CHAPTER 141

EVALUATION OF DESIGN WAVES ALONG THE COAST AND AT THE INLETS OF THE VENICE LAGOON

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Abstract

The prevention of flooding inside the Venice lagoon requires a system to disconnect the North Adriatic sea and the lagoon hydraulically in order to control water level. This paper describe the method followed to define design wave conditions to support the design of the new storm surge barriers. The derivation of design waves was not straightforward because of the presence of an extended continental platform and irregular geografic boundaries.

1. Introduction

The prevention of flooding inside the Venice lagoon (Fig.2) requires a system to disconnect the North Adriatic sea and the lagoon hydraulically to control water level. One of the most feasible ways to achieve this is to use a system of moveable storm surge barriers (Varisco 1992).

Definition of the wave and water level conditions is required for the associated design activities. This paper describes the work carried out in order to define the design waves for normal and extreme conditions. The emphasis is on the statistical methodology to derive the extreme conditions and on the appropriate modelling approach for the simulation of the wave behaviour close to the inlets. A number of numerical models were evaluated to select the appropriate one for the preliminarly and design phases. The derivation of the conditions at the outside boundary of these models is discussed by Hurdle et al.(1993). This paper also discusses the special characteristics of the North Adriatic sea (in particular the extended continental shelf) and the predominant wind conditions. For the purposes of this paper, it is sufficient to know that three wind types are important for the design conditions: the Scirocco wind (from the South East), the Levante wind (from the East) and the Bora wind (a cold wind from East North East).

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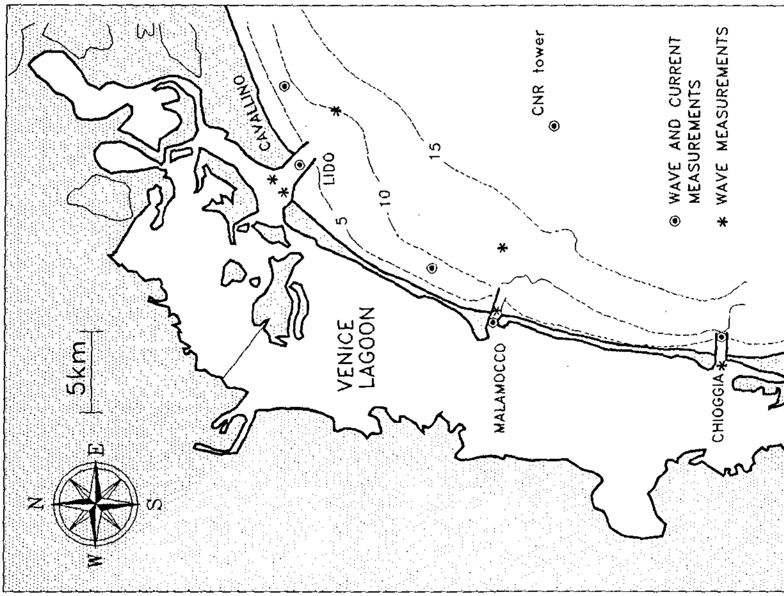

Fig.2– Venice Lagoon

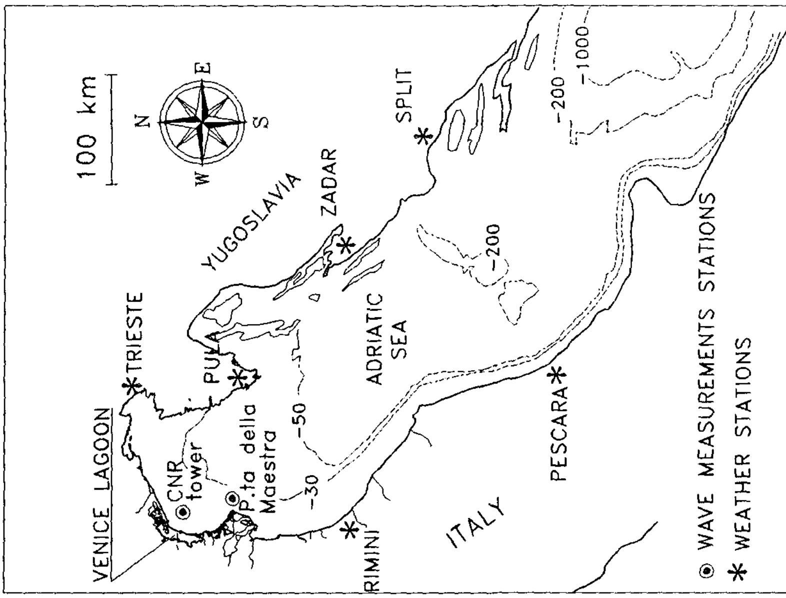

Fig.1– Adriatic Sea.

Even in the preliminary phase, the design of the moveable storm surge barriers required a careful evaluation of the extreme wave conditions in front of the barriers. In fact, initial studies using simple numerical models indicated that a moveable storm surge barrier would not be feasible without the construction of offshore detached breakwaters to reduce the wave penetration. Such structures would have affected the delicate morphological balance of the surrounding coasts. However, the application of a more sophisticated wave model showed that the offshore breakwaters are not necessary; an important result giving both environmental and economical advantages.

2. Methodology to derive extreme design conditions.

Extreme wave conditions are required for the following purposes:

- design of the moveable storm surge barrier (extreme wave conditions, high water levels only, inside inlets);
- design of the associated fixed structures (extreme wave conditions, all water levels, inside inlets).

In principle there are two fundamental ways to obtain extreme wave and water level conditions. These are illustrated in Fig. 3.

In the first method, illustrated by the clockwise route in Fig.3, the input data is the history of meteorological conditions in the area. These are then statistically extrapolated to get a nominal extreme storm (meteorological condition). Wave and flow models are then applied (modelling phase) to predict the extreme wave and water level conditions at the locations of interest. This method has the following drawbacks:

- It is very difficult to define "extreme meteorological conditions". This can be done in a schematised way by obtaining the extreme wind speed in a number of direction classes and assuming stationary and uniform wind conditions.
- It is unlikely that it will be sufficient to model only one condition, since it is not known which combination of extreme conditions gives the most severe results (e.g. if the meteorological conditions are defined by the extreme wind speed in each direction sector, runs will have to be made for several direction sectors);
- The final results depend on the performance of the models used to predict the extreme wave and water level conditions. The models used must therefore be validated for some real cases.

In the second method, (anti-clockwise route in Fig. 3), the basic data is the same set of meteorological conditions. A series of the most severe events is selected and models are used to hindcast the required parameters at the site of interest. These parameters may then be converted to a damage factor of some kind (e.g. significant wave height) which can be statistically extrapolated to obtain the extreme damage. Alternatively, an analysis can be carried out to obtain the joint extreme statistics of the required parameters. This method has the following drawbacks:

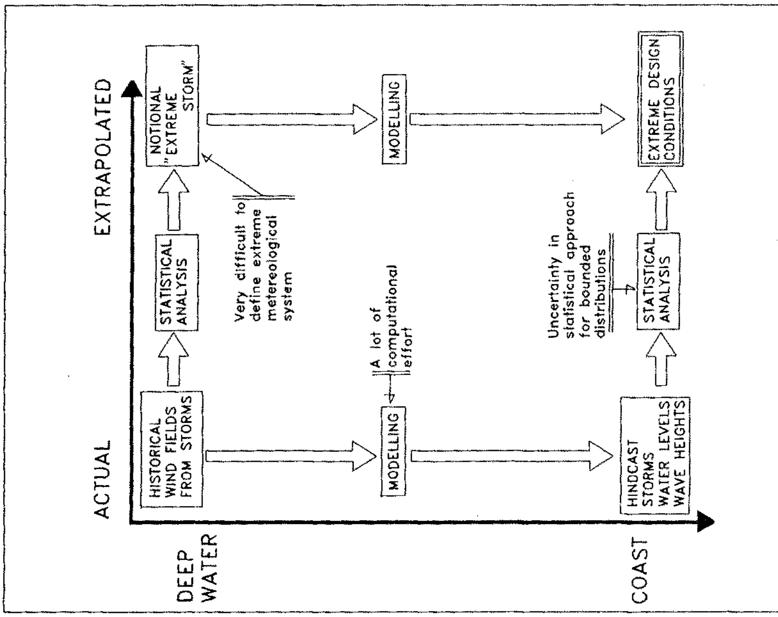

Fig.3 – Alternative approaches to obtain extreme statistics.

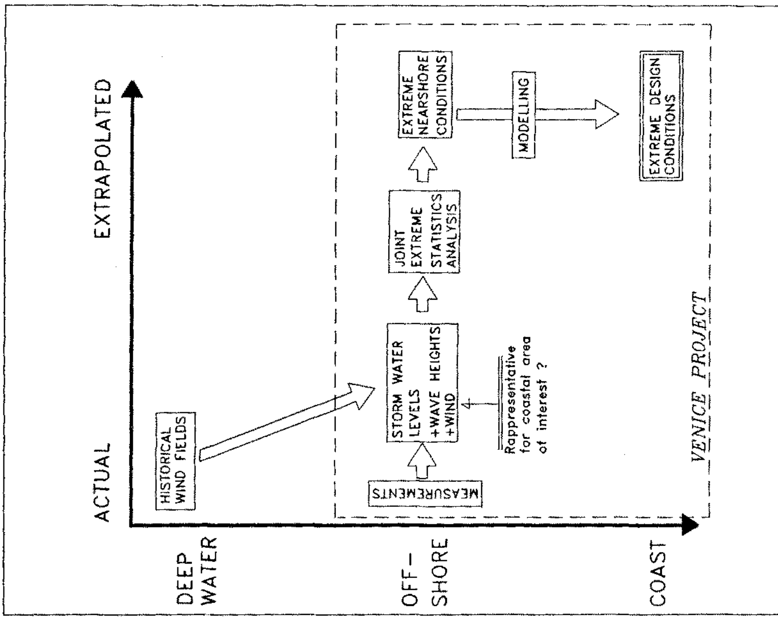

Fig.4 – Hybrid approach to obtain extreme statistics.

- It is difficult to make a restricted and correct selection of the most severe events. For example, if water level and wave height are the parameters of interest, the conditions which give the highest wave height may be very different from those which cause the highest water levels.
- The distribution of parameters at the site of interest is often bounded (e.g. wave height in shallow water). The prediction of the extreme values of such distributions is difficult and often sensitive to errors.

A practical solution to these problems is to use a hybrid approach between the two methods with or without the additional use of measurements of relevant parameters at an intermediate station. Such an approach is illustrated in Fig. 4. In this approach the physical processes are seperated into two phases, between wich the statistical extrapolation is carried out. The phases are:

- A wave generation phase in which depth limitation plays a minor role but in which the wind field is treated as non-stationary and non-uniform in any modelling. Any modelling is large scale and does not have to include accurate representation of the coastal area. Modelling of water levels and currents in this phase is also on a large scale and applies non-uniform non-stationary wind fields.
- A wave propagation phase in which refraction, shoaling and dissipation by bottom friction and by breaking play an important role. However, the area being modelled is sufficiently small to be able to consider wind fields and incident wave conditions to be stationary.

Real storms are modelled in the first phase, thus avoiding any problems of characterising the non-stationary and non-uniform wind fields. Sometimes, this modelling phase can be omitted when a sufficient period of measured values is available. Otherwise, measurements may be used to calibrate the models. The results of the first phase (wave height, period and direction, water levels and wind speeds and direction) are then statistically analysed to get design values which can be applied as stationary boundary conditions for the modelling of the second phase. The application of this method poses some questions about which combinations of extreme values give the most onerous design conditions at each site of interest. In practice the most onerous design scenario is likely to depend on what is being designed (e.g. breakwater, storm surge barrier, refuge harbour) and where it is located. There is therefore no single combination of the design boundary conditions which can be considered to give the design scenario for all purposes.

In the Venice project three design scenarios were considered according to the wind direction in the Venice gulf (Bora, Levante or Scirocco). Each of them has been characterized only by one wave condition according to the wind direction. For each of these scenarios the design wind and wave conditions were taken to be fully dependent. This restricted the number of design scenarios which had to be considered to three (Bora, Levante, Scirocco). The relationship between the extreme water levels and the extreme wave conditions was derived on the basis of a joint probability analysis carried out only for Scirocco/Levante storms. For Bora storms lower levels were considered. Of course, some sensititivity studies were carried out to examine the effect of changes in the boundary conditions for the modelling of the second phase.

The activities carried out to derive the extreme wave conditions at the barriers are shown by Fig. 5. The boundary conditions at the outer boundary of the models of the wave behaviour in the inlets for each scenario (significant wave height H_s, peak period T_p, diectional spreading, and water level h_w) were derived from measuraments and wave modelling in the offshore area is described by Hurdle et al.(1993).

3. Selection of the wave mathematical models.

There is no mathematical model capable of simulating al the relevant physical phenomena over the entire generation and propagation area. Therefore the governing processes were itemized and the area in which they act determined. The area was then divided into sub-area and numerical models selected for each sub-area to model the relevant phenomena to give the degree of accuracy required for each design phase. Relevant physical phenomena and the area on which they act are shown in Table 1.

Although the Table provides a valuable insight into the relevant phenomena, it should be noted that it is generally not possible to account for the phenomena in isolation because of the way they interact. The selected sub-areas are an offshore (OUT) and coastal area (CST) and the three lagoon inlets and the channels leading to them (INL) as it is shown by Fig. 6. In the offshore and coastal area, the wave propagation is dominated by depth refraction, shoaling and external energy effects. In the inshore areas the wave propagation is dominated by refraction, shoaling and diffraction. For extreme waves, wave breaking is also of some importance in these areas.

Apart from the wave dissipation processes, the most interesting non-linear wave aspects are those which give rise to the generation of free long waves from the short wave field. These long waves will not have a significant effect on the short wave propagation but may be of interest in themselves. For example, they may have an onerous effect on the efficency of the storm surge barriers or may excite long waves resonances in the inlets. Such non-linear effects could play a role throughout the area between the CNR tower and the coast.

In all areas, a correct representation of the directional spectrum of the wave field is of importance because of the role that this plays in the wave propagation. A correct transfer of information about the directional spectrum on the boundaries between the areas is also very important.

The criteria applied for the selection of the model for the offshore and coastal area were that the directional spectrum should be properly represented and that refraction, shoaling and external energy effects should be modelled. The wave model applied will be called "spectral wave refraction model" (SRM) (see Hurdle et al.1993).

In the inner area, different models were applied at different design phases. All the applied models accounted for refraction, shoaling and reflection effects while diffraction was accounted for

Property of model	Importance for Venice			Numerical wave model				PM
	OUT	CST	INL	SRM (1)	RDR (1)	MSM (1)	BM (1)	
LINEAR PROPAGATION AND INTERACTION WITH STRUCTURES								
Shoaling	+	+	+	*	*	*	*	*
Depth refraction	+	+	+	*	*	*	*	*
Current refraction	-	-	+	*	* 2	*		*
Diffraction	-	-	+		* 3	*	*	*
Reflection	-	-	+		*	*	*	* 4
Transmission	-	-	-		* 2	*		* 4
NON-LINEAR PROPAGATION								
Long waves from wave groups	-	?	+				*	* 5
long waves from surfbeat	-	?	+					* 5
diffraction	-	-	-				*	*
refraction	-	-	-				*	*
DISSIPATION AND GROWTH								
bottom friction	+	+	+	*	*	*	*	* 4
breaking	+	+	+	*	*	*	?	* 4
generation by wind	+	o	o	*				
DESCRIPTION OF THE WAVE FIELD								
directional spreading of energy	+	+	+	*	*	*	*	* 2
frequency spreading of energy	-	-	6	* 2	* 2	* 2	*	*
AREA TO BE MODELLED								
Area (km x km)	100 x 100	20 x 5	5 x 5	100 x 100	100 x 100	5 x 5	5 x 5	5 x 5
Other limitations								
	n/a	n/a	n/a				7	4 5

LEGEND

Areas:
- OUT – outer area
- CST – coastal area upto depth of 15 m excluding inlets
- INL – area in and around inlets and access channel

Models:
- SRM – spectral refraction model
- RDR – Ray model with diffraction based on analitical sol.
- MSM – mild-slope model
- BM – Boussinesq model
- PM – Physical model in wave basin

Key:
- \+ Important
- \- Not important
- o Limited importance
- * Included in the model
- 1 depth integrated model
- 2 not applied for Venice project
- 3 adaptation for structures diffraction using analytical soln., no bottom diffraction
- 4 at small scales, breaking, bottom friction, reflection and transmission not properly reproduced
- 5 long wave resonance of wave basin?
- 6 spectral form required at storm surge barrier
- 7 only valid in shallow or shallow/intermediate depth water

Tab.1

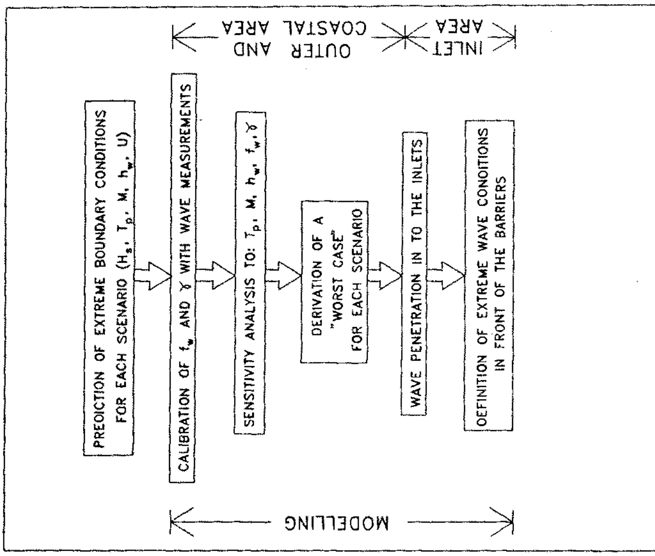

Fig.5 – Activities for the definition of extreme wave conditions.

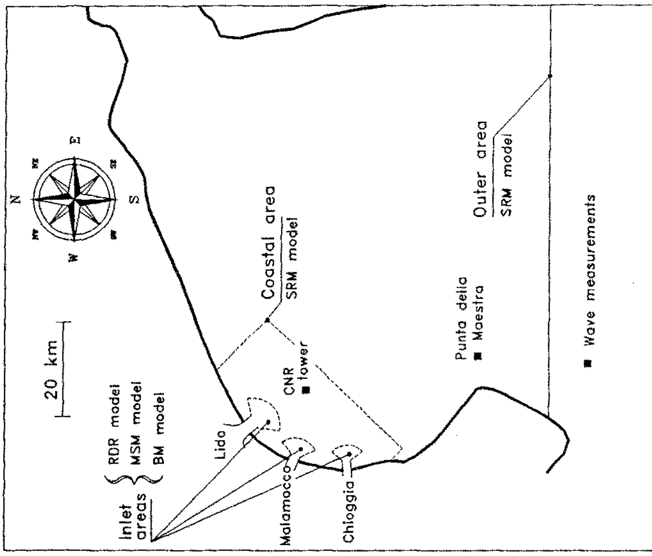

Fig.6 – Division into outher, coastal and inlet areas.

either approximately or exactly. The models were a refraction-diffraction ray model (RDR), a mild-slope model (MSM) and a Boussinesq model (BM). Table 1 shows also the capability of reproducing the physical phenomena for each numerical model. All of the models are depth integrated and the only non linear model is the Boussinesq model.

Some elucidation of the comments in the table about the limitation of physical models is now given. In general, the porosity and roughness of structures are difficult to reproduce at small scales and surface tension effects, which do not play a role at full scale, become increasingly important for waves of small height and lenght. This results in reduced energy transmission and increased reflection by porous structures at model scale. Further it is difficult to distinguish long wave resonances which results from the wave basin from those occurring in reality.

4. Wave penetration into the inlets.

The three inlets which connect the North Adriatic sea to the lagoon (Lido, Malamocco and Chioggia, Fig. 2) are protected by breakwaters of length between 1.5 ÷ 2 km. The bottom topography of the inlets is characterised by the presence of navigational channels maintained by the effect of the tidal current and periodic dredging works. As an example Fig. 7 shows the bottom topography of Malamocco inlet. The new storm surge barriers have been located inside the inlets at 1.5 ÷ 2 km far from the breakwater heads so that they are sheltered from wave activity by the breakwaters.

As mentioned in the introduction, a careful evaluation of the extreme wave conditions at the barriers was required even in preliminarly design phase. This is because the feasibility of a solution using floating barriers is very sensitive to the wave conditions due to the loads acting on their foundations and decrease in their efficency for high incident wave conditions and wave overtopping.

As it is shown in Tab.1, almost all of the wave propagation phenomena become relevant close to and inside the inlets. When the waves approach the navigational channel the concave shape of the bottom causes refraction of waves out of the channel and the concentration of wave energy on the shallow areas bounding the channel. This spreading effect (sometimes known as channel refraction), due to the bottom refraction, is balanced by bottom diffraction which tends to increase the wave energy inside the channel. The concentration of wave energy over the shallows is limited by wave breaking. The tidal current, which increases inside the inlets, influence the wave propagation through a refraction effect. The combined action of waves and current interferes with the floating flap gates during the closing operations of the inlets. During surge events the barriers are subjected to both short and long wave actions. Long waves are associated with wave groups and surf-beat along the beaches located outside the inlets and can excite natural modes of oscillation of the floating flap gates.

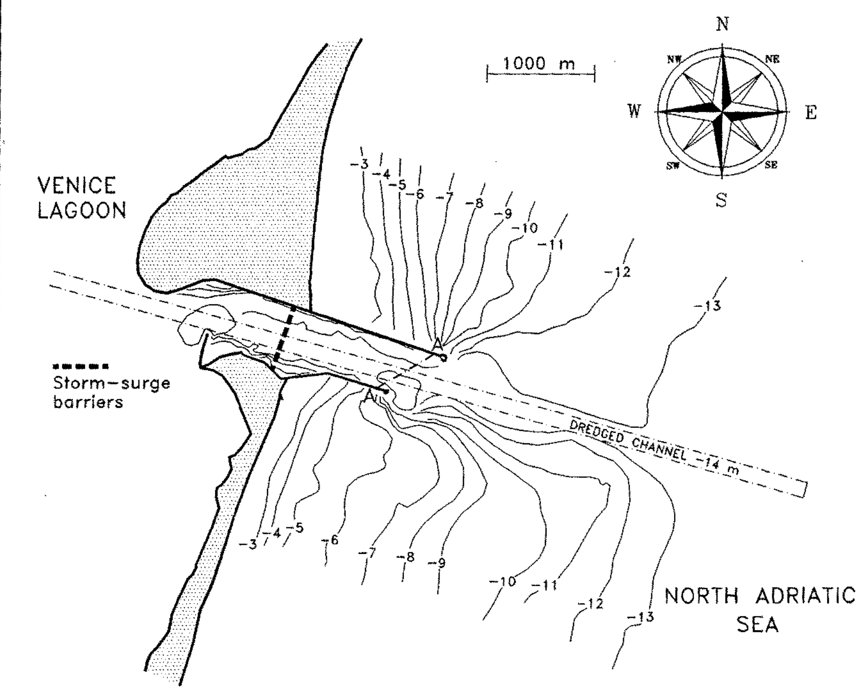

Fig.7 – Topography of Malamocco inlet.

Due to the complexity of the physical phenomena involved, a preliminarly study was carried out in order to analyse the importance of each phenomenon for the wave penetration of the inlets and the capablity of the numerical models to reproduce them.

A first analysis was carried out in order to understand the effects and the importance of frequency and directional spreading of the energy spectrum and of non-linear interactions among wave components. With this purpose a Boussinesq model was applied to the Malamocco inlet for three different wave conditions:

Case 1: long crested monochromatic waves;

Case 2: long crested irregular waves;

Case 3: short crested irregular waves.

All of the mentioned cases were run with the same significant wave height H_s and peak period T_p. The results obtained showed that the wave penetration inside the inlet increases considerably with the inclusion of energy diretional spreading (Case 3). The effect of frequency spreading (Case 2) does not give important differencies with respect to monochromatic waves (Case 1).

It is to be noticed that at the time of the work the available Boussinesq models did not include the effect of wave breaking which is still a research subject. Due to the importance of wave breaking for extreme wave conditions inside and around the inlets, it was decided to study whether linear models, for which the inclusion of wave breaking has proved to be succesful (De Girolamo et al.1988), could be applied. A mild-slope model (MSM) was than applied with the inclusion of directional spreading and compared to the Boussinesq model. The results showed that a proper reproduction of directional spreading was enough to guarantee a correct wave field inside the inlets and that the effect of non-linear interference between wave components was of secondary importance for the purposes of the study.

The reproduction of directional spreading in the MSM was obtained by using the superposition principle for a number of wave direction components. Due to the fact that wave breaking introduces a non-linear condition in the model, this was run using an iterative approach. Fig. 8 shows some results otained for a point located at the site of the storm surge barriers inside the Malamocco inlet. The continuous line shows the obtained amplification coefficients for different offshore directions of incoming unidirectional waves. The spreading effect (channel refraction) due to the concave bathymetry of the inlet increases as the waves approach the navigation channel with a direction close to the inlet axis. This effect causes a strong reduction of wave height at the barriers. The effect of including directional spreading is clearly shown in the Figure by the square points and is stronger for the waves coming along the channel axis for which the wave height can increase by up to three times.

Some applications for the Chioggia inlet including wave breaking using the Batjjes and Janssen (1978) formulation are presented in De Girolamo et al. (1988). Fig. 9 shows an example of the verification of the computation of the wave penetration of the Malamocco inlet during ebb and flood tidal conditions. In this case the model was run simulating current refraction effects (Kostense et al. 1988).

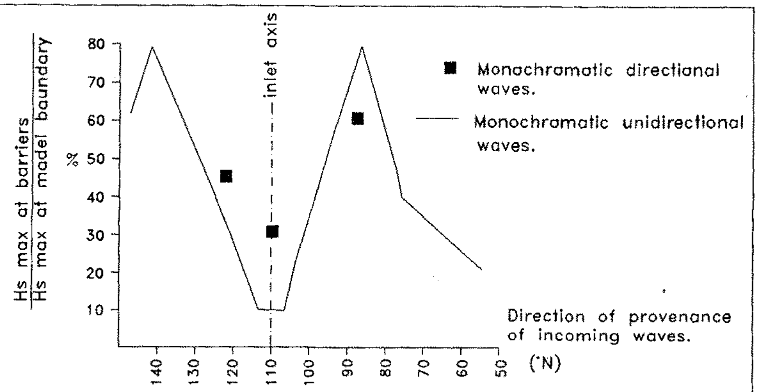

Fig.8 – Influence of directional spreading on wave penetration of the Malamocco inlet (MSM model).

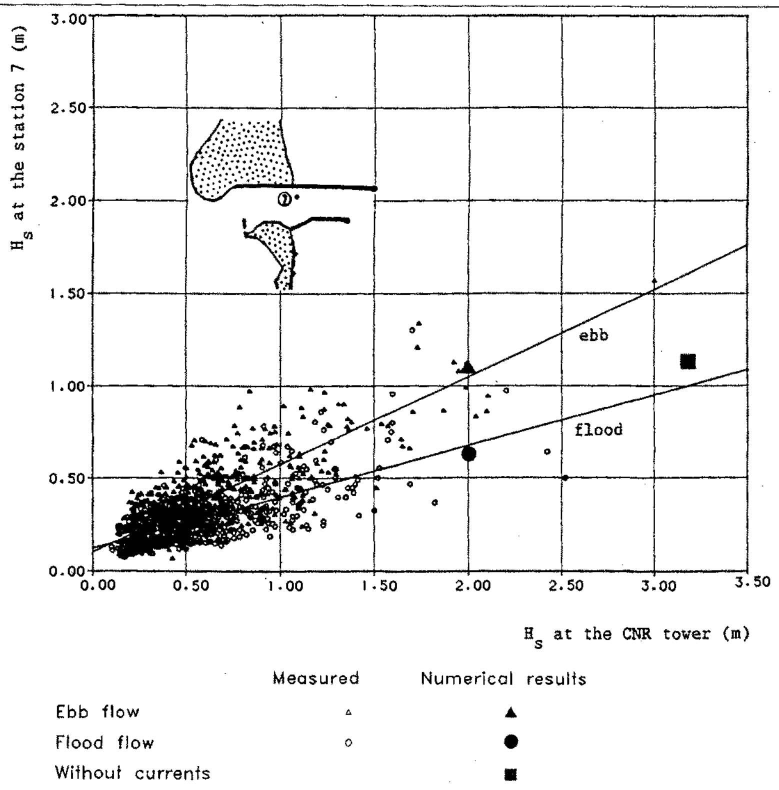

Fig.9 – Comparison between wave measurements and numerical simulations obtained with the mild-slope model (MSM).

The preliminarly design required the study and the comparison of a number of different layouts for each inlet. For this reason it was important to distinguish a simple numerical model which could be used, as an alternative to the MSM, as a pratical tool for such a work.

A very efficient and simple tool was found in a refraction-diffraction ray model (RDR see Tab.1 - Southgate 1985). The model simulates the diffraction effects around obstacles using an analitical approach but neglects bottom diffraction. Further it can be easily run with directional spreading. Even if the model cannot be used in some situations for a correct quantitative analysis (De Girolamo et al. 1989) it can give insight into the wave paths and can be used to compare different layouts. The most important limitation of the model is the neglection of bottom diffraction which in presence of an undersea channel plays an important role in containing the energy spread due to the refraction effects.

Summing up the numerical work was split into two phases using the more suitable model for each of them.

In the first phase the existing situation (before the construction of the new structures) was analysed and various alternative layouts were studied. The simple RDR model was used in order to carry out the large number of required simulations.

For the second phase the more complex models (MSM and BM) were used in order to study the selected layouts for each inlet. The large extent of the inlet areas required up to 150.000 computational grid points for the MSM model. The most important result obtained with the MSM was to show that the construction of new offshore detached breakwaters was not necessary.

For the final design of the structures, physical models in wave basin, reproducing the real topography of the inlets, have been used. The work, which is still being carried out, requires a scale ratio ranging from 1:60 to 1:80 in order to minimize the limitations mentioned at Paragraph 6 for physical models. The maximum modelled area is 11.000 m^2. The models will be used in order to reproduce the effective hydrodynamics of the area including the interference by waves and tidal currents with the floating flap gates, already tested in a three dimensional basin (Varisco 1992) using a constant water depth. The translation waves caused by the closure of the floating flap gates during surge events will also be investigated. Due to the large extent of the modelled area, directional wave spectra will be not reproduced. Consequentely the results obtained using uni-directional waves will be analysed and interpreted with the support of the results for short crested waves obtained using numerical models.

5. Concluding remarks.

The definition of design waves for the Venice project was not straightforward. Diverse models (numerical and physical) have been used to derive the design waves. Simple models were valuable in the feasibility phase and sophisticated models in later phases.

Because of the diverse limitations of both physical and numerical models it was necessary to distinguish three distinct areas where different physical phenomena are dominant: the outer area, the coastal area and the area in and around the inlets.

In the inlet areas directional spreading has an important influence on the wave penetration of the inlets while frequency spreading is less important.

The ebb tidal current, with the barriers open, increases the wave height for normal conditions while the height of extreme waves is limited by wave breaking.

Refraction of uni-directional waves propagating parallel to the access channels leading to the inlets gives a strong reduction in the wave height. The effect of bottom diffraction and directional spreading reduce this effect. The mentioned effects and wave dissipation by breaking limit energy concentartion inside the inlets which can take place for other incoming wave directions.

In spite of the very large width of the inlet entrances (ranging from 460 m to 900 m) the significant wave height, H_s, in front of the barriers does not excede 3÷3.7 m for the 1000 year return period. The three dimensional wave basins simulations showed a satisfactory behaviour of the floating flap gates under these wave conditions.

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