PART II

Long Period Waves, Storm Surges and Wave Groups

Tetrapods in Bari

CHAPTER 59

LABORATORY TESTS ON THE INTERACTION BETWEEN NONLINEAR LONG WAVES AND SUBMERGED BREAKWATERS

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Abstract

This paper deals with the use of submerged detached breakwaters as beach protection, a use that today has become quite popular. This type of structure has been largely studied both theoretically and through experimental analyses in recent years, however its behaviour has not been completely understood, specially if related to the real irregular wave attacks. In particular some laboratory studies carried out by the authors have pointed out some interesting phenomena associated with the interaction between the nonlinearities of wave transformations in shallow water and submerged breakwaters.

Aiming at discerning between the phenomena related to the structure (beach and breakwater) and flume geometry, a new series of laboratory tests have been carried out in a 50 m long wave flume; these tests and the results obtained are described in this work. Besides the study of the behaviour of submerged structures related to the bounded-long-waves, some current velocities have also been measured during this research through directional micro-propeller fluid meters.

Introduction

Among the work aiming to protect ports and beaches the use of detached submerged breakwaters appears today of increasing interest. This is mainly related to the small environmental effects combined with the obvious aesthetic advantages of these structures and to their relatively low costs.

Even if the case of submerged structures have been given significant coverage in literature, certain aspects do not seem to have been treated in enough depth; for example only the first steps have been taken in studying the

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behaviour of such structures under irregular wave attacks (Ahrens, 1989, Van der Meer, 1988, Petti and Ruol, 1991).

The difficulties connected to similar analytical or numerical studies (Kobayashi and Wurjanto, 1989) often lead to a physical analysis of the phenomena related to similar structures in measuring water level oscillations across the structure (Adams and Sonu, 1986, Hedges et al., 1985).

To explain some anomalous water level oscillations in front of the breakwater, which were measured during a similar approach (Petti and Ruol, 1991) the writers supposed that the mass transport, caused by the waves breaking on the structure, was able to create a current directed off-shore that was affecting the incoming wave characteristics.

In particular the authors found that the bounded long waves generated by the well-known non-linear modifications of the wave spectrum on a sloping bottom, problem recently solved also in analytical manner (Petti, 1991), seem to be greatly affected by the joint effect of the structure and by the current opposite to the incoming waves.

These experimental analyses were conducted in a wave flume using a submerged breakwater located on different fixed bottom configurations. These experiments were carried out in a 33 m-long wave flume reproducing a monotonously decreasing bottom profile initially and a barred profile later (Petti and Ruol, 1990, 1991).

In the present work, in order to have a better understanding of the physics of the problem, a new series of experiments carried out using the same structure but in a longer wave flume and with different bottom configuration are described. In particular during these experiments some velocity measures over the structure were also performed in order to estimate the current velocity field induced by the wave attacks in the regions close to the submerged breakwater. At present similar measures are the object of some interesting new research (Losada, 1992).

Laboratory experiments

The series of experiments described in this paper were carried out in the wave flume of the Department of Civil Engineering which is 50 meters long, 0.8 m wide and 0.8 m deep. The analysed structure, located on a 1:50 fixed bottom slope, consisted of an impermeable submerged breakwater 14 cm high, 24 cm wide at the top and sloping 1:3.5 sea-ward and 1:1.5 shore-ward.

The wave transformations were first of all analysed considering the simple sloping beach without any structure and later considering a submerged breakwater located in a 20 cm local water depth at about 34 meters from the wave generator (Fig. 1).

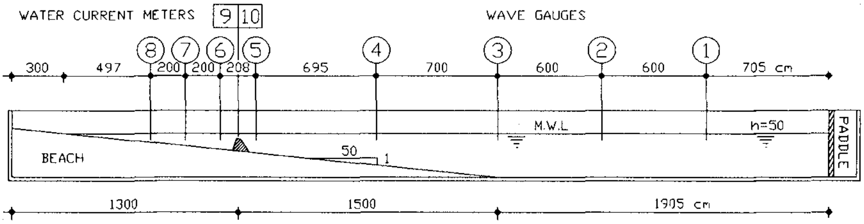

Fig. 1 – *Experimental apparatus and scheme of the tested structure.*

The wave characteristics in the flume were determined measuring water level oscillations with eight parallel wire resistance gauges. Besides these characteristics, reflection coefficient analyses and velocity measurements were also performed.

Both with and without the structure four different wave attacks, characterised by spectra of the JONSWAP type, were reproduced. Significant wave heights, the Phillips constant α, the peak frequency f_p and the peakedness factor γ characteristic of each experiment are summarised in Tab. 1.

Table 1 – *Characteristics of generated waves.*

Test n.	α	f_p *(Hz)*	H_{m_0} *(cm)*	γ
1	0.0180	0.650	14.1	1.0
2	0.0100	0.650	11.7	2.0
3	0.0140	0.833	9.2	3.0
4	0.0180	0.833	8.6	1.0

Test results and discussion

In Fig. 2a and 2b an example of the results obtained through the spectral analysis for both the case with submerged structure and without it is shown.

In these figures the wave spectra measured by the gauges located along the flume are compared; it does appear that in the first case (without structure) the non-linearities of the spectra (due to the shallow waters) are not evident in the deeper waters (gauges n. 1, 2, 3), while, as expected, the build-up of low-frequency and high-frequency components is evident in the shallow waters.

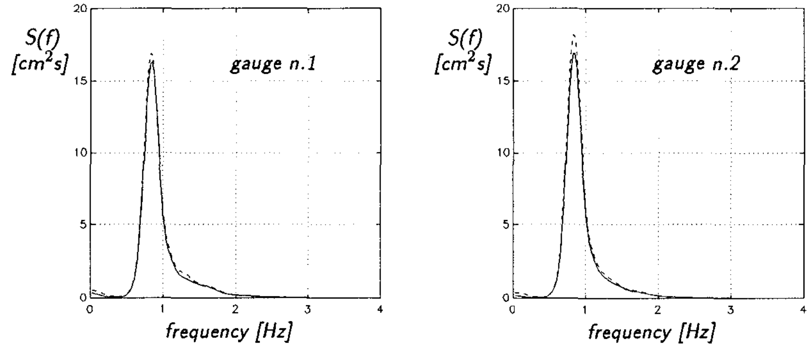

Fig. 2a – *Comparison between spectral densities of the case with submerged structure (dotted line) and without it (solid line), for the test n.3 and gauges n. 1 and n. 2.*

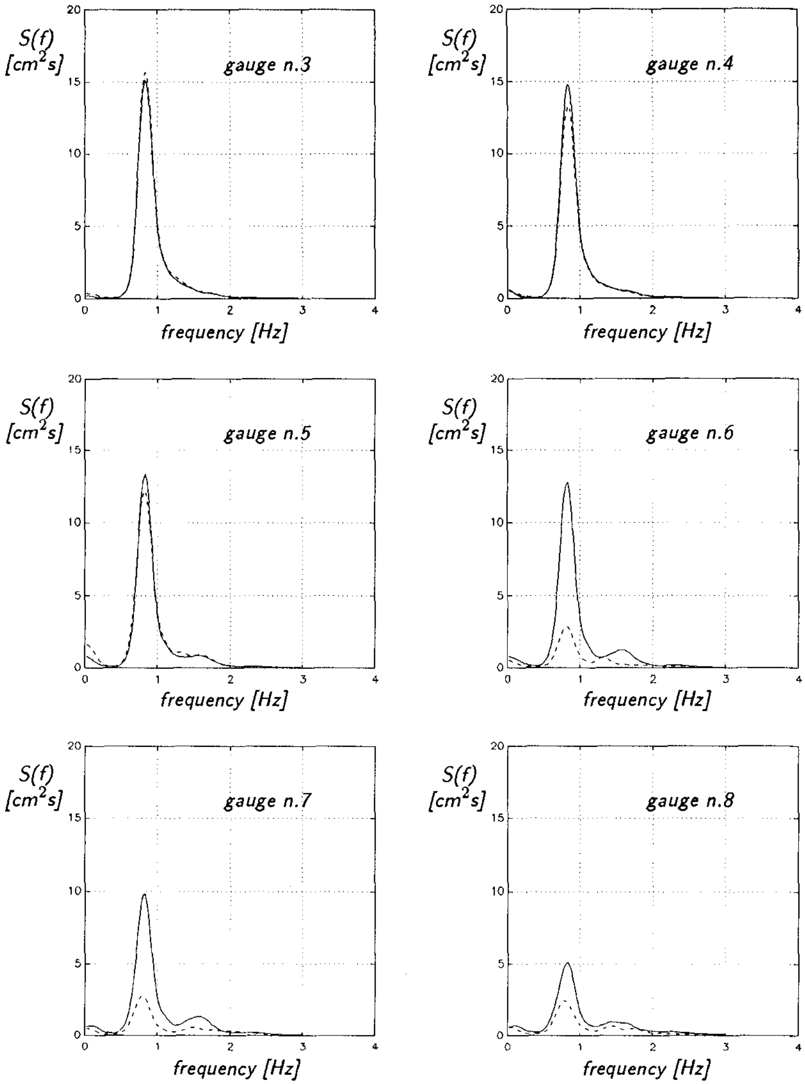

Fig. 2b – *Comparison between spectral densities of the case with submerged structure (dotted line) and without it (solid line), for the test n.3 and gauges n. 3 ÷ 8.*

In the second case also (with structure) the spectra referred to the deeper gauges show the absence of non linearities, while a considerable increase was found in the lower and higher frequency components just in front of the structure (gauge 5).

Of course the spectral densities decrease significantly after the impact of the breaking phenomenon located on the submerged breakwater and do not considerably change in the propagation towards the beach.

This typical non-linear phenomenon was studied in more detail dividing the long waves from the short ones: for this research the time domain records were analysed filtering the signal and considering the higher frequencies ($f > 0.5\ f_p$) and the lower ones ($f < 0.5\ f_p$) separately. An example of the results obtained through such wave data analyses referring to gauge n. 5 and lasting 60 s is shown in Fig. 3.

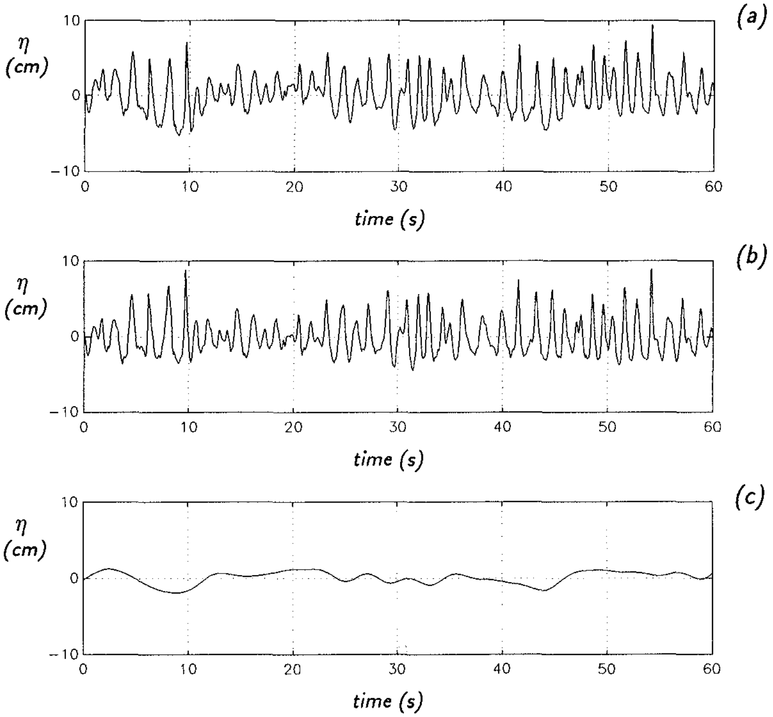

Fig. 3 – *Example of water level oscillation data-recording (a), of the filtered signal with* $f > 0.5 f_p$ *(b) and with* $f < 0.5 f_p$ *(c) for test n. 2 and gauge n. 5.*

For both short and long waves previous analyses of the reflection coefficients (Goda and Suzuky, 1976) were performed in the case without the structure. These coefficients appeared to be close to 4% for short waves and 12% for long ones. The details of the results obtained by means of zero-(up)crossing analyses performed on the 4 reproduced tests are schematically drawn in Fig. 4a and 4b. In the figures significant short-wave heights H_S and periods T_S along the flume are reported.

As expected the periods perhaps appear constant along the flume, while the wave heights, as result of shoaling and breaking phenomena, decrease with decreasing water depths.

As already described, the same four tests were repeated with the submerged breakwater located on the bottom profile; the results obtained through experimental analyses are shown in Fig. 5a and 5b.

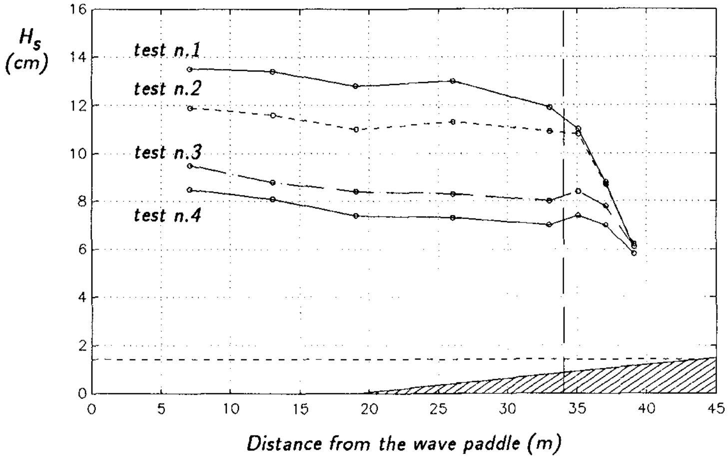

Fig. 4a – *Significant wave heights for all gauges referred to short-waves zero-crossing analyses without the structure.*

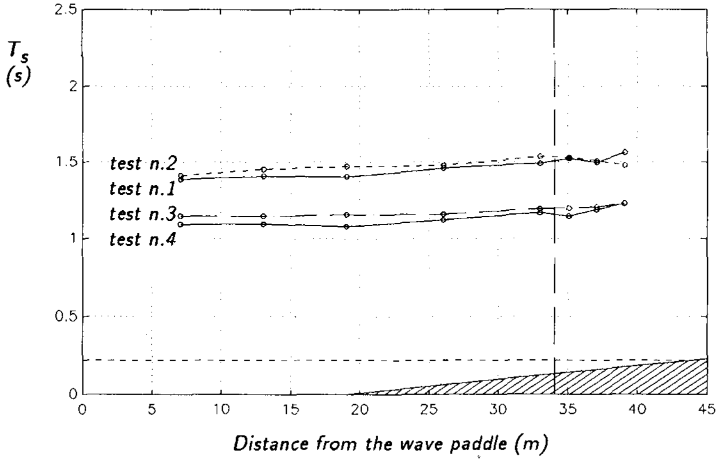

Fig. 4b – *Significant wave periods for all gauges, referred to short-waves zero-crossing analyses without the structure.*

In comparing Fig. 4a and 5a it does appear that in the off-shore region the wave heights do seem not to be greatly affected by the structure and this probably explains that, in the case analysed, the structure is not reflecting waves significantly. Instead, wave heights following the breakwater are strongly affected by the structure itself and this is mainly related to the breaking of some waves over the structure.

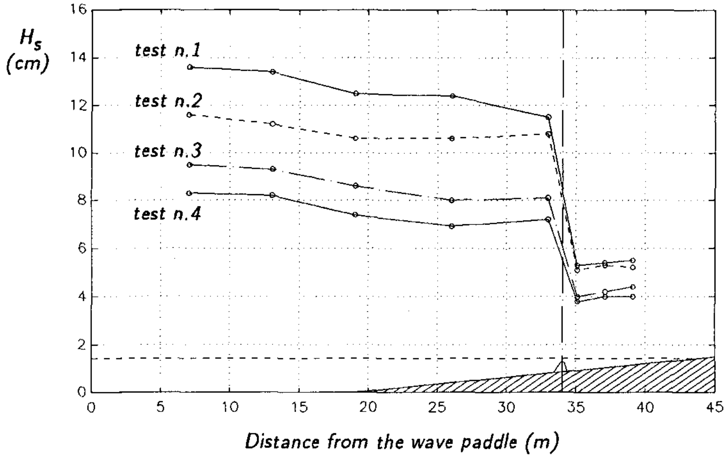

Fig. 5a – *Significant wave heights for all gauges referred to short-waves zero-crossing analyses with the structure.*

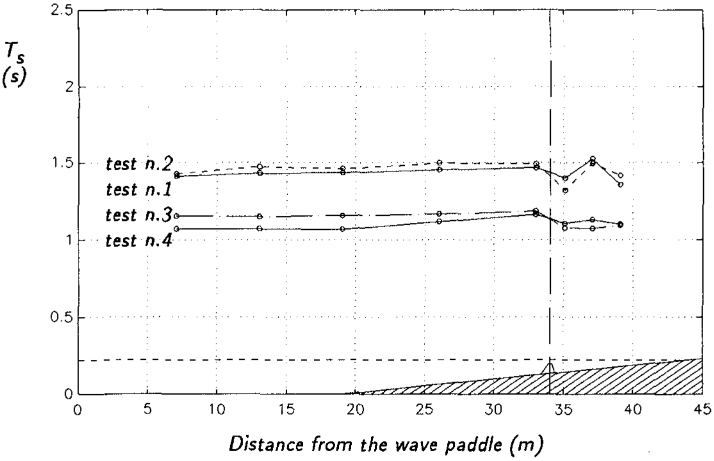

Fig. 5b – *Significant wave periods for all gauges referred to short-waves zero-crossing analyses with the structure.*

As far as periods are concerned (Figs. 4b and 5b) they do not seem to be greatly influenced by the structure, except for very weak instabilities around it.

However, the most interesting phenomenon that did appear is related to the analysis of the bounded-long-waves and in particular to the difference induced by the placing of the submerged breakwater over the bottom profile. In Fig. 6a and 6b the long-wave significant heights evaluated for all gauges during each test are drawn.

It can be observed that a considerable increase of long wave heights just in front of the structure was measured; in fact the long wave heights within the structure were evaluated to be about 40% greater than without it.

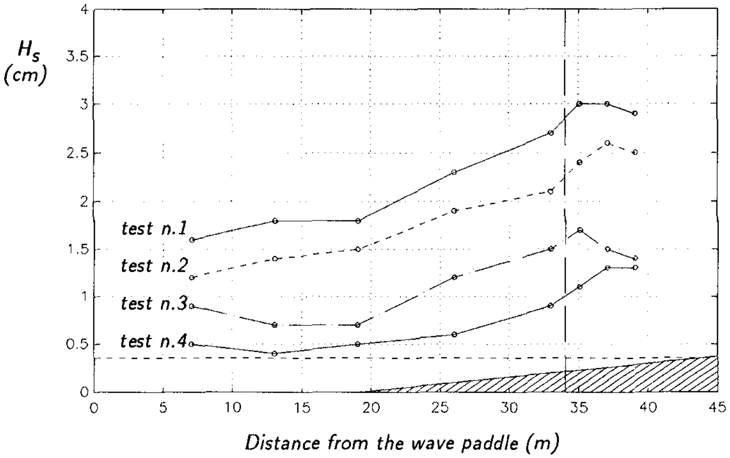

Fig. 6a – *Significant wave heights for all gauges referred to long-waves zero-crossing analyses without the structure.*

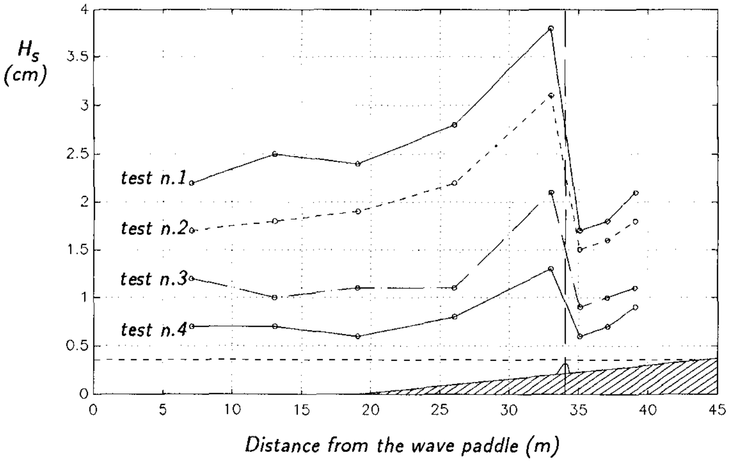

Fig. 6b – *Significant wave heights for all gauges referred to long-waves zero-crossing analyses with the structure.*

Similar results had already been found by the authors in previous experiments (Petti and Ruol, 1990, 1991) performed with the same structure but in a shorter flume and with different bottom configurations. This particular aspect lead to the thinking that the bottom configuration and the flume length affect only slightly the increasing of long wave heights in front of the structure.

As regards the length of the flume, probably some seiches were present because a non absorbing wave maker was used during the experiments. In the writers opinion, however, the results appear not to depend on them.

Frstly if the seiches were present they were very small because their reflection coefficient was small (12%). Secondly because eventual long wave oscillations should have been present in both the cases analysed: as a consequence the comparison of the results (e.g. the increase of the long wave heights) is not affected by the seiches themselves.

So as to be able to get more information about this interesting phenomenon, some velocity measurements over the structure were also performed.

A couple of water-fluid-meters (bi-directional micro-propeller) were located at 2.0 cm over the structure, one beside the other and three additional wave gauges were located in the same section in order to be able to associate the velocities with water levels (Fig. 7).

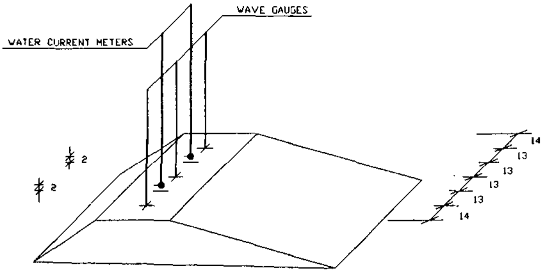

Fig. 7– Location of the micro-propellers and of the gauges over the structure.

An example of the velocity data registered during one test is reported in Fig. 8. As well as for the waves, the signal was also analysed considering the higher frequencies ($f > 0.5f_p$) separately from the lower ones ($f < 0.5f_p$). The results appear similar to ones referred to the wave gauge n. 5 located in front of the structure.

As regards the spectral analyses performed for velocity signals, in Fig. 9 the results relative to the four tests checked are reported.

It can be observed that while at the lower frequencies very high spectral values are present (due to nonlinear phenomena), at the higher frequencies they do not result all too evident. Moreover, while in the wave spectra calculated in front of the structure it was possible to find a frequency (about equal to $0.5f_p$) dividing the low-frequency components from the high ones (Fig. 2), this was not possible for the velocity spectra.

Definitely a different behaviour of the velocity spectra compared to the wave spectra does appear: the frequency components in fact are strongly evolving towards the lower values and only weakly towards the higher values.

With regards to this, during the velocity analyses the mean values of the velocity pointing off-shore (a constant velocity distribution along the vertical was supposed) were also calculated: they were included in the range $6 \div 14$ cm/s.

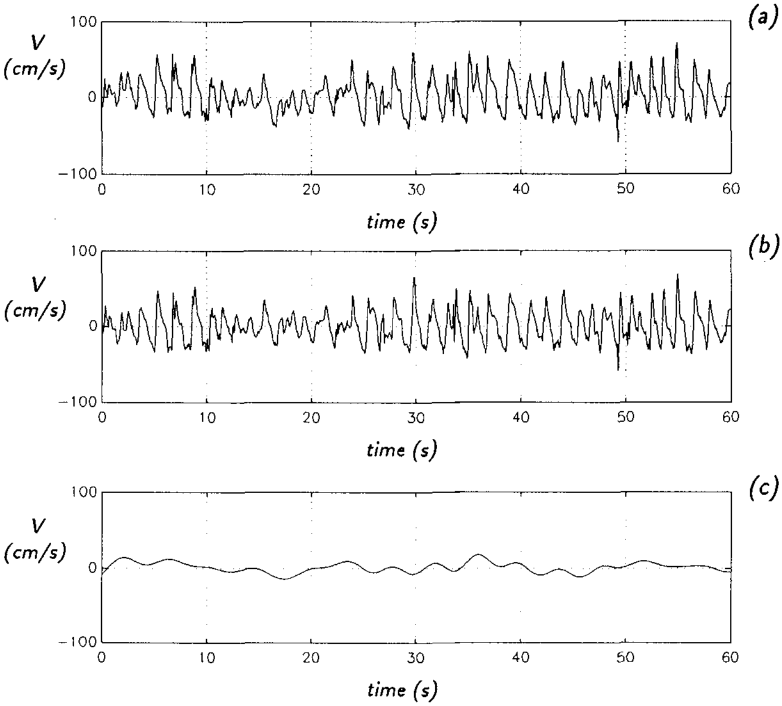

Fig. 8 – *Example of velocity data-recording (a), of the filtered signal with* $f > 0.5 f_p$ *(b) and with* $f < 0.5 f_p$ *(c) for test n. 2.*

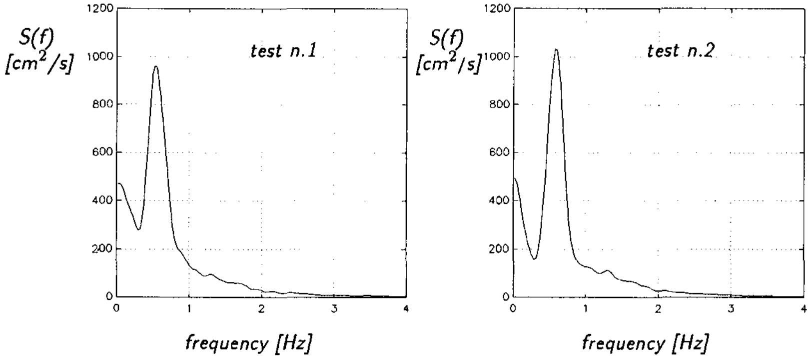

Fig. 9a – *Spectral analyses of the velocities measured over the structure by a micro-propeller for tests n. 1 and 2.*

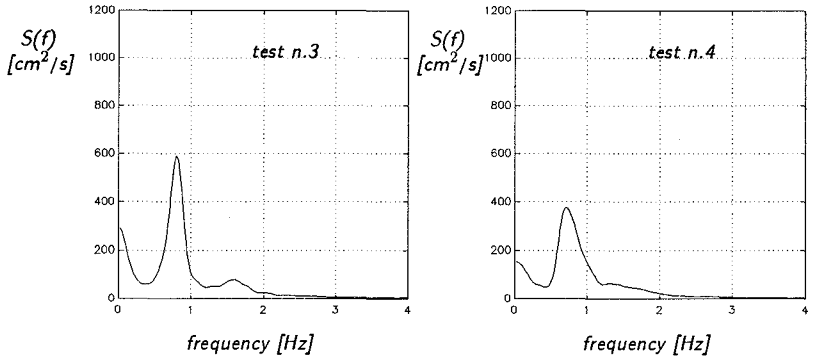

Fig. 9b – *Spectral analyses of the velocities measured over the structure by a micro-propeller for tests n. 3 and 4.*

In the authors' opinion these velocities, associated with the submerged breakwater presence, were able to affect the incoming bounded-long-waves; in fact the measured velocities appeared to be close to the theoretical long-wave orbital velocities (without structure) calculated, at first order, through linear theory (i.e.: $u_{max} = 0.5H\sqrt{g/h}$). In conclusion, the incoming long wave really seems to be interfering with the opposite fluid discharge as if it were affected by a phenomenon similar to the interaction between waves and currents.

To corroborate this hypothesis the described mean velocity pointing offshore was related to the increase of long-wave heights due to the presence of the breakwater for each test (Fig. 10).

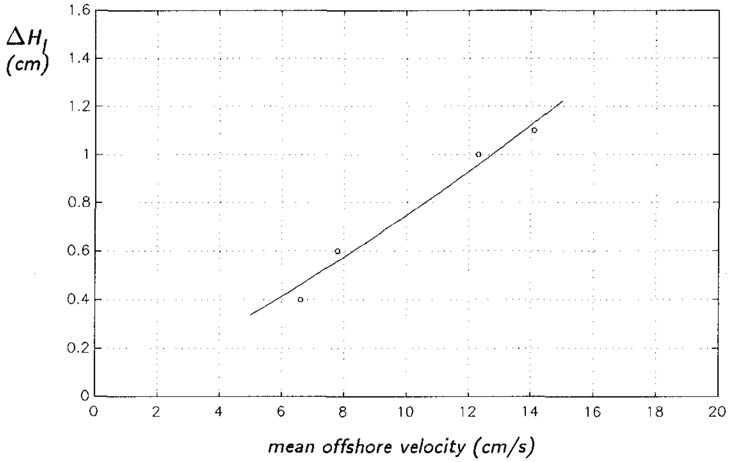

Fig. 10 – *Increase of long wave heights in front of the structure (gauge n. 5) versus mean velocity measured over the structure.*

As it does appear the greater the off-shore velocity over the breakwater the greater the increase of the long wave heights.

Conclusive remarks

Some experimental studies carried out in a 50 m long flume on a submerged breakwater resulted in the definition of its behaviour under irregular waves attacks. In particular it was pointed out that the analysed structure was considerably affecting the bounded long wave heights: in fact the long wave heights were evaluated to be about 40% greater with the defence work rather than without it.

So as to be able to get more information about this phenomenon, some velocity measurements over the breakwater were performed: it did appear that greater the mean velocities pointing offshore (evaluated to be in the range $6 \div 14$ cm/s), the greater the increase of the long wave heights in front of the structure.

Further experimental research with different submerged structures is asked for in order to determine analytical correlations between long wave height increases and geometrical characteristics.

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