WAVE HYDRODYNAMICS OVER A BARRED BEACH

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Abstract: This paper reports the experimental Project "SPANWAVE-SPPORITA" carried out at the "Canal de Investigación y Experimentación Maritima" of the Polytechnic University of Catalonia (Barcelona, Spain). The Project goals were to obtain detailed and accurate measurements of turbulent and mean velocities over the bar and trough regions, for regular and random waves breaking over the bar. Four wave conditions were simulated, and both surface elevation and velocity measurements were carried out at a large number of locations. The experiments are considered successful and provide a unique data set on surfzone hydrodynamics over a barred beach. Preliminary data results reveal quite interesting aspects, deserving further investigation.

1. INTRODUCTION

There have been several extensive experiments addressing the mean flow hydrodynamics over barred beaches (e.g., Kraus *et al*., 1992; Wu *et al*., 1994), which did not address the turbulence generated by the breaking waves. On the other hand, other experiments covered wave-induced turbulence over laboratory planar beaches, (e.g., Stive, 1980; Nadaoka and Kondoh, 1982; Hattori and Aono, 1985; Okayasu, 1989; Cox *et al*., 1995) and field monotonic profiles (e.g., George *et al*., 1994). These experiments comprised a wide range of bottom slopes and wave conditions, including both spilling and plunging breakers.

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None of the above studies, however, analysed turbulence from breaking waves over a bar and wave reforming over the trough, as often happens in nature (e.g., Birkemeyer *et al*., 1997). Rodriguez *et al*. (1995, 1999) analysed wave-induced macro-turbulence over a barred beach at a field location, but their study suffers from non-simultaneity of the measurements at different cross-shore positions. Moreover, it appears that the sea-state generated a single surfzone, where waves did not reform after breaking over the bar.

In this paper we present the experimental Project "SPANWAVE-SPPORITA" carried out at the "Canal de Investigación y Experimentación Maritima" (hereafter referred as CIEM wave flume) of the Polytechnic University of Catalonia (Barcelona, Spain). The Project goals were to obtain detailed and accurate measurements of turbulent and mean velocities over the bar and trough regions, for regular and random waves breaking over the bar. These measurements provided a unique set of data, allowing one to estimate important hydrodynamic parameters, such as energy dissipation and shear stresses, and to better understand the surfzone dynamics.

Section 2 contains a description of the experimental setup, instrumentation and test conditions. A review of the data analysis parameters is given in Section 3, and preliminary results are presented in Section 4. Finally, in Section 5 we provide a summary and conclusions of the present study.

2. EXPERIMENTAL SETUP

2.1. Facility

The tests were performed at the CIEM wave flume, which is 100 m long, 3 m wide and 5 m deep. A barred beach was built in the flume, topped by a non-smoothed soft-concrete layer, with roughness nearly equal to that of coarse sand grains.

The rigid bottom profile was designed to match an equilibrium bar. This was accomplished by scaling-down prototype profiles at Duck (North Carolina, USA), taking into account the SUPERTANK (Kraus and Smith, 1994) and DELTA-flume (Sanchez-Arcilla *et al.*, 1995) movable-bed experiments, and also by tuning the final "equilibrium-bar" shape with the assistance of a numerical Boussinesq-type wave model (Kennedy *et al.*, 2000) adapted to provide tendencies for onshore/offshore sediment transport (Sancho, 1999). From the above, and comparing with the conditions commonly found at Duck (North Carolina, USA), we consider the present experiment a 1:5 scale of field conditions.

The cross-shore bottom profile is shown in Fig. 1, and the wave-maker is positioned at x=86 m. The following parameters characterize the bottom profile and water depth:

- still water depth at wave maker, h_0 = 2.05 m;
- depth at the bar-crest, h_c = 0.39 m;
- depth at the bar-trough, h_t = 0.575 m;
- still water shoreline position, $X_{shoreline}$ = 17.0 m;
- bar-crest to shoreline distance, X_c = 23.0 m;
- bar-trough to shoreline distance, X_t = 12.0 m;
- beach-face slope=1:15;
- beach-toe slope=1:8;
- mean slope=1:25.

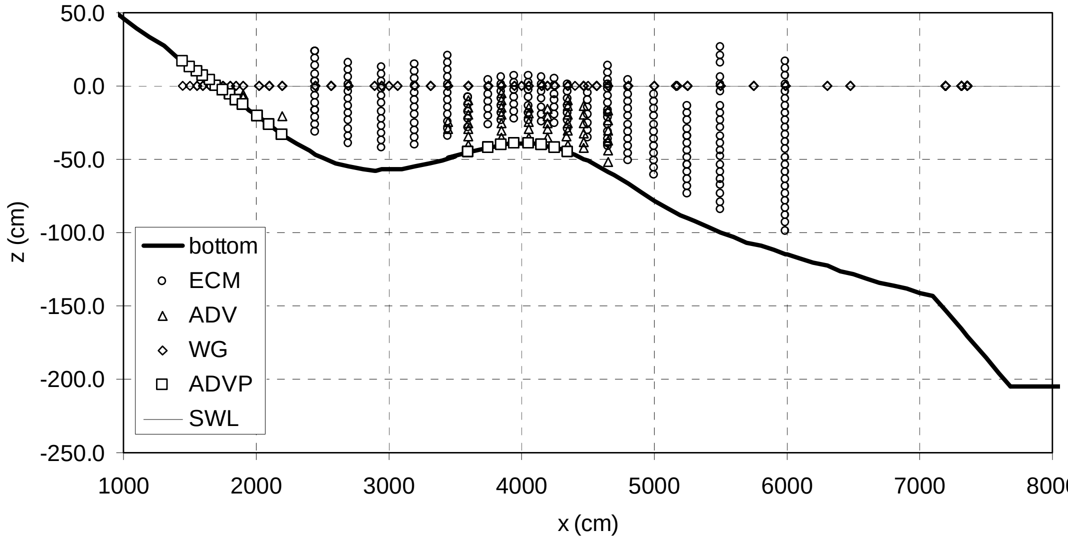

Fig. 1. Beach profile and instruments' locations.

The wave motion is set forward by a wedge-type hydraulic wave generator. A paddle slides up and down in a thirty-degree inclined plane and is controlled by a PC-based wave generating-absorption system, able to eliminate the spurious re-reflections of the wave paddle, for the most energetic wave periods. During the present experiments, the wave absorption system worked quite well for that period range, but was not able to eliminate the *seiching* motions. As an example, Fig. 2 shows the time series of the runup motion for one test, where the low-frequency oscillation is quite visible. *Seiching* periods were identified as $T_1 \approx 55.0$ s, $T_2 \approx 25.6$ s, and $T_3 \approx 19.0$ s.

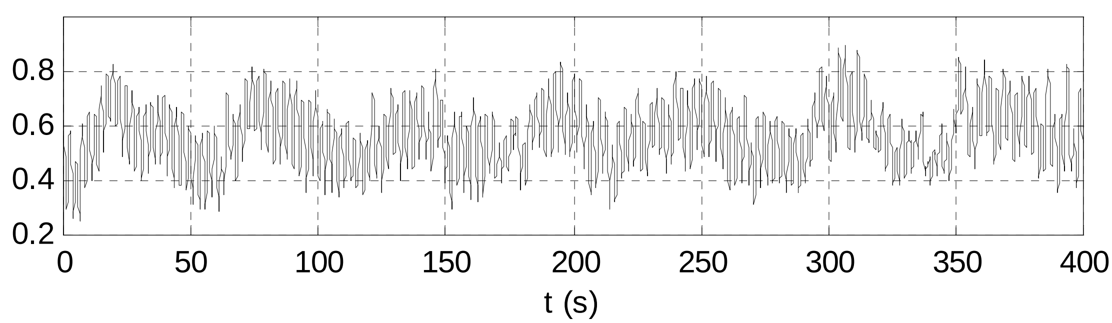

Fig. 2. Time series of the surface elevation at the swash region.

2.2. Instrumentation

A combination of six different equipments was adopted. All instruments were placed primarily in the breaking and post-breaking regions, although other positions were covered as well. Fig. 1 shows the locations for each instrument type. The following is a list of all the instruments, described in detail below:

– Wave Gauges (WG);
– Pressure Transducers (PT);
– Electromagnetic Current Meters (ECM);

– Acoustic Doppler Velocity Meters (ADV);
– Acoustic Doppler Velocity Profilers (ADVP);
– Video and photographic equipment.

The free-surface elevation was registered at 49 different locations by a combination of up to eight resistance-type wave gauges (WG). There were six “standard” one-meter long wave gauges, and three others, specially built to measure the wave conditions nearer the shoreline. Three surface elevation sensors remained the whole time of the experiment at fixed positions, in front of the wave paddle, for repeatability and quality control of the tests. All sensors were mounted from vertical masts standing at the bottom of the flume. At the top of the base-plates of 5 different masts we installed pressure transducers.

Seven spherical S-type Electromagnetic Current Meters (ECM) were used to collect flow velocities at the same sampling frequency as the WG measurements (8 Hz). The sensors were mounted on circular masts, three at each vertical, 20 cm apart. Due to intrinsic limitations, the ECMs could not be placed nearer than 15 cm from the bottom. Thus, the ECM measurements cover the vertical range between the mean surface elevation and 15 cm above the bottom, every 5 cm apart.

Due to physical constraints, both the WG and ECMs were positioned off-centered the flume. This caused, in some situations, the flow to be 3-dimensional, which was visible by the wave crest not being fully perpendicular to the flume axis. Care was taken in recognizing these effects and identifying the correspondent data files.

Two “*Nortek ADV Lab*” ADVs were used to measure the 3-component flow velocities, mostly within the surf region, at both 25 and 50 Hz sampling frequencies. As the ADV uses acoustic sensing techniques, the sampling volume (located 5 cm away from the probe tip) is not disturbed by the presence of the probe. In the present experiment it resulted clear that the probe orientation along a longitudinal vertical plane was quite difficult to obtain, which induced cross-flume velocity readings larger than expected. Therefore, the velocity data needs to be corrected through rotation of the coordinate system.

An Ultrasound Doppler Velocity Profiler DOP1000 (by *Signal Processing S.A.*), hereinafter ADVP, was used to gather velocity measurements along the wave flume. The probes were fixed in PVC supports, located in a longitudinal trench at the bottom (14 cm wide), and running along the beach profile. This setup allowed to obtain near-simultaneous high-frequency velocity profile measurements, over the water column, and undisturbed from any intrusive equipment. The ADVP signal was sampled at frequencies ranging from 3.8 to 141.4 Hz, depending on the number of simultaneous probes, the spatial resolution along each beam, and the local water depth.

The water surface elevation was always measured simultaneously and at the same transect of the ADVP sensors. In the breaking region, two probes were set-up in pairs. In the swash zone, where the water depth was very shallow, the probes were only installed individually. Furthermore, the transducers were installed with its beam oriented 60°-70° with respect to the bottom, so that the measured velocities correspond to the flow velocities projected along that oblique axis.

Video imaging was used to record one full test for each wave condition. The video camera was both located near the swash zone and at the surfzone, and helped to identify the regions corresponding to initiation of wave breaking and wave reforming. The video cameras were also setup aiming vertically, downwards, towards the water surface. It is expected that the analysis of the digital images will enable to estimate several surfzone parameters.

2.3. Test Conditions

Wave conditions were chosen such that prototype measurements over a fixed bed beach simulated those that happen when a near-equilibrium profile condition is attained. Several preliminary runs were performed in order to select a few, most adequate, wave conditions. Therefore, four types of wave conditions were chosen, such that waves broke on the seaward slope of the bar and reformed into the trough region, breaking secondly nearer the shoreline. The 4 wave conditions (3 monochromatic and 1 irregular sea state) were repeated consecutively, giving rise to nearly 230 independent tests. During each test, the measuring instruments were fixed at a single position being then moved for the next repetition.

Table 1 – Summary of Test Parameters

Wave condition	H, H_{rms} (m)	T_p (s)	H_{rms}/L	No. Ursell, $H/L/(h/L)^3$	x_b (m)	H_b (m)	h_b (m)	Breaking type
A (regular)	0.21	2.50	0.024	1.89	42.0	0.30	0.41	Spilling
B (regular)	0.21	3.50	0.015	4.71	43.5	0.35	0.45	Plunging
C (regular)	0.38	3.50	0.027	8.52	46.5	0.58	0.56	Plunging
D (irregular)	0.21	2.50	0.024	1.89	–	–	–	–

Table 1 summarizes the four types of wave conditions analysed here, where H and H_{rms} are the target regular and root mean square wave height in front of the wave maker, T_p is the peak wave period, L is the computed wavelength at the wave-maker (using linear wave theory), x_b, H_b and h_b are the approximate breaking location, breaking height (defined as the maximum wave height from wave height measurements) and depth, respectively. The values for the random wave condition D correspond to those associated with the peak period, satisfying a Jonswap spectrum with a peak enhancement factor of γ=3.3.

For each wave condition, at least 56 independent tests were performed, with repetitions being performed for some tests, if any abnormal event occurred. Generally, the wave conditions A, B, C, and D were run sequentially for each test number, with about 6 minutes of rest between each test. In order to achieve stationarity of each sea-state, the data acquisition was started 360 seconds after the start of the wave-maker for conditions A, B and C, and 240 seconds for condition D. Each data acquisition lasted 400 seconds for wave conditions A, B and C and 1250 seconds for wave condition D.

3. DATA ANALYSIS TECHNIQUE

Frequency and time domain analysis were performed on the data, both during and after the data acquisition. The analysis performed through the experiments helped to detect faults and to improve the setting of the apparatus' parameters. This was particularly helpful for the newer instruments used in this environment, such as the ADV and ADVP sensors.

Due to the fact that the ADV and ADVP contain a lot more noise than the surface elevation data, we pre-processed all the velocity data, whereas the surface records were not. In the case of ADV measurements, it has been assessed the level of the auto-correlation and of the signal-to-noise ratio (SNR) levels, which are an integrant part of the ADV readings. For most of the sampled time series these resulted to be larger than 90% and 20 dB, respectively, yielding quite acceptable velocity readings. For the present pre-processing data analysis, it has been admitted that two consecutive readings are affected by "noise" whenever the correspondent acceleration is larger than two times the gravity ($dv/dt>2g$). For uniformity between the ADV and the ECM data statistics, we applied the same pre-processing procedure to all point-velocity records.

For both the surface elevation and velocity data we followed the same time series data analysis as carried out in the SUPERTANK laboratory Project (Kraus and Smith, 1994). This was performed with a zero-upcrossing definition of a wave. We note that a few data acquisition signals corresponded to the paddle horizontal position. Hence, these signals were processed as if they were surface elevation records, i.e., the surface elevation should be interpreted as the paddle position, and the wave height as to the paddle stroke. In the following we list the parameters calculated from time series analysis, for both the surface elevation and velocity records:

- mean, standard deviation, skewness and kurtosis of surface elevation;
- mean, root-mean-square, significant, one-tenth, maximum and minimum wave heights;
- mean, significant, one-tenth, maximum and minimum wave periods;
- mean, standard deviation, skewness and kurtosis of the point-velocity components;
- maximum and minimum velocity magnitudes.

4. RESULTS

Along this Section we present a few preliminary results of the experimental data collected within the Project. We first analyze the data with respect to quality parameters, and then show a few significant results.

Regarding quality control, and since the experiments reflect over-54 repetitions of the same wave condition, for four distinct situations, a major concern along the whole experiment was the repeatability of the tests. Therefore, we have used the input signals corresponding to the paddle position to assess test repeatability. Fig. 3 shows the stroke root-mean-square, based on the paddle position measurement (the "feedback" signal), for all tests of wave condition A. The solid-thick lines represent the average of the measured values of all tests and the dashed lines represent the average plus or minus 5%. Therefore, the band within the ±5% of the average values is portrayed, and this allows us to reject any test (we assume it is not a repetition of the same stochastic process) whose $stroke_{rms}$ do not fall within the ±5% band.

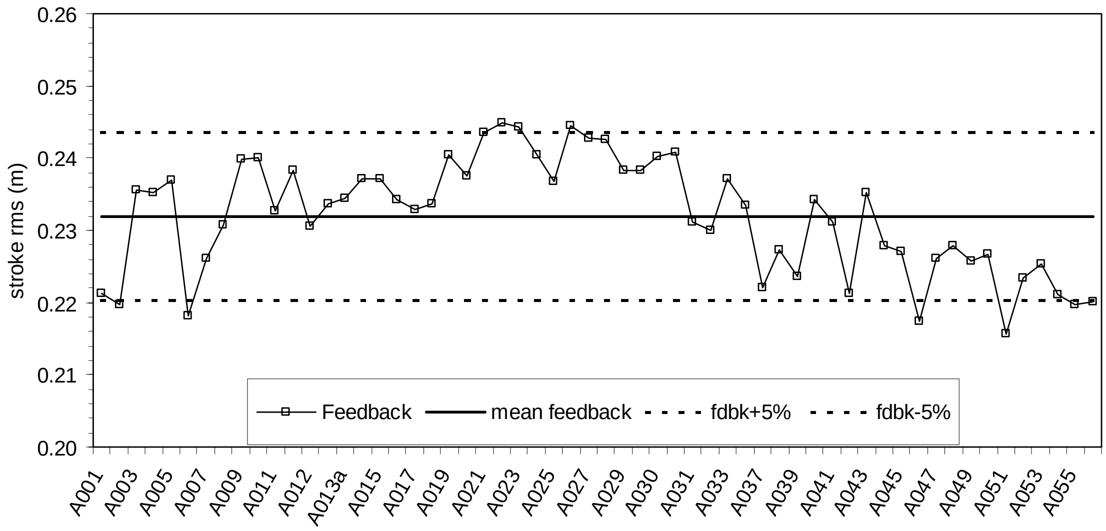

Fig. 3. Stroke root-mean-square for all tests of wave condition A.

Using the repeatability procedure outlined above for all wave tests, we conclude that 96% of them are accepted. Similar conclusions are drawn from the surface elevation records measured at the first three wave gauges that remained fixed during the experiment.

A second concern regarding data quality was maintaining stationarity of the processes during each run. This was verified by means of acquiring a wave record, for each wave condition, much longer than the other standard data records. A detailed analysis of these records (Sancho *et al*. 2001) allowed to conclude that the process is considered to achieve stationarity approximately 360 s past the start of the wavemaker. This condition was satisfied for all acquired wave records.

Most data analysis is underway, but next, we show a few results for the regular wave condition C (see table 1, for details). For this wave condition, the root-mean-square wave height, H_{rms}, and wave setup variation along the flume are presented in Fig. 4. From right to left, we observe wave shoaling up to the breaker height, and then a fast decay correspondent to an intensive plunging breaker. The setup is initiated only past (about 2 m) the start of the wave breaking, as observed in several other previous studies. Afterwards, as waves break, the wave height remains nearly constant all through the first surfzone ($32 < x < 40$ m), over the bar crest, and then waves shoal again over the bar trough and break secondly nearer the shoreline. Interestingly, the wave setup remains nearly constant slightly past the bar crest ($x < 40$ m). Nearer the still water shoreline (at x=17 m), since the sensors were initially at dry conditions, the wave setup measurement is poorly defined, although they should tend to zero as shown.

The mean hydrodynamic flow field generated by the wave condition C is portrayed in Fig. 5. The depicted currents correspond to those measured only by the ECMs; therefore, the 15 cm layer immediately above the bottom has no measurements. Also, the ECMs were not deployed for $x < 24.5$ m because the experiment focused on the wave breaking and reforming regions over the bar. Hence, all the following analysis is preliminary and reports solely to the plotted data.

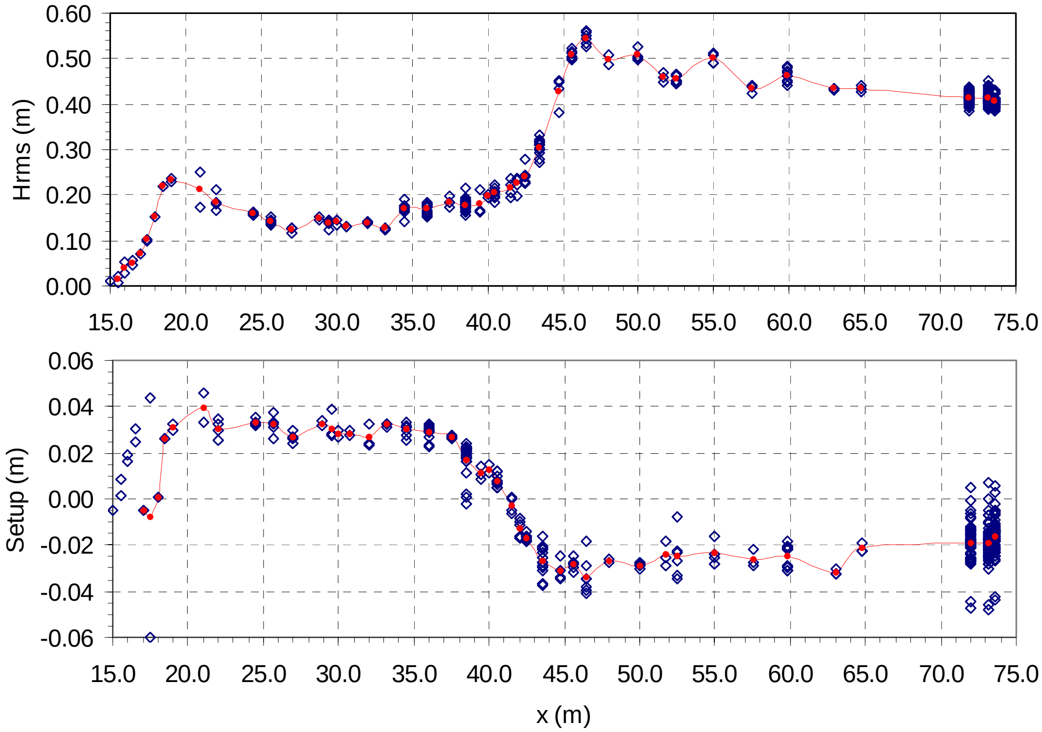

Fig. 4. Wave height and setup for wave condition C.

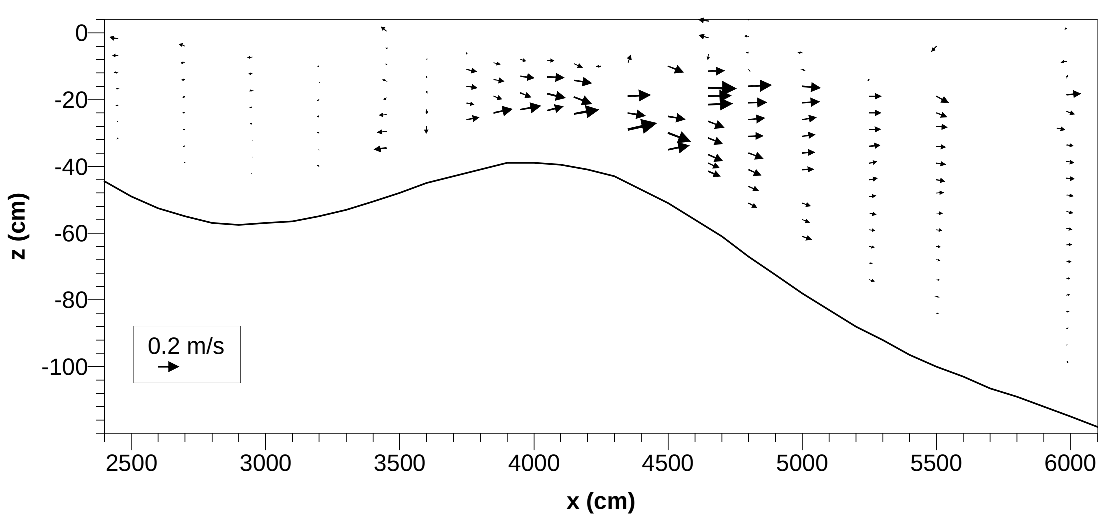

Fig. 5. Mean currents for wave condition C.

Firstly, we note that the maximum velocity magnitude is 0.28 m/s and occurs at the breaking region. Despite the fact that the bottom layer is lacking data, the velocity profiles are in agreement with those presented by other authors for different bottom configurations, both inside and outside the surfzone (*e.g.*, Okayasu, 1989; Putrevu and Svendsen, 1993). It is further interesting to point out that, in the region above the 15 cm layer shown here, we note a flow-direction reversal around x=36 m, which falls still within the surfzone. For x< 36 m, all velocity measurements point towards the shoreline, meaning that, in order to satisfy mass conservation, we either have a 3-dimensional flow (thus, the flow at the flume can not be considered 2-dimensional), or the 15 cm region lacking data will show offshore-directed velocities. Further data analysis will provide light on this issue.

Finally, a few results of the turbulent velocities are promising (Archetti *et al*., 2000). Fig. 6 shows the spectrum of the horizontal velocity from an ADV record. The dashed line has the −5/3 slope of the power law used to describe fully turbulent flows. This indicates that the high frequency energy is mostly turbulent.

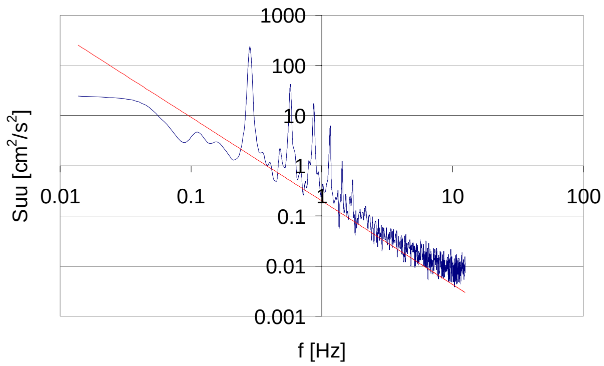

Fig. 6. Horizontal velocity spectrum from ADV measurements, wave condition C, *x*=36 m, *z*=25 cm.

5. CONCLUSIONS

In the present paper we have presented a comprehensive experimental Project, targeted towards understanding the hydrodynamics over a fixed-bed, barred beach. Four wave conditions were generated and both surface elevation and velocity measurements were carried out at a large number of locations. Several different runs of the same wave condition were performed, and were considered to represent the same stochastic process. Flume *seiching* was evident and could not be eliminated by the present wave-absorption system, which worked well in main wave-frequency range. Preliminary velocity results are shown and reveal quite interesting aspects, needing further investigation.

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REFERENCES

Archetti, R., Damiani, L., Lamberti, A., Mossa, M., Rinaldi, A., and Tomasicchio, G.R. (2000). Indagine sperimentale su di una spiaggia con barra. *IDRA 2000 – XXVII Convegno di Idraulica e Costruzioni Idrauliche*, Genova (in Italian).

Birkemeyer, W.A., Donoghue, C., Long, C.E., Hathaway, K.K., and Baron, C. (1997). 1990 DELILAH nearshore experiment: summary report. *Tech. Rep. CHL-97-24*, U.S. Army Corps of Engineers, Waterways Experiment Station.

Cox, D.T., Kobayashi, N., and Okayasu, A. (1995). Experimental and numerical modeling of surf zone hydrodynamics. *Res. Report CACR-95-07* (*Ph.D. Dissertation* of 1st author), Center for Applied Coastal Research, Univ. of Delaware, pp. 293.

George, R.A., Flick, R.E., and Guza, R.T. (1994). Observations of turbulence in the surf zone. *J. Geophys. Res.*, 99 (C1), 801-810.

Hattori, M. and Aono, T. (1985). Experimental study on turbulence under spilling breakers. In Y. Toba and H. Mitsuyasu (Eds.), *The Ocean Surface*, 419-424, D. Reidel Publishing Company.

Kennedy, A.B., Chen, Q., Kirby, J.T., and Dalrymple, R.A. (2000). Boussinesq modeling of wave transformation, breaking and runup. I: One dimension. *J. Waterways, Ports, Coastal and Ocean Engng.*, 126 (1), 39-47.

Kraus, N.C., Smith, J.M., and Sollitt, C.K. (1992). SUPERTANK laboratory data collection project. *Proc. 23rd Int. Conf. Coastal Engng.*, Vol. 3, Venice, ASCE, 2191-2204.

Kraus, N.C. and Smith, J.M. (1994). SUPERTANK Laboratory Data Collection Project. *Tech. Rep. CERC-94-3*, US Army Corps of Engineers, Waterways Experiment Station.

Nadaoka, K. and Kondoh, T. (1982). Laboratory measurements of velocity field structure in the surf zone by LDV. *Coastal Engng. in Japan*, 25, 125-145.

Okayasu, A. (1989). Characteristics of turbulence structure and undertow in the surf zone. *Ph.D. Dissertation*, Univ. of Tokyo.

Putrevu, U., and Svendsen, I.A. (1993). Vertical structure of the undertow outside the surf-zone. *J. Geoph. Res.*, 98, C12, 22707-22716.

Rodriguez, A., Sánchez-Arcilla, A., Gomez, J., and Bahia, E. (1995). Study of surf-zone macroturbulence and mixing using DELTA'93 field data. *Proc. Coastal Dynamics'95*, Gdansk, ASCE, 305-316.

Rodriguez, A., Sánchez-Arcilla, A., and Redondo, J.M. (1999). Macroturbulence measurements with electromagnetic and ultrasonic sensors. *Experiments in Fluids*, 27, 31-42.

Sanchez-Arcilla, A., Roelvink, J.A., O'Connor, B.A., Reniers, A., and Jimenez, J.A. (1995). The Delta Flume'93 experiment. *Proc. Coastal Dynamics'95*, Gdansk, 488-502.

Sancho, F.E. (1999). Equilibrium barred-beach profile. *1st Portuguese Conference on Harbour and Coastal Eng.*, Porto (in Portuguese).

Sancho, F.E., Mendes, P.A., Carmo, J.A., Neves, M.G., Lamberti, A., Tomasicchio, G.R., Archetti, R., Damiani, L., Mossa, M., Rinaldi, A., Gironella, X., and S.-Arcilla, A. (2001). Wave induced turbulence and undertow over barred beaches. *Technical report* (in progress).

Stive, M.J.F. (1980). Velocity and pressure field of spilling breakers. Proc. 17th Int. Conf. *Coastal Engng.*, Vol. 1, Sydney, ASCE, 547-566.

Wu, Y., H.-H. Dette and H. Wang (1994). Cross-shore profile modelling under random waves. *Proc. 24th Int. Conf. Coastal Engng.*, Vol. 3, Kobe, ASCE, 2843-2855.