IMPROVEMENTS IN MODELLING RUBBLE-MOUND BREAKWATERS

G.W. Timco and E.P.D. Mansard*

ABSTRACT

Physical modelling is a technique which is commonly used in the design procedure of rubble-mound breakwaters. For reliable results it is necessary that the model tests accurately represent the prototype situation. In this paper, two significant improvements in modelling of breakwaters are presented. They are the generation of realistic sea states at the test site, and the simulation of the breakage of the armour units by using units which have mechanical properties properly scaled from the prototype units. These techniques have been used to study the recent breakwater failure at Rivière-au-Renard, Canada.

1.0 INTRODUCTION

A common method of protecting harbours and in dissipating wave energy in both inland and ocean ports is by the use of rubble-mound breakwaters. These structures are built up from the sea floor with specific profiles and material layers. Usually the uppermost armour layer consists of large quarry stones or specially designed concrete units. Depending upon the wave climate at the site, armour units can weigh as much as 100 tons. Recently there have been a number of breakwater failures causing enormous financial and environmental losses. Some of these breakwaters failed due to the breaking of individual concrete armour units during storm conditions with an eventual collapse of the structure as a whole. The design of a stable breakwater is a challenging engineering problem.

Physical modelling is a method frequently used to aid an engineer in the design of a rubble-mound breakwater. For this, a model of the proposed breakwater is geometrically scaled in a laboratory flume and subjected to similarly scaled wave conditions. In order to obtain reliable information from these types of tests, it is necessary that certain scaling laws are met. In particular, it is important that geometric (linear), kinematic (velocities) and dynamic (forces) similitude be preserved. This entails maintaining in the model test system, the relative importance of each of the independent forces acting in the prototype system. If all forces are in the same ratio, then the equations of motion will be the same everywhere in the model and prototype. The model and prototype will behave, therefore, in the same dynamical fashion. In early model tests of breakwaters, a regular wave

*Hydraulics Laboratory, National Research Council, Ottawa, Ont. K1A 0R6 Canada

train was propagated onto a scale model of the breakwater and before-and-after profiles were used to define the stability of the structure. In recent years, several important improvements in the modelling techniques have been developed including the use of "random" waves simulating the variance spectral density, damage criterion in terms of the rocking motion of the armour units, and careful selection of materials which influence the hydraulic stability of the breakwater. Although these improvements have contributed to better model-prototype conformity, there still remains a number of important parameters to be considered.

This paper addresses itself to two important improvements achieved by the Hydraulics Laboratory of the National Research Council of Canada in the techniques of physically modelling breakwaters. They are:

(1) the generation of realistic sea states at the test section of the flume, and

(2) the simulation of the breakage of armour units by using a material which has properties scaled from those of prototype concrete units.

In this paper, the details and significance of these two improvements are discussed. In addition, these modelling techniques are applied to a model test study at a 1:25 scale of the dolosse-armoured breakwater at Rivière-au-Renard, Quebec, Canada.

2.0 REALISTIC SEA STATES

Most hydraulic laboratories now have the capability of generating irregular waves for their experimental investigations. The normal practice has been, however, to describe the sea state solely by a variance spectral density and then to reproduce it in the model. Recent studies [Johnson et al (1978), Burcharth (1979)] have shown that simulating just the spectrum is not sufficient because a certain sequence of high waves occurring as a wave group can induce greater damage on the structure than equally high waves occurring individually in a wave train. The large number of high waves present as a sequence in the grouped wave train cause a continuous rocking and eventual displacement or breakage of armour units. Because of this effect it is desirable that the frequency as well as the time domain characteristics of the natural sea states are reproduced in the model whenever possible.

The phenomenon of wave grouping is well known to the oceanographers since prototype waves often exhibit distinct wave group patterns in their records. Considerable research has therefore been carried out in the past particularly to relate the broadness of the spectrum to the wave group characteristics. In fact, the traditional concept of representing the sea state by just its variance spectral density was based on the assumption that the spectral width is an indication of the degree of grouping such that a narrow spectrum corresponded to higher grouping. However, in a recent study Funke and Mansard (1980) showed that there is no apparent relationship between the shape of the spec-

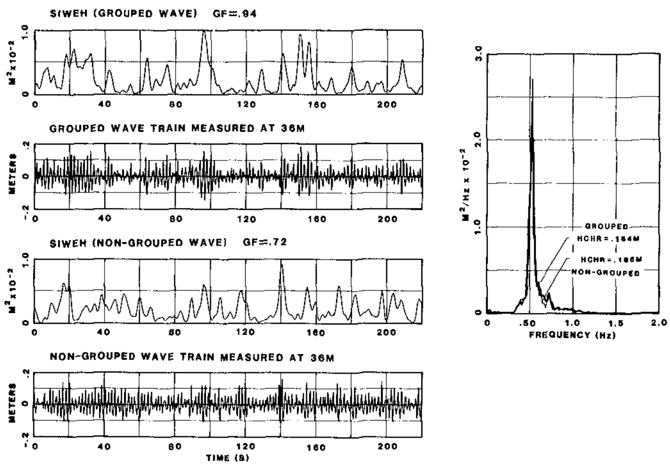

FIG.1 COMPARISON OF THE GROUPED AND NON-GROUPED WAVE TRAINS

trum and the amount of grouping in the wave train. Figure 1 presents two wave trains having a common variance spectral density but different degrees of grouping.

In order to have a physically meaningful description of wave group activity in a sea state, this Laboratory has developed the concepts of a Smoothed Instantaneous Wave Energy History (SIWEH) and a Groupiness Factor (GF). Both the SIWEH and the GF can be easily derived from the water surface elevations of the wave record (Funke and Mansard 1980). As illustrated in Figure 1, this SIWEH E(t) function, which represents the distribution of wave energy in the time axis, effectively describes the wave groups in a time series.

The concept of Groupiness Factor, developed as a tool to measure the degree of grouping in a sea state, is a dimensionless factor, describing the standard deviation of the SIWEH about its mean and normalized with respect to this mean.

The amount of wave grouping increases with increasing Groupiness Factor. Values of GF in the vicinity of 0.9 indicate highly grouped waves.

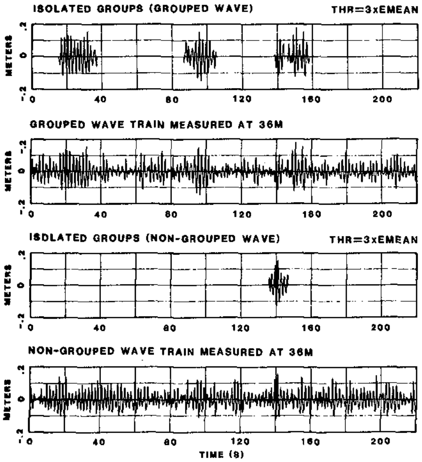

FIG.2 ISOLATION OF WAVE GROUPS

The SIWEH function can serve also as an effective tool to isolate wave groups in the time series. The groups shown in Figure 2 were isolated using a concept of threshold for the SIWEH. Any wave sequence which caused the SIWEH to exceed a given threshold ($3*\bar{E}$ in this case) was defined as a wave group event.

Because it is often not possible to obtain prototype wave records for a desired location of interest, this Laboratory has developed a synthesis technique to generate realistic sea states which include wave grouping. This technique, illustrated in Figure 3, provides the necessary tools for testing the stability of the various structures (be floating or fixed) for the wave grouping effects. The SIWEH spectral density shown in Figure 3 is a theoretical model often encountered in the linear dynamic system analysis. The expression for this SIWEH model is:

$$\varepsilon(\lambda) = \frac{1}{\sqrt{(1-\lambda^2)^2 + 4\zeta^2\lambda^2}} \cdot \frac{\lambda}{\sqrt{(1+\lambda^2)}}$$

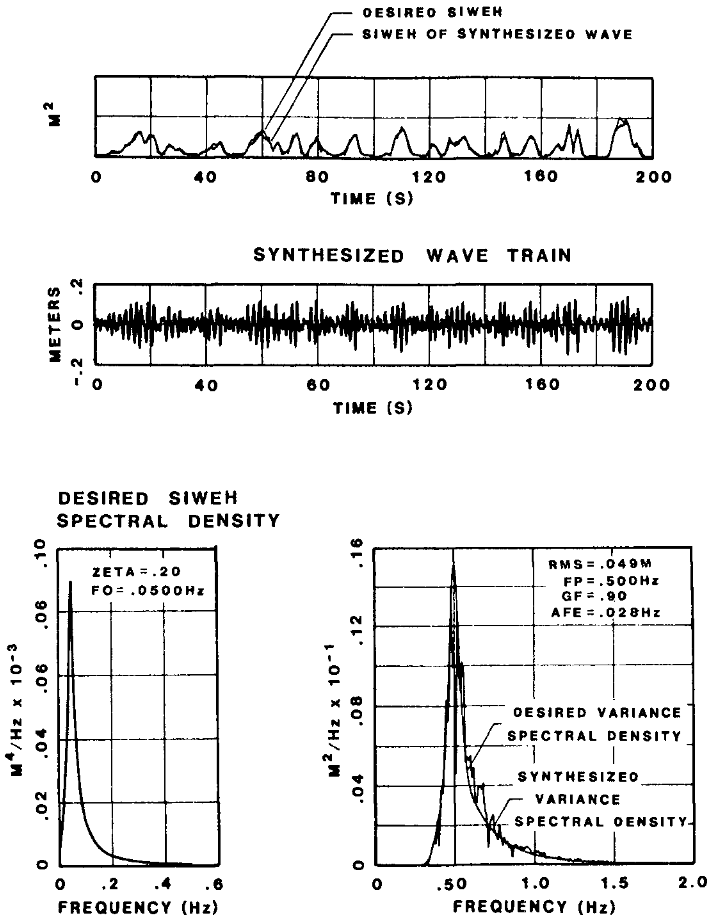

FIG.3 SYNTHESIS OF A GROUPED WAVE TRAIN

where $\varepsilon(\lambda)$ = SIWEH spectral density
λ = normalized frequency f/f_0
ζ = damping factor which controls the width of the spectral peak which occurs in the vicinity of λ=1. The smaller is ζ, the narrower is the spectral peak
f_0 = peak frequency for ζ=0

The time history of SIWEH is derived from this spectral density through an Inverse Fourier Transform using random phases.

In the absence of prototype information on wave groups, this model could be used to synthesize time series with different grouping characteristics (GF) while maintaining a constant variance spectral density. The period of the groups can be changed by varying the peak frequency of this spectrum. The wave train shown in Figure 3 satisfies both the frequency domain characteristics of the desired spectrum and the time domain characteristics defined by the SIWEH function. This technique is well documented in Funke and Mansard (1980).

2.1 Reproduction of Wave Trains at the Test Section

When a time series (derived either from a prototype wave record or by synthesis technique) is to be reproduced in the flume, it is necessary that it is realized at the test section rather than at the wave paddle. But in deep and intermediate water depths the various frequency components present in the sea state travel with their own celerities resulting in continually changing sequences of waves during propagation. However, it is found that these celerities can satisfactorily be described by the linear dispersion relationship. Hence, in order to achieve the desired time domain characteristics near the test section (which may be 30 to 50 m from the wave paddle), the inverse dispersion relationship is applied to the wave train, in order to account for the wave propagation. In addition to the propagation, it is found that important phase changes can occur in the various wave machinery components such as the servo hydraulics, wave paddle, analog filter, etc. Complex transfer functions (which include both the amplitude and phase compensations) are therefore applied to these various components while preparing the driving signal. This technique has been found to be quite successful in reproducing various sea states and even extreme waves in the Laboratory.

Figure 4 compares a prototype wave record with a wave record measured at 36 m from the wave paddle in the model. The severe sequencing of prototype waves has been well preserved in this reproduction of this time series in the wave flume.

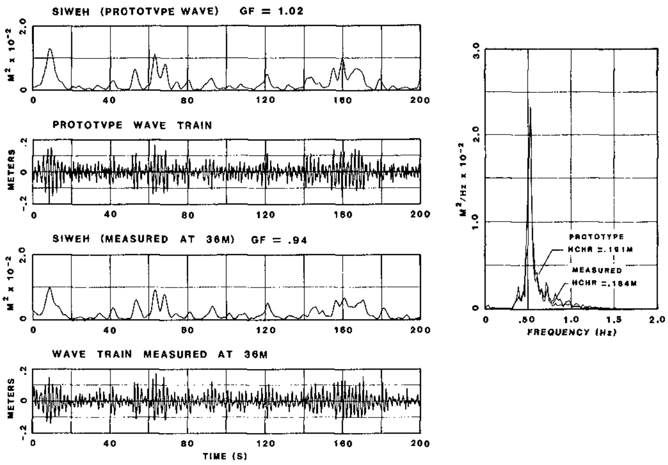

FIG.4 REPRODUCTION OF WAVE TRAIN IN THE FLUME

3.0 SIMULATION OF CONCRETE STRENGTH

In model testing of breakwaters, the interpretation of the results is very subjective. In early tests, the stability of a particular design was usually determined by a comparison of before-and-after storm profiles of a section of the structure. More recently, the stability has been defined subjectively as the onset of rocking of the armour layer. Neither of these techniques is satisfactory. This is so because a common failure mode of prototype breakwaters occurs through a deterioration of individual armour units with pieces breaking off and hammering against other larger units. In addition, the constant slight flexing and continual motion of the units during a storm result in a reduction in strength (and ultimately failure) due to slow propagation of cracks. These two failure modes, although undoubtedly important in the prototype system, are not considered at all in geometrically scaled model tests. In order to simulate these conditions in a model test, it is important that some of the physical properties of the armour units scale by the linear scale factor (λ). In particular, the strength and strain modulus must be scaled whereas the density, Poisson's ratio and frictional factors must not. To date, this has not been done due to the lack of a material which would simulate homogeneously these properties of concrete on a reduced scale. Because of the many advantages of using strength-reduced armour units in model tests, a project was initiated to develop a material which would simulate the properties of concrete for this type of model testing. In this section, the development and properties of this material are briefly discussed.

3.1 Modelling Laws

The first step in developing the model material is to define the appropriate scaling laws and to define representative concrete (i.e. prototype) mechanical properties to which the scaling laws are applied. This defines the properties of the model material.

In model tests, the forces of interest are the gravity (weight), inertial, elastic and frictional (viscous). In order to maintain the relative importance of each of these in the model regime, it is necessary to maintain the Froude number (inertial forces/gravity forces), the Cauchy number (inertial forces/elastic forces), and the Reynolds number (inertial forces/viscous forces). Since it is not possible to simultaneously satisfy all three of these numbers, a compromise is made and the model tests are scaled according to Froude similitude. This is done since gravity and inertial forces predominate. As a consequence of this, the physical properties of the model armour units must meet certain well-defined requirements. In particular, the properties of the model (m) material must scale from the prototype (p) concrete values as

mass	$m_m = m_p/\lambda^3$
density	$\rho_m = \rho_p$
flexural strength	$\sigma_{fm} = \sigma_{fp}/\lambda$
tensile strength	$\sigma_{tm} = \sigma_{tp}/\lambda$
compressive strength	$\sigma_{cm} = \sigma_{cp}/\lambda$
elastic (Young's) modulus	$E_m = E_p/\lambda$
fracture toughness	$K_m = K_p/\lambda^{3/2}$
Poisson's ratio	$\mu_m = \mu_p$
friction	$f_m = f_p$

where λ is the scale factor of the test. For proper results in the model regime, the properties of the armour units must meet these requirements.

3.2 Mechanical Properties of Concrete: Prototype Values

Before it is possible to model the properties of concrete, representative values of the properties must be defined. However, concrete is a complex mixture of calcium silicates and aluminates cement, sand, stone and water. As such, by altering the relative proportions of each of these constituents, the properties of concrete can be varied over a wide range. Moreover, the properties of concrete are known to be affected by temperature, loading rate, moisture content, sample size, etc. This does not allow unique, unambiguous values to be defined. However, since the variation of the properties is reasonably systematic, such that conditions which lead to high compressive strength (say), also lead to high flexural and tensile strengths, representative values can be defined in this way. In the prototype system, usually high quality (35 MPa minimum compressive strength) concrete is used. Assuming a high quality concrete, the relevant properties of concrete, as determined from surveying the literature (Gonnerman and Shuman, 1928; Neville, 1977; Jayatilaka, 1979) as well as the required properties of the model material for two scale factors (λ=20 and λ=40) are

	Concrete	λ=20	λ=40
compressive strength (MPa)	31-38	1.6-1.9	.78-.95
flexural strength (MPa)	4.1- 4.7	.21-.24	.10-.12
tensile strength (MPa)	2.4-3.0	.12-.15	.06-.08
density (g/cc)	2.2-2.5	2.2-2.5	2.2-2.5
elastic modulus (static) (GPa)	29-32	1.5-1.6	.73-.80
elastic modulus (dynamic) (GPa)	43-47	2.2-2.4	1.1-1.2
fracture toughness (MPa-$m^{1/2}$)	.45-1.4	.005-.016	.002-.006
Poisson's ratio	.11-.21	.11-.21	.11-.21

3.3 General Consideration for Producing Strength-Reduced Armour Units

As a further restriction in defining the properties of model armour units, it would seem that in addition to the physical properties which the material must have, it must meet the following conditions:

(1) The material should be macroscopically homogeneous throughout.

(2) The material must be readily mouldable since armour units may have unusual shapes.

(3) The material must be able to be removed from the mould without breaking.

(4) The units made from the material should be relatively quick and easy to make since a large number would be required for a breakwater study.

(5) The material should be reasonably economical.

(6) The material should be non-toxic, non-corrosive and not break up into uncleanable debris.

(7) Since the tests are performed in water, the material must have relative stability in water over a reasonable time span.

In reviewing the properties which model armour units must have, it is clear that no "standard" material has these properties. Usually, for example, relatively weak materials have relatively low densities. As such, it was decided to try to develop a material which would meet as many of the properties as possible. Since one wants a structurally weak, yet dense material, this suggests that a reasonable approach to take would be to choose a binder (matrix) material which is filled with cohesionless inclusions. In this case, the strength of the material would be proportional to the volume porosity of the binder, i.e.

$$\sigma = \sigma_0 \ (1 - \psi)^n$$

where σ = strength of the material, σ_0 = strength of matrix material, ψ = volume of cohesionless material, and n is some exponent. In this way, the strength of the overall material can be decreased by decreasing the amount of matrix material, whereas the density of the overall material can be increased by increasing the density of the filler (inclusions) material. If the particle sizes are small enough, this will result in a homogeneous mix. Such an approach should allow enough flexibility for proper scaling of some strengths and density over a range of scaling factors.

In choosing a binder material for these tests, the general properties of the material (as discussed above) were considered. Although it is possible to choose any number of binder materials (such as waxes, cement, sulphur based binders, etc.), it was decided that a matrix of gypsum plaster ($CaSO_4 \cdot 1/2\ H_2O$) would best meet the requirements for a suitable matrix. This is so since it is economical, easily mouldable, fast setting, requires minimal equipment, etc. With regard to the filler, sand was chosen as a reasonable material to start with.

In setting up these experiments, it was decided that the density and flexural strength were two properties which were essential to scale properly. Clearly, if the density is incorrectly scaled, the armour units will not respond to the incident waves as they should. In observing failures of prototype armour units, it would seem that although there are undoubtedly several failure modes, crack propagation due to flexure (tensile) stresses is a predominate failure mode. This suggests that this failure mechanism must be properly scaled. To this end, a series of experiments were performed to measure the density and flexural strength of a number of different mixtures of plaster, sand, water and several other constitutents. This was done by weighing out the proper amount of each of the ingredients and mixing them to form a creamy paste. This paste was then poured into bar-shaped moulds 2.5 x 2.5 x 30 cm made out of aluminum and allowed to set overnight. A thin film of light oil was used as a parting agent. The bars were then removed from the mould and both the flexural strength and density of the bars were determined. In these tests, it was found that by decreasing the amount of plaster in the mix, the strength of the resulting material could be reduced to the desired range; whereas by increasing the density of the aggregate mix (by adding iron ore ρ = 5.0 g/cm^3), the density could be increased to the proper range for concrete. Unfortunately, due to limitations in space, the complete details of the development and the variation of the properties of the model material with changes in constituent proportions, cannot be reported here. However, the recipe and complete information on the behaviour of the model material can be obtained from the senior author (Timco, 1981a).

3.4 Properties of Model Material

Before using this model concrete material in breakwater tests, it was necessary to know all of its mechanical properties. However, because of the mechanically weak nature of the material, testing of its mechanical properties is quite tricky. For example, at λ=50, a bar of this material 2.5 cm x 2.5 cm x 6 cm, if held at one of the square ends, would not support its own weight. In order to determine the properties, a series of tests were performed similar to those used to document the properties of "model ice" (Timco, 1981b). The full details and results of the tests on the model concrete will not be reported here. They can be found in Timco (1981a). Instead, only the salient features will be presented. In brief, for scale factors of $40 \geq \lambda \geq 20$, the properties of the model material can be summarized as follows:

Density - By properly choosing the ingredients in the mix, the density scales correctly for any scale factor.

Flexural Strength - Since the flexural strength is directly defined by the scale factor, it scales correctly for any scale factor.

Tensile Strength - The tensile strength is related to the flexural strength, and in testing using the ring-tensile test, it scales well for any scale factor.

Compressive Strength - Tests of the compressive strength were performed at two loading rates. In general, it is strain-rate independent and overscales (i.e. is too low) over the whole range of scale factors.

Elastic (strain) Modulus - Tests of the modulus were also performed at two loading rates. At very high rates (ultrasonic), the elastic modulus underscales; whereas at lower rates, the strain modulus overscales over the whole range of scale factors.

Fracture Toughness - The fracture toughness (i.e. resistance to fracture by crack propagation) scales correctly over the whole range of scale factors.

Frictional Properties - The frictional properties scale well over the range of scale factors.

Erosion - Because the amount of binder in the material is necessarily low (in order to produce the low strength), the material does not have good resistance to erosion. This limits the time span in which a model test can be performed (usually less than one hour).

Pourability - In the fluid state, before setting, the material has a low viscosity and can be cast in any shape (see Figure 5).

FIG.5 PHOTOGRAPH OF STRENGTH-SIMULATED MODEL DOLOS , CUBE D'ANTIFER AND TETRAPOD

Setting Time - The material has its initial set within 15 minutes of pouring. After this time, the unit can be removed from the mould.

Cost - The cost of the basic ingredients for these model armour units is extremely low (≈$0.10 each). However, the labour charge and non-reusability of the units significantly increases the overall cost of production.

Shelf-life - After making the armour units, they can be stored on the shelf for at least four months before testing in the flume.

In total, this material has all of the important mechanical properties correctly scaled. As such, if it is used conscientiously in model testing of rubble-mound breakwaters, it should significantly improve the model results. Failures due to tensile cracking and flexing of the armour units due to both static and dynamic loads should be well simulated if the proper scale factor is chosen. The use of this material in model testing is a definite improvement in the physical modelling of rubble-mound breakwaters. Model tests using this material in the armour layer should give good insight into the structural stability of any proposed breakwater design.

4.0 RIVIERE-AU-RENARD BREAKWATER STUDY

In order to apply these two new modelling techniques to breakwater studies, a test was performed on a 1:25 scale of the breakwater at Rivière-au-Renard, Quebec, Canada. This breakwater was chosen since it has recently failed and new designs are currently being tested for its repair (Glodowski et al 1982). This breakwater is 0.5 km long with an armour layer primarily composed of 5 tonne dolos units. In failure, many of the dolosse have broken especially near the mean water level (MWL) resulting in a slumping of the structure in several locations. The water depth at the breakwater site is 6 m which represents a depth limited situation. Many wave spectra typical of that location were tested. Since it was a depth limited situation, there was considerable wave breaking near the structure. The results presented below correspond to a JONSWAP spectrum having a peak period of 11.6 s and a characteristic wave height of 4.9 m. In performing the tests, two different test set-ups were used. For the first test, a cross-section of the breakwater was built using regular (i.e. not strength-reduced) dolosse. During the storm conditions, there was some rocking of several of the dolos units. At the end of the storm, however, there was no change in the initial cross-section of the structure. Assuming that some rocking of these low mass dolos units is allowable without causing breakage, this test would suggest that this was a stable breakwater design. For the second test, the breakwater was rebuilt using the strength-reduced units. During the storm conditions in this test, there was a number of dolosse which were rocking and hammering on other units without intially breaking. As the storm progressed, as a result of the constant hammering, first one, and then a second unit, broke in the area of the centre of the flume. These breakages started an "unlocking" of the units such that at the end of the test, there were numerous broken units in this region and a large area of the underlayer was exposed (see Figure 6). After the storm, there were five features of the model test which were in agreement with the prototype: (1) the dolosse at the top were mostly intact and slightly pushed back; (2) there was dolosse breakage at the MWL; (3) the dolosse were pulled out of that region resulting in some exposure of the underlayer; (4) the units well below the MWL were intact without substantial movement from their original position; and (5) there was a general slumping of the breakwater as a whole. In addition to this, however, in some cases there were compression-type failures of the units evident which were not observed in the prototype. This results from an unavoidable overscaling of the compressive strength of the model material. The results of this test clearly showed the rapid deterioration of the breakwater as a whole once the individual dolos started to break due to the rocking under wave attack. Once breakage of the units occurred, the stability and usefulness of the breakwater was substantially reduced. This test indicated that, as originally designed, the breakwater would fail under the severe storm conditions encountered in that region.

5.0 SUMMARY AND CONCLUSIONS

Two improvements in the techniques of modelling rubble-mound breakwaters have been discussed and applied to the study of a model of a dolosse-armoured breakwater. These improvements, the simulation of both realistic sea states and breakage of the armour units, if used conscientiously in model testing of rubble-mound breakwaters, should significantly improve the accuracy of the model test results.

FIG.6

PHOTOGRAPH SHOWING MODEL OF RIVIÈRE-AU-RENARD BREAKWATER AFTER STORM. THE HAND IS POINTING TO A UNIT WHICH BROKE IN THE TRUNK SECTION. NOTE THE REGION DIRECTLY BELOW THE HAND WHERE THERE ARE SEVERAL BROKEN DOLOSSE AND EXPOSURE OF THE UNDERLAYER.

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