CHAPTER 127

A PROCEDURE FOR THE ANALYSIS AND DESIGN OF CONCRETE ARMOR UNITS

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ABSTRACT

A rational approach to the design of rubble mound breakwaters that incorporates both the hydraulic stability and the structural integrity of individual concrete armor units is presented. A key element of this improved design procedure is the development of instrumentation to measure loads occurring on armor units in a physical model of a breakwater. Numerical methods have been employed to determine stresses throughout the armor unit once the loads are known and interaction design curves were developed from measured data. These interaction curves provide a useful assessment of the structural integrity of the armor units. The curves clearly demonstrate the overall factor of safety associated with the armor unit and the expected mode of failure. Based on the results of this type of analysis, the cost effectiveness and safety associated with different design alternatives may be explored and a breakwater that is both hydraulically and structurally efficient may be designed.

INTRODUCTION

The use of concrete armor units has become increasingly widespread, especially as rubble mound breakwaters have been constructed at locations where quarried rock of sufficient size was not available. In recent years, however, the armor layers of many breakwaters throughout the world have been severely damaged. This damage has often led to a breach of the breakwater structure rendering it only partially effective; the financial costs of such damage have sometimes totalled into the hundreds of millions of dollars. In certain cases, these breakwater failures have been attributed to the breakage of the individual concrete armor units. These problems have arisen because the research and development of concrete armor units has tended to focus on the hydraulic stability of the units with little or no consideration given to the structural integrity. Guidelines do not exist to aid the engineer in the structural design of armor units as there is a complete lack of knowledge of the nature and magnitude of the forces that may occur on the units in the breakwater environment.

The damage that has occurred on many breakwaters has clearly demonstrated the inadequacy of existing design procedures for

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concrete armor units. A rational design procedure for breakwaters must encompass many facets of engineering endeavour including hydraulic, structural, geotechnical and materials engineering. The ultimate goal of an effective design scheme is to improve the hydraulic and structural efficiency of the armor layer, leading to more cost effective breakwater structures.

A comprehensive approach to the design of concrete armor units is presented in this paper. A key component of this design method was the development of instrumentation to determine the structural response of armor units in a physical model when subjected to simulated prototype wave attack. The structural integrity of the armor unit may be assessed once stresses and strains occurring in the unit can be quantified. The design of a unit is facilitated by the development of interaction diagrams which display armor unit structural strength and the unit's load response, and clearly demonstrate the overall factor of safety associated with a selected unit.

THE DESIGN PROCEDURE

Baird and Hall (1983) first suggested an alternate design procedure for concrete armor units that assesses both the hydraulic stability and structural adequacy of the individual units once the forces exerted on the units are defined. This procedure has been adapted in this report and is presented in Figure 1. Such a procedure represents a natural extension of current modelling practice and incorporates the load measuring instrumentation scheme discussed in the next section.

Referring to Figure 1, the first step in the design of any breakwater is to define the environmental conditions to which it will be exposed; the most important factor being the wave climate. An initial design for the breakwater must then be developed on the basis of experience or with the use of design formulas such as Hudson's equation. The selection of the armor unit will depend on a number of variables such as performance data reported in the technical literature, costs, and construction considerations.

The design is then tested using a physical model and modified until the selected armor units are hydraulically stable under the design wave conditions. At this stage, all of the units are assumed to remain structurally sound.

The next step in the design sequence is to determine the forces and/or the structural response of the armor units in the breakwater model. The response to both static and quasi-static loads can now be measured by a specially instrumented armor unit, which is discussed in the next section of this paper. The instrumentation system measures the internal bending and torsional moments at one location in the armor unit. The present investigation focuses on the dolos unit but the application of such techniques is not limited to this particular form of armor

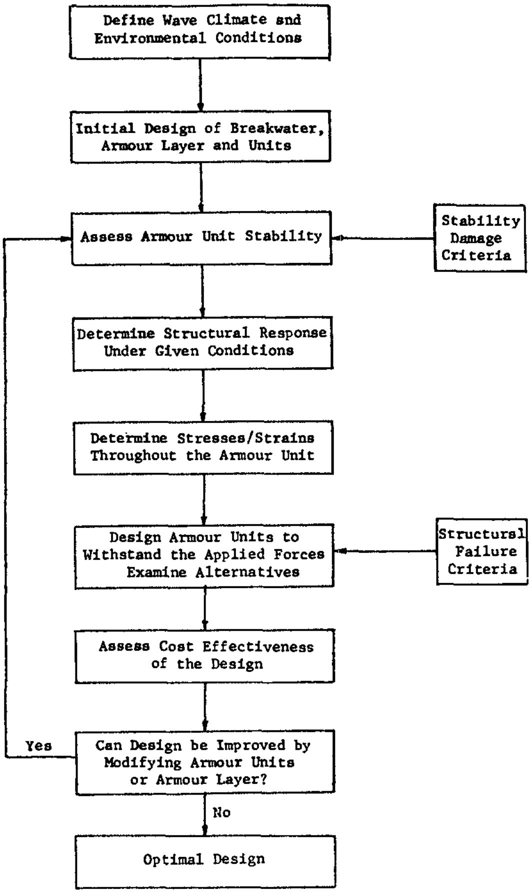


Figure 1 The Design Procedure

unit but to many units where bending and torque may be induced. As well, other similar types of instrumented units can be easily developed. Several instrumented units are placed at various locations in the armor layer and a series of tests conducted with the measured forces/stresses continually monitored.

The measured data are scaled to prototype and the individual armor units must then be analyzed with respect to the scaled forces or stresses. Generally, the armor unit's structural response can only be determined at a specific location on the unit. These stresses must be examined statistically and are then extrapolated to other locations to determine extreme stresses in the most critical regions within the armor unit. This may be achieved most easily by numerical analysis techniques such as the finite element method.

Once the critical stresses are known, the armor unit is designed to resist the applied extreme loading conditions. This entails the adoption of structural failure criteria and safety factors as is done with all structural design. Several alternatives can be examined, including alterations in the geometry and materials of the unit. Different means of increasing the strength of armor units that may be explored include the use of reinforcing, prestressing, fibre-reinforcing and high strength concretes. The effects of such changes on the structural strength of individual armor units may be readily assessed using standard analytic procedures in structural engineering. A sufficient margin of strength should be retained in the unit so that any potential dynamic loads may be resisted, such as may occur during handling and placement, and due to impacts caused by direct wave action, by inter-unit impact and by projectiles.

An important stage in the design procedure is to assess the design and its various alternatives in terms of cost effectiveness. In current design procedures, the economic benefits of altering the structural strength of armor units could only be assessed qualitatively as there was, up until now, no means of evaluating just how strong the units should be.

Finally, the overall breakwater design must be examined in terms of possible modification to either the armor unit or armor layer design. For example, altering the breakwater geometry or modifying the shape of the armor units themselves may be more cost effective than increasing the strength of the individual units.

The design process for concrete armor units outlined above will result in an optimum breakwater design that is both hydraulically and structurally sound under the given wave conditions. This design procedure is analogous to conventional structural engineering practice whereby the loads on a structure are initially defined, stresses throughout the structure determined, and the structure designed to resist the applied loadings.

THE ARMOR UNIT LOAD CELL

The key element in the design procedure discussed above is the load cell or load measuring system. The basis of this system is a thin-walled aluminum tube, which is instrumented with strain gauges and then inserted at the mid-shank location of a model armor unit (in this case a dolos) constructed of a steel-fibre reinforced epoxy, as shown in Figure 2. Strain gauges mounted on the tube measure all of the surface strains due to bending and torsion. Since dolosse primarily experience stresses due to bending and torsion, as exhibited by prototype testing and by the nature of their shape, the axial and shear stresses are considered to be of secondary importance. Details of the design, calibration and evaluation of the instrumentation scheme may be

Figure 2 The Armor Unit Load Cell

found in Scott, Turcke and Baird (1986) and Scott (1986).

The tubes which are inserted are of a different diameter, shape and material than the dolos shank, thereby violating complete similitude, but were designed such that the bending and torsional rigidity of the section were properly scaled from prototype. Such techniques have previously been suggested for structural models by Le Mehaute (1965) and Murphy (1950). Thus, bending and torsional strains were properly scaled but axial and shear strains were distorted. This technique allowed the measurement of strains under even the smallest loads. The output voltages of the strain gauge circuits that measure the bending moments and torques are calibrated against known loading conditions. Thus, two orthogonal moments and torques are measured directly by the system. This creates, in effect, an armor unit "load cell". The net result is that bending moments and torques can be established with a high degree of accuracy at one section in the armor unit under different load conditions.

Two dolosse having overall lengths of 203 mm and 106 mm were constructed using this force measurement scheme. The model units were made of a steel-fibre reinforced epoxy material, Devcon Plastic Steel, modified by the addition of lead pellets to make the density equivalent to that of concrete. This epoxy was utilized because it could be easily cast and then machined and worked in similar manner to any soft metal. Other materials could have been employed if they had a density similar to that of the prototype concrete.

The two dolos load cells were calibrated by the application of static point loads at various locations on the armor units and the strain gauge output measured; this procedure is employed in the calibration of any load transducer. A linear relationship was established between gauge output and the bending or torsional moments.

The calibrations were repeated prior to each test series to ensure that the load cells' characteristics had not changed in time. The calibrations were also performed prior to and subsequent to the application of the waterproofing, and showed that the water protection system had no effect on the load measurements.

An extensive series of tests were designed to fully evaluate the performance of the measurement system in both a dry environment and in the dry/wet environment of a hydraulic flume. Specific objectives of the test program were to examine both the sensitivity and accuracy of the load cell for measurement of forces in a model breakwater. The tests were divided into three categories: (1) static tests under self-weight loading; (2) static tests in a model breakwater; and (3) tests in a hydraulic flume. The results of the tests in the first category were compared against theoretical computations of moments and torques to determine the accuracy of the load cells.

The second set of tests examined the static forces on an amour unit due to placement and settlement in a breakwater. It was noted from the preliminary results that up to 25% of the structural capacity of the dolos unit can be utilized to resist these static loads. Such information is important for the proper design of armor units and may be readily extracted from physical models for different breakwater configurations.

The final set of evaluation tests employed a single instrumented unit rigidly mounted on a smooth slope. These tests were conducted to determine the effect of changes in wave height and location on armor unit response under controlled experimental conditions where the fluid flow was not as complex as which occurs in the breakwater environment.

The evaluation tests demonstrated the viability of the load measurement scheme for determining the structural response of armor units in the breakwater environment. This system had numerous advantages:

i) proper distribution of mass throughout the model,
ii) extremely high sensitivity levels with good accuracy in small scale models,
iii) excellent protection from environmental influences,
iv) flexibility of use: the same instrumentation could be employed in different types and sizes of armor units.

ANALYSIS AND DESIGN OF A BREAKWATER

A typical breakwater of conventional design was selected for the model investigation. The breakwater model was constructed in a two-dimensional hydraulic flume at a length scale of 1:40 as shown in Figure 3.

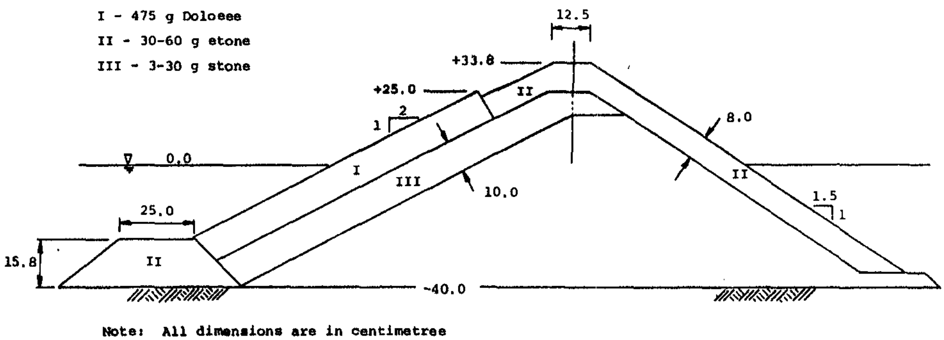


Figure 3 The Breakwater Model

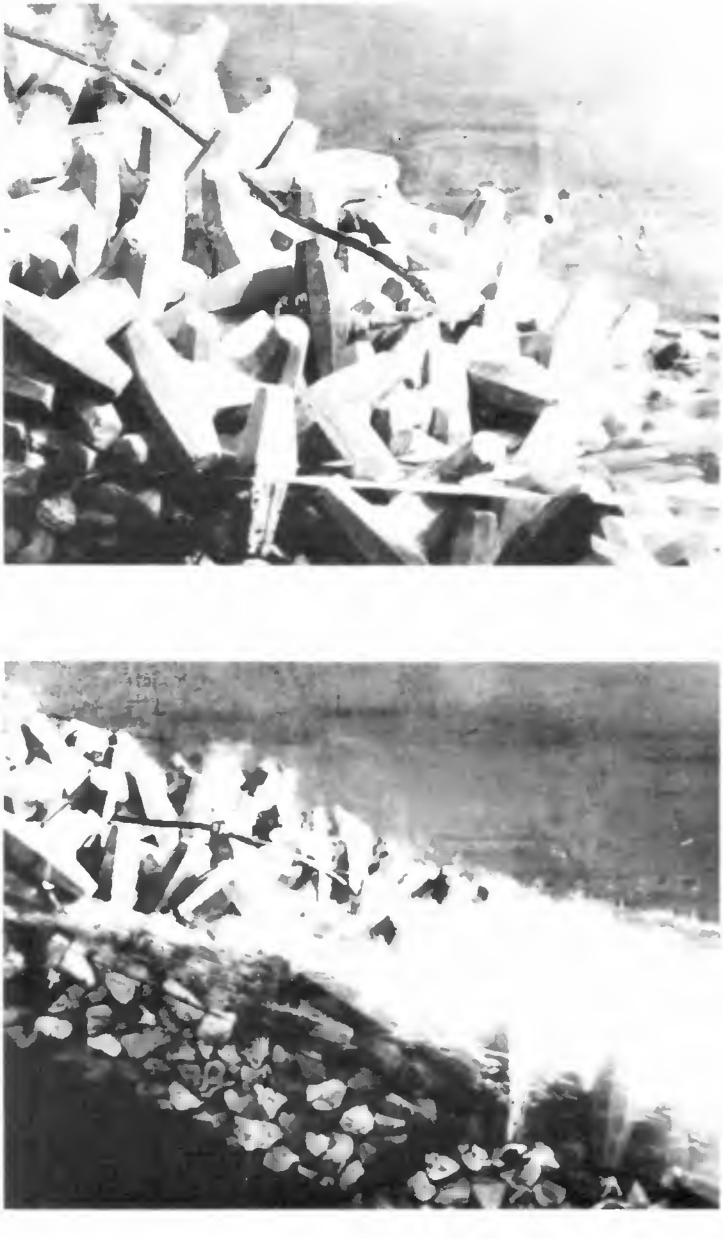


Figure 4 Photographs of the Breakwater Test

The primary armor layer was formed of 475 gram dolosse placed in two layers. At the specified scale, these units corresponded to 30 tonne units in prototype. During the test program, the structure was subjected to regular waves of height 24 cm and a period of 1.75 seconds, corresponding to a wave height of 9.6 metres and a period of 11.1 seconds in prototype. Assuming a K_d value of 15.9 (i.e. two layers of randomly placed dolosse, non-breaking waves, less than 2% damage (no rocking)), Hudson's formula yields a dolos weight of 24.3 tonnes for the given wave conditions [U.S. Corps of Engineers (1984)]. Thus, the 30 tonne units used in the model were hydraulically stable. This was supported by observations during the breakwater tests, in which little or no rocking of the dolos units was observed. The photographs of Figure 4 show the instrumented unit positioned in the armor layer and the breakwater being subjected to wave action.

Tests were conducted at twelve different locations in the armor layer; six were in the top layer and the remainder in the bottom layer. Prior to each test, the instrumentation was zeroed and calibrated. The unit was then placed in the armor layer and the static load response measured. The internal forces were monitored and graphically displayed when the model breakwater was subjected to wave action. Both the nature and magnitude of the forces were examined. These forces are created by both the inertial and drag forces of the water during wave breaking, uprush and downrush. A typical response of the armor unit to wave attack is shown in Figure 5 where the measured response for the two orthogonal bending moments and torque have been plotted against time. The repeatability of the peak signals with the wave period was excellent in all tests and the levels of the static forces may be noted on the plot. There was also excellent correlation of the peak signals from test to test at any one location.

Figure 6 displays some of the results of the test series. Here, torque has been plotted against the vector sum of the orthogonal bending moments for the maximum response recorded in each test as obtained from the time history plots of the internal forces.

Throughout the test series, the load cell performed with a high degree of reliability, and the waterproofing protected the instrumentation even under the severe environmental conditions of the model breakwater. The load cell exhibited high sensitivity levels and was able to measure even the small induced forces of static loading. The presence of lead wires to the instrumented unit did not pose any difficulties in the tests and did not affect the stability of adjacent units.

The next step in the design procedure, once the structural response is known in the model, is to assess whether structural failure will occur and how the armor units may best be designed to resist the induced forces in prototype. Several activities

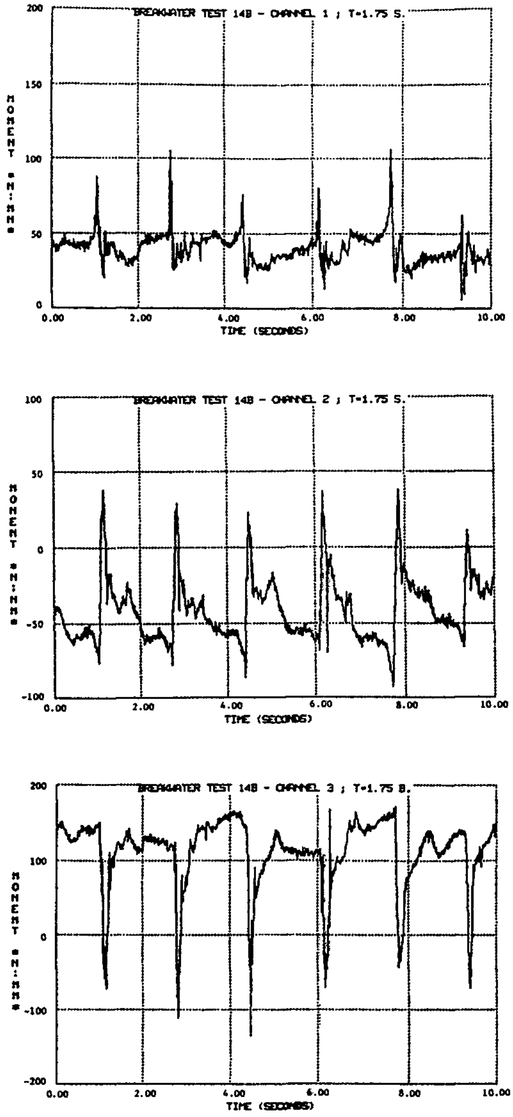


Figure 5 Typical Response of the Local Cell to Wave Attack

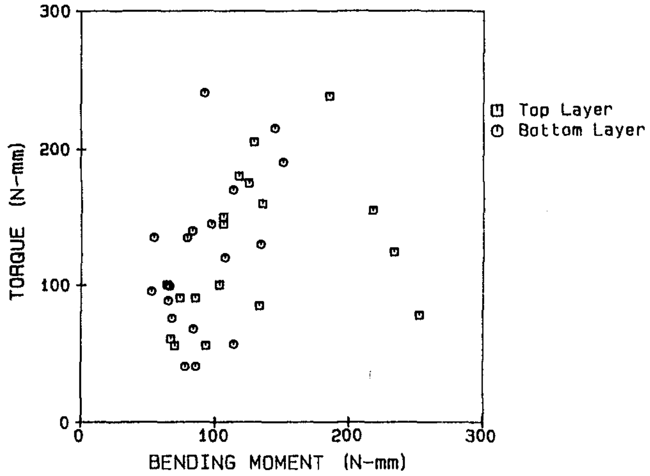


Figure 6 The Peak Internal Forces Measured

are essential to achieving this goal. First, the model forces/stresses must be scaled to prototype using the appropriate scale factors. Second, certain failure criteria for the designed armor unit must be identified and compared to the scaled data. Third, as the forces/stresses cannot be measured at all locations within the armor unit, approximate stress distributions must be determined throughout the unit.

Using the appropriate scaling relationship, the moment and torque levels in the prototype were computed. In order to determine if the combined effect of the moment and torque would cause a section to fail, a failure criteria had to be established. This led to the development of an interaction equation, based on the concrete failure theory of Cowan (1953, 1955), relating failure in the dolos shank composed of plain concrete under the combined actions of bending and tension:

$$\left(\frac{M}{M_{cr}}\right) + \left(\frac{T}{T_{cr}}\right)^2 = 1$$

where:

$$M_{cr} = 0.1597\ (Rh)^3\ f'_t$$

$$T_{cr} = 0.2140\ (Rh)^3\ f'_t$$

M_{cr} and T_{cr} are the pure bending moment and pure torque that would induce cracking in the dolos shank, R is the waist ratio, h is the dolos size and f'_t is the direct tensile strength of the concrete. The above expression is valid within the dolos shank; however, many dolos failures have been known to occur at the fluke-shank interface of the unit. Therefore, it was necessary to extrapolate the measured response to other regions in the armor unit. This was achieved by means of numerical analysis using the finite element method where the stress increase at the fluke-shank interface was examined under different extreme loading and boundary conditions. The finite element grid used for the dolos unit is shown in Figure 7.

A typical result is displayed in Figure 8 where the peak moments and torques at the fluke/shank interface are plotted along with the failure curve for concrete strengths of 30 MPa and 40 MPa. It can be seen very clearly that the results for some of the units lie outside the safe region and, therefore, these units would have failed. These test results showed that despite using armor units which were hydraulically stable under the incident wave conditions, structural failure would occur, consequently demonstrating the inadequacy of the dolos armor unit as designed for this particular application. Fatigue has not been considered, though it can be a very likely source of problems in the breakwater environment.

The next stage in the analysis was to redesign the armor units to withstand the applied forces. This could be achieved by either altering the geometric shape of the unit, increasing the size of the unit or increasing the structural strength of the unit. The strength of concrete may be augmented by numerous means, such as by the use of reinforcing, prestressing, high strength concrete or fibre-reinforcing. These are just a few examples of the different design alternatives and does not by any means represent a comprehensive examination into the various design possibilities. An example of the effect of using reinforcing steel to increase the structural capacity of the dolos unit is shown in Figure 9.

The cost effectiveness of the various alternatives may now be truly examined because the structural requirements can be quantified. Such information is essential to the development of different design alternatives.

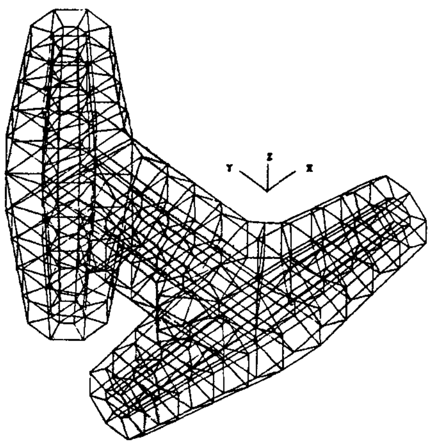


Figure 7 The Dolos Finite Element Method

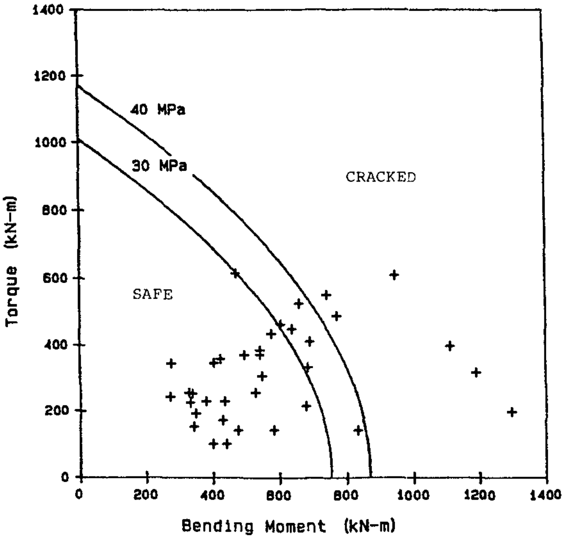


Figure 8 Peak Forces at the Fluke/Shank Interface

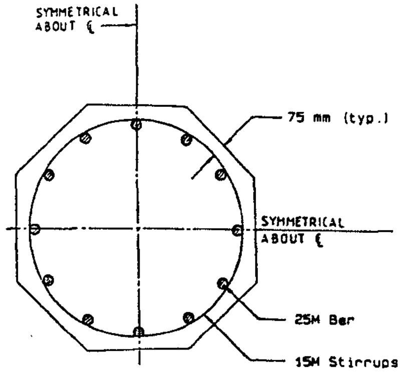
CONCLUSIONS

A rational procedure for the design of concrete armor units has been presented. A unique "load cell" was developed which measures the structural response of armor units in a standard breakwater model. This permits the structural integrity of the armor units to be assessed through the use of interaction curves, thus clearly demonstrating the overall factor of safety associated with the armor unit and the expected mode of failure.

Such a procedure represents the application of existing technologies and a comprehensive engineering approach to the design of rubble mound breakwaters. Some features of the design method are:

1) Methods of standard structural engineering practice are followed where first the loading conditions are assessed and the structure designed to resist the applied loads.
2) Numerical analysis techniques such as the finite element method are employed.
3) It is an extension of current design practice where physical models are utilized.
4) Materials technology and failure criteria are examined.

Consequently, an effective design scheme is available which incorporates both the hydraulic and structural considerations of a breakwater structure and , thus, can provide more cost effective solutions.



(a) Reinforcing Arrangement

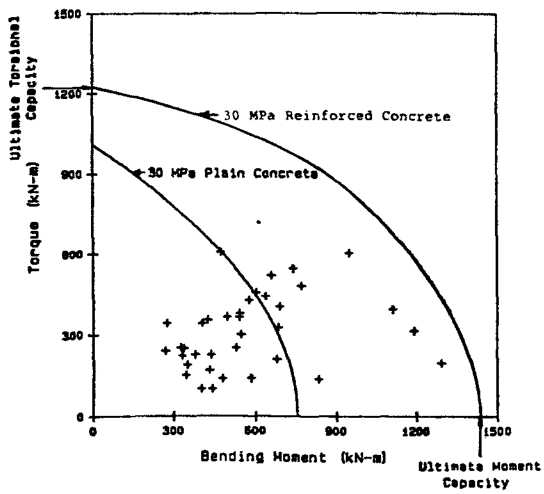


Figure 9 The Effect of a Reinforced Dolos Shank

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