CLASSIFICATION OF WAVE LOADING ON MONOLITHIC COASTAL STRUCTURES

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Abstract

The paper uses the 'parameter map' which has been developed under PROVERBS (Probabilistic Design Tools for Vertical Breakwaters) in the frame of the ongoing MAST III programme of the European Union (EU contract no. MAS3-CT95-0041) to classify the wave loading on monolithic coastal structures and to identify the conditions leading to wave impacts. Data from four different hydraulic model tests have been used to verify and extend the parameter map. As a result an updated version is proposed for further design purposes.

1. Introduction

Waves approaching the shoreline from the open sea are transformed by various processes like shoaling, diffraction and refraction before they eventually break on the sloped foreshore. In conjunction with any coastal structure at the shoreline wave breaking is more complex to estimate and various methods have been developed to account for this phenomenon.

One of the most recent studies on this topic is conducted by a multinational European research group under the MAST III programme of the European Union within the PROVERBS project ('Probabilistic Design Tools for Vertical Breakwaters'). Within PROVERBS a parametric decision map has been developed to provide an easy-to-use guidance for the breaker type to be expected in front of vertical structures as a function of various geometric and wave parameters (*Allsop et al., 1996*; *Oumeraci, 1997*).

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This parameter map (Fig. 1) has been cross-checked against various structures and parameter variations but is still under further development. More work is needed to fill the gaps and add possible modifications of parameters. A contributions into this direction was made by *Kortenhaus and Oumeraci (1997)* who summarized small- and large-scale model tests and gave some advice on the use of slightly varied parameters and parameter ranges.

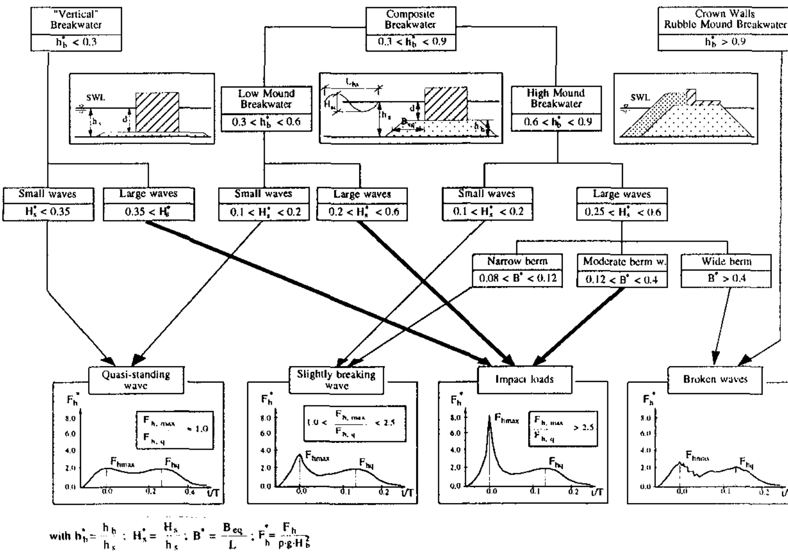


Figure 1. Parameter Map of PROVERBS (*Oumeraci, 1997*)

Very little information within the parameter map is yet available for composite type breakwaters with a very high mound. The aim of this paper is to feed and extend the aforementioned map with more detailed information obtained from large-scale model tests on innovative high mound composite breakwaters (HMCB) performed in the Large Wave Flume (GWK) of Hannover, Germany.

2. The Parameter Map Concept

The parameter map is a simple, easy-to-use map to identify wave loading on monolithic coastal structures. In the following some parameters and notations are defined. Furthermore, the input of the map (structure types) and the output (breaker types) are described in more detail.

(a) Governing Parameter

All parameters related to the various structure types are defined in Fig. 2. Three dimensionless parameters are needed to use the map and identify the breaker type at the structure. The occurrence or non-occurrence of impact breakers at the wall can be predicted by these parameters at the following three decision levels:

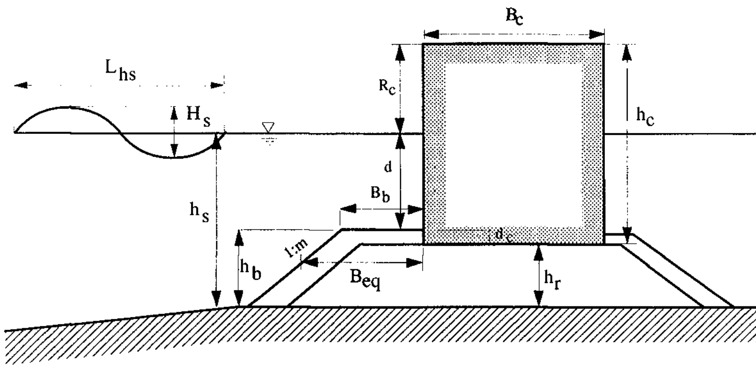


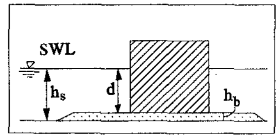
Figure 2. Definitions of Parameters

1. *Relative berm height* $h_b^* = h_b/h_s$: h_b is the height of the berm and h_s is the water depth at the toe of the rubble foundation; h_b^* represents the most important input parameter for the depth limited wave breaking in front of the breakwater, but also defines the type of structure (vertical breakwater, low or high mound breakwater, crown wall).
2. *Relative wave height* $H_s^* = H_s/h_s$: H_s is the significant wave height at the toe of the rubble foundation. H_s^* was found to be decisive for wave breaking where waves with small H_s^* do not break whereas higher waves could break at the structure thus inducing extreme impact pressures and forces. If H_s^* exceeds a certain maximum value (for details see *Muttray et al., 1998*) the wave breaks on the berm and only broken waves will reach the structure.
3. *Relative berm width* $B_{eq}^* = B_{eq}/L_{hs}$: B_{eq} is the equivalent berm width in front of the structure which is defined as $B_{eq} = B_b + (0.5 \cdot h_b \cdot m)$. The wave length L_{hs} is the local wave length in the water depth h_s determined by the peak period of the waves. B_{eq}^* describes the effect of the berm width on the occurrence of the impact loading.

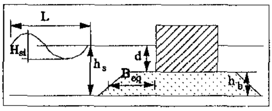
(b) Main Structure Types

Principally, four types of breakwaters can be distinguished. These types can be characterised by h_b^*, together with the most typical type of waves in front of these walls.

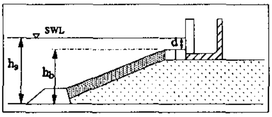
Vertical Wall Breakwater (VWB): this type is characterised by a very low bedding layer without any mound. The relative berm height h_b^* varies from 0.0 to 0.3. There is almost no wave breaking in front of these vertical breakwaters but mostly standing or slightly breaking waves occur. Under extreme wave height conditions wave may break at the wall (wave - wave interaction).



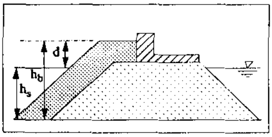
Low and High Mound Breakwaters (LMB and HMB): they consist of a rubble mound layer of various thickness and a caisson structure sitting on top of this mound. The relative berm height h_b^* varies from 0.3 to 0.9. Low mound breakwater (LMB, h_b^* = 0.3 ÷ 0.6) and high mound breakwater (HMB, h_b^* = 0.6 ÷ 0.9) can be distinguished. This type of breakwater can cause severe breaking at the wall and high loads at the structure.



High Mound Composite Breakwater (HMCB): a new type of composite type breakwater developed at PHRI, Japan with a very high rubble foundation and a smaller superstructure than standard vertical breakwaters is characterized by $h_b^* \approx 0.9 \div 1.0$. Depending on the water level at the structure only breaking waves or already broken waves can be observed at the structure, i.e. it represents a transition between a caisson breakwater and a crown wall of a rubble mound breakwater.



Crown walls (CW): crown walls are located on top of a rubble mound layer and usually the water level is below the berm so that generally $h_b^* > 1$. Most crown walls are designed for broken waves only.



(c) Main Breaker Types

From the parameter map four different breaker types may be distinguished. These types are classified by typical force time series showing their characteristics (*Oumeraci and Kortenhaus, 1997*).

Quasi-standing waves in front of vertical structures can be observed for smaller wave heights so that the incident waves are more or less fully reflected by the wall and do not break. The typical force history does not show significant peaks but alters slowly over time (quasi-static force).

Slightly breaking waves occur when the wave height is slightly increased and the waves start to break in front of a breakwater. Sometimes this breaking occurs at the wall, thus inducing a first peak in the force time series which is higher than the second (quasi-static) peak.

Wave impacts generally occur when the berm in front of the structure induces a breaker with the breaking point just in front of the wall. Many different types of impact breakers were already described (*Oumeraci and Kortenhaus, 1997*) but they are very difficult to be classified only by means of wave and geometric parameters. Therefore, the parameter map does not give any detail on the type of breaker or on the frequency of its occurrence. In all cases the force history shows a clear and high first peak which is significantly higher than the second 'quasi-static' peak.

If the breaking point is far enough in front of the wall (e.g. in case of a wide berm or extremely shallow water in front of the structure) only a *broken wave* will reach the structure. In this case a force history is obtained which is generally superimposed by high frequency oscillations due to a large air content in the water. The order of magnitude of the forces is the same as for slightly breaking waves.

3. Experimental Setup

In a joint research project between Port and Harbour Research Institute (PHRI), Japan and Leichtweiß-Institut (LWI), Germany the wave load and hydraulic performance and the loading of an innovative high mound composite type breakwater have been investigated.

Figure 3. Front View of Model Breakwater With Vertical Wall in the GWK

The most important dimensions, locations of measurement devices, information about the test setup and results of these tests can be found in *Muttray et al. (1998)*. A slit-type breakwater and a solid wall breakwater on a very high mound have been tested. Within this study results of the solid wall breakwater have been used only (acronym: CERI) to assure comparison with other data sets on vertical breakwaters.

Fig. 3 shows the front view of the model breakwater in the Large Wave Flume (GWK) where the foreshore, the rubble foundation and the caisson structure can easily be identified. The rubble foundation consists of rock of 0.5 to 5.0 kgs with an armour layer of 40 kg Accropodes. The caisson structure is made of reinforced concrete with a solid wall and a slit-type wall (pillars).

Three more data sets on composite type breakwaters have been used in this paper. These additional data sets were taken from the following large-scale and small-scale investigations performed at various institutes in the U.K. and Germany:

Random waves have been used on a composite type breakwater in a small-scale 2D flume at HR Wallingford. Various modifications of rubble mound geometry have been tested representing the most comprehensive data set (more than 200 tests) to support the parameter map (acronym: HR). These tests have been described in more detail in *Allsop et al. (1996).*

Regular and random waves have been tested in large-scale model tests performed in 1993 and 1994 in the Large Wave Flume of the 'Coastal Research Center', a joint institution of the University of Hannover and the Technical University of Braunschweig, Germany. Due to the large scale only one geometry has been tested but water level and wave parameters were varied extensively thus resulting in about 80 tests with random waves and 60 tests with regular waves (acronym: GWK). For more details on test setup see *Kortenhaus and Oumeraci (1997).*

Regular and random waves have also been used for small-scale model tests performed at the Franzius-Institute of University of Hannover, Germany in 1993 (*Oumeraci et al., 1995*). About 80 tests with regular waves and 120 tests with wave spectra have been conducted which were all used for feeding the parameter map (acronym: WKS).

The type of waves and the range of relative parameters for all tests are summarized in Tab. 1.

Tab. 1: Overview of Data Sets Used for Analysis

Acronym	Waves	$h_b^* = h_b/h_s$	$H_s^* = H_s/h_s$	$B_{eq}^* = B_{eq}/L_{hs}$
CERI	R, S	0.75 - 1.00	0.17 - 0.49	0.03 - 0.07
HR	S	0.43 - 1.00	0.21 - 0.53	0.09 - 0.33
GWK	R, S	0.46 - 0.63	0.12 - 0.56	0.11 - 0.30
WKS	R, S	0.57 - 0.79	0.11 - 0.46	0.18 - 0.54

R = Regular waves, S = Spectra (random waves)

4. Classification of Breaker Types

The breaker types classified in section 2 are sometimes very difficult to distinguish from the force or pressure time series they induce at the wall. Therefore, a procedure had to be found to identify these breakers by means of both video observation and analysis of force histories.

In Fig. 4 a slightly breaking wave is shown when it breaks at the wall. Fig. 5 shows a wave breaking in a reasonable distance before reaching the wall so that this may be classified as 'broken wave' whereas Fig. 6 shows a wave breaking directly at the structure thus inducing high pressure and force peaks. From photos like this and video frames of all of the tests an identification of the respective breaker type was performed. However, it has been found from the analysis that the procedure to classify the breaker types is different for regular and random waves. This will be described in more detail in the following sections.

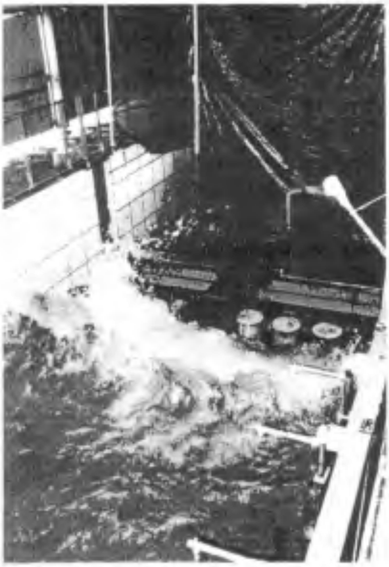


Figure 4. Slightly Breaking Wave

Figure 5. Already Broken Wave

Figure 6. Impact Breaker

(a) Regular Waves

Regular waves are generally easier to handle than random waves as they generate regular signals at wave gauges and pressure transducers given that a wave absorber is available behind the structure and the wave reflection control at the wave paddle works properly. In this case, these waves can easily be characterised by mean values of pressures and forces and only one breaker type exists.

As already mentioned the distinction of breaker types could be very difficult from force histories only, particularly, if complex berm geometries are involved as this is the case for high mound breakwaters. It is therefore strongly recommended (i) to use video analysis of the tests for distinction of breaker types and (ii) to use available time series of pressures (preferably in the vicinity of the still water level) or horizontal forces to check the breaker type identification. The latter step is required because very often it cannot be observed from the video whether a wave breaks as a slightly breaking wave or as an impact breaker. This, however, can easily be identified by the force or pressure signal showing a clear sharp peak in the case of an impact breaker.

(b) Random Waves

(i) Flow Chart Procedure

For random waves it is not practicable to identify each single wave in a wave test by means of video analysis. Furthermore, each breaker type may occur in a single test. The main goal, however, is to identify a characteristic breaker type for each of the tests performed. Therefore, a different approach is needed which may be summarized as follows:

In Fig. 7 the analysis starts with a time series analysis of the random wave test. From this the occurrence probability of impact breakers P_{Fh} can be obtained which is described in more detail within the next section. If P_{Fh} is higher than 5% of all waves in the test, it is assumed to be sufficiently large to design the breakwater for impact breakers. If this is not the case, videos from the test are needed to identify the prevailing characteristics of the waves in the individual test. This allows for a fast video analysis so that a minimum of time is needed.

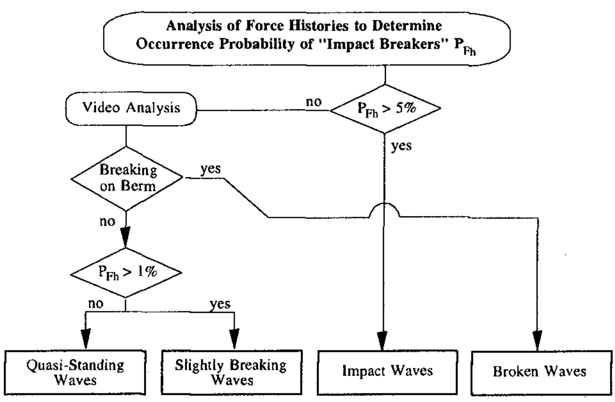


Figure 7. Flow Chart for Identification of Breaker Types for Random Wave Tests

If the video analysis shows some breaking waves at the structure the time series analysis (P_{Fh}) is needed again to distinguish between 'quasi-standing' waves ($P_{Fh} < 1\%$) and 'slightly breaking' waves ($P_{Fh} \geq 1\%$). Thus, the principal breaker type of the test has been found and will be assigned to the related test.

(ii) Time Series Analysis of Impact Breakers

Impact breakers can be identified from horizontal force histories integrated at the front wall of the breakwater. Therefore, an automatic procedure has been set up to identify these impacts.

In Fig. 8 a typical force time series of random waves is shown where the left vertical axis represents the horizontal force in model units and the right axis the relative horizontal force (non dimensionalised by $\rho \cdot g \cdot H_{si}^2$); the horizontal

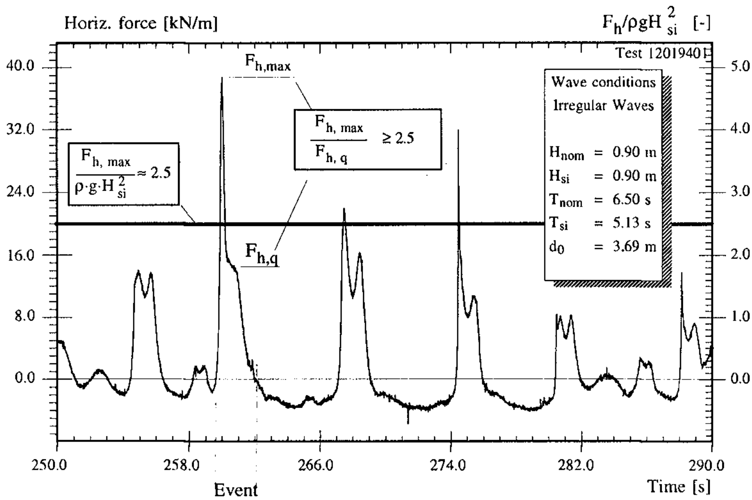


Figure 8. Definition of Impact Breakers from Force Time Series

axis is the time in model units. Two criteria were adopted to identify impact breakers:

1. the relative horizontal force $F_h/\rho \cdot g \cdot H_{si}^2$ should be larger than 2.5; and
2. the ratio of the maximum horizontal force $F_{h,max}/F_{h,q}$ (first peak over second peak for each single event) must be larger than 2.5 as well.

If these criteria are applied to force time series the number of impact breakers can be found by simply counting the number of impacts and dividing by the number of all events (waves) in one test.

5. Results

All data from the various data sets have been analysed as described above and breaker types have been assigned to each of the tests. Therefore, the next step is to identify the areas of the parameter map where these data fit. For this purpose the first two relative parameters h_b^* and H_s^* described in section (b) are plotted against each other (Fig. 9).

The boxes in Fig. 9 indicate the branches of the parameter map as given in Fig. 1. Each box is labelled by the type of breaker which has to be expected for these relative parameter. All observed breaker types for each data point are indicated by different symbols and a second symbol for each point gives the type of tests in which it has been observed.

Following the parameter map for most data points the breaker type seems to be dependent on the relative berm width B_{eq}^*. Within this box all breaker types were observed thus indicating that the relative berm height and the relative wave height are not sufficient to classify the breaker type. However, outside this box some data points can be found with h_b^* = 1.0 (i.e. water level in height of the

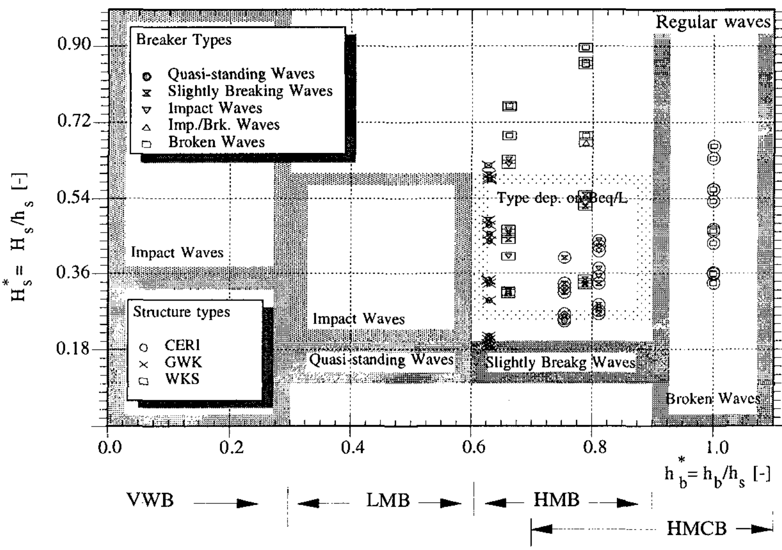


Figure 9. H_s^* vs h_b^* for Regular Wave Tests (All Data Sets)

berm level) which fall in the box of 'broken waves'. The observed breaker types match the parameter map prediction very well so that the map is verified in this region.

For $H_s^* > 0.6$ the data points indicate that the waves will break before reaching the structure. For most of the data points beyond this margin 'broken waves' were observed only. Therefore, the parameter map can be extended in this region.

In Fig. 10 the same plot is shown for random waves. Again, most data points fall in the region of the parameter map in Fig. 1 where a further distinction by the relative berm width B_{eq}^* is required. All other data seem to support the branches of the parameter map in the same way than for regular waves. Additionally, the gap in between 'small waves' and 'large waves' is filled by some data points showing mainly 'quasi-standing' waves but some 'slightly breaking' as well. Therefore, an extension of the parameter map for this region is proposed where a further distinction by the relative berm width will be required.

In a second analysis step all data have been plotted for the region where the predicted breaker type is dependent on the relative berm width. In Fig. 11 the relative wave height is plotted versus the relative berm width B_{eq}^*. Again, all boxes indicate the region of the parameter map which are labelled according to the respective breaker type the parameter map predicts. It should be noted that only data are plotted which fall in the region of the map with a relative berm height of $h_b^* = 0.6 \div 0.9$. All other data were removed from the plot.

From Fig. 11 it can be seen that there are almost no data to support the regions of narrow and wide berms so that most of the data points are within the

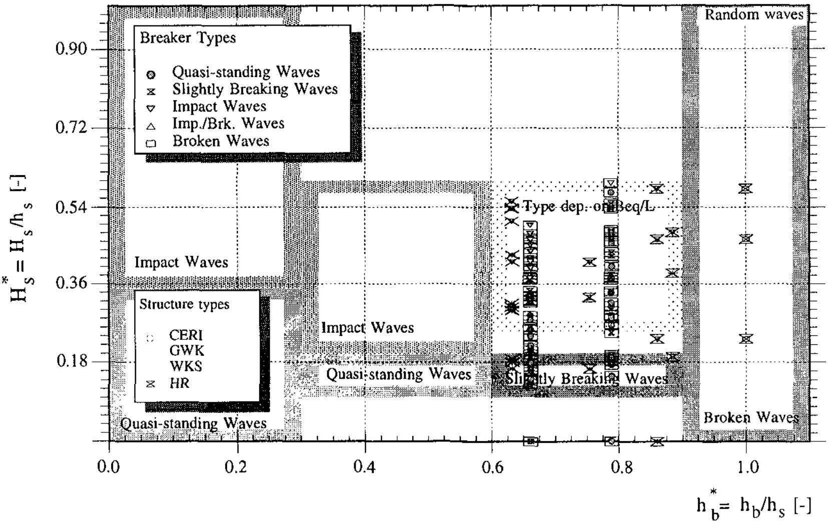


Figure 10. H_s^* vs h_b^* for Random Wave Tests (All Data Sets)

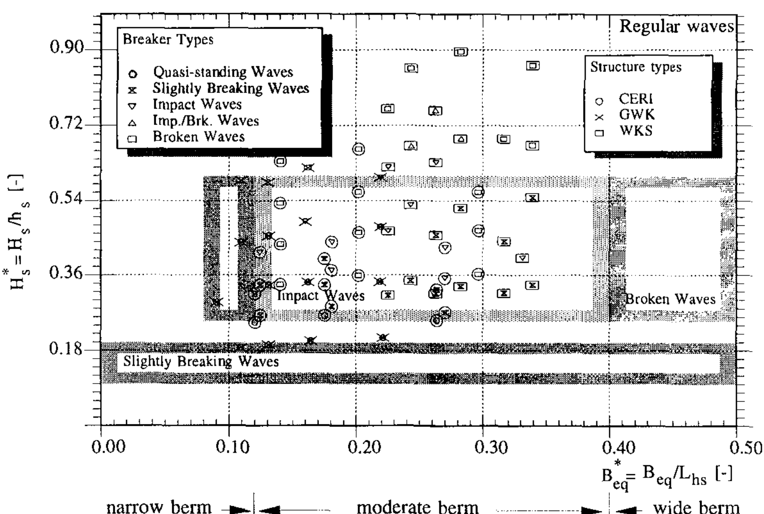


Figure 11. H_s^* vs B_{eq}^* for Regular Wave Tests (h_b^* = 0.6 ÷ 0.9, All Data Sets)

box of 'impact breakers' and above. Within this box no further distinction between breaker types can be made, i.e. that all breaker types are more or less spread all over this area. Therefore, more data would be useful testing the influence of narrow and wide berms, and further analysis is needed to find a criterion for further discrimination of the breaker types. For practical use, however, all data falling in the aforementioned region of 'large waves' and 'moderate berm widths' should be handled as 'impact breakers' and designers have to realise that impacts could occur at the wall.

Together with the amendments of the map already discussed in this paper the following revised parameter map is proposed for the prediction of the most probable loading cases in front of vertical structures (Fig. 12).

The updated map comprises the following modifications and extensions:

- verification of 'broken waves' for 'crown wall' type breakwaters with a relative berm height $h_b^* > 0.9$;
- extension of the map for high mound composite type breakwaters (HMCB) for $h_b^* = 0.9$ to 1.0;
- extension of the parameter map for regions of relative wave heights $H_s^* > 0.6$ ('very large waves');
- modification of range of relative wave heights $H_s^* = 0.20$ to 0.60 for 'large waves'.

6. Concluding Remarks and Future Work

A 'parameter map' has been developed under PROVERBS (Probabilistic Design Tools for Vertical Breakwaters) in the frame of an ongoing MAST III programme of the European Union (under contract no. MAS3-CT95-0041) to classify the wave loading on monolithic coastal structures and to identify which breaker type leads to impact loading.

Data from four different model tests have been used to verify and extend the parameter map so that an updated version (Fig. 12) is proposed for further design purposes.

However, due to some limitation in the data sets the following future work remains to be done:

- All data sets were based on a foreshore slope of 1:50. It is therefore questionable whether the behaviour of waves approaching the structure over steeper slopes is predictable by the present parameter map. More data are therefore needed to extend the parameter map in this respect.
- Almost no data are yet available for very narrow and very wide berms so that the respective regions of the map are based on very few data only. Further model tests or prototype experience are also needed to verify the map in those regions.
- The boundary between high mound breakwater (HMB) and high mound composite breakwater (HMCB) was set to $h_b^* = 0.9$. More data analysis is needed to specify this boundary.

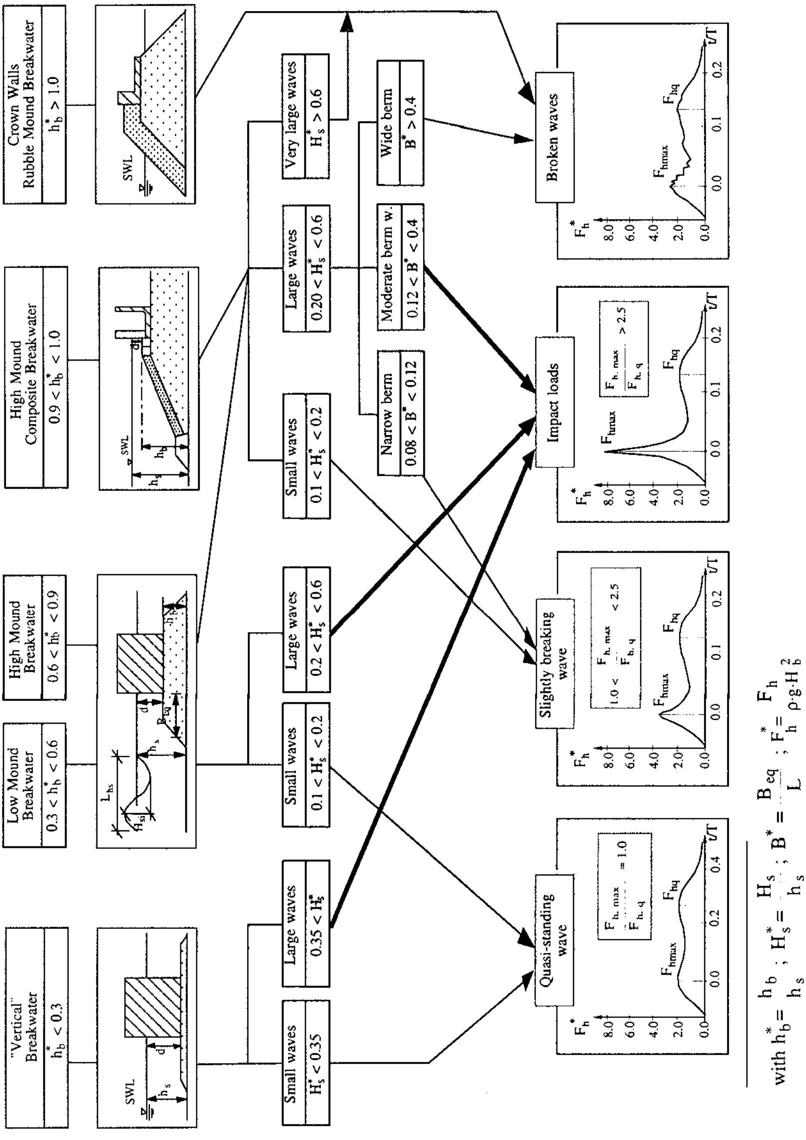


Figure 12. Updated Parameter Map to Identify Loading Cases

Acknowledgements

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