FACTORS OF SAFETY FOR THE DESIGN OF BREAKWATERS

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ABSTRACT

This paper proposes to improve the safety of breakwaters by two important changes in the philosophy of design. When hydraulic model testing is used as a design tool the authors propose to reduce the specific gravity of the model breakwater to introduce a factor of safety in the prototype. They also recommend that the concept of testing for stability with the once in 50 year or once in 100 year wave should be replaced by a more rigorous statistical analysis to determine a design wave which has a probability of exceedence of no more than 5% in the lifetime of the structure.

INTRODUCTION

Severe damage to several breakwaters in recent years has focussed attention on current design methods, which appear in some circumstances to be unreliable. Most designers are aware of the inadequacy of present design formulae, and they therefore rely heavily upon hydraulic model tests. The use of conventional hydraulic models to check the design provides at best an uncertain safety margin against failure. The authors' view is that this is a major factor in the large number of breakwaters which fail.

Parallels are drawn from the design of building structures in which partial factors of safety are applied to the forces and to the properties of constructional materials in order to analyse the design of its ultimate limit state.

The introduction of quantified partial factors of safety in the design process for breakwaters is proposed, not only in theoretical analyses but also in hydraulic model testing procedures.

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DAMAGE TO BREAKWATERS

During the winters of 1978, 1979 and 1980 several rubble mound breakwaters on the western seaboard of Europe and on the North African coast were severely damaged.

Possible causes of damage have been discussed by Brunn (1). Damage to caisson type breakwaters, used most frequently in the Far East, has also occurred in the past and has been summarised by Goda (2). Because of the bad record in service of large breakwaters, both of rubble mound construction and caisson construction, this paper has been prepared to consider improvements to our design philosophy with these two forms of construction chiefly in mind.

PRESENT DESIGN METHODS

The limitations of present design methods have been discussed in a previous paper (3). Present practice for the design of rubble mound breakwaters of the type shown in Fig. 1 is to prepare an outline design using Hudson's formula (4) and then test the cross-section in a hydraulic flume. The design is modified during the testing programme until predetermined damage criteria are satisfied.

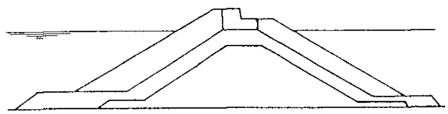

Figure 1 Rubble mound breakwater

In the case of natural rock armour the criterion may be expressed as a percentage loss of armour units over the exposed face, perhaps 1%. This is an inexact definition as "exposed" may have various conflicting meanings and for the same wave climate breakwaters at shallow and deep water sites have very different superficial areas of armour. Because the Hudson formula was developed for rock armour where breakage of units is not normally a problem, loss of armour in the model may have correctly represented the importance of damage in the prototype. Provided that it is relatively easy to mobilise the equipment to reposition armour stones (or providc extra armour) repair is not difficult but if plant is not available the problem of repair can be much more serious than is represented by the percentage of armour lost.

Although the Hudson formula is not strictly applicable to artificial armour units which depend for their stability on interlock, it is often used to obtain a first estimate of unit mass which is then checked by carrying out flume tests. The acceptance criterion is the degree of rocking or movement of individual units. In cases where excessive movement leads to fracture of armour units, repair of damaged sections is quite a different matter from merely repositioning rock armour units.

Interpretation of the model test results should reflect this difference but there is no agreement on how to do this.

Irregular waves are now used in flume testing, except in laboratories which lack up-to-date wave making equipment and sophisticated control systems. The wave spectrum is usually based on JONSWAP or other spectra derived from instrumental recordings. The flume model is tested in stages by increasing the wave height until the armour layer becomes unstable, which gives an indication of the margin against failure.

Although vertical faced caisson type breakwaters of the type shown in Fig. 2 can be designed without tests by using wave pressure theory, it is usual to carry out hydraulic model tests in a flume to check the stability of the design. Failure can occur by either sliding or overturning, but Japanese experience (2) shows that sliding is the most common type of failure.

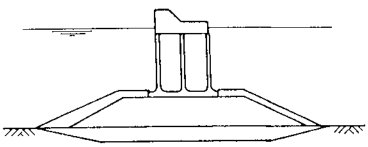

Figure 2 Caisson breakwater

The chief weakness of existing design and hydraulic model testing procedures is that there is no commonly agreed method of introducing a factor of safety against failure (however defined) for either type of breakwater nor is there an accepted set of definitions on which quantitive criteria and measurements are based.

The easiest way of providing a safety margin against failure of any type of breakwater is to increase the height of the design wave. Doing this increases the forces which the structure has to resist. For example in the case of Jubail east breakwater (5) completed in 1979, wave records were inadequate and the 1 in 100 year design wave height was assessed from wind records at 4.5m. Because no direct wave observations were available and because it was considered essential to provide a maintenance free structure the consultants increased the design wave height to 6.5m. This represents a factor of 1.4 on the 1 in 100 year wave height.

For rubble mound breakwaters another simple way of increasing the margin of stability of the armoured slope is to use heavier armour in the prototype than the model tests, or calculations, indicate is required. If artificial armour units are used this does not necessarily lead to a corresponding increase in total volume of concrete used in the armour layer and it normally reduces the number of individual units to be placed. However, the feasibility and costs of producing and handling larger sized armour have to be taken into account. The increase in stability is not as great as it might appear as the wave height which can be resisted is in proportion to the cube root of the weight of armour unit. Doubling the weight of armour units therefore introduces a factor of about 1.26.

Measures such as these give a margin of safety but are purely arbitrary, and there is no generally accepted philosophy to guide the designer in applying them. When this lack of guidance is compared with the extensive use of codes of practice for the design of other types of structure the contrast is quite remarkable.

MODERN BUILDING DESIGN CODES

Consider, for example, the procedures for designing a building structure, in which (in contrast to breakwaters) the applied loads are reasonably known, the properties of the construction materials are strictly controlled and the workmanship is open to inspection at all stages. What is more the different phenomena such as bending, shear, bond etc., can be easily analysed separately; this is not at present the case with armour design, although the authors believe that further research would enable this point to be reached (3). There are however some useful concepts on factors of safety which could be applied to the design of breakwaters.

In the past, building structures have been designed on a "working stress" basis in which it is confirmed that the actual applied loads can be carried without exceeding allowable stresses. The allowable stresses are chosen to provide a margin of safety on stresses which would cause failure. This well established method is still used in many countries but it has weaknesses which have led to the introduction of a different method of design. The most serious weakness arises when the stability of a structure depends partly on its mass and partly on the strength of its members. Working stress analysis provides a margin of safety on the latter but not the former. Consider for example a quay wall design in which a relieving platform is supported on raking piles. The combined factor of safety against failure due to variations in applied load is not equal to the ratio between ultimate strength and working stress. To achieve this requires a different method of analysis.

The present design concept in UK, which was introduced for reinforced concrete structures by a code of practice published in 1972 (6) and is being introduced for other types of construction, is based on analysis of conditions at failure. The analysis, known as the limit state method of design, applies factors both to the values of the applied loads and to the strength of concrete and steel reinforcement. These factors, known as partial safety factors, are chosen to ensure that when its stability has been analysed with appropriate partial factors of safety applied to loads and materials the structure will not become unfit for the use for which it is required, i.e. that it will not reach a limit state in service. In preparing the code of practice the drafting committee state that insufficient statistical data was available to enable a design method to be developed which is in complete accord with probability theory. The choice of partial factors of safety is admitted to be arbitrary but the intention is that as new knowledge of loads and strengths becomes available they can be amended. The factors applied will then vary according to the quality of data on loadings available to the designer, the accuracy of knowledge about material properties and the acceptable probability of failure.

The order of probability of failure which might be considered to be acceptable in the design of a building structure is 1 in 200,000 of failure leading to fatality during the working life of the building (7). This is achieved by adopting characteristic strengths of materials which have a 5% probability of being exceeded, and loadings which are intended to have a similar probability of being exceeded. The safety of the final structure depends upon the combination of events of low probability of occurence.

LIMIT STATE DESIGN OF BREAKWATERS

When designing breakwaters there are many areas of uncertainty where use of a partial safety factor would lead to a more logical design process.

These are:

(i) loadings

- wave heights
- wave periods
- wave form and grouping
- storm duration
- effects of wave refraction and diffraction

(ii) structure

- strength of materials
- specific gravity or bulk density of materials
- interlock achieved (for rubble mound breakwaters)
- accuracy of construction and general standard of workmanship
- breakage of elements

(iii) miscellaneous effects

- scale of model
- foundation settlement
- effectiveness of scour protection

Our present state of knowledge on breakwater design does not permit us to assign a partial safety factor to each of the variables outlined above. The two variables which are generally of the most importance are wave conditions and stability of armour layers or of caissons. Let us therefore consider the possible application of partial factors of safety to these two variables.

Wave conditions are usually assessed using graphical statistical methods to predict (for example) the once in 10, 20, 50 or 100 year wave height. Recorded data seldom fits the probability graph exactly and a judgement has to be made on precisely how the line on the graph should be extended to give the extreme wave heights, or which type of probability graph paper to use for this purpose.

If we then use one of these values for design of a breakwater, there is a high probability of the design value being exceeded. Even if we know exactly what the once in 100 year wave is there would still be a 63 percent probability of it occurring or being exceeded once in 100 years, so this would not be a safe basis for design of a structure which we wish to have a 100 year life. But in fact our data and our methods of analysing it are far from perfect so the probabilities of exceedance may be much greater than 63%.

There is a strong case for adopting a more conservative design wave and also applying a partial factor of safety to the design.

A major consideration in applying factors of safety to wave heights is the length and type of records which determine the quality of our knowledge of the conditions. Perhaps the simplest case is when wave heights are depth limited. Before the concept of irregular waves was introduced it might have been argued that the maximum height of breaking wave was known, depending only on maximum depth of water (or highest water level), but we now know that combinations of waves of different periods are capable of producing "freak" waves even in shallow water. These cannot be predicted mathematically and even when they are reproduced in a hydraulic model we cannot be certain that there is not a more severe combination in nature. Some factor of safety is required to cover this uncertainty. When a final design depends upon model tests it will not be practicable in the depth limited case to provide this safety margin by increasing wave heights and it must be done in some other way. This is discussed later, but we should first consider the case when waves are not depth limited.

If wave heights are not depth limited it is logical to introduce a partial factor of safety by increasing the applied wave height.

By analogy with structural design we should be designing the breakwater to resist the most severe waves which have only a small probability of occurrence in the life time of the structure after making full allowance for the inadequacy of our basic data. It is common to use as a design wave the best estimates of the 1 in 50 year wave - or once in 100 year wave. As Tucker and Fortnum (8) have shown for Seven Stones Light Vessel there is a 63% probability that the 1 in 50 year wave height will be exceeded in a 50 year period. Clearly this is a much higher probability of exceedence than would be accepted in structural loadings. They also showed that there would be a 10% chance that the highest wave in 50 years would be more than 16% higher than the 1 in 50 year wave.

Another problem arises from the relatively short periods of observations which we have to use for projecting long term probabilities. All too often engineers have had to design breakwaters using significant wave heights derived from only one or two years relevant wave records. Variations between individual years can be considerable; at Seven Stones light vessel the maximum 50 year wave height predicted from 12 months records in 1969 was 24.4m and from 12 months records in 1973/4 was 28.8m (8). Assuming a cubic relationship for armour weight, this represents an increase of 64% in weight of armour unit.

These relations depend upon local wave climate and require careful satistical analysis of specific records. The authors propose that statistical analysis to predict the wave height which has no more than 5% (or at most 10%) probability of exceedence during the life time of the structure should replace the use of once in 50 year or once in 100 year design waves.

As wave records are normally not available at the exact site of the structure, and wave heights may be affected by the presence of the structure, it would still be necessary to consider, as carefully as possible, the effects of refraction and diffraction on wave heights at the breakwater and to use increased waves to allow for these effects in the hydraulic model. The quality and duration of base data is also very important in assessing the possible range of variation in wave heights at the structure. Taking all aspects into consideration one would estimate the design wave heights which would have an acceptably low probability of being exceeded within the life time of any particular structure. These could then be used in theoretical analysis or in tests in a hydraulic flume.

We must also make allowance for uncertainties regarding the accuracy of hydraulic modelling of the wave spectrum and of the representation in a model of the true prototype stability.

Whether we are considering armouring of a rubble mound structure, a concrete capping on a rubble mound, or a deep caisson structure on a rubble base, the main disturbing force results from water pressure and the main stabilising forces derived from the weight of armouring, capping or caisson. In theoretical analysis using limit state design a factor of safety would be introduced by increasing the applied loads calculated from the design wave. In theory the same margin of safety could be achieved in model tests by increasing the specific gravity of the fluid used in the flume. This is however not a practicable method to usc in a hydraulic model; water is the only convcnient choice of fluid. The authors therefore propose instead that these uncertainties should be dealt with by a simple reduction in the specific gravity (in the model) of the main elements of construction. This has the same effect as increasing the wave forces.

Current modelling technique is based on the concept of reproducing the prototype as accurately as possible, and the main effort has been devoted to getting weights (specific gravities) correct. Precise reproduction of the prototype is no doubt an cxcellent aim in pure research intended to advance knowledge, say, of the type of collapse which can occur (or to reproduce a failure which has occurred) but in using hydraulic modelling as a design tool it would be much more helpful to the designer to model the structure deliberately with reduced specific gravities so as to incorporate a factor of safety in the prototype. In all the most important failure conditions the critical masses are submerged. The factor of safety introduced by reducing specific gravity would therefore be in the ratio of submerged specific gravities in prototype and model.

A great advantage of doing this, rather than arbitrarily increasing the design wave height used in tests or altering the dimensions of, say, the armour units by testing for one size and building another larger size is that the geometry of the model and prototype would be the same. The hydraulic advantages of this will be obvious but correct geometrical relationship of the disturbing (wave) forces and stabilising (gravity) forces is no less important. Concentration in recent years on "correct" modelling of specific gravity has led to the use of armour units made from plastics rather than mortar. As a result it has not been possible to reproduce the coefficient of friction between units correctly and the geometry of the forces between units has also been wrong.

When modelling with reduced specific gravity, sand-cement mortar will again be a practical solution and it should be easier to produce units with surface friction close to prototype values.

Table 1 shows the effect on model specific gravities of introducing factors of safety of 1.2, 1.5 and 2.0 into tests of concrete armour units.

TABLE 1 - EFFECTS OF FACTOR OF SAFETY ON MODEL SPECIFIC GRAVITY

Factor of safety required	1.2	1.5	2.0
Specific gravity of prototype concrete	2.40	2.40	2.40
Prototype submerged specific gravity (sea water SG = 1.025)	1.38	1.38	1.38
Model submerged SG	1.15	0.92	0.69
Model SG in dry	2.18	1.95	1.72

A great advantage of introducing this concept of reducing specific gravities of breakwater units so as to provide a partial factor of safety in the prototype compared to the model is that in most types of breakwater, and in many different elements of, say, a rubble mound or caisson structure, weight in the final analysis provides all the stabilising forces. Even with interlocking units which derive stability partly from contact with their neighbours it is in the end the weight of a group of units which provides the stability of the structure. This method can therefore be applied consistently to a wide range of different forms of construction.

The exact choice of factor safety to be introduced in this way must be the subject of further research and therefore, another paper, but the authors would strongly advocate the adoption of partial factors of safety in breakwater design and suggest the use of values in the above range in the meantime. The lower value of 1.2 might be adopted for rubble mound breakwaters armoured with rock, or with very robust concrete armour units such as cubes, where substantial movements can be accepted with no risk of breakage. A value of 1.5 might be adapted for caisson structures and for concrete armour units which are liable to break under excessive movement. A factor of 2.0 may be appropriate only where heavy loss of life could result from a failure. Factors of safety below 1.2 could be used for example, in rubble mound designs where the main armour is rock and where equipment could always be mobilised quickly for repair.

Conclusion

The authors' conclusion is that the large numbers of failures of breakwaters can and should be reduced in future by introducing the concept of partial factors of safety into the design philosophy.

When we have reliable mathematical methods of analysis we will be able to do this in exactly the same way as in limit state structural design codes.

Until then we much rely upon the use of hydraulic models to test and develop modifications to our ideas. Factor of safety can be provided by a deliberate reduction in the specific gravity of the elements of construction being tested. This would be the only way of introducing a factor of safety where waves are depth limited.

Where waves are not depth limited it is recommended that the use of design waves based upon return periods of once in 50 years or once in 100 years should be replaced by a more rigorous statistical analysis to determine the wave conditions which are likely to have a probability of occurence of not more than 5 percent during the intended lifetime of the structure.

If the authors' proposals are adopted they believe that there would be a long overdue improvement in the performance of breakwaters. Our choice between different design options would also be made on a more rational basis.

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