CHAPTER ONE HUNDRED SEVENTY TWO

STRUCTURAL DESIGN PROCEDURES FOR CONCRETE ARMOUR UNITS

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ABSTRACT

A rational design procedure for rubblemound breakwater protection which will ensure both the structural integrity and hydraulic stability of individual concrete armour units and the overall armour system is presented. The procedure involves new experimental techniques for measuring strains in model concrete armour units in a hydraulic model of a breakwater subjected to simulated prototype wave attack and analytical techniques for determining equivalent prototype loads on units. Selected design loads are used to define the resultant stress distribution to allow the designer to take the necessary measures to ensure the structural performance of the unit in a breakwater environment.

INTRODUCTION

In recent years, extensive damage has occurred to the armour layers of many breakwaters. In many cases this damage has led to a partial or complete failure of the entire breakwater structure including the core, filter layers and superstructure. In some instances, breakage of individual concrete armour units has been identified as the cause of the damage to the armour layer. This individual unit breakage has clearly demonstrated the inadequacy of existing procedures for successfully designing the armour layer of the breakwater.

Although specific concrete units such as the dolos and tetrapod can be identified as being more prone to structural failure, many other types of units including cubes have been observed to break in the breakwater environment. For this reason it is not sufficient to eliminate the use of units such as the dolos or to design the armour layer with large cubes placed on very flat slopes (to restrict motion). This does not achieve the desired objective of breakwater design which is to provide a safe, reliable, structure as economically as possible.

Existing design procedures must be updated to reflect the current state of the art in other scientific disciplines such as structural design, instrumentation techniques and materials modelling.

A review of existing breakwater design procedures reveals that designers have, consciously or not, accepted that undefined tensile

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stresses can occur in the armour units since movement of the units has been accepted. The procedure outlined in this paper has been developed so that these previously undefined stresses can now be determined and the appropriate action taken to ensure both the structural integrity and hydraulic stability of the armour units.

Several of the technical studies required to develop this rational design procedure are described in this paper. It is important to note that the design procedure was developed using existing technology from other areas of engineering, such as materials modelling, instrumentation, finite element methods and structural design techniques. These technologies were adapted for use in a hydraulic model and to take into account the uniqueness of a breakwater environment. These studies considered the following:

- A review of instrumentation or measuring techniques that could be adapted for use in a hydraulic model study to define the loads (or resulting stresses or strains) that occur on an armour unit. The instrumentation techniques reviewed included accelerometers and high speed photography to define unit movements and load cells, strain gauges, photoelastic techniques and full field strain measuring techniques to determine stress or strain levels in the units. The practicality of working at specified scales and in a hydraulic environment precluded the effective use of some of the identified techniques. As a result of this review, a system utilizing strain gauges placed at strategic locations on the model armour units used in the hydraulic model and directly measuring the strain level during simulated prototype wave attack was selected.
- A review of model materials was undertaken. Selection of a material was made in relation to the scaling down of prototype properties so that the requirements of similitude between the model and prototype are met. However, since the displacement related to the deformation of the prototype units is small, a certain level of strain distortion is permissible in the model and it was therefore advantageous to select a material with a low modulus of elasticity (resulting in a magnification of the low level strains in the model). A reinforced epoxy resin was selected which permitted the use of acceptable geometric scales with an appropriate scaling of material properties.
- A series of specifications for the design of the instrumentation system were developed based on the model material, hydraulic testing techniques, anticipated strain levels and minimum performance criteria.
- A thorough assessment of the reliability and repeatability of the instrumentation system was made for a range of static, dynamic and combined static-dynamic loading. A number of prototype tests described in the literature were duplicated to assist in assessing the accuracy of the system.
- Analysis of measured model data was completed using finite element procedures. Post processing colour graphics capabilities were developed to assist in presenting the data.

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Each of these technical studies is described in more detail in the following sections. The component studies have been integrated into a rational design procedure. This is used to produce a design for a breakwater armour layer which is made both economical and reliable by combining structural integrity with hydraulic performance.

OVERVIEW OF THE DESIGN PROCEDURE

The rational design procedure involves techniques to define the loadings imposed on a model armour unit on a breakwater subjected to simulated prototype wave attack and subsequently, using conventional structural engineering techniques to determine the resulting stress distribution in the armour unit. A detailed design of the individual units can then be undertaken using standard structural engineering procedures that utilize reinforcing (bar, fibre and prestressing) or make use of changes in the geometry of the unit. A general outline of the overall design procedure is given below. The procedure is illustrated in Figure 1.



Fig. 1 Design Chart

Initially, it is necessary to fully understand the environmental conditions to which the breakwater is exposed, of which the most important parameter is the wave climate.

The choice of armour unit is up to the designer and should depend upon a number of variables including economics, material availability, form availability and construction equipment availability. Initially, the design should be developed using a hydraulic model study so that the armour units are not displaced from the armour layer under the design wave conditions. The assumption will be made at this point that each unit has sufficient strength to resist the applied forces.

Model armour units instrumented with a number of strain gauges placed at strategic locations on the unit are placed at random through the design test section. Values of strain are recorded continuously throughout the testing. Tests are undertaken for a variety of instrumented unit placement locations. From the results of the measured data, a history of the internal forces and moments occurring at the instrumented cross-section can be derived. The measured internal forces will include dynamic loads resulting from wave action on the breakwater, from collision between adjacent units and from static loads that are imposed by adjacent units or as a result of differential settlement of the structure.

Simplified equivalent external load conditions and constraints are derived, using numerical analysis, from the internal forces and moments

determined at the instrumented cross-section. The equivalent loads produce the selected measured stress (strain) distribution at the instrumentation location. Because of the random nature of the applied loads in a breakwater environment, it is necessary to undertake a statistical interpretation of the measured data. For each set of strains measured (flexure, torque, shear and axial) a frequency of occurrence distribution is determined. Extreme events from a selected set of strain data are combined with the other corresponding strains to determine equivalent design loads.

The design loads are applied to a finite element model of the armour unit to calculate the resulting stress distribution within the armour unit. The armour unit can now be structurally designed to resist the applied loadings using conventional structural engineering procedures. This may include the use of reinforced concrete, fibre reinforced concrete, prestressed concrete, the use of alternative materials or modification to the geometry of the unit (development of a new unit or armour layer system).

If additional changes to the design are implemented as a result of construction constraints and limitations, then the process of defining the loads in the hydraulic model would be repeated for the new design. The result of this procedure is the development of a breakwater armour design which provides the most economical solution combined with optimum hydraulic and structural performance.

DESCRIPTION OF THE COMPONENTS OF THE PROCEDURE

1. Model Material Selection

Selection of the appropriate model material was based on the fundamental requirements of similitude between the model and prototype. This requires that the relationship between certain strength characteristics of the model material and the geometric scaling factor (in relationship to prototype) be properly assessed. A static dimensional analysis was carried out (Hall 1984, Baird et al, 1983) which showed that for complete similarity the geometric scaling must be identical to the material scaling. However, since the displacements related to the deformations of the prototype are sufficiently small, and not critical to the overall behaviour of the breakwater, some strain distortion and differences in Poisson's ratio is permissible. The results of the dimensional analysis yield,

$$\Theta_{m} = \underbrace{Ep}_{Em} \underbrace{hm}_{hp} \Theta_{p} \tag{1}$$

where, θ = strain level; E = modulus of elasticity; h = geometric linear dimension; the subscript m denotes model and the subscript p denotes prototype.

Clearly, the choice of model size or geometric scale has a direct influence on the expected model strain levels. Since the strain gauging system has a limited resolution, the model material was selected so that the strains induced in the relatively small scale hydraulic model

studies would be of sufficient magnitude to be measured by the gauges.

Consequently, the following general requirements were identified. The material should:

- 1) have approximately the same density as concrete
- 2) be linear, elastic, homogeneous and isotropic
- 3) have a strength that would produce minimum model strain levels in the order of 50 microstrains to ensure that the behaviour of the units could easily be monitored within the resulution of the instrumentation
- 4) have reproducible mechanical properties
- 5) be easily strain gauged
- 6) be easy to use in a casting process
- 7) be relatively inexpensive.

Three major types of material are available for the construction of elastic models - plastics, cementitious materials and metals. It was determined that plastics meet most of the general requirements. Metals could not be found with the critical combination of the correct density and the desired elastic modulus required to ensure measurable strains and cementitious materials could not provide the long term stability required in a hydraulic environment and they are not easy to strain gauge.

There are a wide variety of thermoplastics and thermosetting plastics available with a diverse range of chemical composition and mechanical properties. Thermosetting plastics were identified as the best available material for the following reasons:

1) thermosetting plastics have a limited development of heat of polymerization which assures a homogeneous hardening process and results in a relatively consistent modulus throughout the material.

2) the relatively lower shrinkage that occurs in epoxy compounds after casting results in a significant decrease in the internal stresses.

3) the density, elastic modulus and curing rate can be easily modified by adjusting the amount of hardener or adding an inert material (filler) dispersed homogeneously throughout the model unit.

The material used to construct the model armour units was a steel fibre reinforced epoxy resin which had a bulk density of approximately 2000 kg/cubic metres and a Young's Modulus of Elasticity of 5 GPa.

2. Design of the Instrumentation System

The selection of the type of strain gauges and their placement location on the model armour units requires careful consideration since the forces acting on the unit and hence the stress/strain distributions are unknown. The design of the instrumentation has the fundamental objective of providing an economical, efficient strain gauging system capable of withstanding the environment in which it is operating. This design can only be achieved by taking into account the following fundamental issues:

- 1) Environmental Operating Conditions Factors such as temperature fluctuations, abrasion and hydraulic considerations.
- 2) Loading-Environment Qualitative loads must be identified, such as static loads due to mound settlement, self-weight and weight of adjacent units and dynamic loads due to interunit and projectile collisions and hydrodynamic impact pressures.
- Geometry ~ The geometric size of the model unit and the material used to construct the unit must be optimized.
- 4) Gauge Location The density and placement of the strain gauging array must be selected to ensure adequate definition of stresses induced by torsional, flexural, shear, and axial loading conditions.
- 5) Strain Level The possible magnitude of strains that will occur in the model must be defined so that the appropriate instrumentation can be selected.
- Installation The method of installing the gauges and subsequent water-proofing of the system must be defined.

Based on the requirements listed above and on a review of available strain gauging techniques and systems the following type of instrumentation package was developed.

For bending, torque and shear measurements, the gauge type used is a Vishay Micro-Measurement No. EA-06-125TW-120. The characteristics of this gauge type are as follows:

- constantan (A-alloy) in self-temperature-compensated form
- flexible polymide backing
- self-temperature-compensation number = 06 in/in/degrees F
- 3 mm (.125 in) gauge length
- grid and tab geometry "TW"
- 120 ohms resistance

The gauge type used to measure axial strains is an EA-06-125TE-120 and differs from the EA-06-125TW-120 gauge only in its grid and tab geometry.

The gauge arrays should all be self-temperature-compensating (full bridge) to eliminate the effects of apparent strain in the system.

The EA series of gauges are a constantan (A-alloy) foil in combination with a tough, flexible polymide backing, which is capable of operating in a temperature of -75 to +175 degrees Celcius. The constantan alloy has a high strain sensitivity (gauge factor) which is relatively insensitive to strain level and temperature and its resistivity is high enough to achieve suitable resistance values in very small grids. The polymide backing is a tough, flexible carrier and can be contoured readily to fit very small radii. This backing is also

capable of very large elongation and can be used to measure plastic strains in excess of 20%.

Strain gauge performance is easily degraded by the effects of moisture damage and as a result, gauges require varying degrees of protection according to the severity of the environment in which they operate. For use in a hydraulic model study, the gauges will be subjected to a changing wet-dry environment and may be susceptible to abrasion; therefore, a good protection system is required. The work completed to date has used a system protected with Micro-Measurement M-Coat-G, a polysulfide modified epoxy compound and M-Coat B, a solvent thinned nitrite rubber compound. This system was found to provide excellent protection to the strain gauges.

3. Data Measurement

The instrumented model armour units are placed in the model breakwater which is subjected to simulated prototype design waves. Several considerations must be made at this point.

The random placement of armour units in the armour layer, results in a random pattern of constraint points and loading locations, and as a consequence, the forces acting on a unit will show a large variability based on the units location within the armour layer.

Therefore, it is important to determine the number of units and their placement within the armour layer required to accurately provide a definition of the stress envelope describing all possible unit locations on the breakwater. That is, it is necessary to understand how many instrumented units are required in a given test and how many tests are required (each test will require the test section to be rebuilt) to define this envelope.

Observations of prototype structures indicate that the most extensive breakage of prototype units occurs in the vicinity of the mean water level where the wave induced velocities in the armour layer are the greatest. This would indicate that forces on individual units are probably the largest in this area.

As the breakwater is tested, output from the gauges is a continuous voltage readout. Typically, voltage signals are relayed through a signal conditioner-amplifier and filtered through a high speed data acquisition. Experience has shown that a sampling rate of 100 to 200 samples per second (per channel) provides a suitable definition of the dynamic loads, although more study is required in this area. The signal can then be converted to a digital signal and stored on a computer for subsequent analysis.

In any particular test of a breakwater, in which the instrumented units are placed, the time history of the strains from all gauges is recorded simultaneously, resulting in a large quantity of data. The data must be pre-processed so that the design loads (at a desired level of exceedance) can be determined with a minimal amount of numerical analysis. Several alternatives have been used; however, this is an area in which more research will be conducted in a future study to optimize this part of the design process. In one technique, equivalent load conditions on each instrumented unit are determined for each wave event based on the measured strains. Resultant stress values are then calculated for selected locations in the armour unit. However, because of the large number of events it is necessary that some preselection of the data be undertaken. Alternatively, statistical interpretation of the measured strain data can be made. For each set of strains measured (i.e. either flexure, torque, shear or axial strain) a frequency of occurrence distribution would be determined. Extreme events from a selected set would then be combined with the other corresponding strains to determine equivalent design loads and resulting stress distributions.

4. Data Analysis and Presentation

The objective of the design procedure is to take the strain components measured during the hydraulic model tests and derive, using numerical analysis, loads that can be used for the structural design of the concrete armour units.

Finite element methods and colour graphics postprocessing are used extensively to determine the loads and view the stress distributions throughout the unit. The finite element technique is well established as a powerful tool capable of carrying out complex dynamic non-linear material and geometric analysis. The graphics package permits the analyst to quickly see the flow of stress throughout the model and verify that the model is behaving correctly.

Using the numerical techniques, simplified equivalent load conditions that produce the selected measured stress distributions at the instrumented section location are determined. These equivalent loads or, in fact, imposed boundary conditions are selected in such a way as to maximize the internal generalized forces and moments which are viewed as contributing most to the failure of prototype units at preselected locations.

Figure 2 shows a finite element grid model developed for a dolos.

Several techniques are available for viewing the resultant stress distribution in the armour units including stress flow diagrams which show the magnitude and location of tensile and compressive stress flow patterns and stress block techniques which indicate the intensity of surface stresses in the various elements. Figures 3, 4 and 5 show stress flow patterns for the dolos, tetrapod and tribar units for predetermined load conditions.

6. Model-Prototype Relationship

The relationship between model and prototype is of fundamental importance to the design procedure. Two techniques are available; the first approach is to relate model strains directly to prototype strains and then determine the appropriate loads, while the second approach consists of first determining the model loads and then calculating the

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Fig. 2 Discretized Dolos

Fig. 3 Stress Flow Diagram - Dolos

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Fig. 4 Stress Flow Diagram - Tetrapod



Fig. 5 Stress Flow Diagram - Tribar

prototype values of load and strain. A discussion of both approaches is made below.

In the first approach the ability to relate strains between the model and prototype requires that the model material replicates all the fundamental material properties of the prototype. As a result, with the model material selected, which is essentially homogeneous linear elastic, model and prototype strains can only be related up to cracking for both unreinforced and reinforced concrete prototype units. This type of simplified relationship has been developed and is presented in Hall (1984).

For those units that are reinforced this structural model will not provide direct prototype strain information. In addition, any complete relationship must also take into account the static and dynamic attributes of both the model and prototype materials. Consequently, a direct relationship between model and prototype strains is both complex to develop and limited in its range of application.

An alternative to the above is the second approach which only involves establishing a model to prototype load relationship. Essentially, this method requires that the model material be well defined, that is both the static and dynamic properties be established, and the model loads be determined from the measured model strains. Once these loads are defined, the appropriate model to prototype load factor, based on the geometric scale, can be used to determine the equivalent prototype loadings.

It is important to note that there has been no restriction placed on the prototype material, since the determination of these loads did not require a prototype material definition.

Consequently, this approach can be applied to reinforced concrete units or units made of any other material. Thus the analysis and design of prototype units can be based on the appropriate codes of practice once these design loads are determined.

EXAMPLE APPLICATION

In this section of the paper an example of the design and performance of an instrumented model armour unit is given. The units used as an example are 110 mm dolos units which were subjected to extensive testing consisting of singular static and dynamic loadings in a dry environment and hydraulic model testing using both regular and irregular waves. Complete details of the tests are given in Hall et al (1984).

The design of the instrumentation package for the dolos unit required careful consideration since the forces acting on the unit and hence the strain distribution were unknown.

An approximation of the strain levels anticipated in the model dolos units was made using finite element analysis in which simplistic loading cases were imposed on a discretized dolos unit. Based on the results of this analysis, it was anticipated that strain levels would be in the order of 40 to 200 microstrains for 110 mm units constructed of steel fibre reinforced epoxy resin.

The instrumented unit is shown in Figure 6.

Single point static loads were applied at a number of locations on the unit to place the instrumented section in pure flexure, torsion and axial strain and combined flexure, shear, torque and axial strain conditions. The units were restrained in a fixture designed to provide a solid restraint without inducing apparent stress within the units. Figure 7 shows a sample of the load versus strain curve for a typical test and indicates a linear relationship for both the loading and unloading curves.

A number of tests were performed in which an instrumented unit was placed in an armour layer and consequently, subjected to multiple static loads. Variation was made in the number of layers of dolos, placement density and slope of the armour layer. Figure 8 shows the response for one particular set up and illustrates the variation of static strain with a change in slope of the armour layer.

A number of dynamic tests were also undertaken in a dry environment. These tests consisted of short duration single event dynamic impacts created by dropping the unit onto one of its flukes or fluke ends. Figure 9 shows the type of tests conducted and Figure 10 shows a typical response. The sharp response at the moment of impact is clearly visible in Figure 10. However, the magnitude of the induced strains measured at the centre of the shank of the dolos are relatively small. Subsequent numerical analysis has shown that strain levels near the fluke-shank interface may be 3 to 5 times larger than those in the middle of the shank during this type of loading event.

The most interesting example of the use of instrumented units is given by observing the performance of the instrumentation during a breakwater model test in which the test section is subjected to simulated prototype waves. The units were subjected to both static loads, resulting from self-weight, the weight of adjacent units and mound settlement and readjustment, and dynamic loads resulting from hydrodynamic forces and impact with adjacent units. The instrumented units were placed at random within the breakwater armour layer. The test section was initially subjected to low wave conditions which were increased in small increments until significant armour unit movement was observed. Figure 11 shows the instrumented units in a typical test set up. Figure 12 shows the breakwater being subjected to wave attack.

Figure 13 shows an example of the output measured during a test conducted with regular waves. The repeatability of the strain signal at the same period as the period of the waves is excellent and illustrates the capability of the instrumentation. The strain level recorded exhibited a marked increase with an associated increase in wave height.

Figure 14 illustrates the response of the instrumented unit during tests ran with irregular wave conditions having a peak model wave period





Fig. 7 Load Versus Strain Plot for Static Load



Fig. 8 Variation in Strain with Armour Slope



Fig. 9 Types of Dynamic Load Tests





Fig. 10 Dynamic Impact Response - Strain vs Time

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Fig. 11 Example of Instrumented Unit Placement in the Armour Layer



Fig. 12 Wave Impact on the Instrumented Unit



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of approximately 2 seconds. Both the magnitude of the peak strain levels and the period between peaks is irregular and in fact, in some instances, the strain levels exhibit a groupiness similar to that observed in the irregular wave trace.

The following comments can be made with respect to the performance of the instrumentation used during these tests:

- individual strain levels exceeding the tensile cracking strain level for concrete were recorded in wave conditions in which armour unit motion was observed.
- the response of the instrumentation in irregular waves exhibited excellent repeatability in phase with the period of the waves.
- the instrumentation is not affected by the hydraulic environment of the breakwater.
- 4) the instrumentation is not affected by abrasion occurring as a result of adjacent units moving over the surface and colliding directly onto the gauges.
- 5) the lead wires from the gauges do not affect the movement of the instrumented units or the units adjacent to them.

In general it is concluded that the strain gauging system provides a viable system of measuring strain levels in model armour units subjected to simulated prototype wave attack in a hydraulic wave flume.

CONCLUSIONS

A rational procedure for designing concrete armour units so that the structural and hydraulic performance can be simultaneously guaranteed has been presented. The various aspects that require consideration when designing the instrumentation and developing the prototype design criteria were discussed. The general objectives of utilizing this design procedure is to permit the widespread use of precast concrete units throughout the design life of the structure and represent a least cost investment.

A procedure for defining the loads that occur on a breakwater which enables the engineer to structurally design the unit has been developed and its performance evaluated.

Based on the design loads, the designer can determine the size of unit required, and the necessity for reinforcement (and type of reinforcement required). If necessary the geometry of the unit can be altered to reduce the occurrence of stress concentrations. This may ultimately result in the development of new units which optimize the combined structural and hydraulic performance.

In addition, if fatigue analysis is required, the defined loads can be employed to determine the expected life of a unit so that estimates of maintenance costs over a given period of time, related to replacement of armour units, can be determined.

Alternatively, these procedures could be used to develop codes of practice for concrete armour unit design which would provide a

description of the design loads for the many types of armour units used in breakwater design and for many of the variations in the physical environment of a breakwater.

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