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by

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MANAGEMENT PERSPECTIVE

The damage to the environment from a possible oil spill at an offshore production caisson retained artificial island in the Beaufort Sea could be severe. By understanding the environmental factors at the design stage, the risk to the environment can be reduced. In this paper, the freeboard requirements to protect against wave runup for various caisson island geometries and for typical Beaufort Sea conditions have been defined, using physical models. The most dramatic finding is that the freeboard must be markedly increased if the caissons are built on submerged berms. The results of this work have to be used in conjunction with information on other factors, such as ice loading, in establishing acceptable island configurations.

T. Milne Dick
Chief
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PERSPECTIVE-GESTION

Le déversement accidentel de pétrole en provenance d'un îlot artificiel retenu par des caissons servant à l'exploitation pétrolière dans la mer de Beaufort pourrait provoquer de graves dégats environnementaux. On peut réduire les risques d'une telle éventualité en tenant compte des contraintes environnementales à l'étape de conception. En essayant des maquettes reproduisant diverses formes d'îles, on a déterminé les hauteurs minimales de franc-bord qu'il faut pour contrer les paquets de mer dans des conditions typiques de celles de la Mer de Beaufort. On a été étonné de découvrir qu'il faut considérablement augmenter la hauteur du franc-bord si les caissons reposent sur des bermes submergées. Les résultats de ces travaux combinés aux informations recueillies sur d'autres facteurs tels que la charge due à la glace ont servi à mettre au point les formes d'îlots souhaitables.

Le chef
T. Milne Dick
Division de l'hydraulique

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ABSTRACT

Hydraulic model tests at a scale of 1:75 were conducted in a wave basin to obtain preliminary data on freeboard requirements due to wind waves for caisson retained artificial islands. This type of island is envisaged for use as petroleum production facilities in the Beaufort Sea. Parameters varied include caisson planform, presence or absence of a berm, slope of caisson walls. The diffraction effect, sometimes referred to as Mach-stem reflection, is examined. The presence of the berm resulted in increased freeboard requirements. There were no major differences in freeboard requirements beween circular and octagonal caissons.

RÉSUMÉ

Des essais ont été menés sur des modèles réduits (échelle 1:75) dans un bassin à houle, afin de recueillir des données préliminaires sur les besoins de franc-bord, liés à l'effet de vagues de vent sur les îles artificielles retenues par des caissons. On envisage de se servir de ce type d'îles pour les installations de production pétrolière dans la Mer de Beaufort. Les paramètres utilisés sont la forme en plan du caisson, la présence ou l'absence d'une berme, l'inclinaison des parois du caisson. On a étudié l'effet de diffraction, parfois désigné en anglais sous le terme "Mach-stem reflection". La présence d'une berme justifiait un franc-bord plus élevé. On n'a pas noté de différences majeures entre le franc-bord des caissons circulaires et celui des caissons octagonaux.

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INTRODUCTION

The search for hydrocarbon resources to fuel the modern Canadian economy has lead the petroleum industry to more and more remote and hostile regions. As a result, the dangers to the environment posed by exploration and production facilities have increased. It has become vital, not only from an economic standpoint, but also from an environmental standpoint that these facilities be designed and constructed in a manner such as to ensure their integrity over their operational life.

With this in mind the Hydraulics Division, National Water Research Institute undertook a series of experiments to investigate the interaction of waves and caisson retained artificial islands. This work has focussed on structures of the type that may be used in the Beaufort Sea for the production of oil. The aim of the research has been to provide information of a general nature about the wave field around the islands and their freeboard requirements to assist the petroleum industry in designing production islands. By providing data on wave-structure interation to the industry beforehand, it should be possible for the companies to design structures with more certainty and hence reduce the threat to the environment of structural failure. The results presented here have to be integrated with information on all the other environmental factors, for example, ice loading, in determining final configurations.

TYPICAL ISLANDS

At the time of this work, specific designs for caisson retained production islands for the Beaufort Sea had not been established. After discussions with officials of the petroleum industry, the following general descriptions were selected as being the most likely to be adopted for production facilities:

- typical diameter: 200 m;
- octagonal or circular;
- vertical or inward sloping walls;
- water depth: 30 m;
- with or without a berm foundation;
- berm slope 1:7;
- diameter of top of berm: 240 m;
- water depth at top of berm: 10 m.

The models were subjected to a variety of wave conditions, both regular and irregular, which covered the range of waves likely to be encountered. These conditions ranged from 2.9 m, 7.2 s to 11.1 m, 14.0 s, for regular waves, and 3.2 m, 8.0 s to 9.0 m, 12.0 s for irregular waves. While it is recognized that regular waves may not provide realistic data, they were useful for visual observations.

EXPERIMENTAL METHOD

The experiments were conducted on 1:75 scale models in a wave basin in the Hydraulics Laboratory of the National Water Research Institute.

A typical layout is shown in Figure 1. The waves were generated with a piston type wave board, driven by a hydraulic servo system. Irregular waves were generated using a pseudo-random technique (Fryer et al, 1973). The berm was constructed of gravel covered with a veneer of mortar. The octagonal caissons were made of plywood, covered with self-adhesive vinyl to reduce the roughness. The circular caissons were made from galvanized sheet steel. The heights of the caissons were such that the runup was never as great as the wall height. Details are given in Judge (1984). The probes used to measure the runup were 0.75 m (prototype) from the caisson wall. This gap was chosen partly for reasons of ease of experimentation and partly to attempt to make a meaningful measure of solid or "green" water runup. After dicussions with representatives of the petroleum industry, this notion of green water was adopted as having a useful meaning as far as the structure would be concerned. As the layer of water running up an infinitely high wall becomes much thinner than 0.75 m, one would expect that it would tend to break up and become a spray and overtopping problem.

The waves and the runup were measured using capacitance probes of 24 gauge teflon coated wire (0.084 m prototype outside diameter). The probes were calibrated routinely throughout the experiments. Three probes were used to measure the offshore wave conditions. Nine probes were mounted on the caissons, 22.5 degrees apart, starting at the front face centreline, to measure the runup. The signals from the wave probes were collected by a data acquisition system incorporating a minicomputer.

The wave and runup data were analyzed in the following way. The characteristic height was determined for each probe, as four times the root mean square water surface displacement for both the wave height probes and the runup probes (denoted H_{co} for the offshore probes, and H_c for the probes on the structure). The runup was described in two ways. The first was simply the maximum runup (R_{max}) above the still water level. The second was termed the characteristic runup (R_{max}). To calculate this number, it was assumed that the ratio of the maximum runup to the maximum change in water level represented the average ratio of the crest elevation to the wave height. The characteristic runup was then defined as this ratio times the characteristic height for that probe. Then dimensionless runups (the ratios of maximum runup and characteristic runup to the offshore characteristic wave heights) were tabulated and graphed along with the ratios of local heights to offshore heights.

Video cassette recordings of most experiments were made and have been archived at NWRI. These video recordings were used to make visual comparisons of different island configurations and to supplement the wave probe data.

The following geometries were tested:

- submerged conical berm;
- vertical walled octagonal caisson on the berm;
- vertical walled circular caisson on the berm;

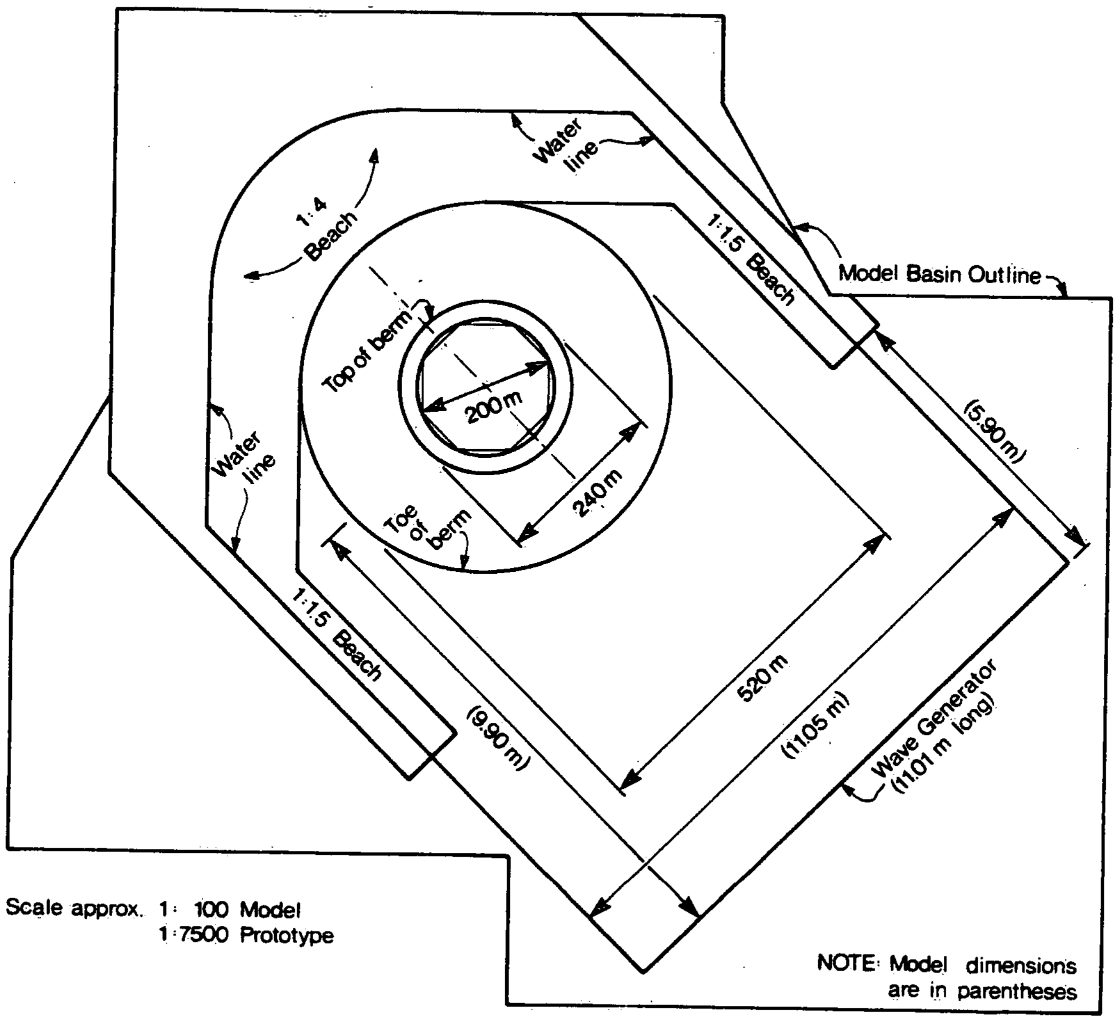

FIGURE 1 PLAN OF BASIN MODEL

- vertical walled circular caisson on the berm, artificial roughness on the caisson (0.95 m high by 0.36 m deep horizontal box sections above the still water level, 3.75 m centre to centre);
- sloping (30 degrees) walled octagonal caisson on the berm;
- vertical walled octagonal caisson without the berm.

In addition, several tests of the vertical walled circular caisson were recorded.

RESULTS

The first series of tests were conducted on the berm without a caisson island in place. These tests were used to get background data on the wave field over the berm in the absence of the islands, and to assess the general operation of the basin. The waves propagated over the berm in a fashion that was to be expected. Of particular note was the fact that the waves for the more severe conditions (10 and 12 s periods) tended to focus and break at the top of the front face or just on to the horizontal platform of the berm. The description of results in the remainder of this section focuses on the 3.2 m, 8.0 s and 6.0 m, 10.0 s wave conditions.

The results for the octagonal and circular caissons on the berm were similar: in general terms, the maximum runups were of similar magnitude. The location on the circumference of the maximum was sometimes different for the two caisson types. The maximum runups for the three irregular wave conditions are summarized in Table 1.

For the octagonal caisson, the maximum runup always occurred at the front centre line, with a secondary maximum at 45 to 67.5 degrees. The maximum runup for the 3.2 m, 8.0 s waves was 2.0 (normalized by the offshore significant wave height, as are all runups described here). The minimum occurred at the rear of the caisson, and was only 0.4. The distribution of the runup is shown in Figure 2. The maximum runup for 6.0 m, 10.0 s waves was 4.9. The runup at the back of the caisson was about 0.8, and the minimum, 0.5, occurred at 135 degrees. The runup distribution for this case is shown in Figure 3. The secondary peak is associated with the reflection/diffraction of the wave energy around the second and third faces of the octagon, and has been referred to as Mach-stem reflection (see, for example, Wiegel, 1964).

For the circular caisson, the maximum runup occurred either at the front centre line or at the probe located 22.5 degrees off the centre line. A secondary peak was not observed. For the 3.2 m, 8.0 s waves the maximum runup was at the front centre line and was 2.1, and the minimum was 0.4 at the rear. The distribution of runup is shown in Figure 4. For 6.0 m, 10.0 s waves, the maximum runup was 4.6, at 22.5 degrees off the centre line, and the minimum, 0.5, was at 135 degrees from the front centre line. The runup distribution for this case is shown in Figure 5. It was observed that there was more spray thrown up in front of the circular caisson, and that this spray was

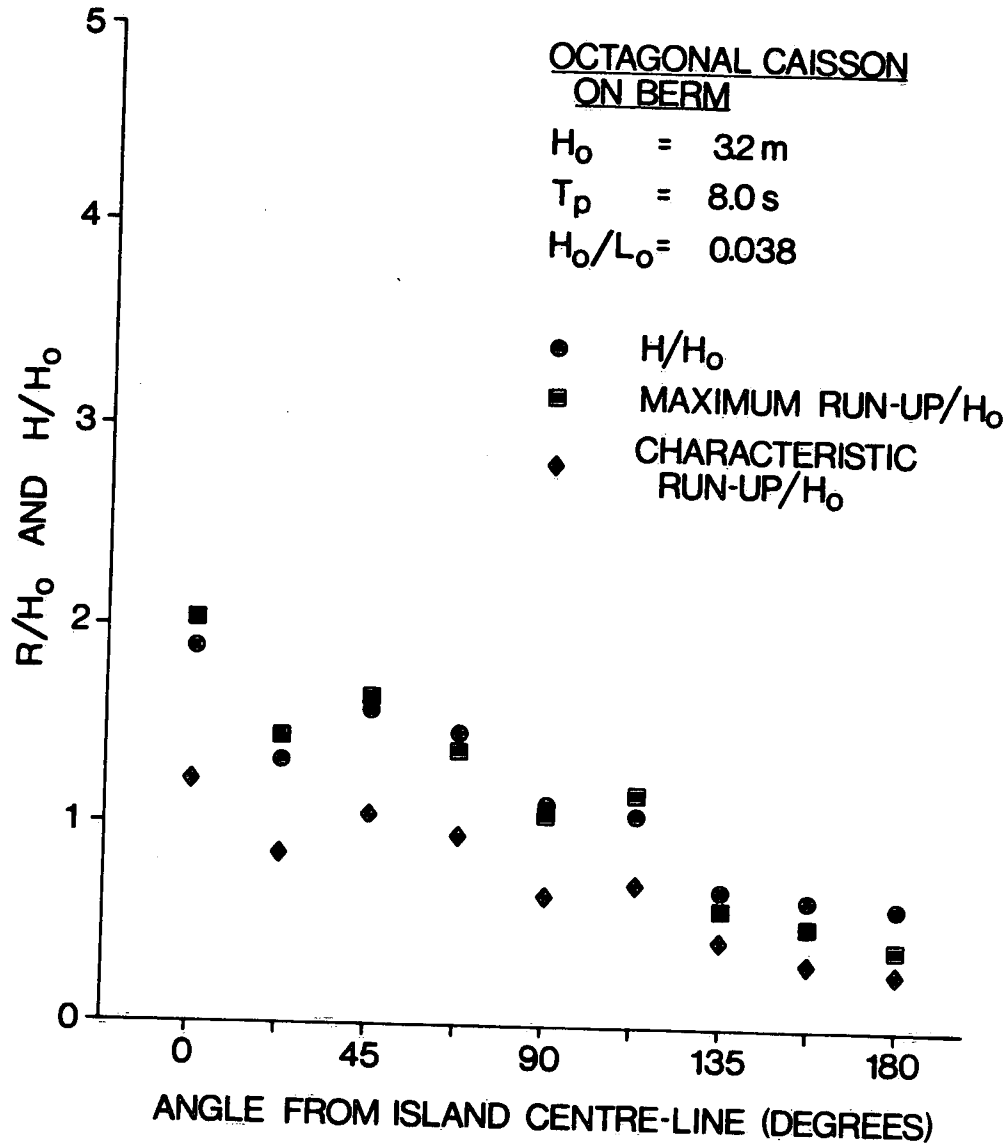

FIGURE 2 NON-DIMENSIONAL WAVE HEIGHT AND RUN-UP vs ANGLE FROM FRONT CENTRE LINE

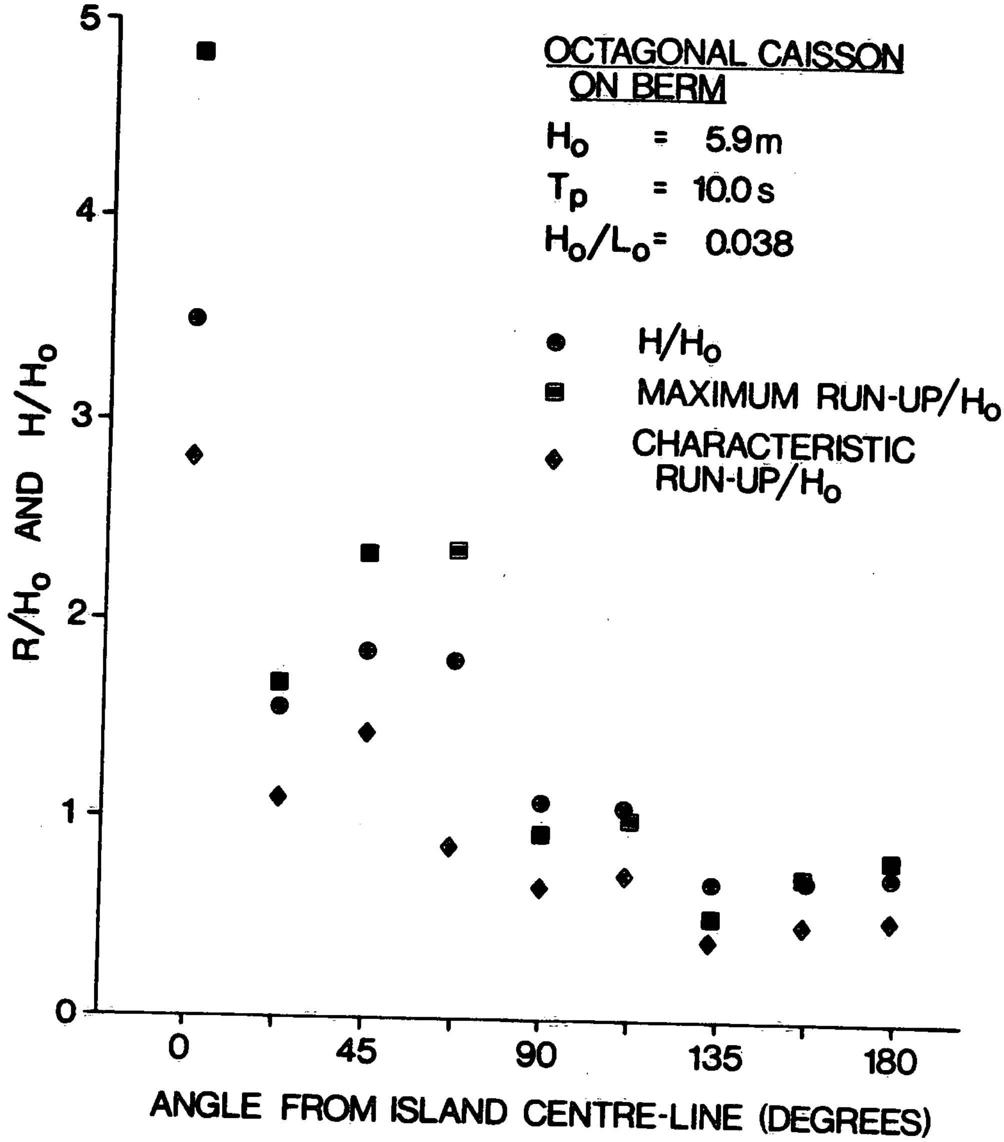

FIGURE 3 NON-DIMENSIONAL WAVE HEIGHT AND RUN-UP vs ANGLE FROM FRONT CENTRE LINE

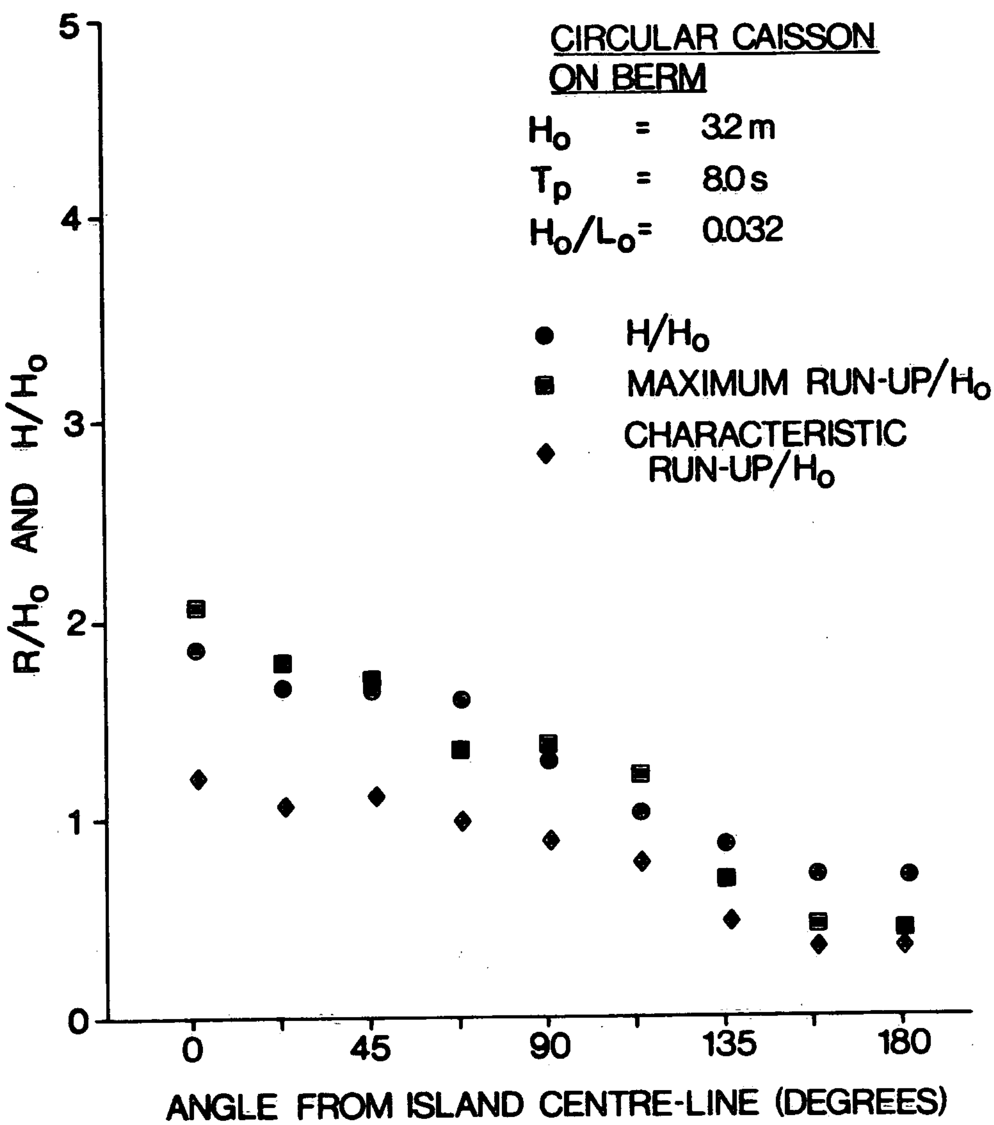

FIGURE 4 NON-DIMENSIONAL WAVE HEIGHT AND RUN-UP vs ANGLE FROM FRONT CENTRE LINE

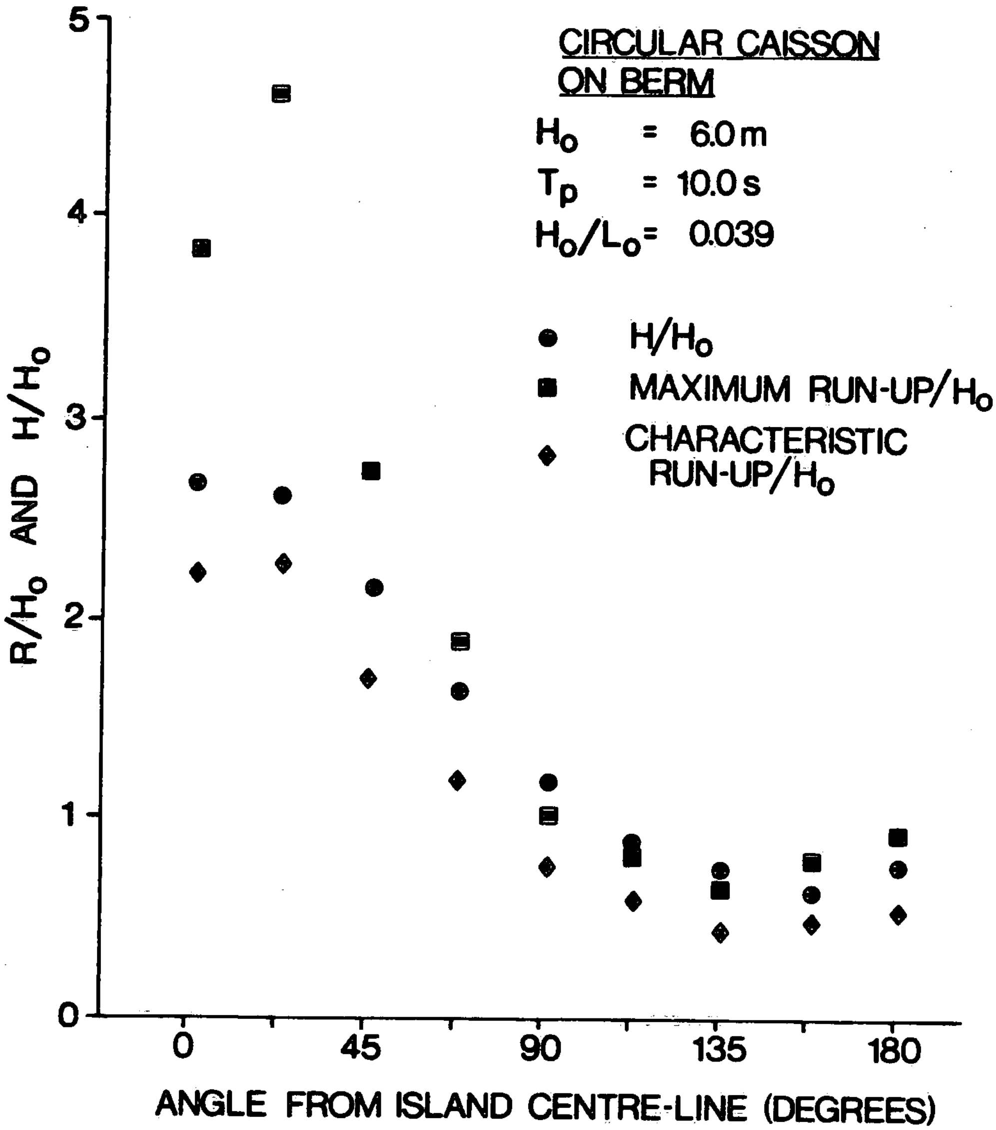

FIGURE 5 NON-DIMENSIONAL WAVE HEIGHT AND RUN-UP vs ANGLE FROM FRONT CENTRE LINE

TABLE 1. Listing of Normalized Extreme Values for the Irregular Wave Climates for all Caissons Tested

Wave Climates	T_p = 8 s, H_{co} = 3.2 m			T_p = 10 s, H_{co} = 6 m			T_p = 12 s, H_{co} = 9 m		
Island Type	$\frac{H_c}{H_{co}}$	$\frac{R_{max}}{H_{co}}$	$\frac{R_c}{H_{co}}$	$\frac{H_c}{H_{co}}$	$\frac{R_{max}}{H_{co}}$	$\frac{R_c}{H_{co}}$	$\frac{H_c}{H_{co}}$	$\frac{R_{max}}{H_{co}}$	$\frac{R_c}{H_{co}}$
Octagonal on berm	1.9	2.0	1.2	3.5	4.9	2.8	4.6	5.3	4.0
Circular on berm	1.9	2.1	1.2	2.7	4.6 *	2.3 *	3.8 *	4.8 *	3.2 *
Artificially roughened circular on berm	-	-	-	2.5 **	3.6 **	2.2 **	2.6 **	2.6 **	2.2 **
Sloped octagonal on berm	2.8	2.4	1.6	4.0	5.2	3.2	4.4	4.4	3.6
Full depth octagonal (no berm)	1.9	1.9	1.2	2.2	1.8	1.2	2.3	2.3	1.5

Notes: Care should be taken to consider data quality (Chapter 4) prior to applying the data given above.

All extreme values are from probe #4 (caisson front centre) except where marked by '*' or '**'.

* Data from probe #5 (22.5 degrees from front centre).
** Data from probe #5 (22.5 degrees from front centre) as probe #4 was not installed.

thrown back to sea. Thus, while this spray did not affect the measured runup, it could be of some concern, because it would be available to be driven back over the island by the wind. The relatively large amount of water in the spray contrasted with the case of the octagonal caisson where the reflected/diffracted wave contained much more water than the spray (based on visual observations).

Artificial roughness was added to the circular caisson, as described in the previous section. The runup was reduced substantially: for 6.0 m, 10.0 s waves, the runup was 3.6, a reduction of more than 20 percent. It was, however, noted that there was considerably more water thrown up in front of the caisson, above the elevation measured by the probes. This water could be driven over the island by the wind, and so diminishes the apparent benefit of the roughness.

The tests on the caisson with sloping walls are somewhat academic because it is likely that any island built with sloping walls would have a recurved portion at the top to maintain a useful working area on the top, and to deflect the water seaward. Nevertheless, the results are reported for completeness. The runup was 5.2 for the 6.0 m, 10.0 s waves, about the same amount as for the vertical walled caisson. Water was observed to travel up the wall substantially farther, but it was not detected by the probes, so must have been in a layer less than 10 mm (model), the distance the probes were offset from the wall.

The results for the caissons founded directly on the bottom were similar to those for the caissons on the berm for the smallest irregular waves, but were dramatically different for the two higher wave conditions. Only the octagonal caisson with vertical walls was instrumented, but the wave action on the circular one was recoreded on video, and the results were similar. For the smallest waves (3.1 m) the runup on the front face was nearly identical at 1.9, while the minimum, at the rear, was only 0.2. The runup for the 6.0 m waves was drastically reduced, being a maximum of 1.8 compared to 4.9 at the front, and a minimum of 0.2 (at 158 degrees) compared to 0.5. The distributions around the island are shown in Figures 6 and 7 for these cases.

DISCUSSION

The runup on the octagonal and circular caissons did not differ greatly but runup on the circular caisson was somewhat less than on the octagonal one. There were some relatively minor differences due to the geometries. The greatest runup on the octagonal caisson occurred at the front centre line whereas it often occurred slightly off centre on the circular caissons. The water appeared to be thrown forward, back towards the approaching waves on the latter, so that the total effect when wind driven spray is taken into account could be very similar. The Mach-stem effect at about 45 to 68 degrees on the octagonal caisson did not show up on the circular caisson. However, the runup at that location off the centre line was not significantly less on the circular caisson, so that there would not be any saving in freeboard requirement. The runup associated with the Mach-stem on the octagonal caisson was not nearly as high as on the front face, but it did appear to contain much more water. Therefore, the runup in that portion of the island must be considered for catastrophic overtopping, especially when defining minimum finite freeboard requirements. The minimum runup for all the caissons, with or without the berm present, occurred at the back centre line for the smaller waves. In contrast, for the larger waves it occurred between 135 and 158 degrees from the front face. This was attributed to the fact that the waves were travelling around both sides of the island and breaking as they met at the back centre line.

The large reduction in freeboard requirement in the absence of the berm, for the larger waves, was attributed to the absence of shoaling and refraction. Examination of the video for the tests with the berm only, revealed that the larger waves were indeed shoaling and refracting to the extent that they were breaking close to the top of the berm.

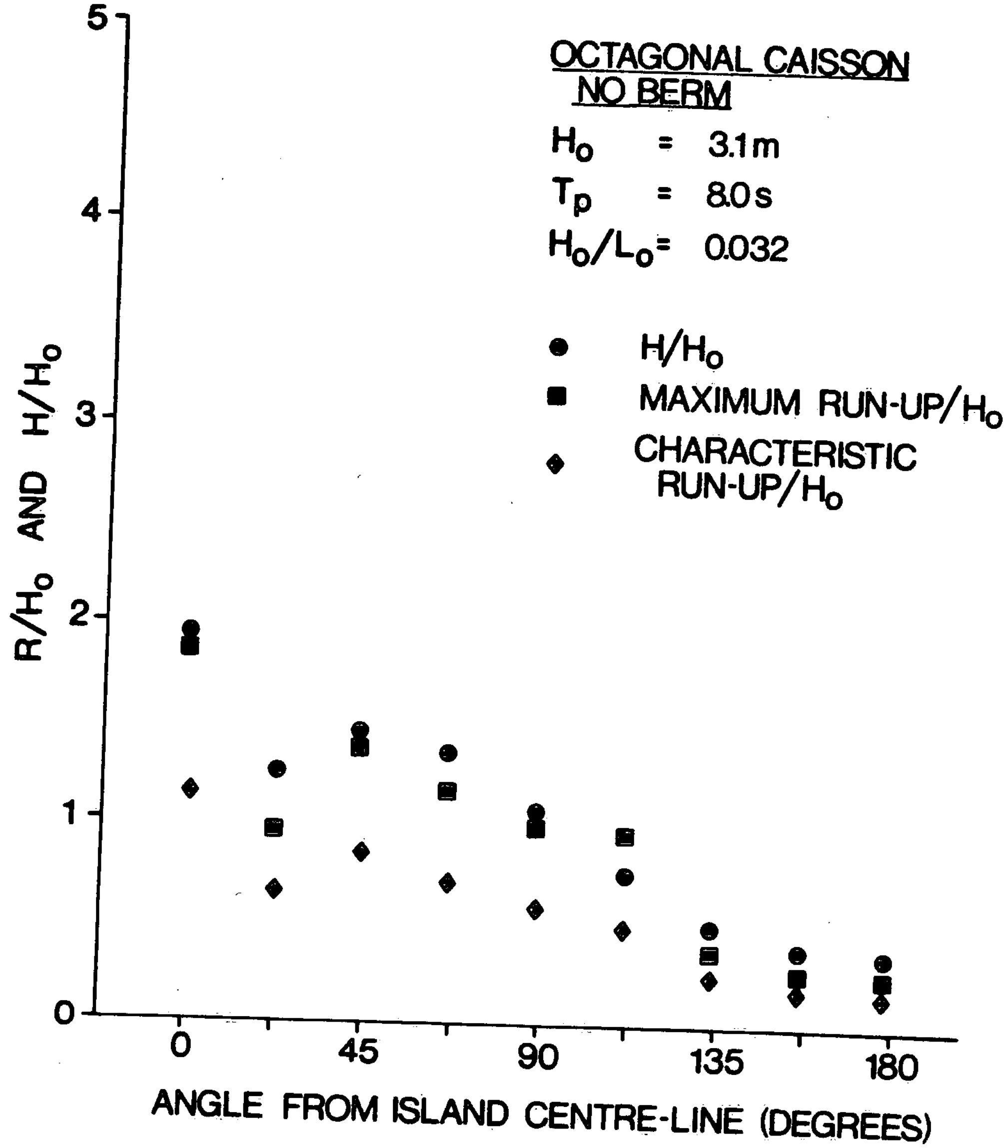

FIGURE 6 NON-DIMENSIONAL WAVE HEIGHT AND RUN-UP vs ANGLE FROM FRONT CENTRE LINE

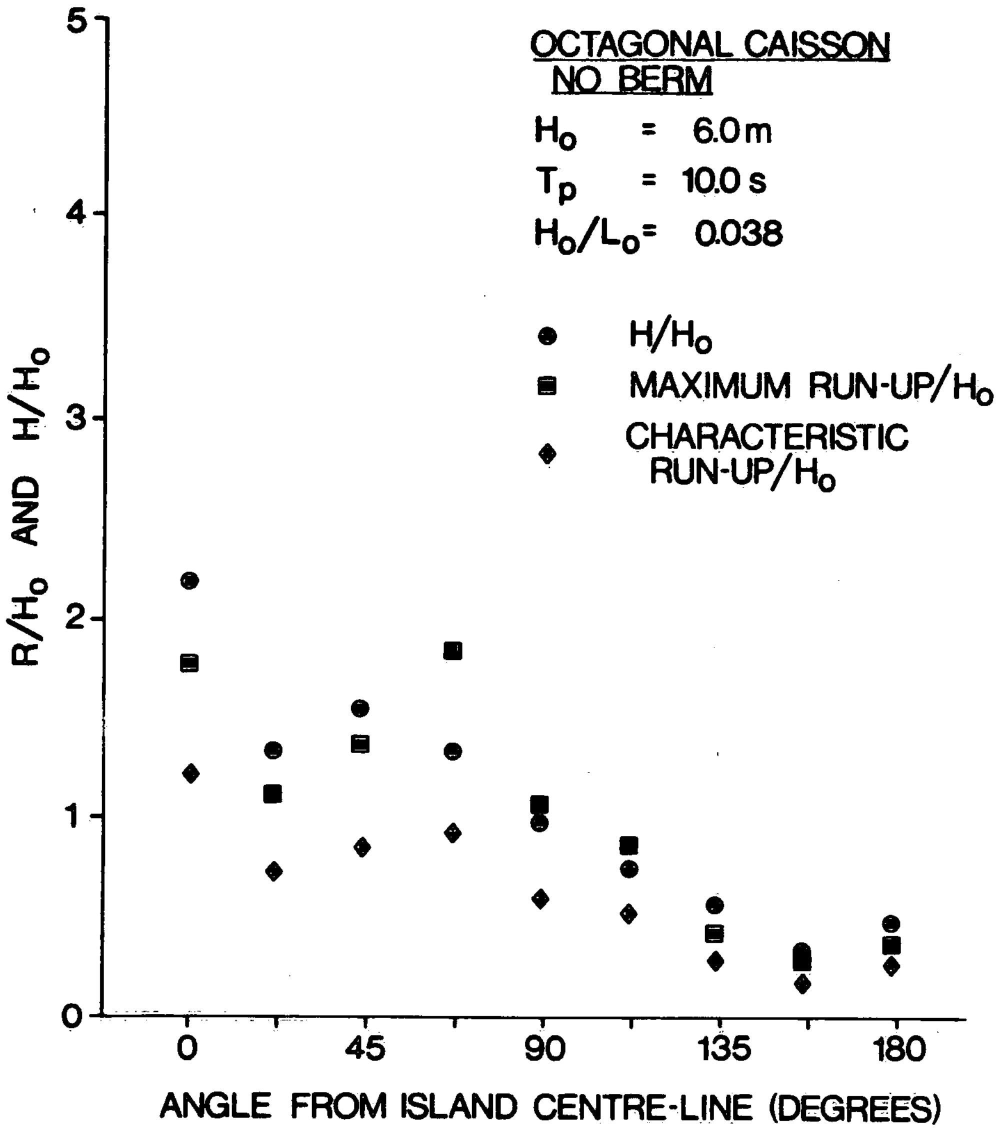

FIGURE 7 NON-DIMENSIONAL WAVE HEIGHT AND RUN-UP vs ANGLE FROM FRONT CENTRE LINE

Thus the waves were in the process of breaking at the location of the caisson, and this amplified the runup. This effect is in contrast with the tests using the most severe regular waves. In this case the waves were breaking farther in front of the caisson, resulting in a reduced runup. It would appear that the dimensions chosen for typical berm and caisson geometries of production platforms interact with the more severe wave conditions so as to aggravate the runup.

CONCLUSIONS

For the two planforms tested there was not a significant difference in the freeboard requirements. Artificial roughness may reduce the runup but appears to generate more spray. A recurved wall might reduce this spray problem. Clearly, the water depth at the caisson should be kept as deep as possible, for this reduces runup markedly, by eliminating shoaling and refraction and breaking at the wall.

For the geometries and wave conditions tested, a freeboard of about five times the offshore characteristic wave height is required when the caisson is on a berm but less than two times without the berm. Thus for berm founded caissons some overtopping may have to be accepted, and in addition the volume of water contained in the Mach-stem wave, available for flooding will be of particular concern. The freeboard requirement for caissons without a berm appears to be realistically attainable.

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