CHAPTER 73

LONG WAVES IN A SPANISH HARBOUR

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ABSTRACT

Short and Long Wave data recorded in Bilbao Harbour (Spain) have been analyzed in order to study water movements at the inner basins under storms conditions . Some of the trends obtained in prototype have been correlated with model test (regular long wave and irregular short waves) .

This harbour has been chosen for this research on the one hand because of tha availability of the physical model and on thge other hand because of the means provided by the Bilbao Port Authority

1.- INTRODUCTION

For a long time, there has been a great concern to know the behaviour of harbour basins with regard to long waves. These long waves can induce resonant effects in water bodies, and consequently, in moored ships. As a result, moored ship operations become much less efficient.

After the well known Longuett-Higgins'article, in 1964 (Longuett-Higgins, 1964), the amplitude of the long waves associated to wave grouping (β) , was calculated. The expression for this magnitud was the following :

$$\beta = - 3 \cdot g \cdot a^2 / 2 \cdot \omega^2 \cdot h^2$$

Where : a = short wave amplitude ; $\omega = 2\pi/T$; T = wave period ; h = water depth.

The wave set-down period (T_s) corresponds to the wave grouping, being the former a function of the wave grouping grade and the wave peak period (T_p). The experimental evaluation of T_s can be done in different ways : based in the number of waves in a group (Sand, 1982 a), from the SIWEH spectrum (Funke & Mansard, 1980), and also, as a mean value of the up-zero crossing period, obtained from the SIWEH spectrum T_z (SIWEH) (Iwagaki, 1986).

This set-down wave is feeded by a second order mechanism from the short wave, in different ways (Bowers, 1977). In a harbour, this long wave will as a bounded long wave (BLW), as a free long wave produced by the energetic inbalance at the harbour entrance, due to water

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depth differences (FLW) , and as caused by wave breaking phenomena on a beach , located near a harbour , such as surf-beats and edge waves.

The resulting long wave can be in resonance with the different harbour basins if T_{sig} is close to the natural period of the basins, giving rise to resonant amplifications.

The BLW has been widely studied and its parameters have been correlated with waves characteristics outside the harbour, for both unidirectional and directional waves, having a kind of energy spreading Dθ for the latter (Sand,1982 a, and 1982 b). An application of the BLW parameters was carried out for Sines Harbour by Vis et all, 1985.

This piece of work shows the results obtained in Bilbao Harbour where the BLW, FLW, and resonant amplifications were simultaneously detected under severe storm conditions. Regular long wave model tests were carried out to characterize harbour resonant responses. Also, irregular wave model tests were performed to compare trends in the prototype and model, in regard to long wave energy transfer outside and inside harbour basins.

2.- FIELD DATA ANALYSIS

Waves outside the harbour were recorded in a Datawell Waverider , located at a water depth of h=50 m (Fig.1). The signal transmitted by the buoy is collected at a station where it is recorded every 1 ó 3 hours, depending on whether there is an "alarm signal" or not (wave conditions such as H_{mo} >4 m., and T_m > 16 seg). The recording equipment consists of a HP-86 computer. The 5,000 data of each record are stored on a hard disk (Dt = 0.5 seg), transferred later to a moveable disk, and sent to the CEPYC, in Madrid. Sampling characteristics were chosen after studying the stationary and representative conditions of the calculated statistical and spectral

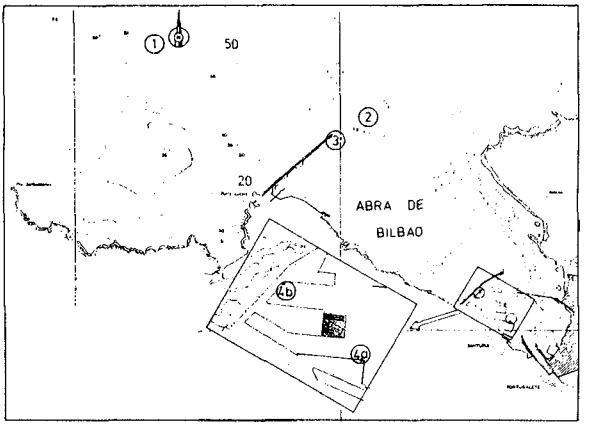

Fig 1: Position of measurement systems : Outside Waverider (1) ; "Morro" Waverider (2) ; Metheorological Station (3) and Pressure Sensors (4a & 4b) .

parameters (A.Fernandez , 1988). A bdeep description of this system is shown in Martinez , Santás and Sanz , 1988 .

Long waves were registered by a pressure sensor, manufactured at the CEPYC, consisting of a differential thin film strain gauge, located in a watertight chamber, filled with silicone oil. The outer connexion was made by two openings in the sensor. One of these openings was feeded by a hydraulic filter to remove the tide long wave. The filter characteristics are : 6 dB high pass, crossing frecuency 1/(6hr). The high frecuency removing is done by the hydrodynamic attenuation of the water column in the sensor, installed at a water depth of 6 meters.

The information supplied by this pressure wave sensor was digitalized (Dt= 2.5 seg), using series of 4096 points, and recorded on other HP-86 system, transferred to a moveabl disk system later, and sent to the CEPYC, in Madrid.

The data analysis carried out later , based on the above mentioned information, is summed up bellow :

A) Waverider :

- Standard statistical parameter calculations
- Spectral calculations : FFT previous filtering (T<4 seg, and T>25 seg), and later smoothing (18 freedom degrees). The resulting time series will be called "*Outside Short Wave*" (OSW), and its corresponding spectrum S(OSW).

- SIWEH calculations : long wave time series and spectrum , statistical analysis of typical values, estimation of T_{σ} and grouping factor GF (Funke & Mansard, 1980). The SIWEH long wave will be called "*Outside Long Wave* " (OLW), and its corresponding spectrum S(OLW).

B) Inner Wave gauge

- Surface wave recomposition, in amplitudes and phases, for the 10 min. > T > 10 sec. band, using the hydrodynamic wave attenuation factor K, given as :

$$K = \cosh (k.h) / \cosh (k.b)$$

where h = instantaneous water depth ; k = wave number ; b = distance from the bottom.

A frecuency filter transference function was used to correct FFT data. Short and long wave band differentiation were defined in the following way :

Long wave : 1/(10 min) < f <0.04 Hz (ILW)
Short wave : 1/(35 seg) < f <0.1 Hz (ISW)

Typical statystical parameter calculations, for both time series, called "Inside Long Wave" (ILW), and "Inside Short Wave" (ISW)were made

Spectrum calculations for both time series with a previous Bingham smoothing, and a later Bartlett smoothing . The number of freedom degrees for ISW and ILW were 30 and 18, respectively.

2.1.- PROTOTYPE WAVE DATA STORAGE

Wave data storage began in March, 1986. The long wave pressure gauge was initially placed in position 4a (Figure 1), changing this position to 4b, in March 87, where it is still placed.

It was considered interesting to analyze the data only where long wave height was higher than 10 cms. The storms analyzed corresponded to the following days :

Position 4a : a) March 24-27, 1986
Position 4b : b) April 20-21, 1987; c) September 4-5,1987 ; d)January 22-26, 1988; e) January 30-February 12,1988; f)March 16-17, 1988.

Figure 2 shows the time series for H(z,s), corresponding to the Waverider (OSW), the inside short wave (ISW), and the inside long wave (ILW) for the stage a).

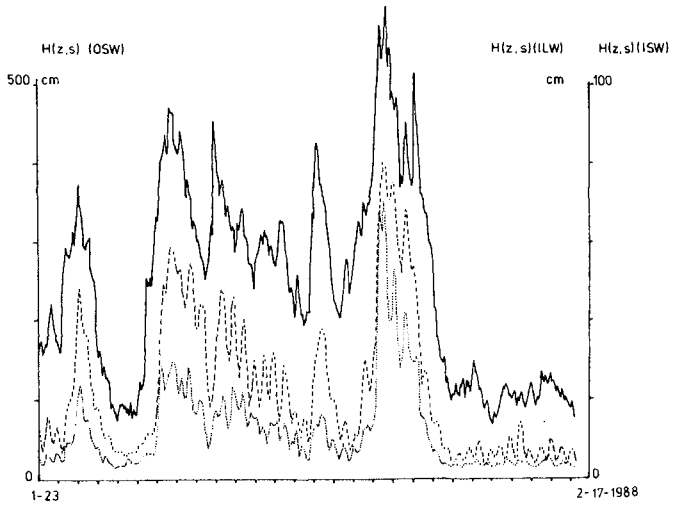

Fig.2 : Wave Time Series H(z,s) : (_____) Outside Short Wave (OSW), (-----) Inside Short Wave (ISW), (.....)Inside Long Wave (ILW) . Data from 1.23.1988 to 2.17.1988 .

3.- RESULTS OBTAINED FROM PROTOTYPE MEASUREMENTS

First of all the short wave data OSW and ISW were correlated and compared. Two interesting aspects were found :

-The correlation between significant wave heights H(z,s) inside (ISW), and outside (OSW) was in the range of 8 and 13% (fig.3a), depending on the wave period.

- The significant and mean wave periods T(z,s), and T(z) have a small increment, between 7% and 9%. This fact is also found for the peak period T_p. (Fig. 3b).

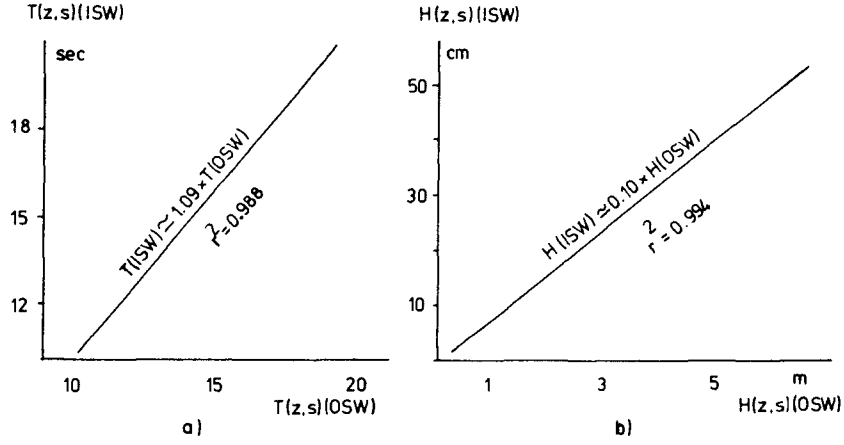

Fig. 3 : Comparison of Statistical Results between ISW and OSW
3a) : T(z,s); 3b) : H(z,s).

As it will be explained later, similar trends appear in the physical model. Moreover, the values obtained for wave agitation coefficient inside the harbour, from both mathematical and physical models, appear to be within the above mentioned range for H(z,s).

In regard to the long wave measured (ILW) inside the harbour and the short wave outside it (OSW) , the main findings are as follows :

- The correlation between H(z,s), (OSW), and (ILW) depends very much on the measurement area, which is indicative of some resonant mechanism. For location 4a(Fig.1) this correlation was found to be

$$H(z,s)\ (ILW) = 1.586 \cdot 10^{-3} \cdot [\ (H \cdot T)\ (OSW)\ /\ h\ ]$$

This kind of correlation fits better than the quadratic one used in Sand's, with data obtained from the stage a). However, for position b), which is more favorable for resonant effects due to its basin location, the correlation was found to be (with $r^2 = 0,8050$) :

$$H(z,s)(ILW) = 0,0732 + 4,841 \cdot 10^{-5} \cdot [\ (H.T)^2\ (z,s)\ (OSW)\ ]\ /\ h$$

Whereas for a best fit of (H,T), the following formula is obtained ($r^2 = 0.72$) :

$$H(z,s)(ILW) = -\ 0.1177 + 6,319 * 10^{-3} \cdot [\ (H.T)\ (z,s)\ (OSW)\ ]\ /\ h$$

This last expression shows a degree of five times better for position 4a than for 4b (Fig. 4a and 4b). This explains a resonant effect for the long wave energy.

The unexpected fact that the quadratic expression for (H,T) is not clearly accomplished , could be explained by considering an

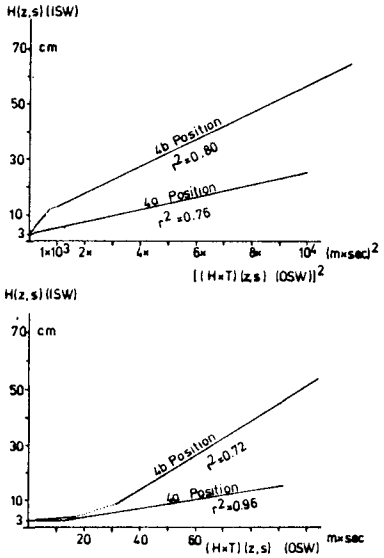

Fig. 4.- Correlation between H(z,s) (ILW) and the Product (H * T(z,s) (OSW)) : 4a) Lineal Fitting. 4b) Quadratic Fitting

amplification of the set-down proportional to H , instead to H^2 , in the inner harbour area. This amplification is due to an attenuation of the amplification factor caused by flow separation at the harbour entrance (Bowers, 1977).

The results calculated from the ILW, OLW, and SIWEH waves, obtained from the outside wave record, have also been correlated.

It was expected to obtain characteristic values of the number of waves in a group (Df/f(p)), taking into account the grouping factor GF. These values would allow to evaluate the transfer function Gnm between the short waves and the long set-down wave. However, the authors were not able to find a good correlation between the parameters GF and (Df/f(p))

The comparison between the values of T(z)(SIWEH) or T(z)(OLW) with T(z) (OSW) has not given a high level of correlation. There seems to be a tendency to show increasing values towards the storm peak, and then decreasing slowly . The correlation between T(z) (OLW) and Tz(OSW) was found to be somehow better in the following way :

$$Tz(SIWEH) = 6.6.\ T(z,s)\ (OSW)\ ;\ R^2 = 0.42$$

This expression is close to the value of the parameter fp/Df = 5, as found in Sedivy (Sand, 1982 a).

However, a certain value was systematically found for Tc(SIWEH) covering the range of 40-70 seg, coincident with the second spectral peak interval.

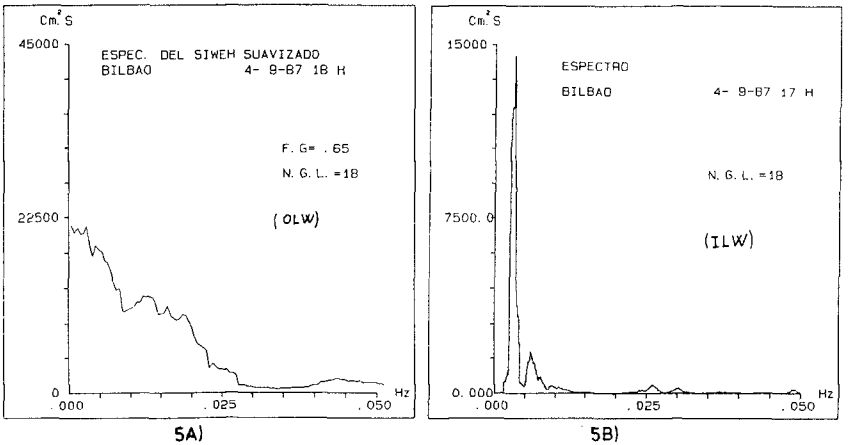

Fig.5.- Energy Spectra : A) SIWEH for the Outside waves (OLW)
B) Inside Long Wave (ILW).

When the SIWEH was smoothed by using a nine bands moveable rectangular window, the first spectral peak showed within the 250-350 sec. range, with other peaks within the ranges of 100-150 seg, and 40-50 seg. These results might indicate the existence of a main grouping period for the set-down, around the 40-50 secs, together with higher groupings, related to the subharmonics, being the latter responsible for the most important energy peaks in the SIWEH. Thus, the set-down should be understood as a wave family which is able to cause harbour resonance for some characteristic periods.

The ILW spectra show a well determined structure, with the maximum spectral peak in between 280 and 366 secs, and other peaks which only appear under storm conditions, around 40 and 180 seconds, respectively (fig.5a)

4.- MODEL TESTS

Different model tests were carried out for Bilbao Harbour (with regular and irregular waves, and also with moored ships). Some aspects of interest, related to the above mentioned long wave analysis performed in prototype, are presented hereafter. An undistorted scale 1:150 was used.

4.1.- REGULAR LONG WAVE MODEL TESTS

The purpose of these tests was to obtain a broad and detailed information of the resonant behaviour of the different harbour basins. The wave period range tested was from 30 s. $< T <$ 300 s.

4.1.2.- METHODOLOGY

The two main basins were filled with fluorescent cork spheres in order to observe the general way of oscillation of the two basins, for each exciting wave period. Maximimum horizontal and transversal peak to peak water displacements, near the berthing places, were measured in detail, for the outer and inner harbour basins. Also, the existence of vortexes was remarked. Additionally , surface water displacements were measured in other points of interest alongside the berthing places. A very detailed information on the behaviour of the two basins was elaborated, remarking the bollard numbers at which characteristic water displacements were observed.

It shoud be remarked that , although wave periods were calibrated, wave heights were estimated visually. Therefore, the measurements of water surface displacements should not be understood quantitatively, since long waves could not to be defined exatively by any known characteristic parameter such as the Ursell parameter.

4.1.3.- ANALYSIS OF RESULTS

The results were analyzed in two ways :

A) Representing in a plan view of the harbour (Fig.6A) the observed displacements in front of their corresponding bollards (crossing bars) ,together with the interpolated displacements in the bollards were no measurements were taken (white bars). Even though the spatial amplitude displacement distribution is sinusoidal , a linear distribution was adopted for comparative purposes. (Figs. 6b and c). The theoretical positions of nodes (χ_0 : main; χ_1 : first; χ_2 : second) were also indicated in the aforementioned figures, for each exciting wave period, using the simplificative formulations for rectangular basins.

In regard to the use of the above mentioned simplificative assumptions for rectangular basins, the following conclusions were drawn , after analyzing the behaviour of the two basins in the present physical model:

- The inclination of the quay called "Muelle Adosado", located at the end of the outer basin, induces a reflection of the standing wave, which makes the inclined basin behave in a different way than a rectangular one. Two interesting aspects should be pointed out :

- The antinode does not clearly appear in the vertical wall, at the basin end , due to the existence of horizontal water displacements in the direction of the inclined quay , caused by the above mentioned reflective effect of the standing wave.

- The section reduction at the change of alignement, in the inner main basin, causes an increment of the horizontal velocities of the standing wave. This effect is increased by the relative closeness of the first oscillating node.

B) Representing the maximum horizontal displacements (peak to peak) against the exciting wave periods (within the range of 30-300 secs), for the two main harbour basins.

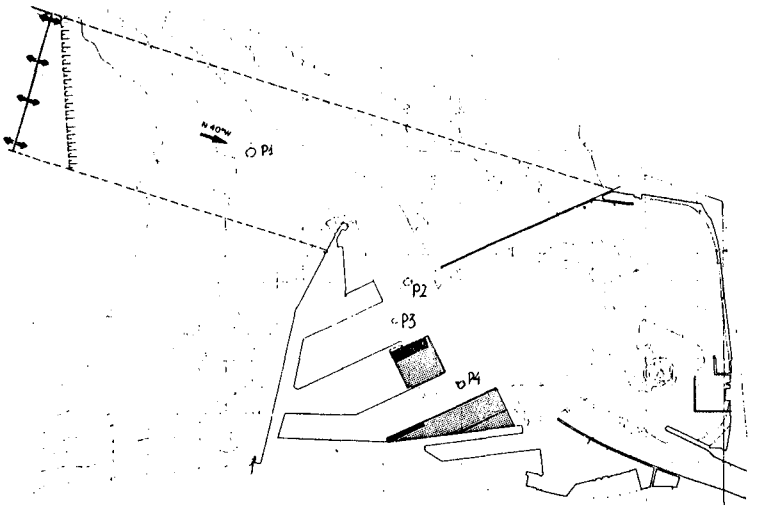

Fig.6.- Physical Model : a) General Lay-out.

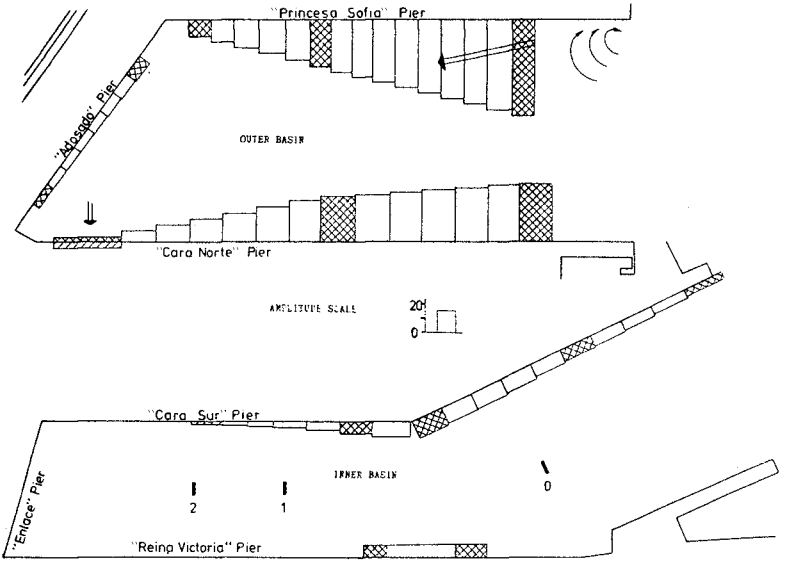

Fig.6.b&c- Example of Horizontal Water Displacements Parallel to Quays : b) Outer Basin(T = 250 s.), c) Inner Basin (T = 200 s.) XXXXX Measured Data, ▭ Interpolated, ▨ Perp. displacement towards the berthing, ⇐ Drifting, G Vortex, ■ Theoretical node position.

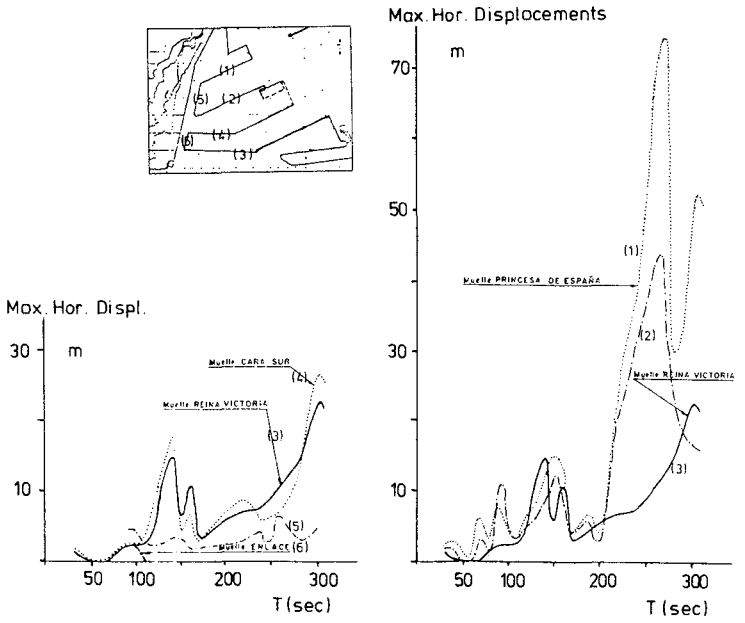

Fig.7.- Results of the Physical Model with Regular Waves : Max. Horizontal Displacements at the Two Basins against the Exciting Wave Periods.

4.1.4.- MODEL TEST CONCLUSIONS

After analyzing the figures shown in A), the following conclusions were obtained, related to the behaviour of the two harbour basins.

Outer Harbour Basin (Fig.6b)

It can be seen, from the figures, that the osciLlatory displacement amplitude distribution looks like one corresponding to a standing or quasi-standing wave, with maximum displacements located near the node.

The "theoretical" resonant period of the basin was found in the range of 200-235 seg., depending on the oscilating length adopted (from the center of the Adosado Quay , or from the end). This range could be extended because of the longer wave standing trajectories caused by the reflection in the inclined pier at the botton of the basin.

The above mentioned long wave reflective phenomenum was also shown in the model tests, by the transversal displacements experimented in the Cara Norte Quay , specially in bollard 5 (see bollard plan).

Another point to be remarked is the higher displacements found at the Princesa de España Quay with respect to its opposite one (Cara

Norte). Horizontal displacements up to 75 meters were measured at the Princesa de España Quay (bollard 3, near the entrance). Also, a drift displacement of 45 m. was observed in that bollard.

Inner Harbour Basin (Fig.6c)

The movements observed at the inner basin are significatively smaller than those found at the outer basin, and they are also distributed more uniformely.

The largest displacements are found at the change of alignement in the inner basin. The reasons for this could be as follows :

- The oscillation node is close to this area.

- This change of alignement is coincident with a reduction of the transversal section of this basin, which causes an acceleration of the confined mass of water.

- The antinode appears to be located at the end of the basin, which does not occur at the outer basin.

After analyzing the figures explained in B) (Fig.7), the following conclusions are drawn :

The Princesa de España Quay seems to be very sensitive to small wave period increments. For instance, for the range of T = 200- 260 secs.,the horizontal water displacement shifts from a value of 6 m., to the maximun one of 75 m., and then decreases down to 30 m., for the range of T = 260-280 secs, increasing again up to a new maximum (52.5 m.), for T = 280-300 secs., showing a decreasing trend after it.

The outer basin shows two distinctive peaks for its longitudinal oscillation, for the two parallel quays (Princesa de España and Cara Norte).The firt peak is located near T = 150 secs., and the second peak around T = 240- 260 secs. This second peak induces the largest water displacement (about five times more).

The outer and inner basins show similar trends in longitudinal oscillations (two distinctive peaks), although they both differ considerably in the oscillation amplitudes, as it was already explained.

The position of the main oscillating node seems to be a significant parameter for the way in which longitudinal water oscillations occur at the two parallel piers. The more simmetrical location of the main node at the inner basin, due to the lower inclination of the quay at the end , makes the two parallel piers (Cara Sur and Reina Victoria) oscillate in a very similar way.

The transversal water movements of the two basins are very small compared to the longitudinal ones.

4.2.- IRREGULAR WAVE MODEL TESTS

After analyzing wave spectra at different harbour areas (Fig.6a), energy transfer was found from the main peak period (T_p = 17 secs.) towards much higher periods in the range of 103-310 secs. The fact

that the maximum basin amplifications in the regular wave model tests are found around wave peak periods of 150 and 260 secs, could establish the existence of some kind of resonant effect, around these periods, when irregular waves are used in the model.

It should be remarked that the spectral analysis carried out in the model was based on 512 points, which only allow to know the range of wave energy transference, without clearly distinguishing the peak periods for the long wave. At the present, a more detailed wave spectral analysis (4096 ponts) is being performed at the CEPYC (Iribarren et al) to distinguish the spectral peaks much better.

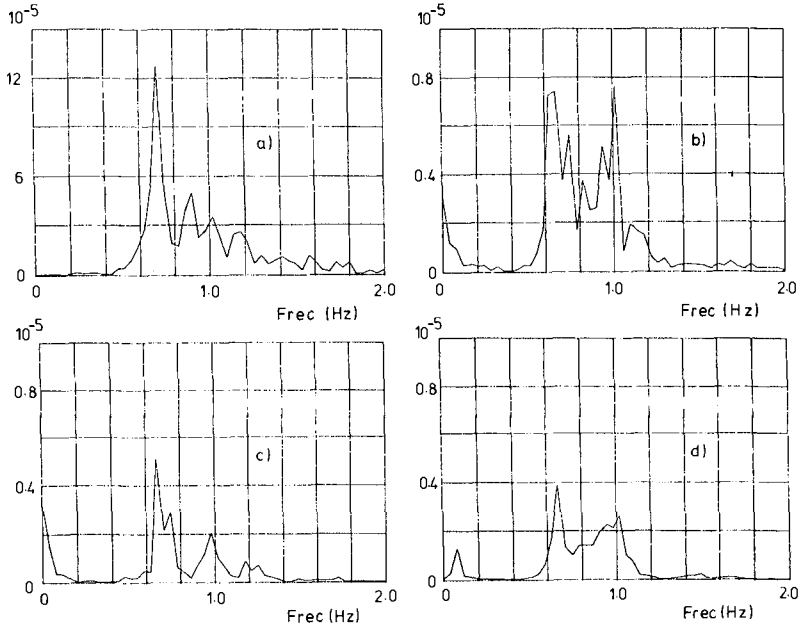

Fig. 8.- Example of Wave Energy Spectra Obtained in the Physical Model:
a) Outside Waves (P_1); b) Same for Santurce Entrance (P_2) ; c) Outer Basin Entrance (P_3); d) Inner Basin Entrance (P_4).(Points shown in Fig.6A; max. frec. 2 Hz).

5.- DISCUSSION

The set-down amplitude has been parametrized by Sand (1982) by means of the transfer function $G_{nn}(D\theta).h$. For the case of deep or shallow water, the following asymptotic expressions for unidirectional waves ($D\theta = 0$) were found, function of the P parameter ($P = SQR(h/g)/T_p$) :

$$P < .15 \quad ---- \quad G_{nn}(D\theta=0).h = (3/8.\pi^2) . P^{-2} . (1/(1+Df/fp))$$
$$P > 3 \quad ---- \quad " \quad .h = 2 . \pi^2 . P^2 . (Df/fp) . (2+(Df/fp))$$

For the case of directional waves ($D\theta \neq 0$) , the solutions were presented in a graphic way.

The considered depth h corresponds to the measurement point of the incident waves. However, this transference function grows when decreasing water depth, in the following way :

$$G_{rm}\ (D\theta = 0).h \quad \alpha \quad (\ 1\ /\ k^{2}\ .\ h^{3}\ )$$

This implies thatset-down will grow with water depth decrease. Thus, an increase in the mean water level will be expected in the recordings. Comparisons between the results obtained from the waverider and those from the Bilbao Port in this zone showed that such a variation could not be detected as far as the entrance of the inner basin, located at 18 m. water depth. Furthermore, the results from the physical model testes seemed to confirm this fact, the peak not appearingin the range of 40-60 secs., up to this point.

The above mentioned findings made possible to estimate the wave set-down amplitude for a water depth of 22 m, considered as a mean value for the outer zone.

As for directional waves, a mean value of Dθ = 27º was obtained, for a directional buoy (wavescan), located outside the harbour (h ≈ 300 m.), during December-87 (Arribas and Morón, 1988). A value of Dθ = 20º was adopted, corresponding to the tabulated results showed below. The number of waves in a group may be of 5, as considered by Sand, whose value is in the order of the data (item 3). The wave peak periods, under storm conditions, are within the range of 12 and 20 secs., and the P parameter results : .075 < P < .125 , which corresponds to shallow water conditions.

In order to evaluate the set-down amplitude, $A_{rr} = A_{rm}$ was taken which is equivalent to consider two wave amplitudes very close in frecuency, and thus creating a wave energy train equivalent to the original one, having H_{ms} as a significant wave height. Under these conditions, the values obtained for β/H_{ms}^{2} were as follows :

$$\beta = (\ G_{rm}\ (D\theta=0)\ .\ h)\ *\ Hs^{2}\ /\ 16\ h$$

Dθ	Tp=12	Tp=15	Tp=18	Tp=20
0	.0068	.0106	.0153	.0189
20	.0018	.0020	.0022	.0023
P =	.124	.0998	.083	.075

When these values are referred to real values measured in prototype, the results are as follows :

Date		O.S.W.		β		I.L.W.	
Day	/ Time	Hs	Tp	Dθ=0	Dθ=20	Hs(ILW)	Posición
4.9.87	14	2.57	15.0	.07	.013	.016	4b
10.2.88	11	5.81	14.4	.36	.068	.72	4b
25.3.86	3	6.5	15.0	.44	.080	.12	4a

For small wave heights, H_{ms}(OSW) <1.5 m., in position 4a, wave heights in the range of 0.02 were detected almost continuosly, probably corresponding to the case of a free wave generated by the change in water depth at the harbour entrance. Taking this fact into account, the measured wave heights ILW obtained in position 4b are higher than the calculated set-down, and they must correspond to resonant amplifications induced by the set-down. Wave spectra obtained from the physical model show similar tendencies.

If wave spectra at the entrance of Basins 1 and 2 are compared to the wave spectrum considered as "exciter" (Figs. 6a and 8), the peak corresponding to the long wave appears in the range of 50-250 secs., growing towards the end of the basins.

Therefore, it seems possible to confirm the hypothesis that the set-down is amplified by resonant oscillations, although not in its principal mode, but in the subharmonic ones whose periods are close to the natural periods of the basins studied . That is way the peak period of waves at the end of the basins grows simultaneously with the decrease of the total energy, acting the set-down, because of its second order characteristics, as an energy transfer .

6.- CONCLUSIONS

1) The mechanism of set-down comes out as a wave packet whose frecuency distribution corresponds approximately with that adopted by the SIWEH spectrum outside the harbour, being able to generate resonancies according to its frecuency band.

2) Set-down generates an energy transfer from the usual wave frecuencies towards lower frecuencies, producing an increase of the peak period, altogether with a general decrease of the total energy. In the present case, a decrease around 7-9% for T_p, coincident with a decrease for H_m of 90-92%. has been detected

3) Calculations of statistical parameters carried out from the SIWEH have only permitted to obtain an imprecise idea of the number of waves in a group, as well as of the main set-down period, from the $T(z,s)$ and T_c parameters, respectively.

4) SIWEH spectrum shows approximately the existence of several waves, corresponding with the set-down subharmonics. Furthermore, SIWEH spectra peaks coincide with bands of accused energy detected for Long Wave spectra analyzed at the end of the basins, thus being the probable origin of resonances depending on the natural periods of the basins.

5) The resonant modes detected in the physical model, using regular waves, show in a semiquantitative way, the existence of amplitudes of a certain importance, for the horizontal water displacements in the outer harbour basin whereas the inner basin is less susceptible to resonances.

6) The model tests with regular waves have allowed to study the behaviour of the outer and inner harbour basins, analizing the response of those basins with respect to a large range of wave exciting periods. In the neighbourhood of the natural modes of oscillation, the amplification grows rapidly and resonant effects may appear , even with energies not being exactly in the natural frecuency of oscillation. The non strictly regular geometry of the basins fosters the lack of a well determined frecuency of oscillation but a relatively narrow frecuency band where resonant effects could be developed under severe storm conditions.

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