CHAPTER 168

EXPERIMENTAL STUDY OF IMMERSED PLATES USED AS BREAKWATERS

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ABSTRACT

Under certain wave conditions, an immersed plate which is free to move horizontally produces what has already been called the oscillating water wall phenomenon. When this happens, the plate and the volume of fluid located under the plate move back and forth and then behave as a wave reflector. This type of breakwater was studied in a wave flume with monochromatic and irregular wave trains. Tests have provided a better understanding of the influence of certain parameters that define a plate and the hydraulic conditions under which the plate is used. Results show some interesting efficiencies and also transfert of the energy to harmonic frequencies.

1. INTRODUCTION

The reflective capacity of a freely moving and immersed plate has been shown in a recent study (Guevel et al., 1985). In this paper, it was demonstrated that under certain wave conditions, this kind of plate and the fluid located under it move back and forth. This movement generates in the rear part of the plate a radiation wave which interferes with the incident one; therefore, the plate behaves as a wave reflector (Figure 1). The French researchers developed a diffraction-radiation model which gave results similar to those obtained in their laboratory. However, when wave steepness was too high, the rear part of the plate became the seat of strong turbulence which seemed to generate harmonic waves, and, depending on the immersion depth of the plate, waves broke on its top. The numerical model did not account for these two phenomena.

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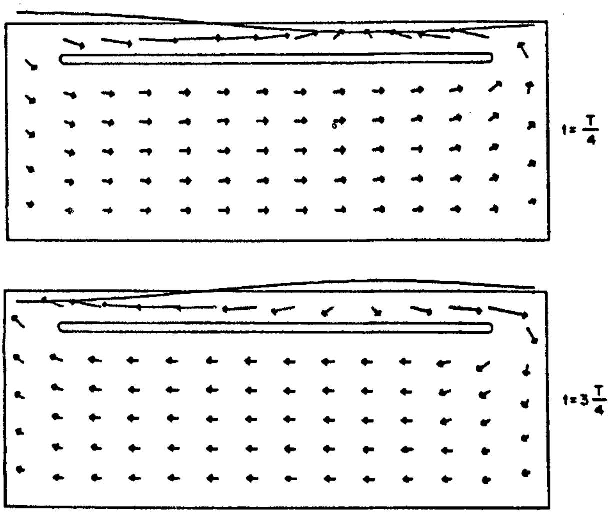

Figure 1 - Velocity distribution and free surface obtained with the oscillating water wall phenomenon (from Guevel et al., 1985)

The present work consists mainly of an experimental study on mobile and immersed plates (Drouin, 1988). The purpose was to determine if that kind of structure could be used as a breakwater under high steepness wave conditions. Plates were subjected to monochromatic and irregular waves, and some regular wave results were subsequently compared to those obtained with a fixed plate used in the same conditions. The fixed plates have been considered in many earlier studies which were well summarized in a paper written by Patarapanich in 1978.

2. EQUIPMENT AND DATA

The study was conducted in a 1.2 x 1.8 x 34.0 meter wave flume which was divided into three corridors of 0.45, 0.90 and 0.45 meters respectively. Studied structures were placed in the main corridor; therefore, the side flumes served essentially to dissipate waves reflected on breakwaters.

In order to maximize the information from the tests performed, time domain and frequency analyses were carried out. To reach the highest frequency of 4.0 Hz to which the spectrum would be evaluated, a data sampling interval of 0.125 second was chosen. In each case studied, eight records of 32 seconds were taken; therefore, the resulting increment in frequency between adjacent estimates of spectral density was 0.03125 Hz, and the stability obtained for these estimates was satisfactory.

In the time domain, the zero down crossing method was used, while the basic frequency analysis was completed with Goda and Suzuki's algorithm (Goda and Suzuki, 1976) so as to account for multiple wave reflections. For that purpose, three groups of four probes permitted the defining of incident as well as transmitted waves; the assessment of incident waves was checked with measures taken in a side flume. Finally, measurement of the horizontal displacement of each structure was also done.

3. REGULAR WAVE TESTS

A first group of tests was performed using regular wave trains. The parameters of the plate studied in tests 1 to 12 were the width, the specific mass and the mobility (Table 1), while the plate thickness was constantly maintained at 5 cm. As illustrated in Figure 2, chains placed at corners kept the mobile plates immersed, and pieces of foam were added to avoid passage of water and friction along the flume walls. A rigid support was used to fix the immobile structure studied (plate 4); therefore, the specific mass of this plate is not indicated in Table 1 because it is not significant.

Table 1 - Definition of plates studied in tests 1 to 12

PLATE IDENTIFICATION	WIDTH (cm)	SPECIFIC MASS (g/cm^3)
1	100	0.27
2	150	0.27
3	150	0.42
4	150	-

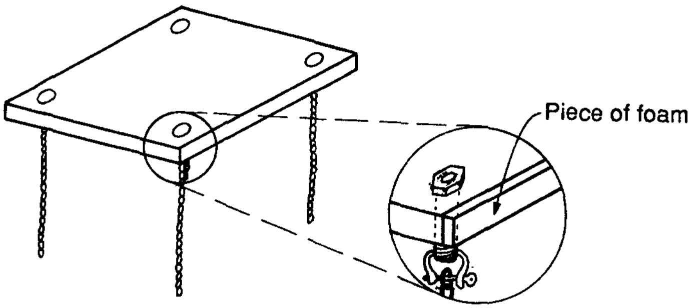

Figure 2 - Sketch of a typical mobile plate

For tests 1 to 12, plates were subjected to the fifteen wave conditions presented in Table 2, and each of these were considered with three different immersion depths of the plates (9.0, 13.5 and 18.0 cm). Water depth was kept at 75 cm; therefore, most of the waves were generated in intermediate water depth. In fact, only waves corresponding to the 0.95 second period were produced in deep water conditions.

Table 2 - Characteristics of regular waves used in tests 1 to 12

PERIOD (s)	HEIGHTS (cm)	WAVE LENGTH (cm)	WAVE STEEPNESSES
0.95	6.7, 5.3, 3.3	141	0.048, 0.038, 0.023
1.15	9.1, 7.0, 5.0	203	0.045, 0.034, 0.025
1.33	11.8, 8.8, 5.2	261	0.045, 0.034, 0.020
1.67	11.3, 8.1, 5.0	372	0.030, 0.022, 0.013
2.22	12.9, 9.9, 6.3	541	0.024, 0.018, 0.012

The effect of an increase in water depth was the object of tests 13 to 15, althought it was not possible, considering the dimensions of the flume, to raise the water level already used. In order to obtain deeper water conditions, incident waves, immersion depths and dimensions of plate 2 were reproduced at scale 1:1.4 with respect to the Froude's similitude law. The use of this scale gave an equivalent water depth of 105 cm.

Incident waves generated in tests 13 to 15 are presented in Table 3. For those tests, which were performed with plate 5, deep water conditions resulted when the two smaller periods were used. The width of the plate was 107 cm, its thickness 3.6 cm, and the plate was immersed to depths of 6.4, 9.6 and 12.9 cm.

Table 3 - Characteristics of regular waves used in tests 13 to 15

PERIOD (s)	HEIGHTS (cm)	WAVE LENGTH (cm)	WAVE STEEPNESSES
0.80	4.8, 3.8, 2.4	100	0.048, 0.038, 0.023
0.97	6.5, 5.0, 3.6	146	0.045, 0.034, 0.025
1.12	8.4, 6.3, 3.7	193	0.044, 0.033, 0.019
1.41	8.1, 5.8, 3.6	288	0.028, 0.020, 0.013
1.88	9.2, 7.1, 4.5	437	0.021, 0.016, 0.010

Although incident waves were monochromatic, transmitted ones appeared to correspond to a superposition of waves at harmonic frequencies (Figure 3). Efficiencies of tests performed in regular wave conditions, obtained using equation (1), are given in Table 4.

With the equation (1), an efficiency value near zero indicates that almost all the incident energy has been transmitted behind the structure.

$$\text{Efficiency} = \left(1 - \frac{\text{transmitted energy}}{\text{incident energy}} \right) \times 100 \qquad (1)$$

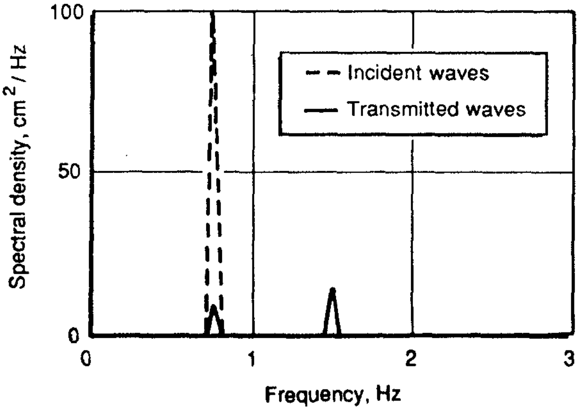

Figure 3 - Typical incident and transmitted waves spectra

Table 4 - Efficiencies obtained with regular waves

a) Immersion depth: 9 cm *

INCIDENT WAVES PERIOD (s)	HEIGHT (cm)	PLATE 1	2	3	4	5
0.95	6.7	67	86	77	77	85
	5.3	59	84	81	49	76
	3.3	23	41	36	30	53
1.15	9.1	85	77	80	79	73
	7.0	73	83	78	81	72
	5.0	44	85	76	73	68
1.33	11.8	77	87	87	87	85
	8.8	82	79	81	81	69
	5.2	68	72	72	69	54
1.67	11.3	78	96	95	91	91
	8.1	79	86	88	93	72
	5.0	55	62	61	79	55
2.22	12.9	51	75	69	79	84
	9.9	44	77	76	81	86
	6.3	76	77	80	85	83

b) Immersion depth: 13.5 cm *

INCIDENT WAVES PERIOD (s)	HEIGHT (cm)	PLATE 1	2	3	4	5
0.95	6.7	45	51	56	41	51
	5.3	25	49	37	28	53
	3.3	23	39	36	23	42
1.15	9.1	78	55	79	66	61
	7.0	48	54	67	49	57
	5.0	36	35	31	20	38
1.33	11.8	84	73	84	83	82
	8.8	69	57	62	61	73
	5.2	39	2	6	16	48
1.67	11.3	58	90	79	88	96
	8.1	44	82	82	75	74
	5.0	51	29	59	11	40
2.22	12.9	34	72	58	75	78
	9.9	64	69	54	81	80
	6.3	62	63	61	75	85

c) Immersion depth: 18.0 cm *

INCIDENT WAVES PERIOD (s)	HEIGHT (cm)	PLATE 1	2	3	4	5
0.95	6.7	10	28	38	25	30
	5.3	4	31	33	18	42
	3.3	0	35	44	14	26
1.15	9.1	56	37	40	50	43
	7.0	41	27	30	35	32
	5.0	38	31	29	32	21
1.33	11.8	80	69	91	74	77
	8.8	67	27	49	56	52
	5.2	47	27	23	41	26
1.67	11.3	61	79	74	83	74
	8.1	54	44	61	68	62
	5.0	54	23	49	16	52
2.22	12.9	32	62	38	47	74
	9.9	26	67	35	65	74
	6.3	25	61	66	83	83

* Frequencies, heights and immersion depths were reproduced at scale 1:1.4 for tests with plate 5.

Efficiencies obtained with plate 5 are illustrated in Figure 4 as a function of the kinematic energy per unit area of incident waves. Results shown in this way are representative of those obtained with other plates used.

The unusual choice of energy as a parameter to represent breakwater efficiencies can be understood by the implicit relationship between kinematic wave energy and an oscillating movement. This parameter was the only one which permitted the gathering of efficiency results in a relatively narrow range of values. Had adimensional parameters currently used, as the ratio of structure width to wave length or the wave steepness, been employed, efficiency results would have exhibited a significantly greater dispersion pattern.

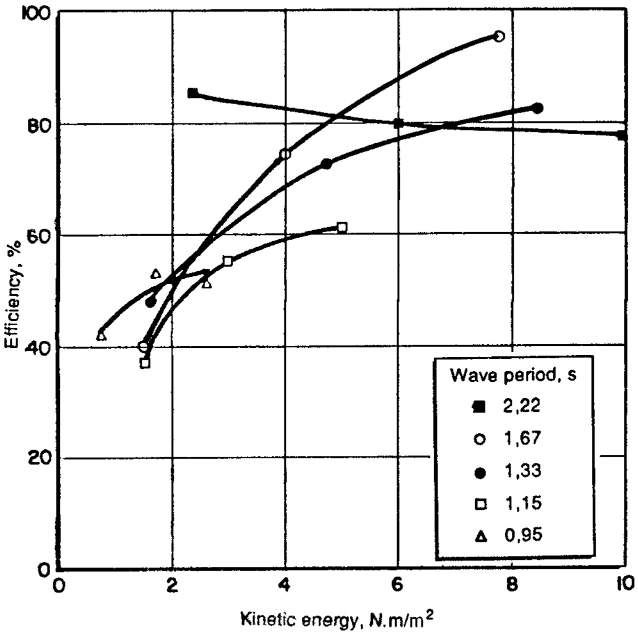

Figure 4 - Efficiencies of the plate 5 obtained with an immersion depth of 13.5 cm

4. DISCUSSION OF REGULAR WAVE RESULTS

The following analysis of results already given in Table 4, has been presented in such a way as to highlight the influence of wave and plate parameters studied.

Immersion depth

In almost all cases, efficiency decreased as the immersion depth became more important. This influence can be explained in two ways. When the immersion increased, there was less kinematic energy under the plate to initiate the water wall phenomenon as described by Guevel et al. Secondly, there was also less energy dissipated by wave breaking on the plate.

Wave height

As shown in Figure 4, with the exception of the higher period studied, the performance of plates increased as incident wave energy (proportional to height) also increased. As well as in the case of the immersion depth, results can be related to the dissipation of wave energy due to the wave breaking, and to the energy available under the plate to initiate the water wall phenomenon.

Plate width

With an immersion depth of 9 cm, plate 2 (width of 150 cm) performed better than plate 1 which was only 100 cm wide. When the plate 2 was immersed at 13.5 cm, efficiencies were equivalent to those of plate 1, except in certain cases including those with wave periods of 1.33 second. Finally, with a immersion depth of 18 cm, the second plate gave better results only with extreme wave periods studied (0.95 and 2.22 seconds); with other periods, smaller efficiencies were obtained with the larger plate.

Specific mass

With the smallest immersion depth, efficiencies calculated with plates 2 and 3 (specific masses of 0.27 and 0.42 g/cm^3) were quite similar. With other immersion depths, an increase of the mass resulted in efficiencies similar or better, except with higher waves having a period of 2.22 s.

Plate mobility

Compared to the fixed plate, the efficiency of the mobile one was better when exposed to the lower energy waves of those described in Table 2. However, the fixed structure gave better results in higher wave energy cases. With both types of plate, a part of the transmitted energy had a harmonic relationship with incident wave frequency.

Water depth

Especially when highly immersed, plate 5, which was in deeper water, gave better results than plate 2. These results and the movement of the plates help, as it will be discussed next, to understand the effect of water depth on this kind of breakwater.

As described by Guevel et al, it was observed that an upward pressure was applied under the rear part of all mobile plates during their backward movement (Figure 5). If the pressure was important enough, it seemed to limit the horizontal displacement of these plates.

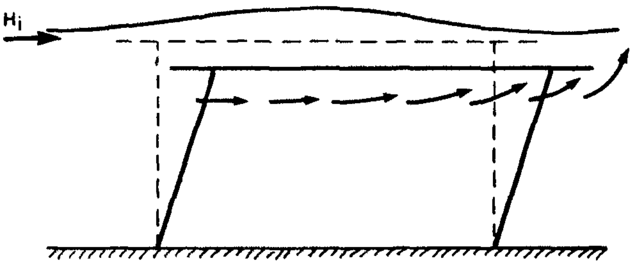

Figure 5 - Velocity distribution directly under the plate

When mobile plates 1, 2 and 3 were subjected to the longer wave periods (1.67 and 2.22 seconds), their movements were not as that described in Figure 6a, but rather like those illustrated in Figures 6b and 6c. However, when plate 5 was subjected to the same incident wave conditions, but in deeper water, its movements were as presented in Figure 6a. Especially with the two deeper immersions, the amplitude of plate 5 movements was, proportionally, bigger than those of plate 2 used in shallower water. Therefore, the horizontal displacement of the mobile plates was a function of the anchoring length.

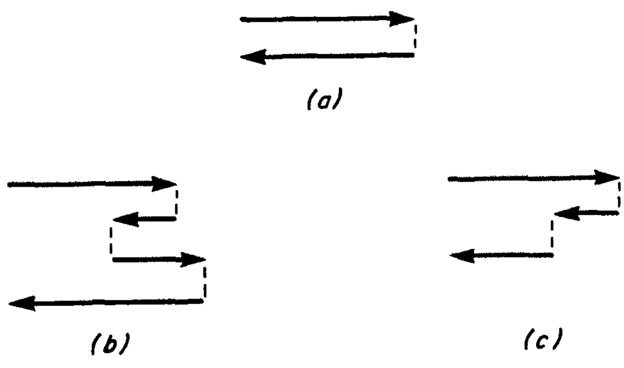

Figure 6 - Typical movements of the mobile plates

Considering geometric relations, it appears that a given horizontal displacement implies a larger vertical displacement of that structure when the anchoring length is shorter. Added to the efficiencies obtained, it seems to indicate that when a plate is limited in its horizontal oscillation, it cannot force as efficiently the horizontal displacement of the mass of water located under itself; therefore, the reflective capacity would be decreased.

It may be paradoxical to note that the fixed plate performed better than the mobile ones when subjected to the higher wave periods used. However, the mobile plates were agitated, in those cases, by strong vertical jolts which resulted, when added to the horizontal movement limitation, in lower efficiencies.

Finally, the movement of the plates described in Figures 6b and 6c seemed to create bigger strains in anchorings than that illustrated in Figure 6a; however, this assumption was not verified in tests performed, since no anchoring stresses were measured.

5. IRREGULAR WAVE TESTS

A limited amount of tests were performed using irregular incident waves. In order to permit direct comparison with regular wave tests, significant wave heights and peak periods were chosen such that they were equivalent to some of those used in monochromatic conditions. Spectra generated in the laboratory were based on the JONSWAP definition (Holmes, 1977). Efficiencies calculated with equation (1) and obtained with plates 1 and 2, already defined, are presented in Tables 5 and 6.

Considering the effect of the parameters studied, the results of irregular wave tests had a tendency to vary in the same manner as those obtained with regular wave trains. However, differences between extreme efficiencies were diminished, since lower and higher performances obtained with regular waves were more concentrated around mean values.

Table 5 - Efficiencies obtained in irregular wave conditions with plate 1

PEAK PERIOD (s)	SIGNIFICANT HEIGHT (cm)	IMMERSION DEPTH (cm)		
		9.0	13.5	18.0
1.15	9.1	65	58	50
	7.0	63	46	43
	5.0	40	34	41
1.67	11.3	74	65	51
	8.1	74	62	47
	5.0	67	57	49

Table 6 - Efficiencies obtained in irregular wave conditions with plate 2

PEAK PERIOD (s)	SIGNIFICANT HEIGHT (cm)	IMMERSION DEPTH (cm) 9.0	13.5	18.0
1.15	9.1	68	47	32
	7.0	67	42	35
	5.0	55	39	37
1.67	11.3	82	75	62
	8.1	76	66	45
	5.0	55	35	37

As well as with regular waves, transmitted energy was carried over to higher frequencies, especially to harmonics of the incident peak frequency (Figure 7).

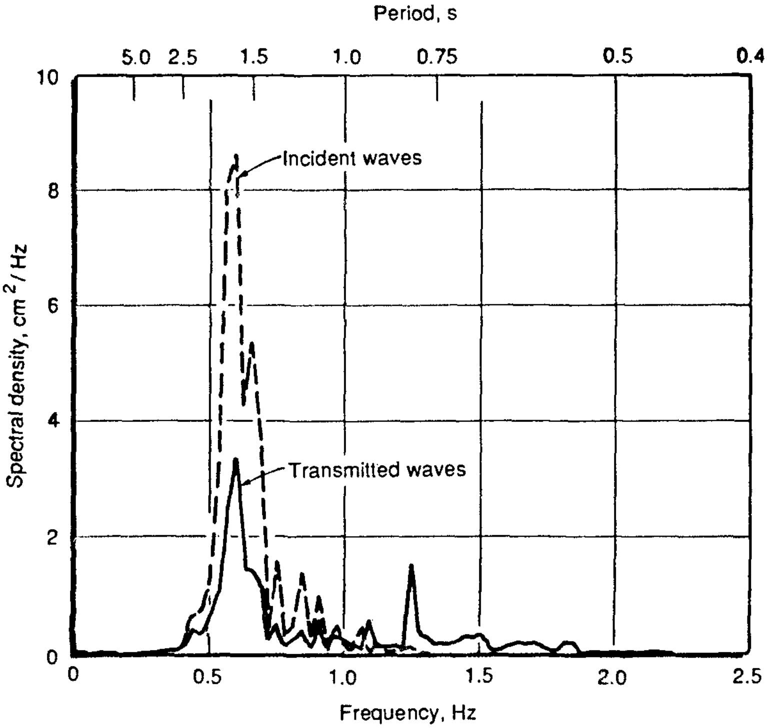

Figure 7 - Incident and transmitted waves spectra obtained with plate 1 immersed at 18.0 cm Incident waves: T_p = 1.67 s, $H_{1/3}$ = 5.0 cm

6. CONCLUSIONS

From tests performed, the plate width, the immersion depth and the distance between the plate and the bottom appeared to be the parameters having the most influence on the efficiency of a mobile plate used as a breakwater. Under severe wave conditions, horizontal displacement of the plate, and consequently its efficiency, were observed to be limited by the length of the anchoring chains (distance between the plate and the bottom) and the ascendant pressures on the rear part of the plate. In these cases, the rear part of the plate was agitated by strong vertical jolts. Under such conditions, a fixed plate of equivalent dimensions was found to be more effective.

Interesting efficiencies were obtained, even when ratios of plate width to wave length were small. These good performances occurred especially when plates were slightly immersed. With the exception of the higher wave periods studied, the efficiency of the plates as breakwaters increased as incident wave energy increased. Moreover, a variable part of this energy was carried over as a harmonic of the incident wave frequency.

More detailed studies should be done, using irregular wave conditions and variable incident wave angles, in order to better define the performance of the plates. The measurement of tensions on anchoring chains, when structures are subjected to these incident waves, will also give important information that must be known before considering the use of such mobile plates in the field as breakwaters.

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