CHAPTER 116

LABORATORY MEASUREMENT OF OBLIQUE IRREGULAR WAVE REFLECTION ON RUBBLE-MOUND BREAKWATERS

Charles TEISSON [1] and Michel BENOIT [2]

Abstract

The present work aims to improve our knowledge of reflection coefficient of waves on a breakwater through a programme of laboratory tests. The experiments are conducted on a linear rubble-mound breakwater under random long-crested wave conditions. The wave signals are recorded through an array of 8 wave probes. Three wave reflection analysis approaches are applied and compared on the laboratory recorded data : Least-Squares Methods, Directional Analysis Methods, Modified Directional Analysis Methods. These methods are briefly presented, their assumptions are highlighted and their characteristics are discussed on numerical tests. The Directional Analysis Methods appear to be unable to properly model the superimposition of incident and reflected wave fields. When applied to laboratory experiments, the Least-Squares Methods and the Modified Directional Methods show concordant results, but nevertheless exhibit some differences. The effect of oblique incidence on reflection coefficient is then tentatively analysed.

1. INTRODUCTION

The reflection of waves on a marine or coastal structure is a rather complicated physical process to analyse, depending both from hydrodynamical conditions (wave steepness, wave period, wave obliquity,...) and characteristics of the structure (type of breakwater, slope of the reflective face, permeabilities of the various layers,...). The wave field in front of the reflective structure results from the superimposition of incident an reflected wave field and one has to use special analysis techniques in order to achieve the decomposition. The scope of the present work is to compare various such reflection analysis techniques on laboratory data.

In order to study the reflection coefficient of waves on a linear rubble-mound breakwater, a programme of laboratory tests in a long-crested random wave basin has been performed at Laboratoire National d'Hydraulique (LNH). These tests aimed to study the effects of the three following parameters on the reflection process : wave steepness, wave obliquity and mound slope. In order to determine the reflection coefficient of waves on the breakwater two problems have to be successively addressed and are briefly summarized hereafter.

1 Head of Maritime Group
2 Research Engineer — Maritime Group
EDF - Laboratoire National d'Hydraulique, 6, quai Watier 78400 CHATOU, FRANCE

a. firstly a wave measurement system must be set up to record simultaneously several wave properties (elevation, pressure, velocities,..) at one or more locations. Such measuring devices may be co-located probes (e.g. Hughes, 1994) or wave probe arrays (e.g. Goda and Suzuki, 1976 ; Isaacson, 1991 ; Bird *et. al.*, 1994). In the present experiments we have only made use of an array of 8 wave gauges, recording the free-surface elevations.
b. secondly a reflection analysis method must be used to proceed to the separation of incident and reflected components and determine the reflection coefficient. This problem has been addressed by several authors both for laboratory and field experiments (e.g. Mansard and Funke, 1980 ; Isobe and Kondo, 1984 ; Hashimoto and Kobune, 1987). There is however up to now no unique approach for the analysis of obliquely incident waves. The core of the present study is thus to compare three different approaches to model and analyse the wave field in front of the structure, namely :
   * Least-Squares Methods (section 2)
   * Directional Analysis Methods (section 3)
   * Modified Directional Analysis Methods (section 4)

   All these methods are applied to the laboratory data (sections 6 and 7) recorded during the experiments described in section 5.

The present experiments have been conducted in the continuation of LNH tests on the effect of wave obliquity on breakwater stability (Galland, 1994).

2. THE LEAST-SQUARES METHOD (LSM)

This type of methods has been initially proposed by Goda and Suzuki (1976) for reflection analysis in a wave flume through two wave probes set up on the axis of the flume. The technique has been improved by Mansard and Funke (1980) for a linear array of three gauges. They provided spacing rules for the gauges and their method is now widely used for reflection analysis in random wave flumes. Recently Isaacson (1991) generalized the method to two-dimensional gauge arrays for basin experiments. Hughes (1994) also used this technique with a co-located gauge for oblique wave reflection measurement.

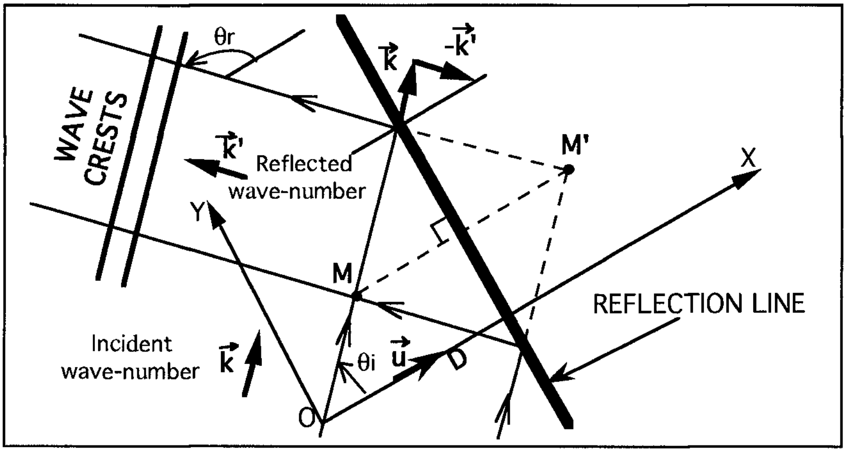


Figure 1 : Definition sketch for reflection analysis.

The main assumptions of this analysis approach are listed hereafter :

—> Both incident and reflected waves are long-crested and linear. The random wave fields are expressed using a linear superposition of numerous long-crested monochromatic components. For instance the incident wave field (referred by subscript i) reads (see figure 1 for definition sketch) :

$$\eta_i(M,t) = \sum_{j=1}^{J} A_j \exp(i.\omega_j.t) \exp\left(i.(-\vec{k_j}.\overrightarrow{OM} + \psi_j)\right)$$

A_j is the amplitude of the j component, ω_j is the cyclic frequency, k_j is the wave-number given by the dispersion relation and ψ_j is the phase, which is generally assumed to be uniformly and randomly distributed over $[0\ ;\ 2\pi]$.

—> Each component is assumed to reflect independently. In the following we thus focus on a particular component and drop the j subscript.

—> Frequency and wave-number remain unchanged during reflection.

—> The incident wave direction is assumed to be known and must be given as input to the method.

—> The incident and reflected wave directions are symmetrical : $\theta_r = \pi - \theta_i$

—> The reflection coefficient is taken to be complex : $R_j = Cr_j.\exp(i.\varphi_j)$

The modulus Cr_j is equal to the ratio of reflected and incident wave amplitudes and φ_j is the phase lag during reflection.

By using these assumptions the resulting contribution of the component reads :

$$\eta(M,t) = A.\exp(i.\omega.t).\Big\{ \exp\left(i.(-\vec{k}.\overrightarrow{OM} + \psi)\right) + Cr.\exp\left(i.(-\vec{k'}.\overrightarrow{OM} + \psi - 2.k.D.\cos(\theta_i) + \varphi)\right)\Big\}$$

Through this approach we have only three unknown quantities at each frequency of analysis : — the incident wave amplitude A.
— the modulus of reflection coefficient Cr.
— the phase lag during reflection φ.

The analysis may thus be carried out from the measurements of only two wave gauges as in the wave flume, but it is preferable to increase the number of gauges (3 or more) and to perform a least-squares resolution of the system in order to improve the stability of results.

In order to study the effect of deviating from some of the above assumptions, several numerical tests have been performed prior to the experiments. For these numerical simulations we used the 3-gauges linear array presented on figure 2.

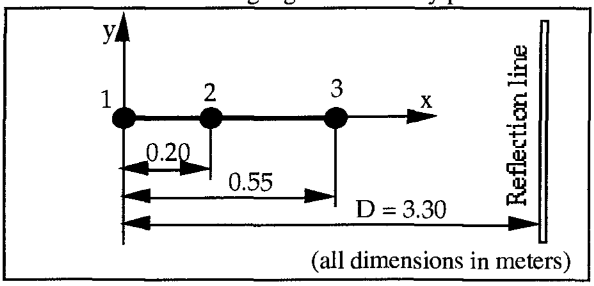


Figure 2 : Linear gauge array used for numerical simulations with LSM.

The numerical simulation characteristics (simulation method, wave period, water depth, time step, record duration,...) are identical to the ones used for the random wave laboratory experiments and presented in section 5.

We only report here some results related to the violation of the assumptions on incident and reflected directions to illustrate the sensitivity of the method :

— effect of wrong estimation of incident wave direction : Several simulations are performed with an actual incident wave direction varying from 0 to 60 degrees. For all these simulations the reflected wave direction is symmetrical of the incident direction. The direction given as input to the analysis method is however taken to be constant at a value of 0 degrees (figure 3-a), 30 degrees (figure 3-b) and 60 degrees (figure 3-c). Examination of results shows that the effect of a difference between actual and assumed incident directions is quite slight if both these directions are close to be normal to the reflection line (figure 3-a). In other words, one can assume an incident direction of 0 degrees for the analysis of wave fields with actual incidence up to 30 degrees : the resulting error is feeble. If the assumed direction is 30 degrees (figure 3-b) the actual incident direction must remain in the range [20° ; 40°] to keep reliable results. On the other hand, figure 3-c shows that almost no estimation error is allowed for the incident direction when working at large angles of incidence. These observations are largely explained by the fact that only the cosine of incident direction is used by the analysis method.

— effect of angular deviation during reflection : Several simulations are performed with an actual incident wave direction of 40 degrees. For all these simulations the incident direction taken for the analysis is equal to this value of 40 degrees (figure 3-d). The reflected wave direction is however no more symmetrical of the incident direction and there is an angular deviation during reflection. Figure 3-d shows the effect in the estimation of reflection coefficient and incident wave height of an angular deviation varying from -10 to +10 degrees. It appears that the sensitivity of estimated parameters is rather slight, at least at this value of incident direction.

These numerical tests (and additional ones, not reported here) lead to the conclusion that the method is quite stable, even if its basic assumptions are slightly violated. The effect of slightly misjudging the incident wave reflection for instance (say ± 5 to 10 degrees) is quite acceptable as long as the actual incident direction is lower than 45 degrees. At large angles of incidence however, great attention should be paid to the precise estimation of incident wave direction. The hypothesis that the incident and reflected wave directions are symmetrical is not very sensitive as long as angular deviations are lower than ± 10 degrees.

3. DIRECTIONAL WAVE ANALYSIS METHODS

In order to invoke less restrictive assumptions than the former approach, one may think to use (multi-)directional wave analysis methods. The LNH has acquired a good experience in this field, by implementing most of the available methods currently used in the world (Benoit, 1993). Very recently, these methods have been applied on laboratory simulated data for various types of recording systems : co-located or "single-point" gauges as well as probe array (Benoit and Teisson, 1994b). These tests have in particular shown that the gauge array has a unique resolving capability when associated with sophisticated methods (such as Maximum Entropy Method or Bayesian Directional Method) for severe bimodal test-cases.

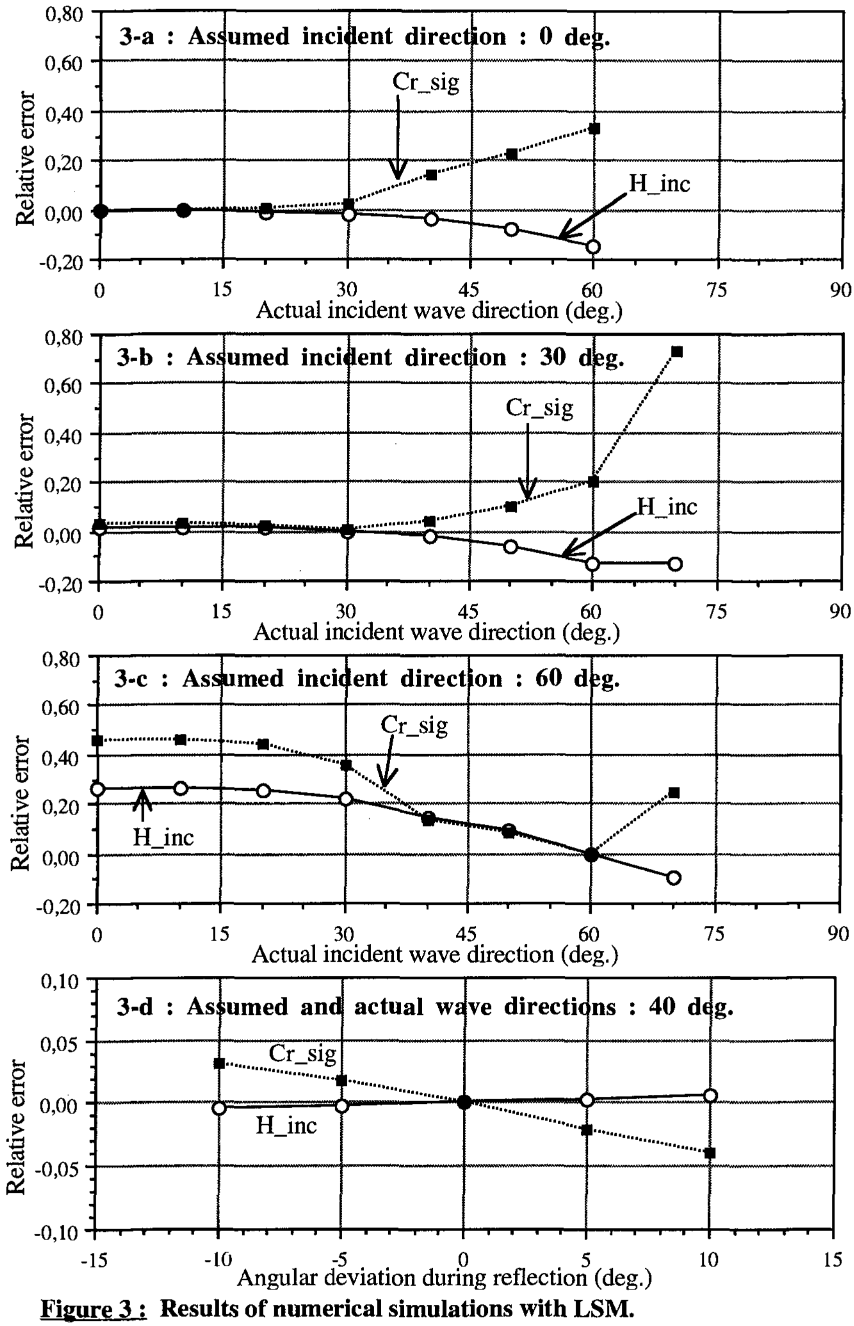


Figure 3 : Results of numerical simulations with LSM.

The theoretical background of the directional wave analysis is based on the following pseudo-integral relationship between the free-surface elevation field $\eta(x,y,t)$ and the directional spectrum $S(f,\theta)$:

$$\eta(x,y,t) = \int_0^{\infty} \int_0^{2\pi} \sqrt{2.S(f,\theta).df.d\theta} \;.\cos\left[2\pi ft - k.(x.\cos\theta + y.\sin\theta) + \varphi\right]$$

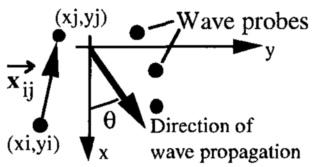
— The directional wave spectrum $S(f,\theta)$ is a function of wave frequency f and direction of propagation θ and is decomposed as : $S(f,\theta) = E(f).D(f,\theta)$

— $E(f)$ is the 1D-variance spectrum and $D(f,\theta)$ is the Directional Spreading Function (DSF) satisfying two important properties :

$$D(f,\theta) \geq 0 \text{ over } [\,0\,,2\pi\,] \quad \text{and} \quad \int_0^{2\pi} D(f,\theta)\,d\theta = 1$$

— φ is the phase, which is here assumed to be uniformly and randomly distributed over $[0\,;2\pi]$.

By using an array of N wave probes, it is possible to record the sea-surface elevation at N different locations simultaneously (see figure 4).



$$\eta(x_1, y_1, t) = \eta_1(t)$$
$$\eta(x_2, y_2, t) = \eta_2(t)$$
$$\vdots$$
$$\eta(x_N, y_N, t) = \eta_N(t)$$

Figure 4 : Definition sketch for probe array configuration.

The computation of the cross-spectra $G_{ij}(f)$ between each couple $[\eta_i(t), \eta_j(t)]$ is performed by spectral analysis. The following relation yields between the measured complex cross-spectra $G_{ij}(f)$ and the unknown directional spectrum $S(f,\theta)$:

$$G_{ij}(f) = C_{ij}(f) - i.Q_{ij}(f) = \int_0^{2\pi} S(f,\theta).\exp(-i.\vec{k}.\vec{x_{ij}})\,d\theta \qquad i = 1,....,N \text{ and } j \geq i$$

The purpose of directional analysis is to solve the above inverse problem by considering the N.(N+1) real equations obtained from the cross-spectra $G_{ij}(f)$ ($j \geq i$). There is no unique way to deal with this awkward inverse problem and plenty of methods have been proposed (e.g. Benoit, 1993 ; Benoit and Teisson, 1994-b). Among them, the Maximum Entropy Method (MEM2) and the Bayesian Directional Method (BDM) are retained for this study as they have shown the highest resolving capabilities. They are only briefly presented hereafter. The reader is invited to consult the given references for more details.

— Maximum Entropy Method - version 2 (MEM2) (e.g. Kobune and Hashimoto, 1986 or Nwogu, 1989). This version is based on the definition of Shannon for the entropy function :

$$\chi = -\int_0^{2\pi} D(f,\theta).\ln(D(f,\theta))\,d\theta$$

This entropy has to be maximized under the constraints given by the cross-spectra. This results in a non-linear system of equations whose solutions are Lagrange multipliers μ_I (I=1, ..., N(N-1)+1) and the estimate of DSF then reads :

$$D(f,\theta) = \exp\left\{ -1 + \sum_{I=1}^{N(N-1)+1} \mu_I . q_I(\theta) \right\} \qquad \begin{aligned} & q_I(\theta) = \cos\left[\vec{k}.\vec{x_{ij}}\right] \quad I = 1,\ldots, N(N-1)/2 \\ & q_I(\theta) = \sin\left[\vec{k}.\vec{x_{ij}}\right] \quad I = N(N-1)/2+1,\ldots, N(N-1) \\ & q_I(\theta) = 1 \quad I = N(N-1)+1 \end{aligned}$$

— Bayesian Directional Method (BDM) : (Hashimoto *et al.*, 1987). No *a priori* assumption is made about the spreading function which is considered as a piecewise-constant function over [0 , 2π]. The unknown values of D(f,θ) on each of the K segments dividing [0 , 2π] are obtained by considering on one side the constraints of the cross-spectra and on the other side additional conditions on the smoothness of D(f,θ). Both these constraints are combined using an "hyper-parameter" whose value may be computed by minimizing the ABIC (Akaike Bayesian Information Criterion). This method is quite difficult to implement, but its main features are to be model independent, data-adaptive and to consider the possibility that the recorded data may be contaminated by some noise.

In order to compute a reflection coefficient at each frequency of analysis with the directional analysis methods, one has first to integrate the computed DSF function over the range of incident directions on one hand and over the range of reflected directions on the other hand and then to compute the ratio of these values.

The application of directional analysis methods in the above described procedure is not fully well-founded in the sense that these methods are based on the assumption that the phases φ are uniformly and randomly distributed over [0 ; 2π], and thus that the directional spectrum S(f,θ) is an homogeneous function. This assumption is however clearly violated close to a reflective structure because of the phase relationship between the incident and reflected components at each frequency. Isobe and Kondo (1984) provide a deeper discussion of this problem. Figure 8 shows an example of recorded 1D-variance spectra E(f) at various gauges of the array used for laboratory experiments. It is clearly noticeable that the sea-state can not be regarded as homogeneous and thus that the directional analysis methods may fail in the estimation of the DSF. Both MEM2 and BDM will however be tentatively considered when analysing laboratory data.

4. MODIFIED DIRECTIONAL WAVE ANALYSIS METHODS

In order to take into account the above remark on the phase relationship between incident and reflected components, Isobe and Kondo (1984) proposed to limit the determination of the directional spectrum to the range [0 , π] and to modify the basic expression of the wave field in the following way :

$$\eta(x,y,t) = \int_0^\infty \int_0^\pi \sqrt{2.S(f,\theta).df.d\theta} \; . \left\{ \cos\left[2\pi ft - k.(x.\cos\theta+y.\sin\theta) + \varphi\right] \right.$$
$$\left. + \, r(f,\theta).\cos\left[2\pi ft - k.(x.\cos\theta-y.\sin\theta) + \varphi\right] \right\}$$

In this expression the directional spectrum is an incident directional spectrum only, defined on [0 , π] by using the definition sketch of figure 5. The directional reflection coefficient r(f,θ) is an additional unknown, also defined on [0 ; π]. The main other assumptions of the above relationship are the following ones :

— the phase φ is assumed to be uniformly and randomly distributed over [0 ; 2π] for the incident spectrum only.
— the incident and reflected directions at each frequency are taken to symmetrical, as for the LSM methods.
— the phase lag during reflection is assumed to be negligible.

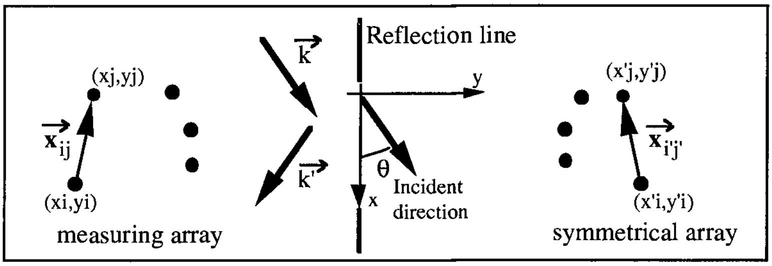


Figure 5 : Definition sketch for directional wave reflection.

By using the above expression and the definition sketch of figure 5, the inverse problem to be solved now reads :

$$G_{ij}(f) = \int_0^{\pi} S(f,\theta).\Big\{\exp(-i.\vec{k}.\vec{x_{ij}}) + r^2(f,\theta).\exp(-i.\vec{k}.\vec{x_{i'j'}}) + r(f,\theta).\big[\exp(-i.\vec{k}.\vec{x_{i'j}}) + \exp(-i.\vec{k}.\vec{x_{ij'}})\big]\Big\}\, d\theta \qquad i = 1,....,N \text{ and } j \geq i$$

In order to solve this problem, two methods have been implemented at LNH and validated on numerical simulations :

— Modified Maximum Likelihood Method (Isobe and Kondo, 1984)
— Modified Bayesian Directional Method (Hashimoto and Kobune, 1987)

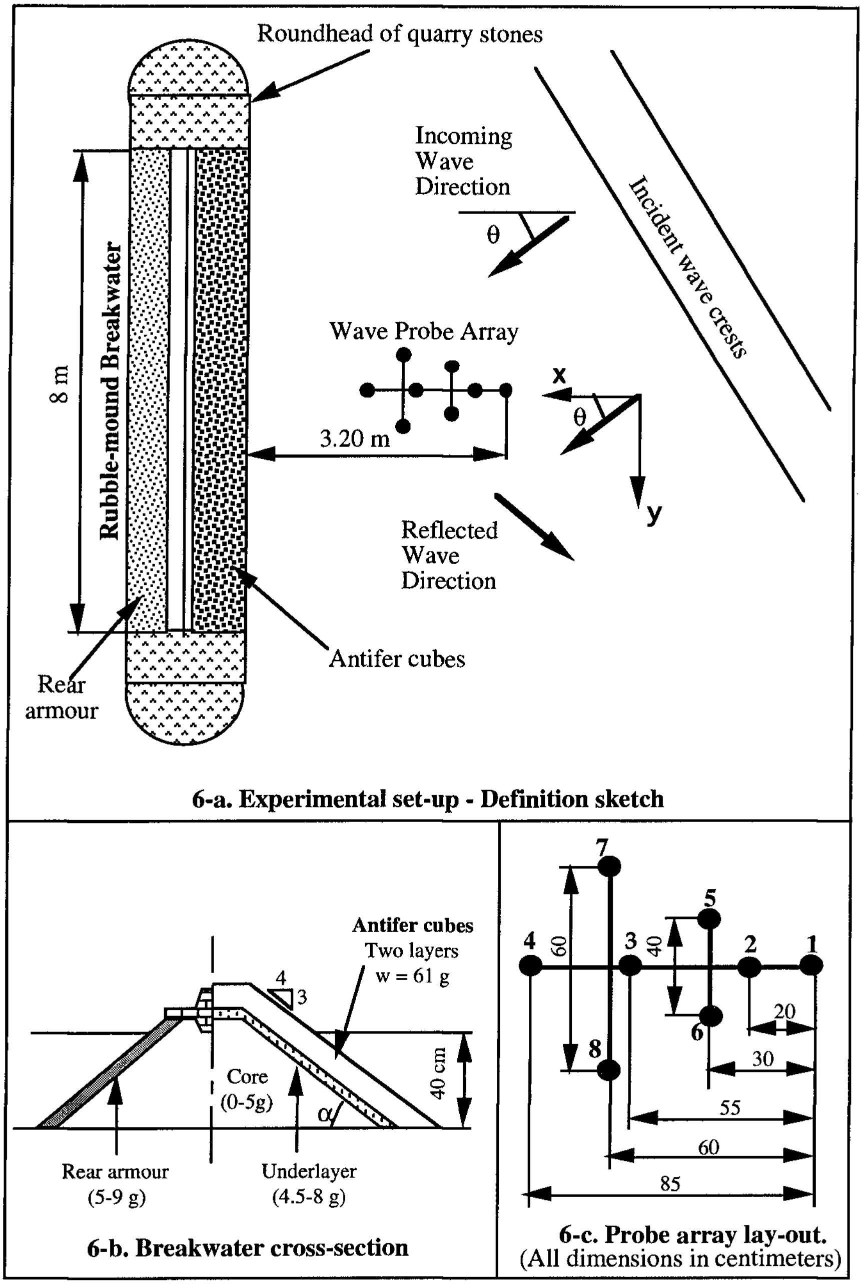
Numerical tests have shown that the MBDM is more powerful than MMLM, but it is also more difficult to implement and to operate (tuning, stability,...). Moreover both these methods assume that the distance from the gauge array to the reflection line is known, which is not always easy to insure (in particular in the case of a permeable slope). In this case, additional developments, such as the ones reported par Bird *et. al.* (1994), would be necessary.

5. EXPERIMENTAL LAY-OUT AND TEST CONDITIONS

We only report here for clarity a brief description of experimental conditions and test parameters (see Teisson and Benoit (1994-a) for more details).

— Wave tank and wavemaker :

The experiments are performed in a semi-circular wave tank equipped with a 17 m long flap-type wavemaker. The wavemaker is able to rotate around the center of the breakwater in a range of [-90°;+90°] (see figure 6-a). It is computer monitored in order to produce regular or random waves according to a given energy spectrum. All tests have been conducted with a constant water depth of 0.40 m.



6-a. Experimental set-up - Definition sketch

6-b. Breakwater cross-section

6-c. Probe array lay-out. (All dimensions in centimeters)

Figure 6 : **General description of experimental conditions.**

— Breakwater description :

The breakwater is a 8 m long linear breakwater armoured with cubic blocs and terminated at each side by roundheads of quarry stones. The blocs are grooved Antifer-type cubes, laid on two layers (weight : 61 g ; density : 2.4). The core and filter-layers are reproduced following scaling rules used for this type of breakwater. The breakwater is designed to face without any damage all the test conditions of this study. In addition, the breakwater is almost never overtopped, so that no energy loss should occur through transmission by overtopping. An example of cross-section is presented on figure 6-b. In the present study we only report results of the 3/4 mound slope, but two other slope values have been tested (2/3 and 1/2) in order to study the effect of mound slope on wave reflection (Teisson and Benoit, 1994-a).

— Simulated wave characteristics :

During the various tests of this study a JONSWAP-type spectrum is used, with a peak enhancement factor of 3.3. Random waves sequences composed of about 1000 waves are generated. Five tests are considered with the following characteristics :

* The peak period used for the five tests is Tp=1.3 s. The corresponding wave-lengths are : $L_p = 2.17$ m for the water depth of 0.40 m.
  $L_{0p} = 2.64$ m for infinite water depth.
* The significant wave height used for the five tests is H_s=0.06 m. The corresponding value of steepness, defined as $s_{0p} = H_s/L_{0p}$, is 2.3 % and The surf-similarity parameter, defined as $Ir_p = \tan\alpha / \sqrt{s_{0p}}$, is equal to 5.
* The incident wave direction is changed from one test to another and takes the values : 0°, 15°, 30°, 45° and 60° successively.

— Wave probe arrangement and sampling characteristics:

An array of 8 resistive-type wave probes is used for each experiment. The probes lay-out is reported on figure 6-c. Several different probes combinations may be extracted from the whole array. The time series of free-surface elevation are recorded simultaneously with a sampling rate of 12.5 Hz and a duration of 819.2 s.

6. DETAILED ANALYSIS OF A PARTICULAR TEST (INCIDENT DIRECTION : 45 °)

In this section, the application of the various proposed reflection analysis methods on a particular test corresponding to an incident direction of 45° is presented and discussed in order to highlight the characteristics of the methods. Figure 7 shows both the incident spectrum and the significant reflection coefficient analysed by the various methods on this particular test.

— Least-Squares Methods (LSM) — figure 7-a :

Figure 7-a illustrates the results obtained with LSM by using on one hand only 3 wave probes (probes 1, 2 and 3) and on the other hand all the 8 probes of the array.

It is first noticeable that there is no great difference in the estimated incident spectra and reflection coefficients between the 3-probes array and the 8-probes array. Only at higher frequencies, the reflection coefficient computed from the 3-probes array appears to be somewhat higher than the one computed from the 8-probes array. In fact the 3-probes array is mainly designed for the peak frequency region of the spectrum and it is quite normal that its efficiency becomes somewhat lower as one moves away from this region. In addition, the reflection coefficient obtained from the 8-probes array is a little bit smoother than the one obtained from the 3-probes array, what may also indicate some more physical reliability. An important comment is thus that there is no need to use complex measuring devices

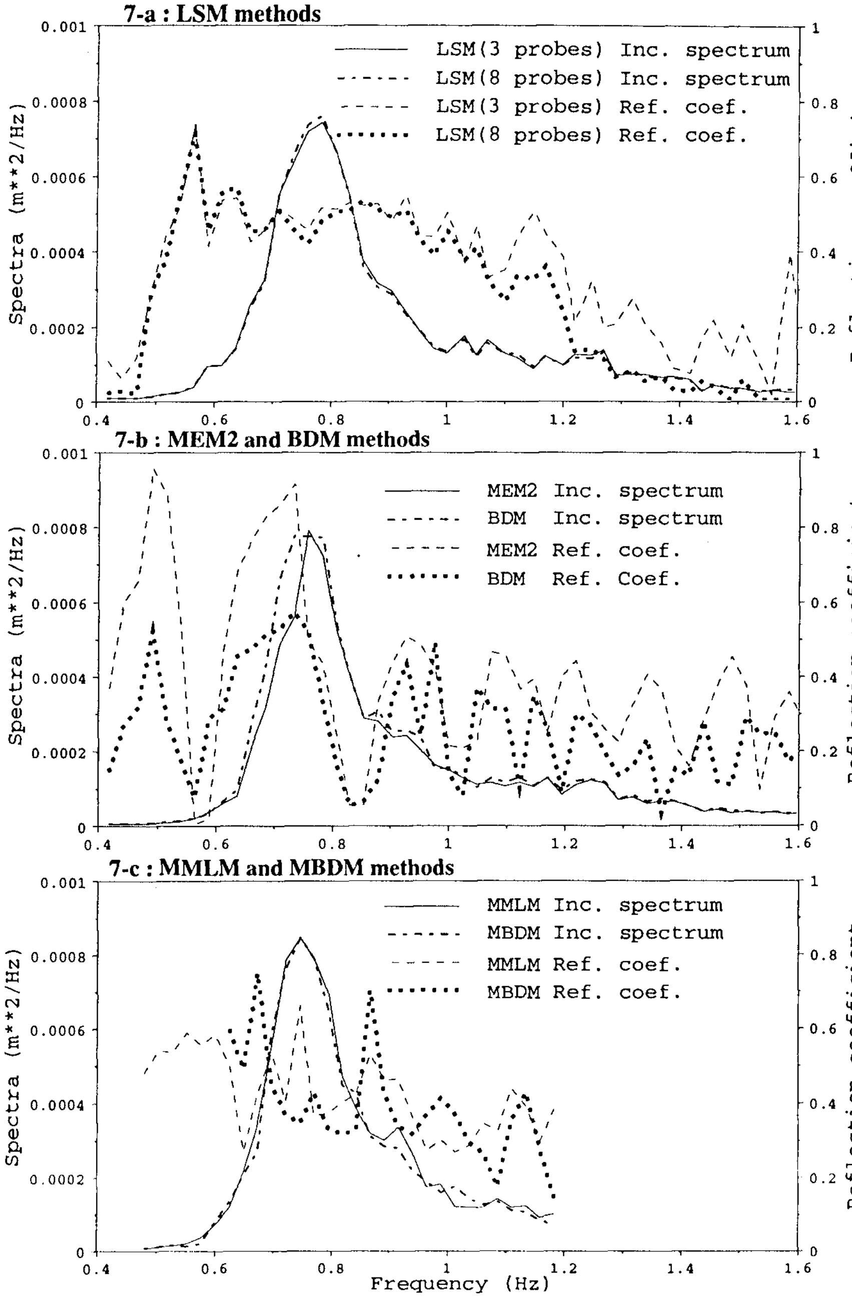


Figure 7 : Reflection analysis on a particular laboratory experiment (direction 45 deg).

with a lot of gauges for the LSM method and that stable estimates may be obtained from 3 probes. The explanation is clearly related to the fact that there are only few unknown parameters by using LSM, as discussed in section 2. On the other hand an important drawback of this method is the rather strong assumptions it requires in order to set this quite simple problem.

The value of the reflection coefficient is quite stable in the peak frequency region (between 45 and 50 %). This value seems in agreement with results of previous experiments performed in wave flumes (e.g. Seelig, 1983 ; Allsop and Hettiarachchi, 1988).

— Directional analysis methods (figure 7-b) :

The incident spectra obtained by MEM2 and BDM (figure 7-b) are in good agreement between each other and also compare quite well to the one obtained with LSM. Major discrepancies however appear when considering the reflection coefficients. Compared to the LSM estimates, the reflection coefficients computed both from MEM2 and BDM exhibit strong variations with frequency. These variations are quite similar for MEM2 and BDM estimates, except that their amplitudes are higher for the MEM2 method. Even if the mean value seems to keep a physical sense, the frequency dependency is definitely meaningless. This spurious behaviour of reflection coefficient is clearly related to the main shortcoming of this analysis approach that does not take into account the phase relationship between incident and reflected components, as discussed in section 3.

To illustrate that point, figure 8 shows the 1D-variance spectra recorded by various probes of the measuring array (see figure 6-c for the array geometry). It is clearly noticeable that the hypothesis of spatial homogeneity of energy is no more applicable and thus the directional analysis methods in their standard form do not seem to offer an obvious modelling approach for that kind of problems where reflection is quite important.

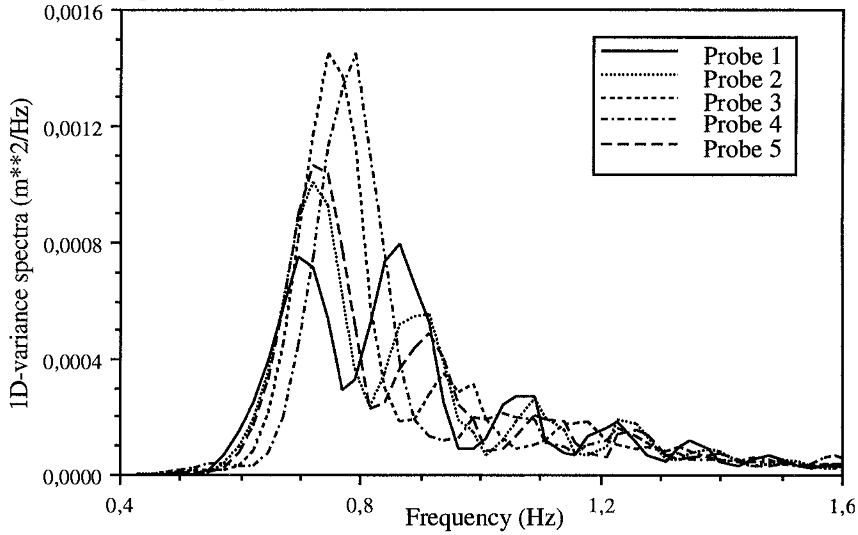


Figure 8 : 1D-variance spectra recorded at various gauges (direction 45°).

— Modified directional analysis methods (figure 7-c) :

The incident spectra obtained both from MMLM and MBDM are quite similar with each other and also compare quite well with the ones obtained from the previous methods. The reflection coefficients computed both from MMLM and MBDM show some oscillating behaviour, but clearly not as much as for the previous standard directional analysis methods. Their mean values are quite concordant, but appear to be a little bit lower than the ones obtained from the LSM methods (about 40 % here versus 45 % for LSM methods).

Even if they exhibit some deviation in absolute value of reflection coefficient, these methods seem to give converging results with the LSM methods. It must however be emphasized that the results obtained with the modified directional analysis methods might undoubtedly be improved by additional tests and developments. First of all, there are still work to be done on numerics (in particular with MBDM) in order to insure a more stable convergence towards the solution. Secondly, the effect of misjudging the distance from the array of gauges to the reflection line should received some attention (through numerical sensitivity tests for instance). It would be worthwhile to consider this distance as an additional unknown parameter of the problem. Finally, but this remark also holds for the standard directional methods, one may discuss the fact that we tried to apply directional approaches (and assume a continuous directional distribution of energy) to analyse long-crested waves (whose energy should be concentrated over one direction). This latter point could also be studied by additional numerical tests.

7. ANALYSIS OF A SERIES OF TESTS — EFFECT OF INCOMING DIRECTION

In this section, the results of the five tests described in section 5 are presented for the various analysis methods. We recall that only the incident direction changes from one test to another, in the range [0 ; 60 deg]. The reflection coefficients computed by all the methods are plotted as function of frequency on figure 9.

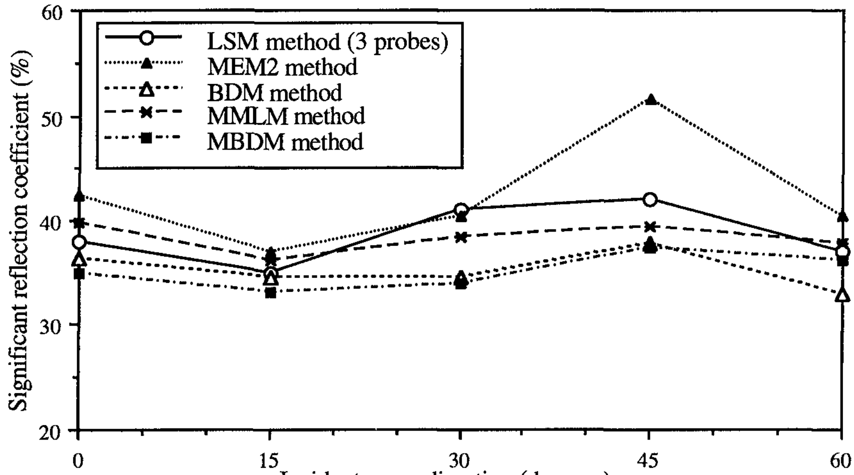


Figure 9 : Effect on incident wave direction on reflection coefficient. (Laboratory tests — Mound slope 3/4 — Wave steepness 2.3 %)

All methods indicate quite the same variations of reflection coefficient with incident wave direction, even if the range of variation of the reflection coefficient is quite feeble. Starting from normal incidence, the reflection coefficient decreases to become minimum at an incidence of about 15 degrees and then increases again to become maximum at an incidence of 45 degrees. For most of methods, the maximum value at 45 degrees is greater than the value obtained at normal incidence. For the incidence of 60 degrees, the reflection coefficient starts decreasing, but the results obtained at such large incidence have to be handle carefully because of the possible occurrence of Mach reflection which is not taken into account in the present analysis methods. This typical behaviour has been observed on the other tests, performed at different values of wave steepness and different mound slopes (Teisson and Benoit, 1994-a). Recent experiments performed by Juhl and Sloth (1994) in order to examine the effect of incoming direction on the amount of overtopping seem to confirm this trend, as the amount of overtopping appears to be maximum for an incidence of about 10 degrees.

8. CONCLUSIONS - FUTURE WORK

The main comments arising from this study are expressed hereafter :

— the Least-Squares Methods (LSM) seem to produce reliable results. This modelling approach requires rather strong assumptions, but it has been shown through numerical tests that this method is quite stable in its results even if one slightly departs from its assumptions.

— these Least-Squares Methods are quite easy to implement and to run. Furthermore, as there are only few unknown parameters in the problem, there is no need to use sophisticated arrays for wave measurement. A linear array of three wave probes or a co-located gauge recording 3 wave signals at the same location (Hughes, 1994) is sufficient for the analysis.

— the directional analysis methods MEM2 (Maximum Entropy Method - version 2) and BDM (Bayesian Directional Method) are not advised for this kind of problem where reflection is important. The relationship that exists between incident and reflected components violates the basic assumption of random phases needed by the methods and results in spurious variations of reflection coefficient with frequency. The mean value of reflection coefficient seems however to keep some physical sense.

— the modified directional analysis methods MMLM (Modified Maximum Likelihood Method) and MBDM (Modified Bayesian Directional Method) take into account the above mentioned phase relationship. Although they assume a continuous directional distribution of energy, these methods have been applied to the present tests performed with long-crested waves. The results seem concordant with the ones obtained from LSM methods, but these methods still need some developments to be fully efficient.

Based on these experiments, the LSM approach appears to be the obvious operational solution for laboratory experiments. The tests of the whole programme have been analysed with this method (Teisson and Benoit, 1994-a) and a typical variation of reflection coefficient with incoming direction has been highlighted. Future research interests will address the optimization of Modified Directional Analysis Methods, in order to study the sensitivity of the distance from the gauge array to the reflection line and possibly to incorporate this distance as an additional unknown parameter to the problem.

9. ACKNOWLEDGEMENTS

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