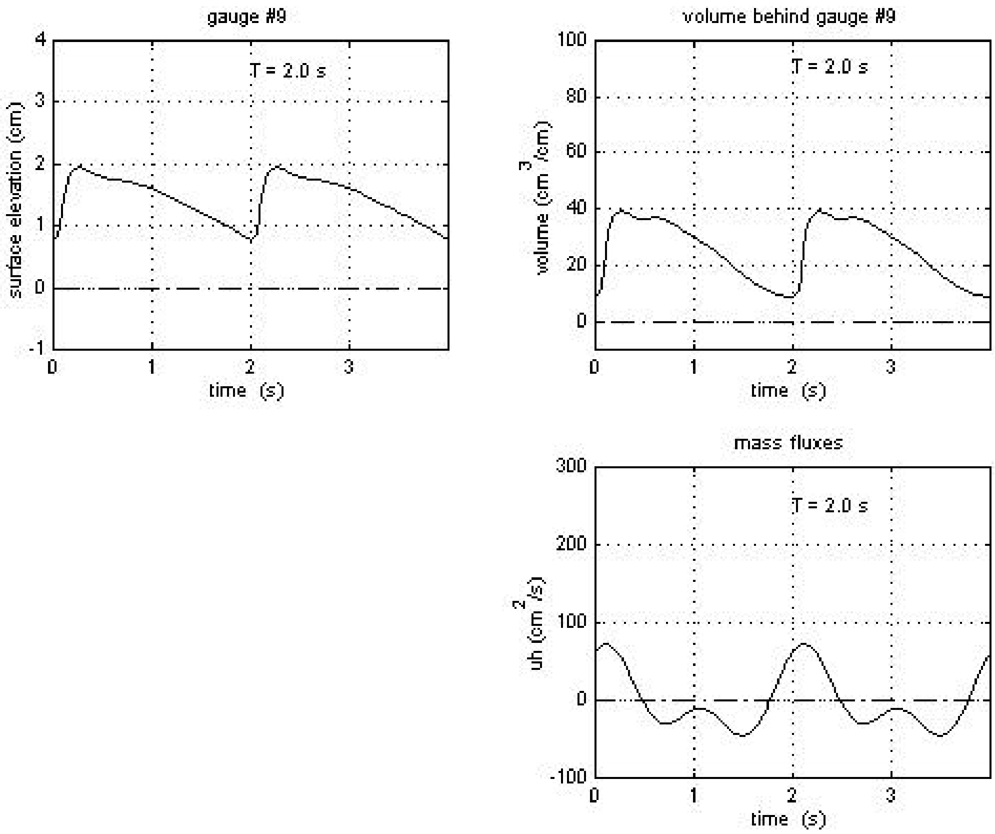

Fig. A4-1. ***Test RH040T20****: flux analysis in the mid section (gauge S9).*

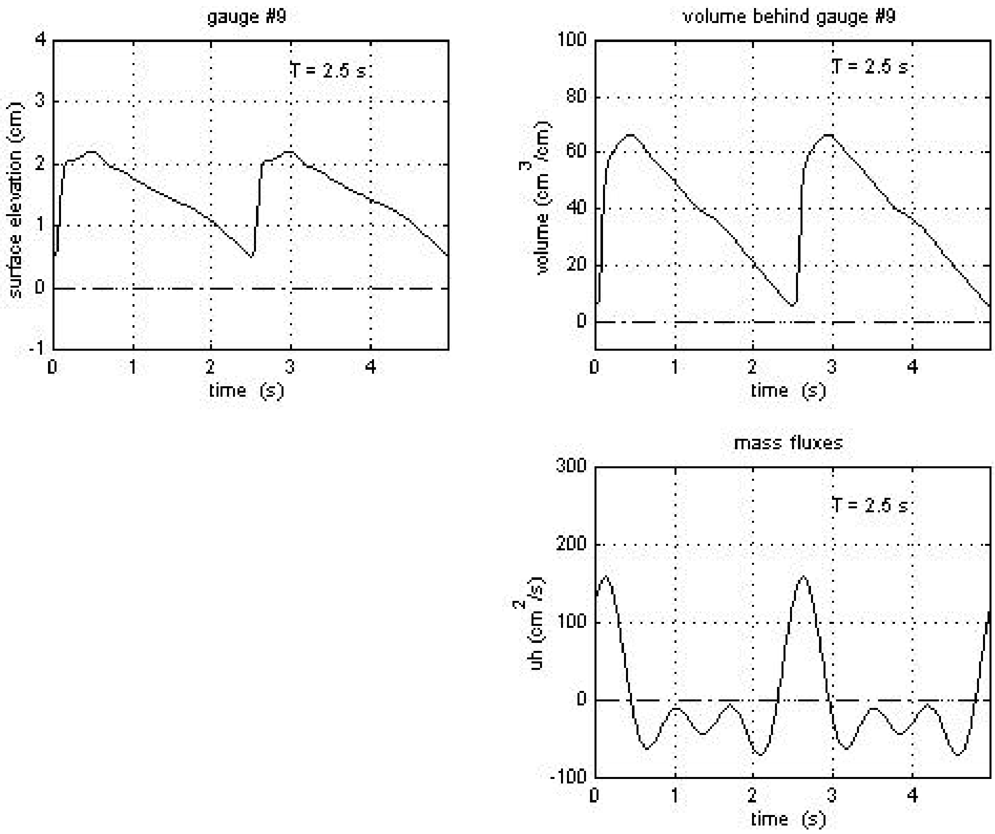

Fig. A4-2. ***Test RH040T25***: *flux analysis in the mid section (gauge S9).*

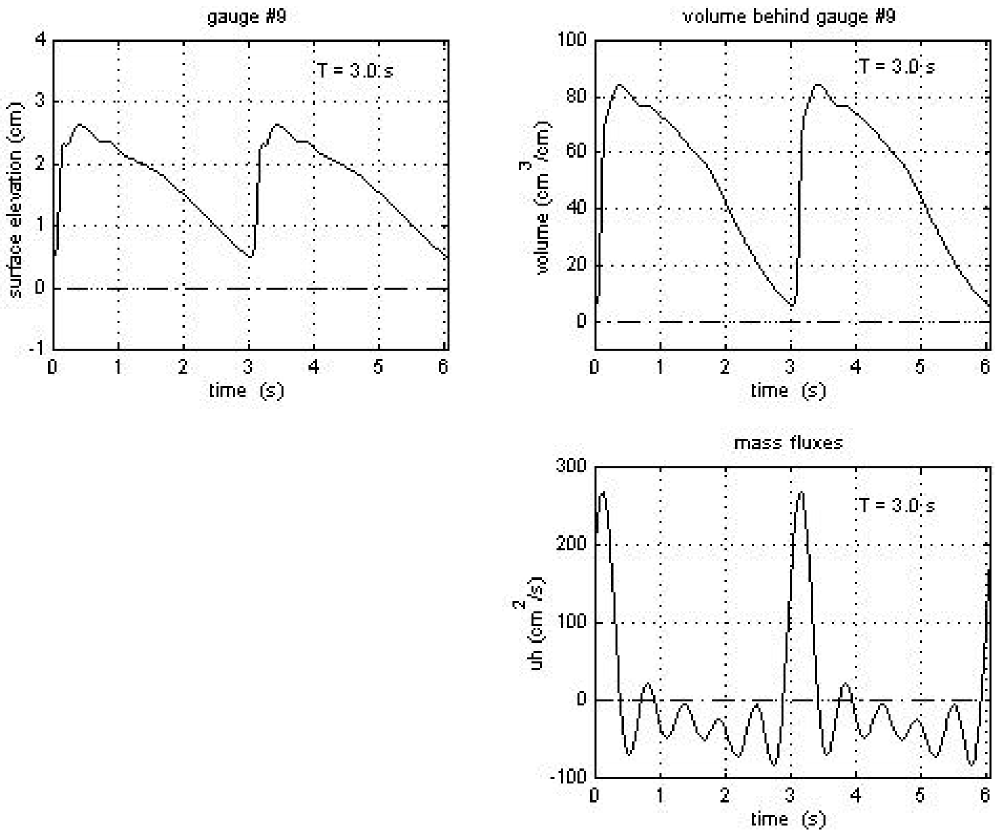

Fig. A4-3. ***Test RH040T30****: flux analysis in the mid section (gauge S9).*

Annex 5

Velocity measurements of regular and irregular wave tests:

- RH040T20
- RH040T25
- RH040T30

Regular wave test *T20 – section 8*	Conditions	Duration (min)	Xlaser (cm)	Zlaser (mm)	Locking time (%)	Remarks:
RH04T20-1l	H=3.5 cm T=2.0 s bottom slope 1 : 15 water depth = 13.3 mm Freq. Acq. = 100 Hz	5	- 20	0.5	32.4	disturbance of the laser signal
RH04T20-2l		5	- 20	1.5	10.3	disturbance of the laser signal
RH04T20-3l		5	- 20	2.5	70.1	disturbance of the laser signal
RH04T20-4l		5	- 20	3.5	32.7	disturbance of the laser signal
RH04T20-5l		5	- 20	4.5	46.8	
RH04T20-6l		5	- 20	5.5	68.6	
RH04T20-7l		5	- 20	6.5	71.7	
RH04T20-8l		5	- 20	7.5	55.5	
RH04T20-9l		5	- 20	8.5	55.5	
RH04T20-10l		5	- 20	9.5	35.0	
RH04T20-11l		5	- 20	10.5	16.6	
RH04T20-12l		5	- 20	11.5	35.7	
RH04T20-13l		5	- 20	12.5	30.6	
RH04T20-14l		5	- 20	13.5	23.3	
RH04T20-15l		5	- 20	14.5	17.9	disregarded laser signal

RH04T20-16l		5	- 20	15.5	16.5	disregarded laser signal
RH04T20-17l		5	- 20	41.5	17.6	disregarded laser signal

Tab. A5-I. *Measuring programme, series RH04T20, lower section (**17 points**).*

Regular wave test ***T20 – section 9***	**conditions**	**duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks :**
RH04T20-1m	H=3.5 cm	5	0	0.5	58.7	
RH04T20-2m	T=2.0 s	5	0	1.5	54.7	
RH04T20-3m	bottom slope	5	0	2.5	47.2	
RH04T20-4m	1 : 15	5	0	3.5	34.7	
RH04T20-5m	depth = 0 mm	5	0	4.5	24.8	disturbance of the laser signal
RH04T20-6m	Freq. Acq. =	5	0	5.5	30.6	disregarded laser signal
RH04T20-7m	100 Hz	5	0	6.5	17.3	disregarded laser signal

Tab.A5-II. *Measuring programme, series RH04T20, mid section (7 **points**).*

Regular wave test *T20 – section 10*	**conditions**	**duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks :**
RH04T20-1u	H=3.5 cm	5	+05	0.5	8.9	disturbance of the laser signal
RH04T20-2u	T=2.0 s	5	+05	1.5	20.8	
RH04T20-3u	bottom slope	5	+05	2.5	28.5	
RH04T20-4u	1 : 15	5	+05	3.5	21.1	disregarded laser signal
RH04T20-5u	Freq. 100 Hz	5	+05	4.5	11.6	disregarded laser signal

Tab.A5-III. *Measuring programme, series RH04T20, upper section (**5 points**).*

Regular wave test *T25 – section 8*	**conditions**	**Duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks:**
RH04T20-1l		5	- 20	0.5	78.2	disturbance of the laser signal
RH04T20-2l	H=3.5 cm	5	- 20	1.5	47.3	
RH04T20-3l		5	- 20	2.5	76.3	
RH04T20-4l	T=2.5 s	5	- 20	3.5	45.6	
RH04T20-5l		5	- 20	4.5	67.2	

RH04T20-6l	bottom slope	5	- 20	5.5	58.8	
RH04T20-7l	1 : 15	5	- 20	6.5	61.6	
RH04T20-8l		5	- 20	7.5	51.8	
RH04T20-9l	water depth	5	- 20	8.5	52.5	
RH04T20-10l	= 13.3 mm	5	- 20	9.5	48.4	
RH04T20-11l		5	- 20	10.5	36.7	
RH04T20-12l	Freq. Acq.	5	- 20	11.5	33.0	
RH04T20-13l	= 100 Hz	5	- 20	12.5	41.0	
RH04T20-14l		5	- 20	13.5	31.4	
RH04T20-15l		5	- 20	14.5	26.0	disregarded laser signal
RH04T20-16l		5	- 20	15.5	28.7	disregarded laser signal
RH04T20-17l		5	- 20	41.5	22.4	disregarded laser signal
RH04T25-18l		5	- 20	17.5	29.7	
RH04T25-19l		5	- 20	18.5	25.3	disregarded laser signal
RH04T25-20l		5	- 20	19.5	15.8	short locking time
RH04T25-21l		5	- 20	20.5	33.6	short locking time

Tab.A5-IV. *Measuring programme, series RH04T25, lower section (**21 points**).*

Regular wave test ***T25 – section 9***	**conditions**	**duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks :**
RH04T20-1m	H=3.5 cm	5	0	0.5	63.2	
RH04T20-2m	T=2.5 s	5	0	1.5	54.2	
RH04T20-3m	bottom slope	5	0	2.5	49.1	
RH04T20-4m	1 : 15	5	0	3.5	49.5	
RH04T20-5m	depth = 0 mm	5	0	4.5	40.9	
RH04T20-6m	Freq. Acq. =	5	0	5.5	36.5	
RH04T20-7m	100 Hz	5	0	6.5	32.2	
RH04T25-8m		5	0	7.5	23.4	short locking time
RH04T25-9m	water depth =	5	0	8.5	26.1	short locking time
RH04T25-10m	0 mm	5	0	9.5	19.9	short locking time

Tab.A5-V. *Measuring programme, series RH04T25, mid section (**10 points**).*

Regular wave test ***T25 – section 10***	**conditions**	**duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks :**
RH04T20-1u	H=3.5 cm	5	+20	0.5	67.4	disturbance of the laser signal
RH04T20-2u	T=2.5 s Freq. 100 Hz	5	+20	1.5	65.7	disturbance of the laser signal
RH04T20-3u	bottom slope 1:15	5	+20	2.5	75.1	short locking time

Tab.A5-VI. *Measuring programme, series RH04T25, upper section (**3 points**).*

Regular wave test ***T30 – section 8***	**conditions**	**Duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks:**
RH04T20-1l		5	- 20	0.5	61.3	
RH04T20-2l	H=3.5 cm	5	- 20	1.5	45.8	
RH04T20-3l		5	- 20	2.5	78.1	
RH04T20-4l	T=3.0 s	5	- 20	3.5	29.9	
RH04T20-5l		5	- 20	4.5	55.5	

RH04T20-6l	bottom slope	5	- 20	5.5	57.6	
RH04T20-7l	1 : 15	5	- 20	6.5	63.1	
RH04T20-8l		5	- 20	7.5	53.3	
RH04T20-9l	water depth	5	- 20	8.5	47.3	
RH04T20-10l	= 13.3 mm	5	- 20	9.5	38.5	
RH04T20-11l		5	- 20	10.5	29.2	
RH04T20-12l	Freq. Acq.	5	- 20	11.5	33.2	
RH04T20-13l	= 100 Hz	5	- 20	12.5	38.5	
RH04T20-14l		5	- 20	13.5	30.0	
RH04T20-15l		5	- 20	14.5	24.4	
RH04T20-16l		5	- 20	15.5	22.9	
RH04T20-17l		5	- 20	41.5	24.7	
RH04T25-18l		5	- 20	17.5	19.0	
RH04T25-19l		5	- 20	18.5	19.1	
RH04T25-20l		5	- 20	19.5	15.4	

RH04T25-21l		5	- 20	20.5	9.2	short locking time
RH04T30-22l		10	- 20	21.5	13.3	short locking time
RH04T30-23l		10	- 20	50.5	4.3	disregarded laser signal

Tab.A5-VII. *Measuring programme, series RH04T30, lower section (**23 points**).*

Regular wave test ***T30 – section 9***	**conditions**	**duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks :**
RH04T20-1m	H=3.5 cm	5	0	0.5	64.6	
RH04T20-2m	T=3.0 s	5	0	1.5	60.0	
RH04T20-3m	bottom slope	5	0	2.5	52.0	
RH04T20-4m	1 : 15	5	0	3.5	51.7	
RH04T20-5m	depth = 0 mm	5	0	4.5	33.9	
RH04T20-6m	Freq. Acq. =	5	0	5.5	36.8	
RH04T20-7m	100 Hz	5	0	6.5	32.6	

RH04T25-8m		5	0	7.5	30.7	
RH04T25-9m	water depth =	5	0	8.5	23.9	
RH04T25-10m	0 mm	5	0	9.5	16.8	
RH04T30-11m		5	0	10.5	17.7	
RH04T30-12m	Freq. Acq =	5	0	11.5	10.8	short locking time
RH04T30-13m	100 Hz	5	0	12.5	3.9	short locking time

Tab.A5-VIII. *Measuring programme, series RH04T30, mid section (**13 points**).*

Regular wave test ***T30 – section 10***	**conditions**	**duration (min)**	**Xlaser (cm)**	**Zlaser (mm)**	**Locking time (%)**	**Remarks :**
RH04T20-1u	H=3.5 cm	5	+20	0.5	61.7	disturbance of the laser signal
RH04T20-2u	T=3.0 s	5	+20	1.5	70.1	disturbance of the laser signal
RH04T20-3u	bottom slope	5	+20	2.5	51.8	disturbance of the laser signal
RH04T20-4u	1 : 15	5	+20	3.5	68.3	disturbance of the laser signal
RH04T20-5u	Freq. 100 Hz	5	+20	4.5	68.7	disregarded laser signal

Tab.A5-IX. *Measuring programme, series RH04T30, upper section (**5 points**).*

Regular wave test	conditions	X(cm)	LDV measured points	Remarks :
RH04T20-*l	H=3.5 cm	-20	17	
RH04T20-*m	T=2.0 s	0	7	
RH04T20-*u		+20	5	
RH04T25-*l	H=3.5 cm	-20	21	
RH04T25-*m	T=2.5 s	0	10	
RH04T25-*u		+20	3	
RH04T30-*l	H=3.5 cm	-20	23	
RH04T30-*m	T=3.0 s	0	13	
RH04T30-*u		+20	5	

Tab.A5-X. *Recorded characteristics of regular wave tests in the measuring sections.*

Irregular wave test	Frequency 1st component	Amplitude 1st component	Frequency 2nd component	Amplitude 2nd component	duration
IH04T20 (.a01)	f = 0.52 Hz	A = 1.00 cm	f = 0.47 Hz	A = 1.00 cm	10 min
I4T20H13 (.a01)	f = 0.52 Hz	A = 1.10 cm	f = 0.47 Hz	A = 1.10 cm	3 min
I4T20HRM (.a01)	f = 0.52 Hz	A = 1.63 cm	f = 0.47 Hz	A = 1.63 cm	3 min
IH04T25 (.a01)	f = 0.43 Hz	A = 1.00 cm	f = 0.37 Hz	A = 1.00 cm	10 min
I4T25H13 (.a01)	f = 0.43 Hz	A = 1.10 cm	f = 0.37 Hz	A = 1.10 cm	3 min
I4T25HRM (.a01)	f = 0.43 Hz	A = 1.45 cm	f = 0.37 Hz	A = 1.45 cm	3 min
IH04T30 (.a01)	f = 0.35 Hz	A = 1.00 cm	f = 0.31 Hz	A = 1.00 cm	10 min
I4T30H13 (.a01)	f = 0.35 Hz	A = 1.20 cm	f = 0.31 Hz	A = 1.20 cm	3 min
I4T30HRM (.a01)	f = 0.35 Hz	A = 1.61 cm	f = 0.31 Hz	A = 1.61 cm	3 min

Tab.A5-XI. *Recorded characteristics of irregular wave tests in the measuring sections.*

Annex 6

Turbulence analysis of regular wave tests:

- RH040T20
- RH040T25
- RH040T30

LOWER SECTION T = 2.0 s

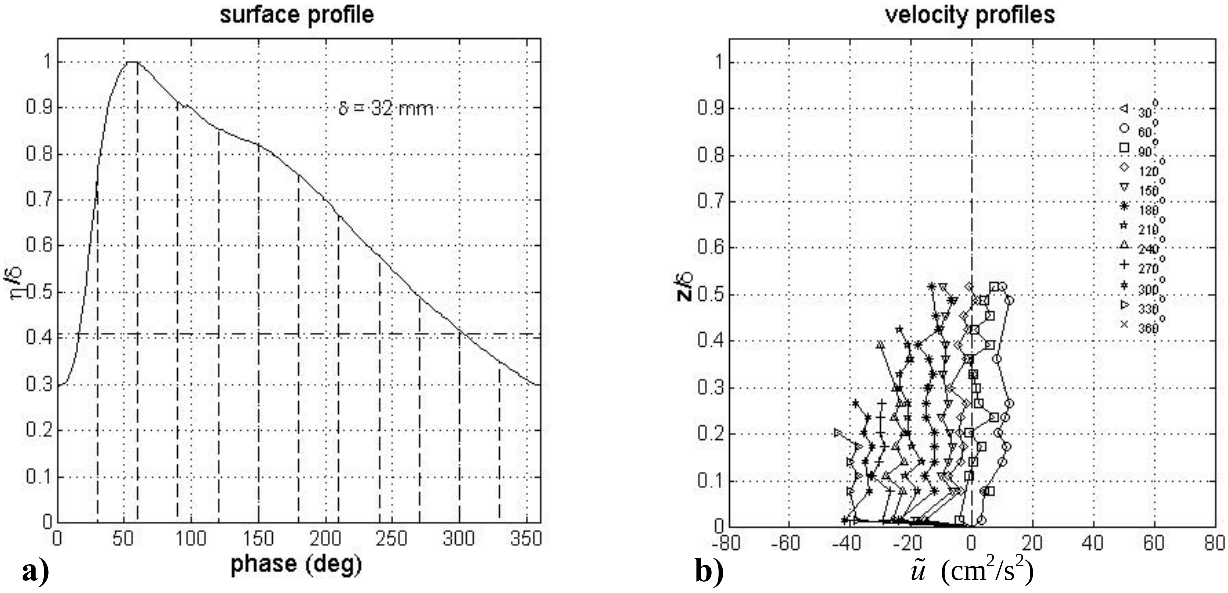

Fig.A6- 1. Test RH040T20*:* **a)** *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth. Lower section.*

Up rush phase **Back wash phase**

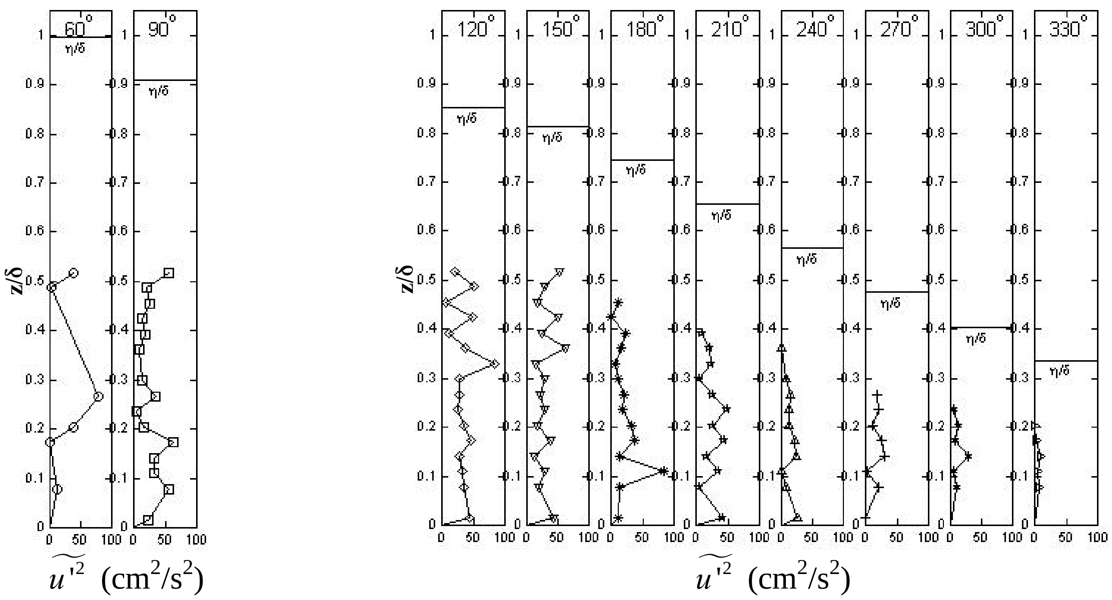

Fig.A6- 2. Test RH040T20*: Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the up rush phase and the backwash phase. Lower section.*

MID SECTION T = 2.0 s

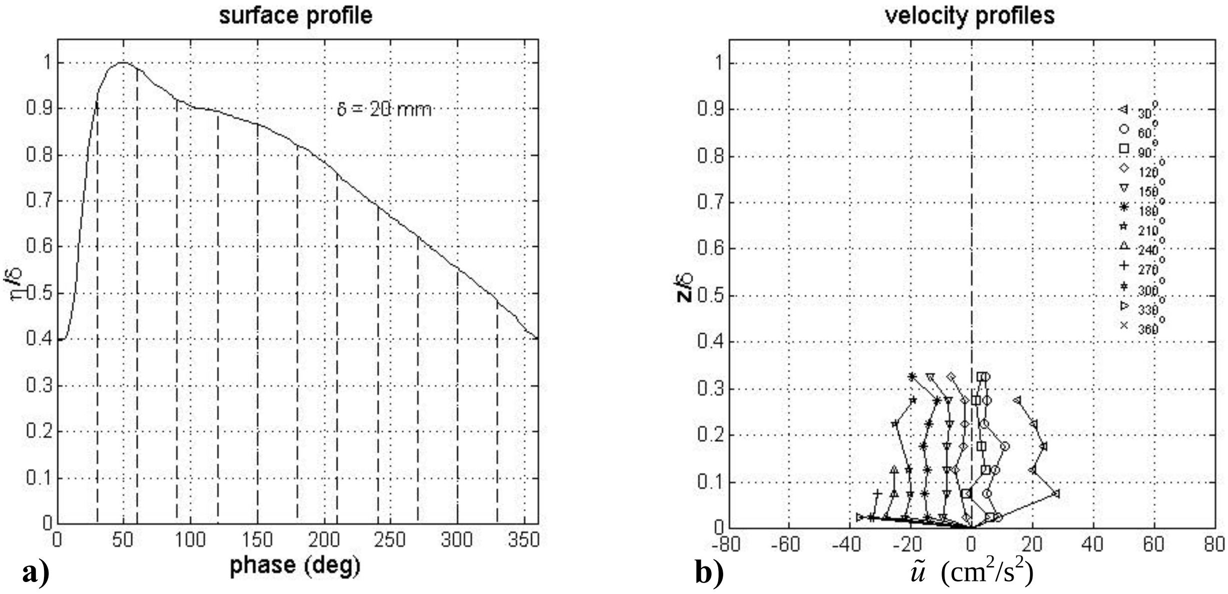

Fig.A6- 3. Test RH040T20*:* a) *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth. Mid-section.*

Up rush phase **Back wash phase**

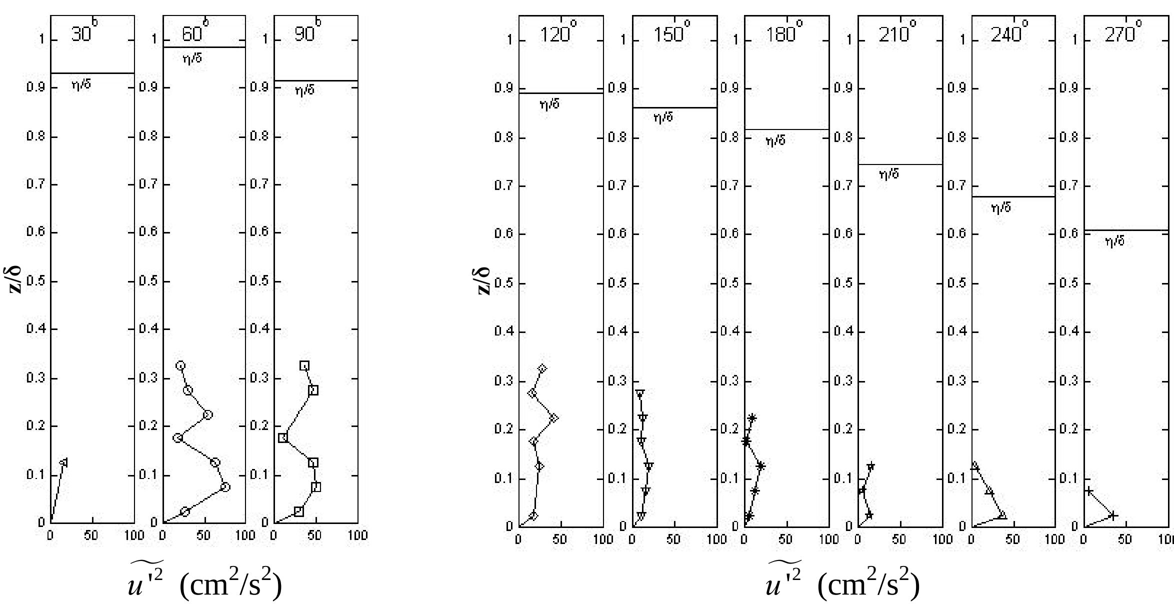

Fig.A6- 4. Test RH040T20*:* *Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Mid-section.*

UPPER SECTION T = 2.0 s

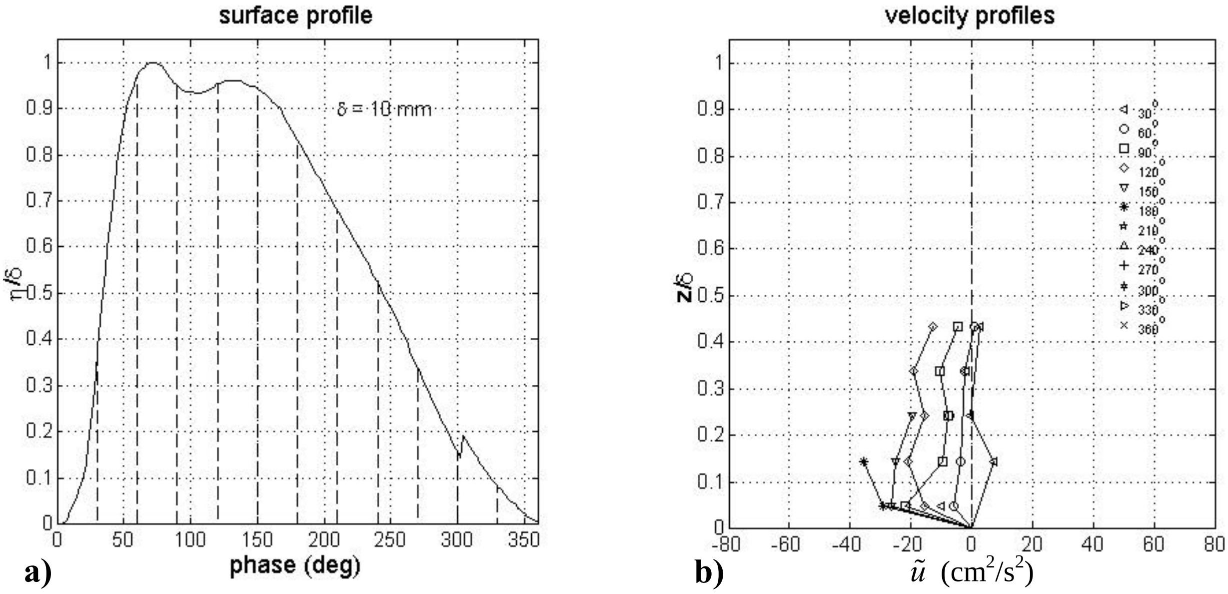

Fig.A6- 5. Test RH040T20*:* **a)** *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth. Upper section.*

Up rush phase **Back wash phase**

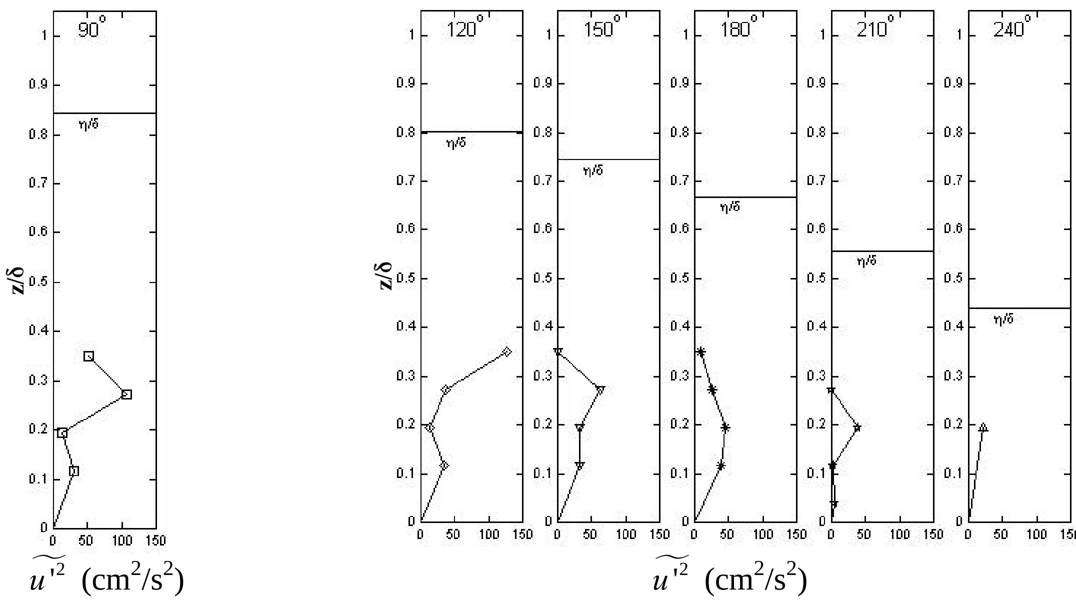

Fig.A6- 6. Test RH040T20*:* *Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Upper section*

LOWER SECTION T = 2.5 s

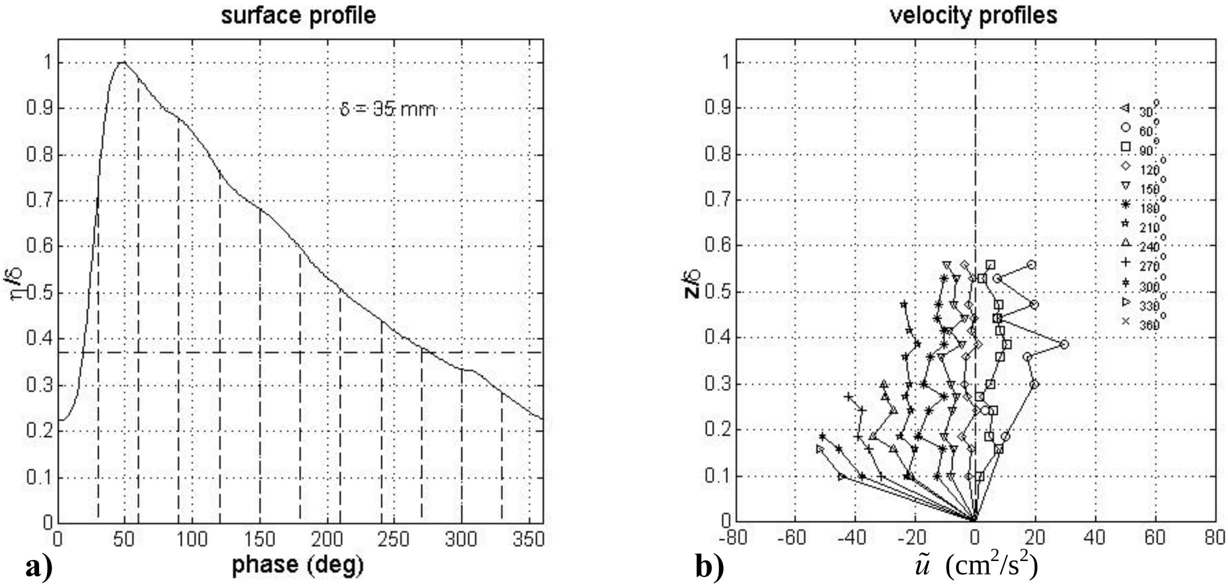

Fig.A6- 7. Test RH040T25*:* **a)** *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity as function of non-dimensional depth. Lower section.*

Up rush phase **Back wash phase**

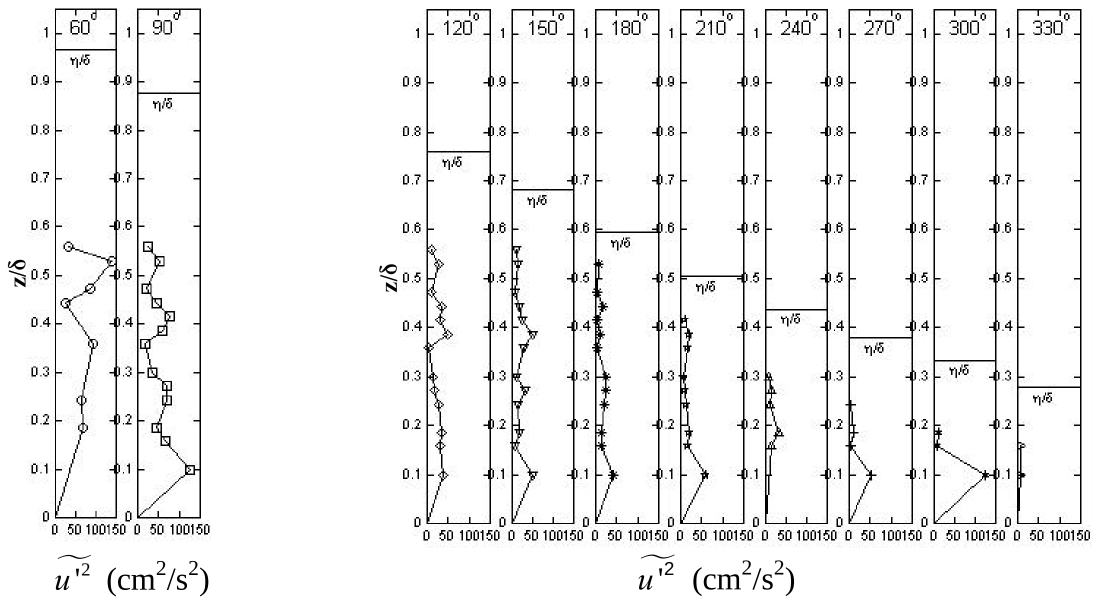

Fig.A6- 8. Test RH040T25*: Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Lower section.*

MID SECTION T = 2.5 s

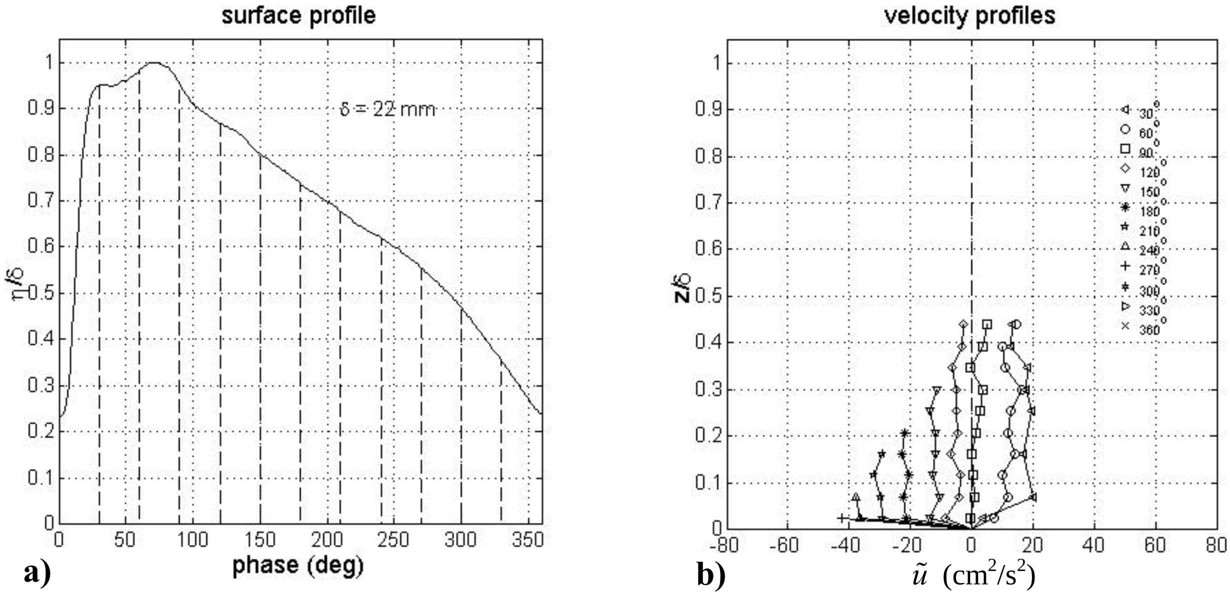

Fig.A6- 9. Test RH040T25*:* a) *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth. Mid-section.*

Up rush phase **Back wash phase**

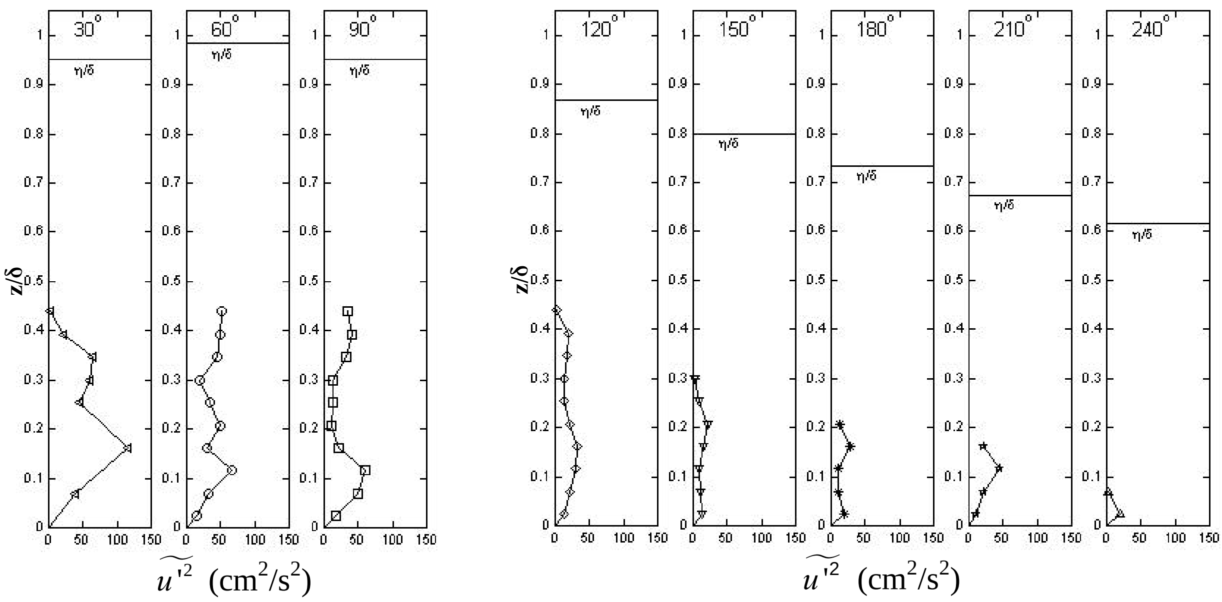

Fig.A6- 10. Test RH040T25*:* *Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Mid-section.*

UPPER SECTION T = 2.5 s

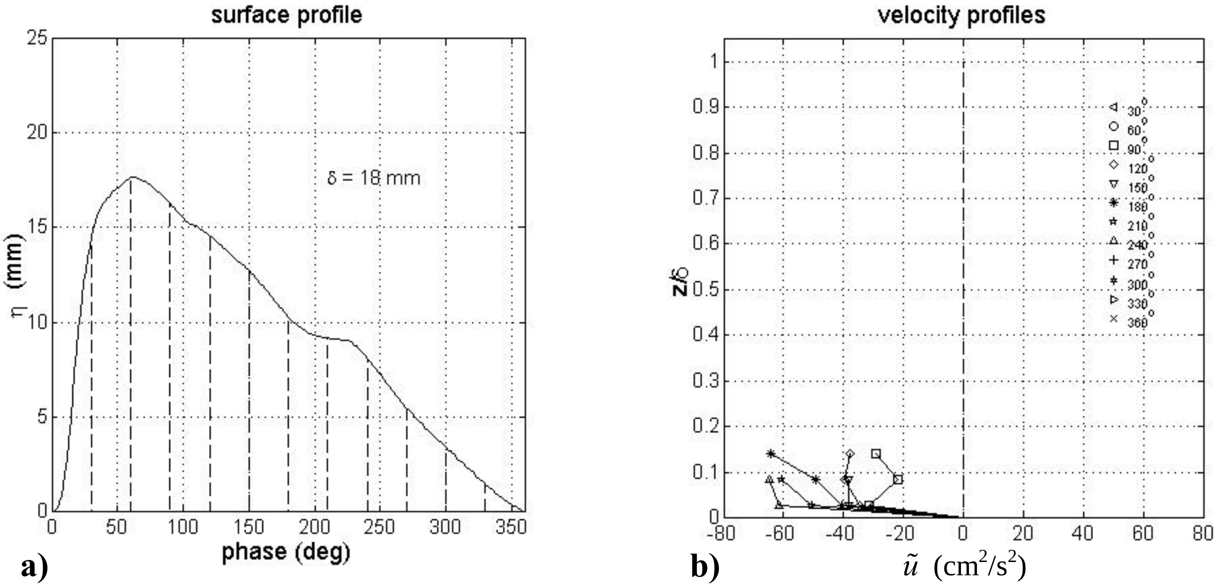

Fig.A6- 11. Test RH040T25*:* a) *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth. Upper section.*

Back wash phase

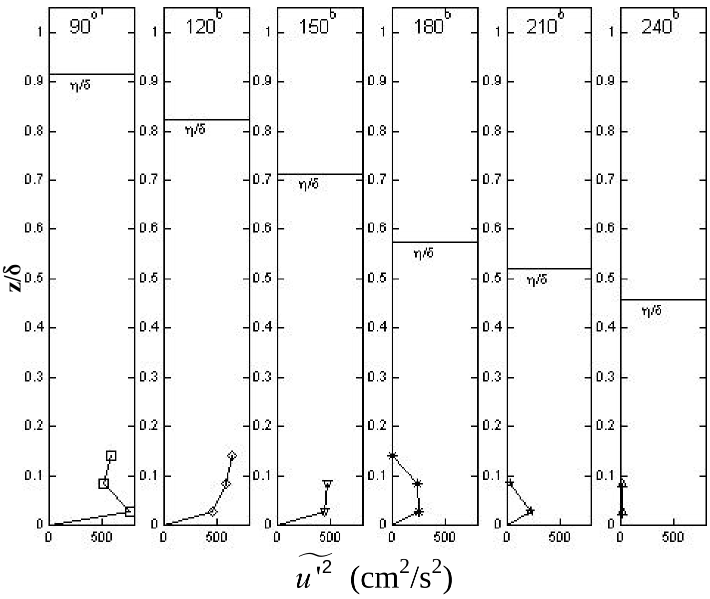

Fig.A6- 12. Test RH040T25*:* *Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Upper section*

LOWER SECTION T = 3.0 s

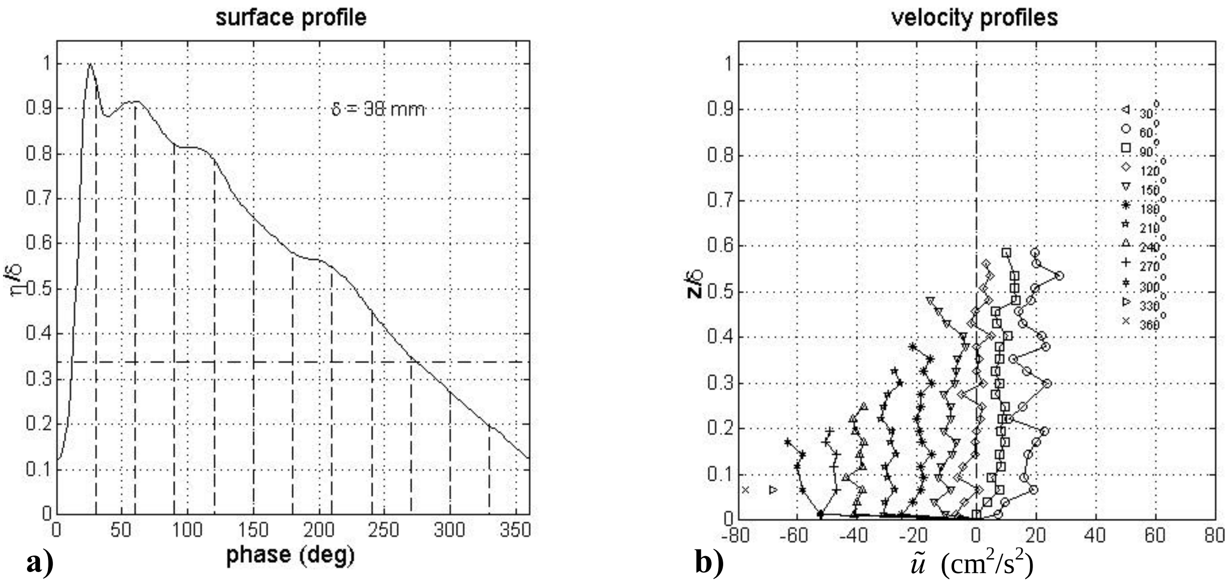

Fig.A6- 13. Test RH040T30*:* a) *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth***.** *Lower section.*

Up rush phase **Back wash phase**

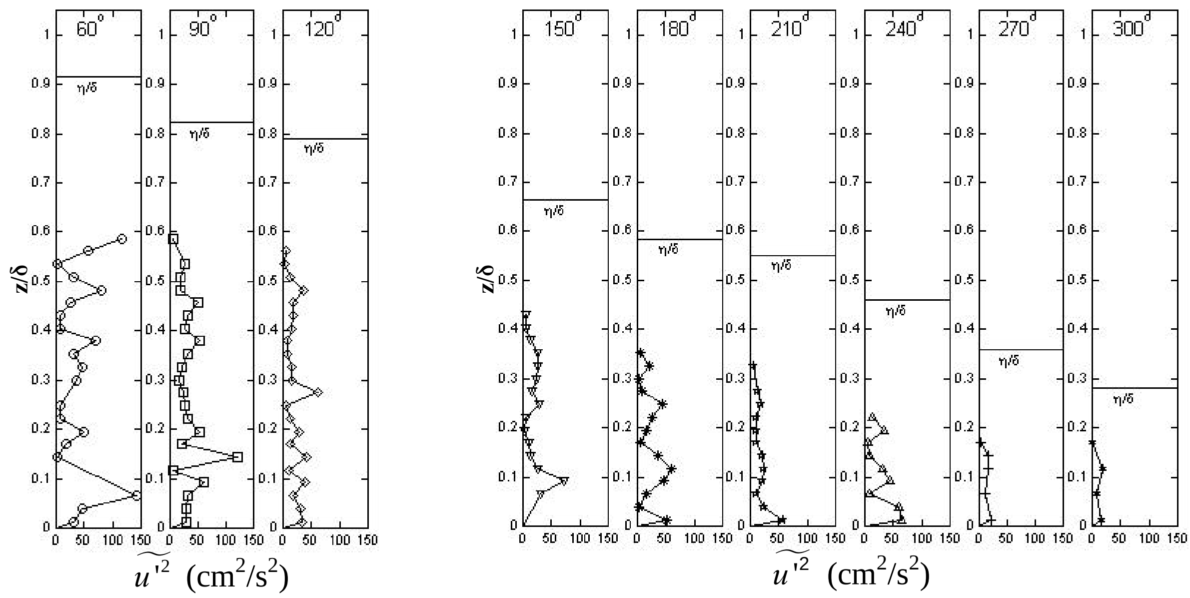

Fig.A6- 14. Test RH040T30*:* *Phase averaged horizontal turbulent energy and relative free surface height (*h*/δ) during the uprush phase and the backwash phase. Lower section.*

MID SECTION T = 3.0 s

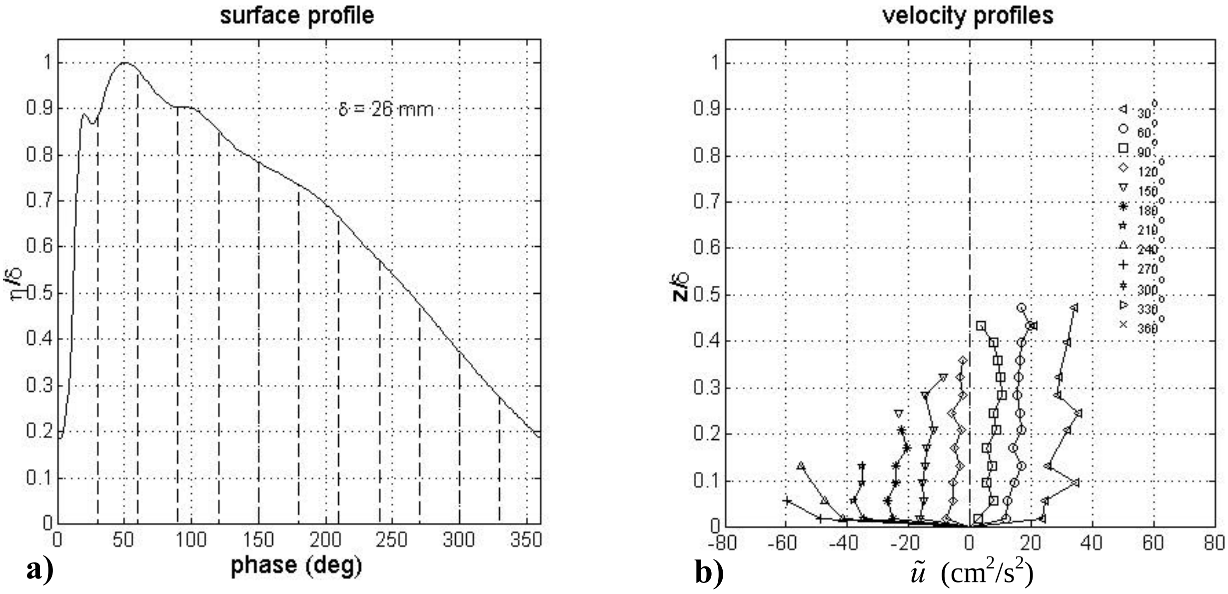

Fig.A6- 15. Test RH040T30: a) *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity vs. non-dimensional depth. Mid-section.*

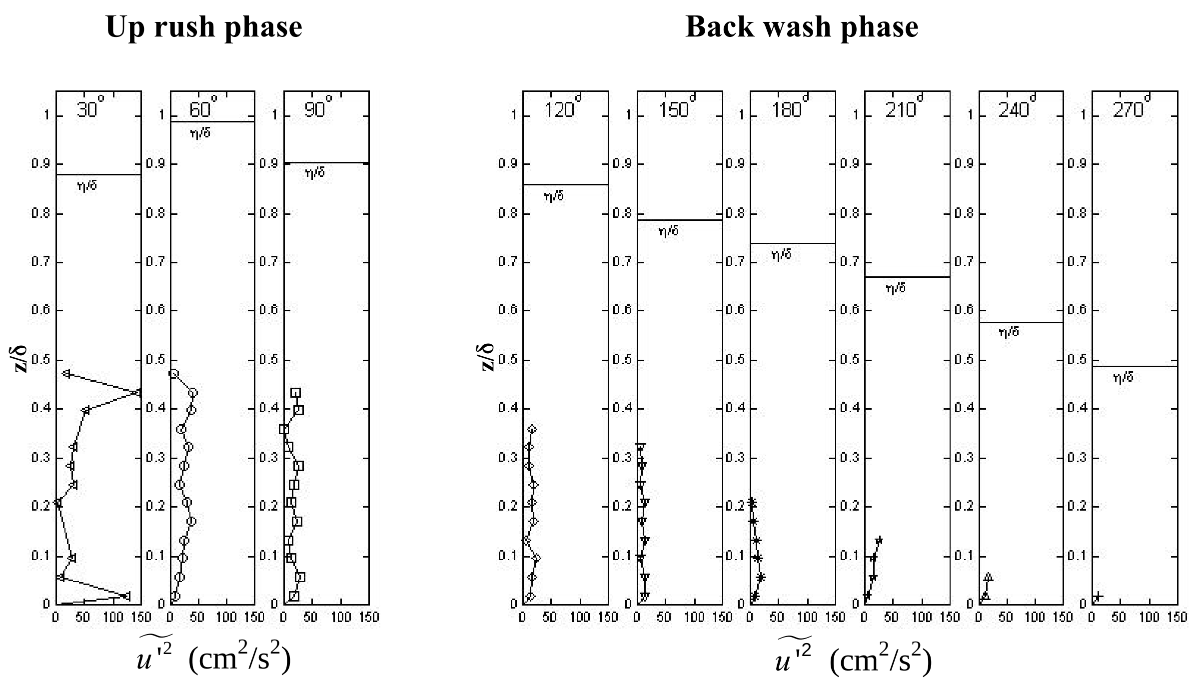

Fig.A6- 16. Test RH040T30: *Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Mid-section.*

UPPER SECTION T = 3.0 s

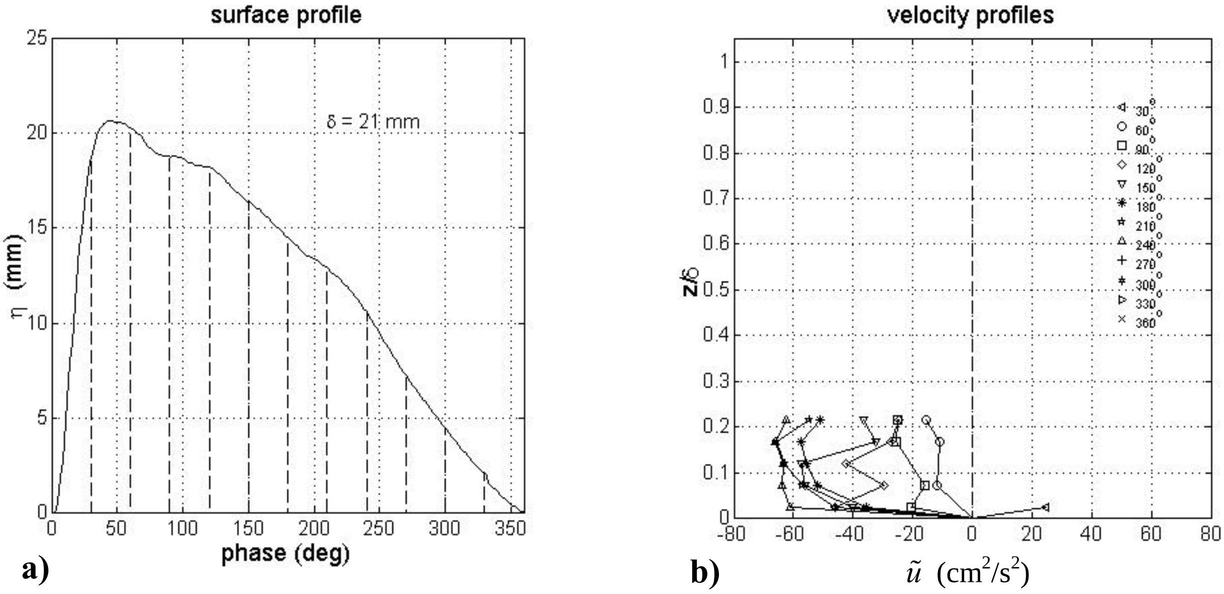

Fig.A6- 17. Test RH040T30*:* **a)** *Phase averaged free surface.* **b)** *Phase averaged horizontal velocity as function of non-dimensional depth**.** Upper section.*

Back wash phase

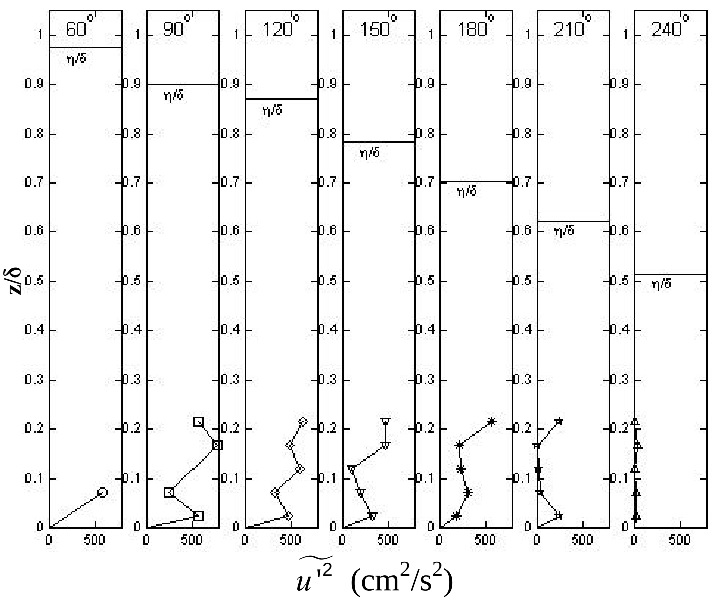

Fig.A6-18. Test RH040T30*:* *Phase averaged horizontal turbulent energy and relative free surface height (h/δ) during the uprush phase and the backwash phase. Upper section.*