CHAPTER 93

EVALUATION OF INCIDENT WAVE ENERGY IN FLUME TESTS

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ABSTRACT

A two dimensional model study, carried out for a structure in a flume using irregular waves, presents the problem of determining the relationship between the total incident wave energy attacking the structure and its response to that attack (displacements, forces, etc.) in various sea states. The total incident wave energy can be evaluated indirectly only, because the wave energy measured in the flume contains an extent of residual wave energy in addition to that generated by the wave machine. This residual energy consists of the re-reflected wave energy from the paddle of the wave machine, assuming the existence of quasi-stationary wave conditions in the flume. A method originally presented by Gravesen et al. (1974), was applied in this study to evaluate the total incident wave energy. In view of the results obtained by this method, a physically more sound refinement is proposed for the evaluation of the total incident wave energy (and characteristic wave height). Results of model tests were analyzed by the CAMERI refinement and compared with the Gravesen method and with a cross-spectral least squares method, separating incident and reflected wave spectra from wave spectra measured in the flume. Good agreement was found between the results obtained employing the CAMERI refinement and the cross-spectral least squares method. Advantages and drawbacks of these methods are indicated.

INTRODUCTION

The study of wave effects on structures in flumes using irregular waves, for example two dimensional breakwater stabilitiy studies, requires the determination of the incident wave energy in order to relate resulting wave effects (forces, displacements, overtopping, etc.) to the waves and by them to their probability of encounter.

Assuming quasi-stationary wave conditions in the wave flume, the incident wave energy (and the characteristic wave height) can be evaluated indirectly only, because the waves generated by the wave machine are partially reflected by the structure tested, then re-ref-

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lected by the paddle of the wave machine back towards the structure and so on. Thus, a residual incident wave energy is added to the incident wave energy originally generated, resulting in a new total incident wave energy (and characteristic wave height).

Nowadays the most popular methods used for the determination of the incident wave energy in flume tests are as follows:
a) Division of the flume longitudinally into two (or more) sections of which one is used for the structural test, while the other is equipped with a mild sloping - wave absorbing beach and is used to measure the "incident" wave energy.
b) Two points cross spectral analysis, originally proposed by Goda and Suzuki (1976).
c) Three points least squares cross spectral analysis, proposed by Mansard and Funke (1980).
d) Preliminary determination of the coefficient of wave energy re-reflection using the method proposed by Gravesen et al. (1974), hereafter referred as the Gravesen method, or a refinement to it proposed by the authors in this article, referred as the CAMERI refinement.

The two points cross spectral method is based on the main assumption that irregular waves may be described as a linear superposition of an infinite number of discrete components, each with its own frequency, amplitude and phase. Another important assumption is that these components travel at their own individual phase velocity, described by the dispersion relationship. The method consists of measuring simultaneously the co-existing wave trains moving in opposite directions at two wave gauges located in constant water depth, close to each other and aligned parallel to the direction of wave propagation in the flume and cross spectral analysis to evaluate the incident and reflected spectra.

The third method attempts to overcome certain limitations of the two points cross spectral method such as limited frequency range, critical wave gauge spacing and high sensitivity to errors in the measurement of waves. It uses the two points method to measure the co-exsting wave trains moving in opposite directions at three or more locations of constant water depth (to prevent wave shoaling effects) and aligned on a line parallel to the direction of wave propagation in the flume. Spectral analysis of the signals at each wave gauge and cross spectral analysis between the signals of each pair of wave gauges by means of Fourier transform is done to express the wave activity at each wave gauge location in terms of an incident wave, a reflected wave and a noise signal. A least squares method is applied to resolve the Fourier expressions of the signals at each wave gauge in order to minimize the noise for all wave gauges.

The Gravesen method to determine the total incident wave energy is based on the preliminary determination of the re-reflection coefficient of wave energy from the paddle of the wave machine and on the evaluation of the coefficient of reflection of wave energy from the structure afterwards. This method and the proposed CAMERI refinement are described in detail in the following lines.

GRAVESEN METHOD

The evaluation of the coefficient of wave energy re-reflection is accomplished by preliminarily carrying out two separate series of tests in absence of the model structure investigated, but on the same bathymetry and for the same sea states to be generated on the model structure. The first series is performed with a non-reflective beach, while the second series is carried out with a reflecting vertical (rigid) wall, located at the position at which the model structure will be placed in the flume. Finally, the third series of tests is carried out with the model structure, under identical sea states as generated in the two preliminary test series.

For each sea state of any series of tests the assumptions of the cross spectral methods are also accepted. Consequently, the following expresions can be written by measuring the variance of the water elevation at a fixed position in any test:

$$Hm^2 = Hi^2 + Hr^2 \qquad (1)$$

where: Hm is the measured characteristic wave height,
Hi is the total incident characteristic wave height and
Hr is the reflected characteristic wave height.

The reflected energy coefficient Br and the re-reflection coefficient of wave energy Brr are derived from expressions (2) and (3) given below:

$$Hr^2 = Br * Hi^2 \qquad (2)$$

$$Hi^2 = Hg^2 + Brr * Hr^2 \qquad (3)$$

where: Hg^2 represents the wave energy generated by the wave machine.

By inserting (2) in (3) and extracting Hi and then introducing the result in (1), the resulting expressions obtained are:

$$Hi^2 = Hg^2 * [1 / (1 - Br * Brr)] \qquad (4)$$

$$Hm^2 = Hg^2 * [1 / (1 - Br * Brr)] * (1 + Br) \qquad (5)$$

To determine the unknown values of the coefficient of re-reflection of wave energy from the wave machine paddle (Brr) and the incident wave energy generated by the wave machine (Hg), the Gravesen method assumes a Br value of zero (0) for the tests with a spending beach, which means that in the first series of tests it is assumed that Hm = Hg. In the second series of tests with the vertical wall, it assumes that Br takes the value of one (1). Hence, for each sea state it is possible to determine Brr since Hm remains the same as in the previous series of tests. Finally, in the third series of tests with the model structure, the reflection coefficient of wave energy (Br) from the structure and the total incident characteristic wave height (Hi) can be determined (see schematization in Figure 1).

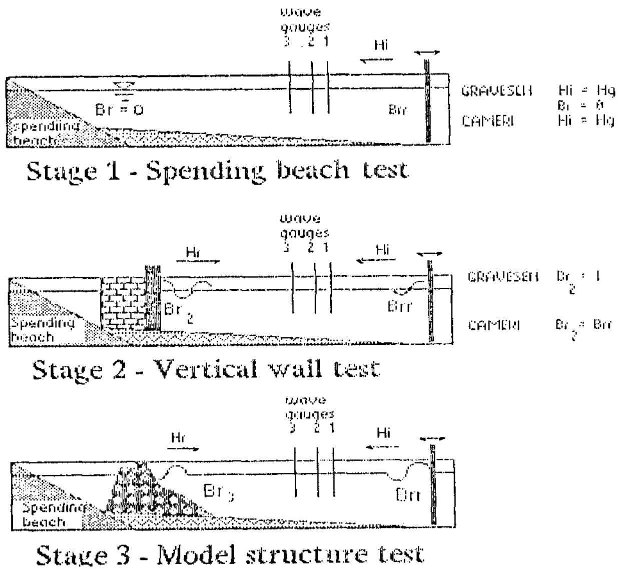

Figure No. 1 - Schematization of Gravesen method and of CAMERI refinement for evaluation of incident energy

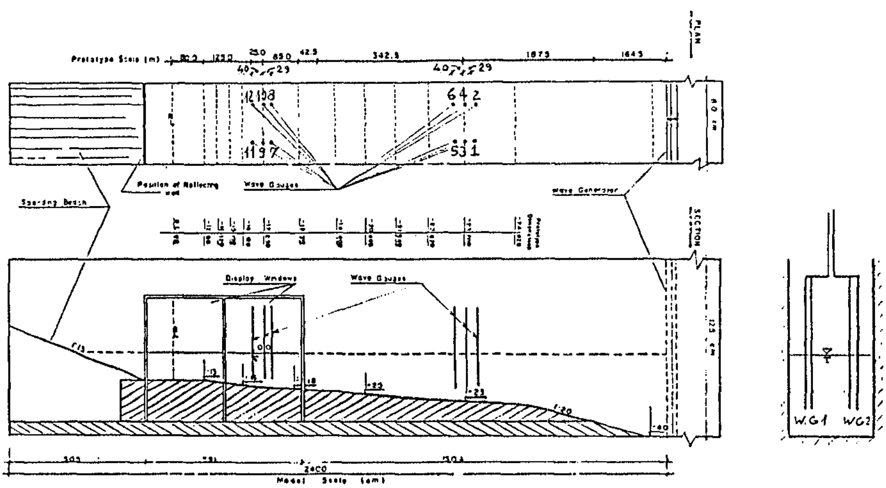

Figure No. 2 - Testing set-up in preliminary testing series (Geometric model scale 1:65)

CAMERI REFINEMENT

The methods described above were considered for use in a two dimensional stability model study for the rehabilitation of the main breakwater of Ashdod Port (Rosen and Gottlieb - 1985). The design storm for this study included various sea states of increasing characteristic wave height. The higher sea states included a large fraction of waves which were expected to break or to be at near breaking point. Under such conditions non-linear effects may be strong and affect the reliability of cross spectral methods based on linear assumptions regarding wave profile and wave transformation. Therefore, the Gravesen method was considered an appropriate alternative. However, this method's assumption of Br = 1.0 from the vertical wall and the expectation of a different value for Brr from the paddle of the wave machine, did not seem physically justified. Consequently, two refinements were introduced to the Gravesen method:

a) In the testing series with a vertical wall, Br would be approximately equal to Brr, especially if a piston type wave machine is used.

b) The value of Brr to be used in the tests with the model structure, should be the average of the values of Brr obtained in the vertical wall testing series with low sea states only.

EXPERIMENTAL SETUP

A preliminary experimental study was conducted to investigate the applicability of the Gravesen method, the CAMERI refinement and the cross spectral least squares method in order to choose the most reliable method for the evaluation of the incident wave energy and characteristic height on the model breakwater.

The investigation was performed in one of CAMERI's wave flumes. Twelve resistance type wave gauges were used to measure the waves in the flume (two groups of three pairs located at two sites). The locations of the wave gauges were in two regions of mild bottom slopes of about 1:80 near the -17m and about 1:100 near the -23m contour lines. The wave generator was located in relatively deep water (-40m) and in the first series of tests a spending beach of rubberized coir material enclosed in wire mesh (slope 1:13) was placed at the end of the flume (see Figure No.2).

The shape of the spectral variance distribution of the synthetic time series was of a JONSWAP type with slightly modified values of the parameters (see Figure No.3). The duration of the sea states was varied (see Figure No. 4) to simulate storm development pattern from low to extreme conditions. The structure used in the preliminary investigation consisted of a smooth slope of 1:5, while the model study consisted of a tetrapod breakwater cross section with an initial slope of 1:1.33 (see Figure No.5).

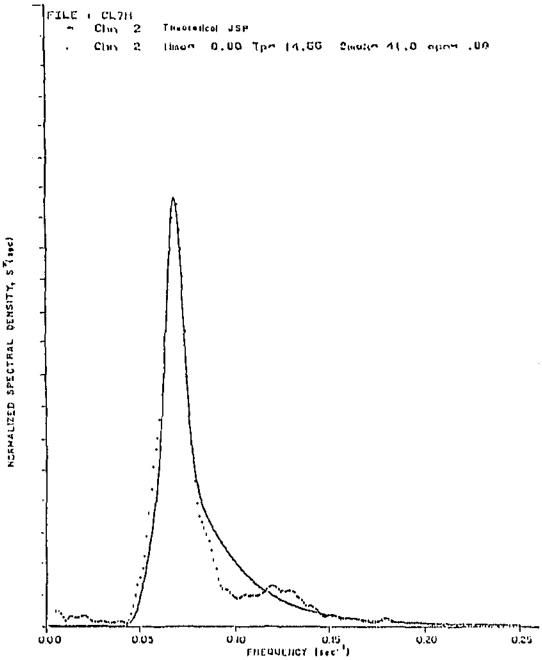

Figure No. 3 - Spectral distribution of modified JONSWAP used in the tests

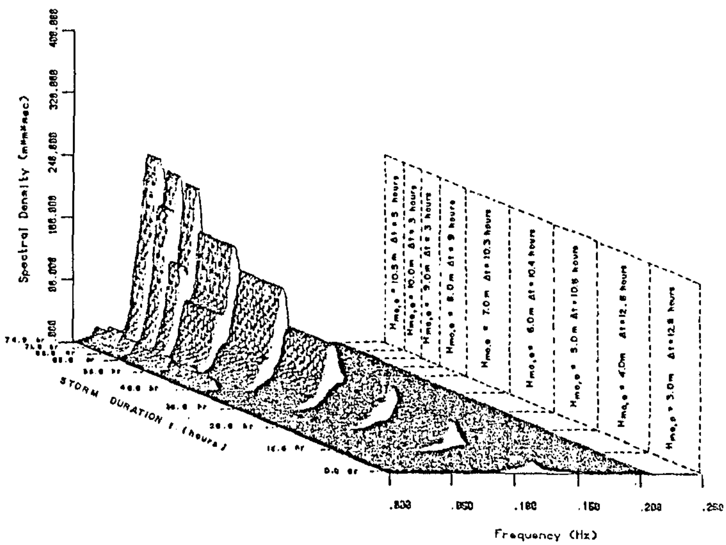

Figure No. 4 - Combined storm growth and decay simulation by sea state steps of varying duration

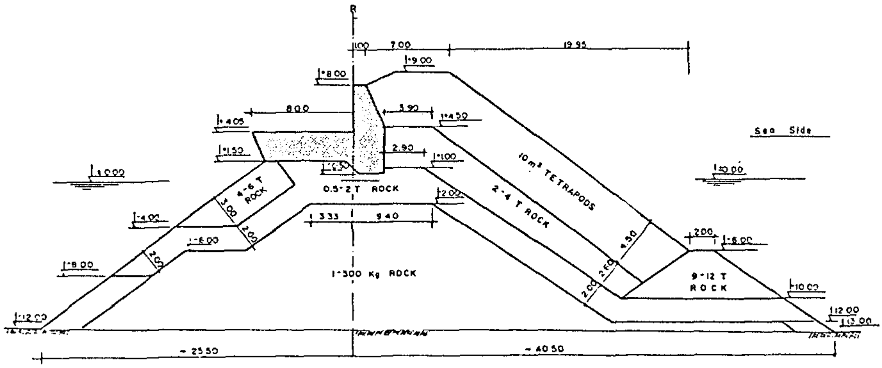

Figure No. 5 - Cross section of the tetrapod breakwater

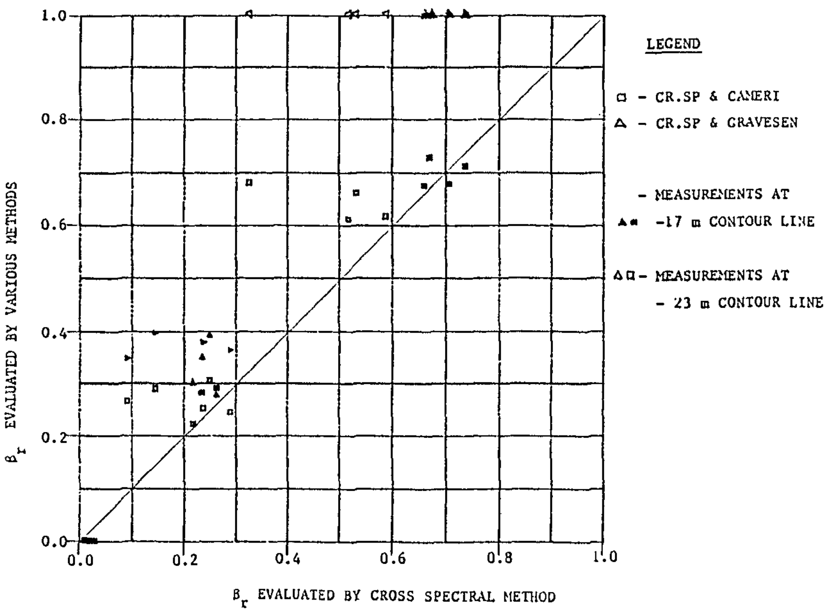

Figure No. 6 - Comparison of coefficients of wave energy reflection obtained for all tests (spending beach, vertical wall, smooth slope 1:5)

DISCUSSION OF EXPERIMENTAL RESULTS

A set of typical results for the preliminary investigation is presented in Tables 1 and 2 based on the wave gauges located on the -17m and -23m contour lines respectively.

It should be noted that in the testing series with the vertical wall, the wave energy reflection coefficients (Br) obtained by the CAMERI refinement are in good agreement with the corresponding values evaluated by the cross spectral least squares method. Both methods give Br values between 0.65 to 0.70, while the Gravesen method assumes a Br value of 1.0. Furthermore, inspite of the fact that a vertical paddle piston type wave machine was used, re-reflection coefficients (Brr) of about 0.3 were obtained using the Gravesen method. These values were significantly different from 1.0, which was the value assumed for the reflection coefficient (Br) from the vertical wall.

The results obtained in the test series with the spending beach by the cross spectral method, confirm the prerequisite assumption of complete energy absorption by the spending beach for both Gravesen method and CAMERI refinement.

The wave energy reflection coefficients (Br) obtained for the 1:5 smooth slope structure, show that the values evaluated by the CAMERI refinement are in better correspondence with the cross spectral method than those evaluated by the Gravesen method.

Similar results from the actual stability model study with the tetrapod breakwater are given in Table 3.

The Br values evaluated by the various methods are plotted against the values determined by the cross spectral least squares method in Figure No.6.

Comparisons of the values of the characteristic incident wave heights evaluated using the various methods are presented in Figures No. 7 through 12 against the characteristic incident wave height values determined by the cross spectral least squares method.

Improved estimates of the total incident wave energy are obtained by the CAMERI refinement using more realistic reflection coefficients, for relatively low to moderate sea states.

It should be mentioned that the accuracy of the cross spectral method is limited in high sea states because the wave profile and the wave length are no longer well described by the linear theory , even if breaking does not occur. On the other hand some minor differences between the results are due to the fact that the wave gauges were not located in a constant depth zone.

The results indicate that better estimates are obtained for the high sea states with breaking waves, employing an average re-reflection coefficient obtained for the low sea states.

Type of reflecting structure	Measured data		Cross-spectral method			CAMERI		Gravesen et al		Incident wave heights		
	Hm (m)	T_p (sec)	Hi (m)	Hr (m)	β_r	β_r	β_{rr}	β_r	β_{rr}	Cross-spectral	CAMERI method	Gravesen method
Spending beach	2.63	9.49	2.58	0.25	0.009	0.000	-	0.000	-	2.58	2.63	2.63
	3.49	10.90	3.46	0.37	0.012	0.000	-	0.000	-	3.46	3.49	3.49
	4.66	12.51	4.59	0.57	0.015	0.000	-	0.000	-	4.59	4.66	4.66
	5.59	13.31	5.55	0.85	0.024	0.000	-	0.000	-	5.55	5.59	5.59
	6.53	14.55				0.000	-	0.000	-		6.53	6.53
Vertical wall	4.99	10.86	3.75	3.07	0.671	0.722	0.722	1.000	0.444	3.75	3.80	3.53
	6.43	12.22	5.06	4.35	0.741	0.705	0.705	1.000	0.411	5.06	4.92	4.55
	8.14	13.48	7.13	6.00	0.708	0.672	0.672	1.000	0.345	7.13	6.29	5.76
	9.71	17.72	8.86	7.20	0.661	0.669	0.669	1.000	0.337	8.86	7.52	6.87
Model Structure (Slope 1:5)	3.32	9.98	2.95	1.41	0.230	0.281	0.700	0.348	0.444	2.95	2.93	2.86
	4.49	10.86	4.10	2.03	0.245	0.304	0.700	0.390	0.411	4.10	3.93	3.81
	5.61	11.79	5.17	2.38	0.212	0.223	0.700	0.300	0.345	5.17	5.07	4.92
	7.11	13.3	6.30	3.20	0.258	0.290	0.700	0.277	0.337	6.30	6.26	5.87
	8.04	17.74				0.250	0.700				7.19	

Table 1 - Preliminary testing series results (wave gauges located on the -17m contour line)

Type of reflecting structure	Measured data		Cross-spectral method			CAMERI		Gravesen et al		Incident wave heights		
	Hm (m)	T_p (sec)	Hi (m)	Hr (m)	β_r	β_r	β_{rr}	β_r	β_{rr}	Cross-spectral	CAMERI method	Gravesen method
Spending beach	2.76	9.46	2.68	0.19	0.005	0.000	-	0.000	-	2.68	2.76	2.76
	3.58	10.79	3.47	0.25	0.005	0.000	-	0.000	-	3.47	3.58	3.58
	4.76	12.14	4.60	0.44	0.009	0.000	-	0.000	-	4.60	4.76	4.76
	5.74	13.31	5.53	0.56	0.010	0.000	-	0.000	-	5.53	5.74	5.74
	6.59	14.42				0.000	-	0.000	-		6.59	6.59
Vertical wall	4.83	10.40	4.01	2.28	0.323	0.673	0.673	1.000	0.347	4.01	3.74	3.42
	6.09	12.63	5.02	3.66	0.531	0.654	0.654	1.000	0.309	5.02	4.73	4.31
	7.58	12.44	7.40	5.32	0.516	0.606	0.606	1.000	0.211	7.40	5.98	5.36
	9.21	12.70	10.07	7.72	0.588	0.612	0.612	1.000	0.223	10.07	7.26	6.51
Model Structure (Slope 1:5)	3.41	9.58	3.16	0.93	0.086	0.264	0.650	0.344	0.347	3.16	3.03	2.94
	4.51	10.86	4.28	1.61	0.141	0.289	0.650	0.394	0.309	4.28	3.97	3.82
	5.82	12.46	5.61	2.70	0.253	0.251	0.650	0.376	0.211	5.61	5.20	4.96
	6.98	13.20	6.78	3.63	0.286	0.244	0.650	0.360	0.223	6.78	6.26	5.99
	8.07	14.48				0.253	0.650				7.21	

Table 2 - Preliminary testing series results (wave gauges located on the -23m contour line)

Type of reflecting structure	Measured data		Cross-spectral method			CAMERI		Gravesen et al		Incident wave heights		
	Hm (m)	T_p (sec)	Hi (m)	Hr (m)	β_r	β_r	β_{rr}	β_r	β_{rr}	Cross-spectral	CAMERI method	Gravesen method
Spending beach	2.89	9.35	2.89	0.25	0.008	0.000		0.000		2.89	2.89	2.89
	3.89	11.27	3.89	0.99	0.058	0.000		0.000		3.89	3.89	3.89
	5.25	12.15	5.18	1.28	0.046	0.000		0.000		5.18	5.25	5.25
	6.26	13.69	6.05	1.71	0.030	0.000		0.000		6.05	6.26	6.26
	7.34	14.68	7.12	2.02	0.024	0.000		0.000		7.12	7.34	7.34
	8.40	16.64	8.13	2.41	0.022	0.000		0.000		8.13	8.40	8.40
Vertical wall	5.15	10.06	3.96	3.10	0.540	0.690	0.690	1.000	0.370	3.96	3.99	3.64
	7.76	11.42	5.45	4.49	0.630	0.750	0.750	1.000	0.500	5.45	5.88	5.50
	9.65	13.07	7.41	5.42	0.640	0.700	0.700	1.000	0.410	7.41	7.35	6.83
	10.63	16.18	8.48	6.11	0.620	0.650	0.650	1.000	0.310	8.48	8.24	7.54
	12.00	17.04	8.92	6.24	0.420	0.630	0.630	1.000	0.250	8.92	9.45	8.48
	13.15	18.79	9.80	6.53	0.440	0.590	0.590	1.000	0.180	9.80	10.40	9.28
Tetrapods breakwater	3.18	9.56	2.88	0.98	0.114	0.114	0.700	0.146	0.370	2.88	3.00	2.97
	4.43	11.69	4.19	1.96	0.202	0.156	0.700	0.181	0.500	4.19	4.12	4.08
	5.39	13.16	5.05	2.46	0.217	0.031	0.700	0.038	0.410	5.05	5.31	5.29
	6.92	12.89	6.58	3.32	0.430	0.120	0.700	0.162	0.310	6.58	6.54	6.42
	8.33	17.85	7.98	4.10	0.141	0.151	0.700	0.217	0.250	7.98	7.76	7.54
	10.03	17.76	9.05	4.97	0.176	0.213	0.700	0.337	0.180	9.05	9.10	8.67

Table 3 - Breakwater tests (wave gauges on -17m contour line)

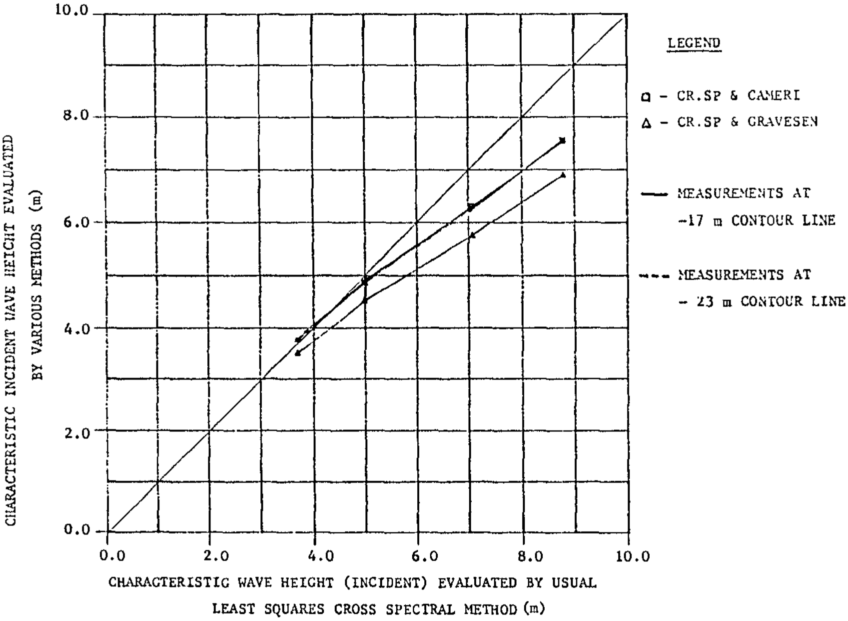

Figure No. 7 - Comparison of incident characteristic wave heights (vertical wall, wave gauges on -17m contour line)

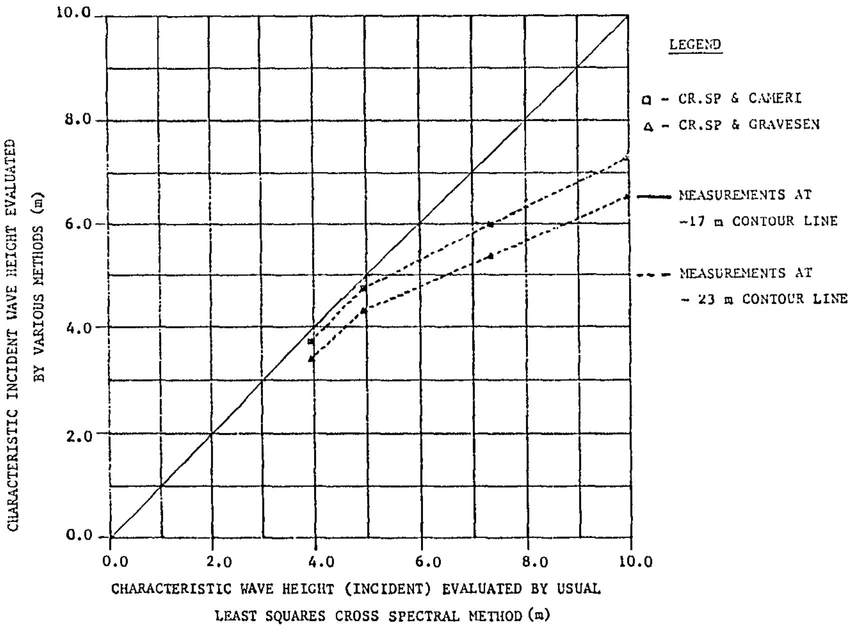

Figure No. 8 - Comparison of incident characteristic wave heights (vertical wall, wave gauges on -23m contour line)

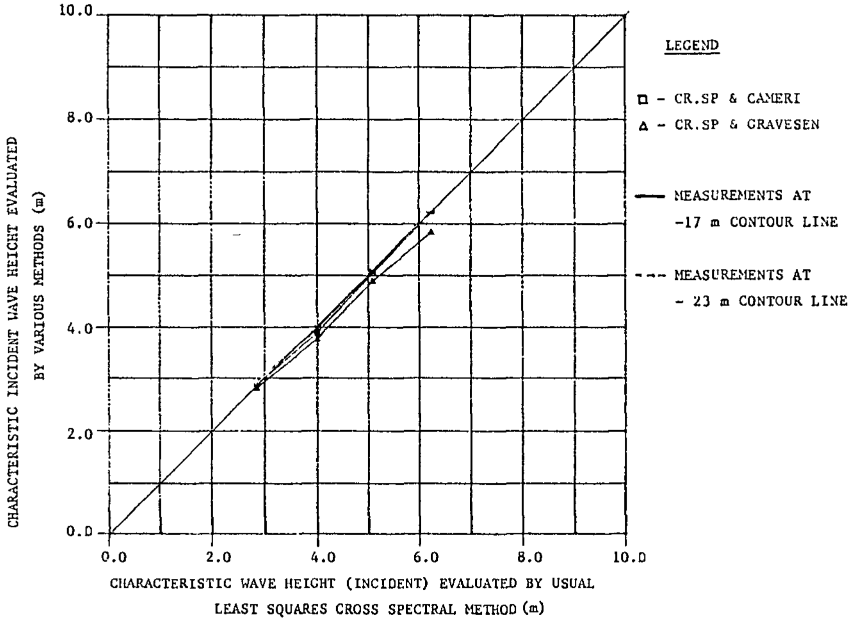

Figure No. 9 - Comparison of incident characteristic wave heights (spending beach, wave gauges on -17m contour line)

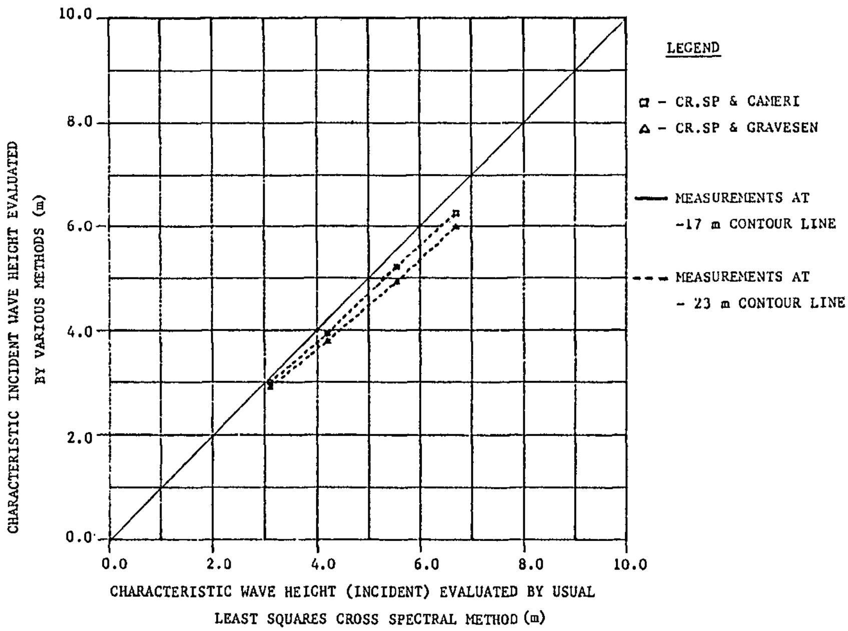

Figure No.10 - Comparison of incident characteristic wave heights (spending beach, wave gauges on -23m contour line)

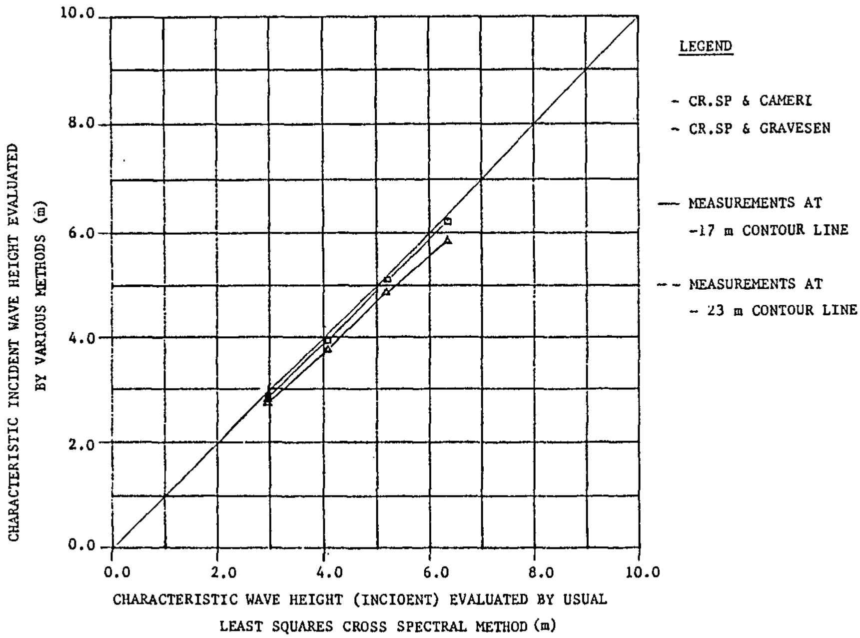

Figure No.11 - Comparison of incident characteristic wave heights (smooth slope 1:5, wave gauges on -17m contour line)

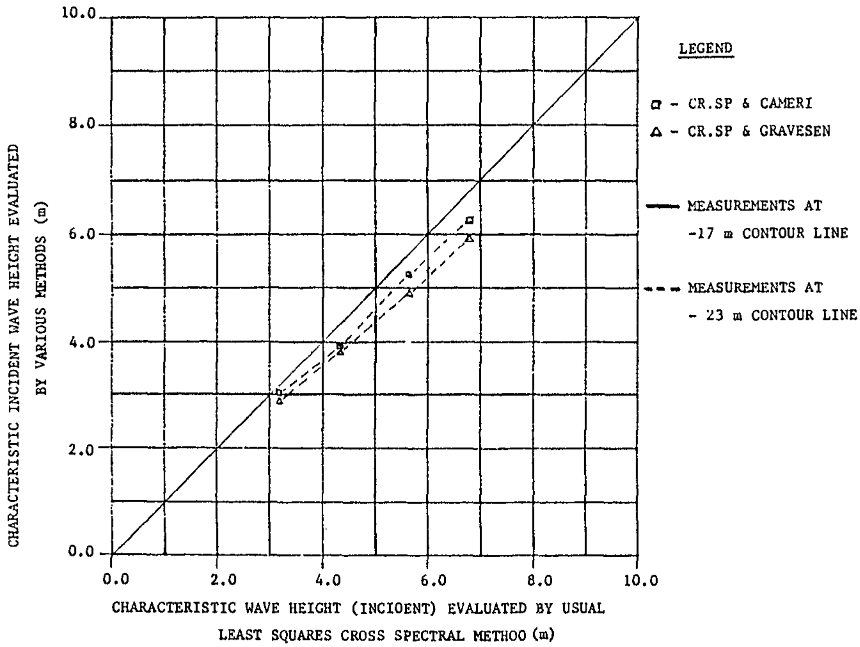

Figure No.12 - Same as Figure No.11, but gauges on -23m line

CONCLUSIVE REMARKS

The CAMERI refinement enables the evaluation of total incident wave energy (characteristic wave height) with almost no dependance on the bathymetry, easily providing real-time results, without any requirements for sophisticated software and comprehensive computer hardware. Its advantages versus the Gravesen method, result from a physically more sound approach, as proven by the analysis performed. Although the Gravesen method leads to lower estimates of the values of the total incident characteristic wave heights which might be considered to lead to conservative designs, the costs related to such conservative estimates, especially those of high sea states can not be reasonably justified.

The cross spectral least squares method provides off-line spectral distributions for incident and reflected waves, unavailable by the former approach, but it requires extensive computer resources and is of limited accuracy in the evaluation of high sea states with near breaking and breaking waves. Its use is also limited to horizontal or mild sloping sea bottoms. The results obtained using the CAMERI refinement can be used to verify results obtained by the cross spectral least squares method, increasing the reliability of the results of any flume study.

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