CHAPTER ONE HUNDRED SIXTY SIX

STABILITY OF BREAKWATERS WITH VARIATIONS IN CORE PERMEABILITY

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ABSTRACT

In setting-up a breakwater test in a laboratory flume, the conventional practice is to scale geometrically the armour units, underlayer rocks and core material based on the Froude scaling criteria. However, because some of the properties of the water are not scaled for a model test, the Reynolds scaling law is violated. This can result in improper water flow distribution through the model breakwater. To investigate this problem, a series of tests were performed with a model breakwater in which the permeability (and porosity) of the core was varied over a wide range, and the hydraulic response and breakage of the armour units were measured. It was found that the overall stability of the breakwater could be drastically affected if the flow in the core is scaled incorrectly.

1.0 INTRODUCTION

Physical modelling of rubble-mound breakwaters is a common practice in many hydraulic laboratories. In order to model realistically these structures in a laboratory flume, there are several parameters which must be properly simulated since they can influence the test results. It has been shown, for example, that correct reproduction of the sea state must be made in both the time and frequency domain [6] and that the strength of the armour units must be properly simulated in the model regime [11] for the most reliable results. There are other factors, however, which to date have not been investigated, but which could influence the test results. In this paper, the effects on both the hydraulic and structural stability of a breakwater are investigated in terms of the permeability of the core material. This was done by comparing the response to the same storm conditions of a number of different breakwaters which were identical in all respects except for the permeability of the core.

2.0 STATEMENT OF THE PROBLEM

In physical modelling, the forces involved in a specific interaction process are reduced but, by careful selection of the experimental arrangement, maintained in the same ratio as in the prototype. In this way, the interaction process can be investigated at reduced scale. This is highly desirable since model tests are much more economical to do than a corresponding full scale test, and it allows an examination of the process under controlled experimental conditions. For

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accurate results, however, it is important that all of the forces involved are scaled in the correct proportion. For model tests of rubble-mound breakwaters the forces of interest are gravity $F_g = Mg = \rho g L^3$ where M is the mass, g is gravitational acceleration, ρ is the density and L is a linear dimension; the inertial forces $F_i = Ma = \rho L^3 L t^{-2}$ where a is acceleration and t is time; and the viscous forces $F_v = \upsilon \rho t^{-2} L^2$ where υ is kinematic viscosity. The relationship between the gravitational and inertial forces is given by the Froude number (F_n)

$$F_n = \frac{v_p}{\sqrt{L_p g_p}} = \frac{v_m}{\sqrt{L_m g_m}} \tag{1}$$

where v is velocity and the subscripts m and p denote model and prototype respectively. Similarly, the relationship between the viscous forces and inertial forces is given by the Reynolds number (R_e)

$$R_e = \frac{L_p v_p}{\upsilon_p} = \frac{L_m v_m}{\upsilon_m} \tag{2}$$

To ensure total similitude in the model tests, both these numbers should be satisfied. This is virtually impossible to do unless a tank fluid can be found where (equating equations (1) and (2)) $\upsilon_p = \lambda^{3/2}\ \upsilon_m$ where λ is the linear scale factor of the model test. Since water is the normal working fluid in these tests, this is not accomplished and the viscous forces are not modelled correctly. For flow in the armour layer, it has recently been shown [4,9] that this is not a problem, even in tests with high scale factors. However, for flow in the filter layers and especially the core, this may not be the case due to the much smaller size of units and the correspondingly lower permeability of these regions. To test this is the purpose of the paper.

If the flow distribution in the core is not scaled correctly, this will influence the flow in the armour layer and consequently alter and distort the relative amount of wave energy dissipated in each of these regions. Because a breakwater dissipates the incident wave energy through rocking of the armour units and water turbulence within, the water flow and distribution should be the same in the model as in the prototype. If it is not, then the response of the armour units and energy dissipating processes are not properly reproduced in the model. This can affect the stability of the breakwater. This problem has been discussed by Yalin [12] who predicted that the restoring forces on the armour layer units will be scaled incorrectly and this could affect both the hydraulic and structural stability of the units. Burcharth [3] has suggested that this viscous effect will result in too high an internal water table within the breakwater. For the armour, this means that there will be a larger destabilizing pressure gradient and a reduction in the reservoir effect, thereby leading to larger overflow velocities.

3.0 EXPERIMENTAL APPROACH

The severity of this problem can be investigated using the physical modelling techniques which have been developed in this laboratory [8,10]. These techniques include: (1) the generation of realistic sea states in which both the variance spectral density and time domain characteristics of the wave field are correctly reproduced in the flume; (2) the use of a material to make the armour units in which the mechanical properties of concrete are scaled correctly for the model test (i.e. the strength of the armour units is scaled correctly based on the modelling laws). This material is a mixture of plaster-of-Paris, sand, iron ore and water. By varying the ratio of plaster to sand, the flexural (tensile) strength of the material can be altered over a wide range of interest ($40 \geq \lambda \geq 15$); whereas by properly choosing the iron ore to sand ratio, the density of the material can be adjusted to that of concrete. Measurements of the mechanical properties of this material have shown that the flexural strength, density and fracture toughness are correctly scaled over a wide range of scale factors. The use of this material allows breakage of the armour units at realistic stress levels, thereby allowing an examination of the structural as well as hydraulic stability of the armour layer in the test; and (3) the use of a photographic technique which automatically takes pictures of the face of the breakwater with both a 16 mm movie camera at every wave trough and a 35 mm SLR camera at every 50 wave troughs. This gives a continuous record of the damage to the breakwater during a storm.

To investigate the influence of the permeability of the core, a very simple approach was taken as follows: A series of different model breakwaters of 0.9 m sections were built in a 1.8 m wide flume. In each case the slope and height of the breakwater, the size and type of the armour units, and primary and secondary underlayer stones were identical. The only difference was the permeability of the core. Each breakwater was subjected to identical storm conditions. After the storm, the damage to each breakwater was assessed in terms of both the number of armour units which either broke or had large displacements, and the amount of underlayer exposed. Since the breakwaters were identical in all respects except for the permeability of the core, any differences in their stability during storm conditions was attributed to differences in the viscous flow in the breakwater.

4.0 TEST SET-UP

The tests were performed in a 1.8 m wide flume (see Figure 1) which was equipped with an hydraulically driven wave generator. The model breakwater was built with four individual layers comprising the core, primary and secondary underlayer and the armour layer. It was built with a 1:1.5 slope. In constructing the breakwater, the armour units were placed by hand in a random fashion with care being taken to ensure that it was of the same density and packing arrangement each time. For all of these tests, the armour layer consisted of dolos units of length 9 cm packed in two layers to a density of 330 units - m^{-2}. A cross-section profile of the model breakwater indicating the relative dimensions of each layer is shown in Figure 2. It should be noted that since the strength-simulated dolos units must be made individually, it was decided to limit the number of breakable units to 60 for each test. These were placed in a "nest" pattern centered about the mean water level in the centre of the model breakwater. The photographic equipment was set up to provide continuous documentation of the response of each breakwater to the storm conditions. After the storm, the flume was

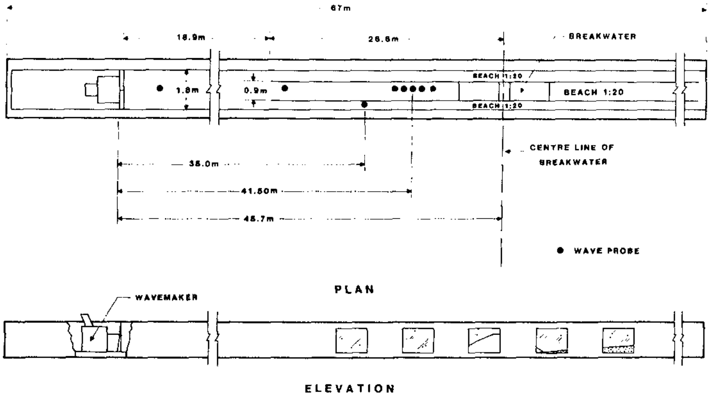


FIGURE 1: WAVE FLUME WITH PROBE LOCATIONS

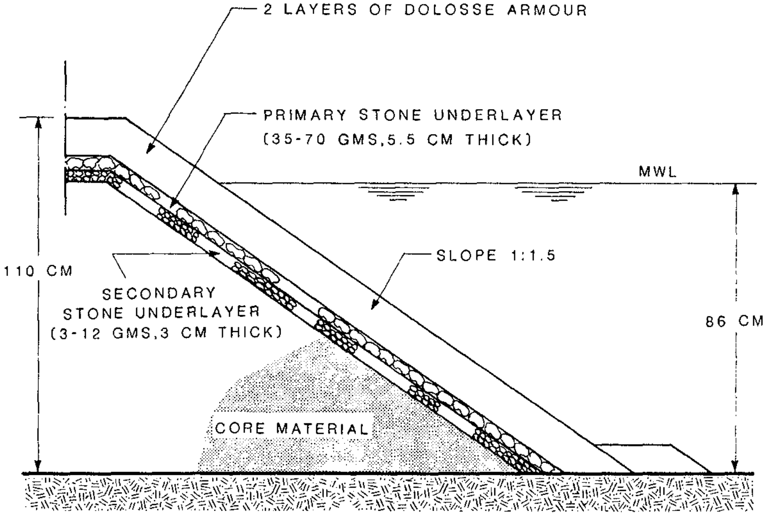


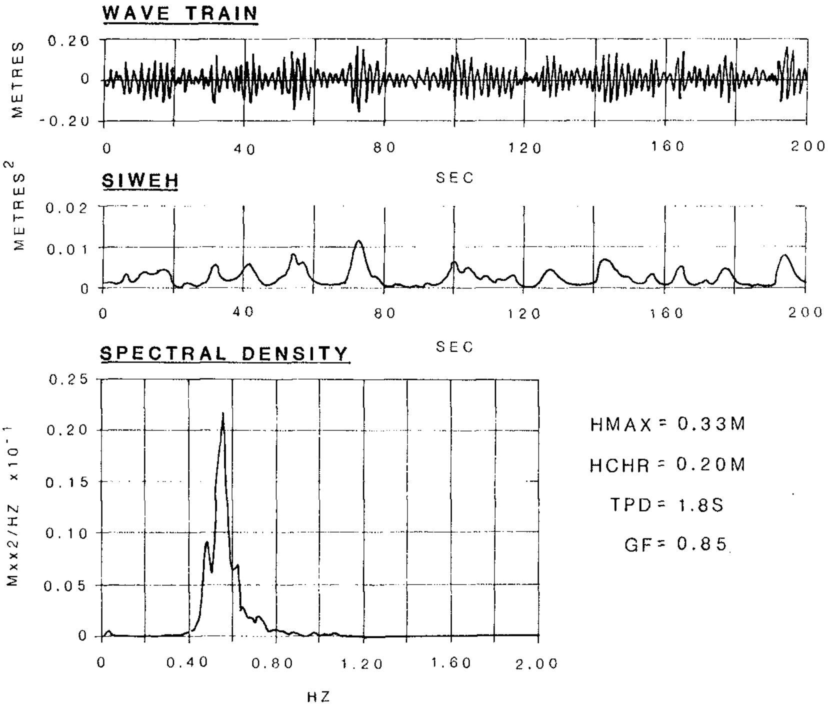
FIGURE 2: CROSS-SECTION PROFILE OF MODEL BREAKWATER

drained and the damage was assessed in terms of the number of broken and displaced armour units.

To alter the permeability of the core, three different core arrangements were used. To represent a very open core, the core was constructed from relatively large angular stones (diameter range from 3 to 6 cm). This was very porous with high permeability and an average Reynolds number of 6 x 10^3. To represent a more restrictive core, the core was constructed from much smaller angular stones (diameter range from 0.2 to 2 cm) with a correspondingly lower permeability and an average Reynolds number of 1 x 10^3. A core of this type is used in this laboratory in many tests of rubble-mound breakwaters since it is based on Froude geometric scaling of typical prototype cores. To represent a closed, restrictive core, a thin sheet of polyethylene plastic was inserted at the top of the core at the interface between the core and the secondary underlayer. This prevented flow within the core. In this case, all wave energy dissipated within the breakwater occurred in the armour layer and primary and secondary underlayer. This is the extreme case which represents zero permeability with a corresponding Reynolds number of zero for the core. These three cases were chosen simply to cover as wide a range of core permeabilities as possible. They are not meant to represent any particular prototype situation. This approach of looking at the response to a wide range of core permeabilies was taken since information on the permeability of prototype cores is scarce. Because of this, it is not possible at this time to know what the permeability, pressure and flow distribution should be within the core for a model test. In the present case, the permeability of the core is simply altered over as wide a range as possible in an attempt to determine the sensitivity to the core permeability of the overall stability of the breakwater.

In setting up the experiment, it was necessary to choose a suitable scale factor (λ) for the test. When using the strength-reduced armour units, it is possible to scale the strength of the units over a wide range of scale factors (15 to 40). Based on the size of the armour units (285 gm dolos units), this would correspond to prototype dolos weights of 1 to 18 tonnes. Since it is known that there is a "size-effect" with concrete armour units such that the larger units will fracture much more readily than the smaller units for the same relative amount of movement [2], and since the problem of incorrect viscous flow becomes more severe with increasing scale factor, a test at any single scale factor produces limited information. Because of this, it was decided to perform the test series for scale factors at both $\lambda = 15$ and $\lambda = 40$. These values bracket the range of scale factors which are typically used for model investigations of rubble-mound breakwaters. The first series was performed with the low scale factor ($\lambda = 15$) since it is known that if there is a difference seen in these tests, it will be much worse at higher scale factors.

In order to test their relative stability, it is important that the storm conditions be identical for each test. This is accomplished since the flume is equipped with a hydraulically driven irregular wave generator which is controlled by an on-line computer. This wave generator can produce a variety of natural sea states and wave transients in the flume. Figure 3 shows the time and frequency characteris-



WAVE TRAIN

SIWEH

SPECTRAL DENSITY

HMAX = 0.33M

HCHR = 0.20M

TPD = 1.8S

GF = 0.85

FIGURE 3: WAVE CHARACTERISTICS FOR THE TESTS

tics of the wave conditions generated for each of the test series. The reflection of the waves off of the breakwater was measured using an array of five gauges (see Figure 1) by the least squares method developed by Mansard and Funke [7]. The Smoothed Instantaneous Wave Energy History (SIWEH) which is shown in Figure 2 is used to determine the amount of wave grouping in the wave train [5]. Since the wave board in the flume is controlled by an on-line computer, these wave conditions could be stored and generated in each of the test series. In all tests, the storm conditions were run for 45 minutes.

5.0 RESULTS

The results of the tests for series I and II are tabulated in Tables I and II respectively. These tables list the information on the set-up for each test, as well as the damage sustained by the breakwater due to the storm. Note that the reflection coefficient (R) of the primary spectrum ($R = \sqrt{E_R/E_I}$ where E_R and E_I are the total energies of the reflected and incident spectra respectively) was similar for all three types of core. This indicates that, regardless of the type of core, the overall energy transmitted into or dissipated at the front face of the breakwater was always the same (91-93% of the total incident energy) within experimental accuracy.

For test series I at $\lambda = 15$ representing one ton dolosse, both the regular core and open core had very little damage done to the armour layer due to the storm. There were relatively few broken units or large scale displacements of the dolosse. There was virtually no difference in response between these two cases at this scale factor. For the case of the impermeable core, on the other hand, the response of the breakwater and amount of damage was quite different. In this case there was considerable rocking, displacement and breakage of the units. The destruction was so severe that in several places the underlayer was exposed since a considerable number of dolos units rolled off the face of the breakwater to the toe. This can be seen in Figure 4. During the storm, the whole face of the breakwater was almost continually under water since it took considerably longer for the water to drain off the breakwater than in the other two cases. In many instances for the impermeable core, the water from one wave would still be on the face of the breakwater when the next wave would hit. This caused a constant state of agitation of the dolos armour units. In observing the tests, it was evident that the response of the armour units to improper viscous flow was in agreement with the predictions by Yalin [12] and Burcharth [3] as discussed earlier. The complete hydraulic and structural stability of the armour layer was drastically influenced due to the improper viscous flow in the core.

For test series II at $\lambda = 40$ representing 18 ton dolosse, the test with the impermeable core was not repeated. Since there was extensive damage for this case at the lower scale factor, there would be considerable damage for any similar test at a higher scale factor representing larger dolosse. For the open and regular core at the low scale factor, there was no difference in response between these two cases. Since the problem of improper viscous flow should become more severe with increasing scale factor, these two cases were repeated at the higher scale factor of $\lambda = 40$. At this scale factor, there was a signi-

TABLE I

TEST SERIES I ($\lambda = 15$)

	TEST #1 (Open Core)	TEST #2 (Regular Core)	TEST #3 (Impermeable Core)
<u>TEST SET-UP</u>			
Height of breakwater (cm)	116	116	116
Slope of breakwater	1:1.5	1:1.5	1:1.5
Water depth (cm)	86	86	86
Type of armour unit	dolos	dolos	dolos
Height of armour unit (cm)	9	9	9
Mass of armour unit (gm)	285	285	285
Number of breakable units	60	60	60
Placement density of armour units (units - m^{-2})	330	330	330
Thickness of primary underlayer (cm)	5.5	5.5	5.5
Mass of primary underlayer stones (gm)	35-70	35-70	35-70
Shape of primary underlayer stones	angular	angular	angular
Thickness of secondary underlayer (cm)	3	3	3
Mass of secondary underlayer stones (gm)	3-6	3-6	3-6
Shape of secondary underlayer stones	angular	angular	angular
Diameter of core stones (cm)	3-6	0.2-2	closed
Shape of core stone	angular	angular	-
Porosity of core	0.53	0.29	0
Permeability of core (cm - s^{-1})	10^0-10^2	0.6	0
Reynolds number of core	$(4\text{-}8)\times10^3$	$(.2\text{-}2)\times10^3$	0
Characteristic wave height during storm (cm)	20	20	20
Peak wave period (s)	1.8	1.8	1.8
Groupiness factor - GF	0.85	0.85	0.85
<u>TEST RESULTS</u>			
Mean reflection coefficient (R)	0.27	0.29	0.28
% of energy dissipated by the breakwater $(1-R^2) \times 100$	93	91	92
Damage - units broken in trunk section	2	0	8
Damage - units broken in leg	3	6	3
Damage - severe rocking	8	5	21
Damage - large scale displacement	-	7	18

TABLE II

TEST SERIES II ($\lambda = 40$)

	TEST #4 (Open Core)	TEST #5 (Regular Core)
TEST SET-UP		
Height of breakwater (cm)	116	116
Slope of breakwater	1:1.5	1:1.5
Water depth (cm)	86	86
Type of armour unit	dolos	dolos
Height of armour unit (cm)	9	9
Mass of armour unit (gm)	285	285
Number of breakable units	65	62
Placement density of armour units (units - m^{-2})	330	330
Thickness of primary underlayer (cm)	5.5	5.5
Mass of primary underlayer stones (gm)	35-70	35-70
Shape of primary underlayer stones	angular	angular
Thickness of secondary underlayer (cm)	3	3
Mass of secondary underlayer stones (gm)	3-12	3-12
Shape of secondary underlayer stones	angular	angular
Diameter of core stones (cm)	3-6	0.2-2
Shape of core stone	angular	angular
Porosity of core	0.53	0.29
Permeability of core (cm - s^{-1})	10^0-10^2	0.6
Reynolds number of core	$(4-8)\times10^3$	$(.2-2)\times10^3$
Characteristic wave height during storm (cm)	20	20
Peak wave period (s)	1.8	1.8
Groupiness factor - GF	0.85	0.85
TEST RESULTS		
Mean reflection coefficient (R)	0.26	0.29
% of energy dissipated by the breakwater $(1-R^2) \times 100$	93	92
Damage - units broken in trunk section	7	15
Damage - units broken in leg	5	25
Damage - severe rocking	3	6
Damage - large scale displacement	1	14

FIGURE 4: PHOTOGRAPH OF THE FACE OF THE BREAKWATER WITH THE IMPERMEABLE CORE AFTER THE STORM. THE ARROWS INDICATE UNITS WHICH HAVE ROLLED DOWN THE FACE OR BROKEN, AND ALSO AREAS WHERE THE UNDERLAYER IS EXPOSED.

ficant difference in the response of the breakwaters. As summarized in Table II , there was considerably more damage to the breakwater built with the regular, less-porous core.

6.0 DISCUSSION

These tests clearly show two things. First, the permeability of the core has a very definite effect on the overall stability of a rubble-mound breakwater. The core clearly plays an important role in the overall energy dissipating process of the breakwater. Secondly, for model testing of rubble-mound breakwaters, the influence of incorrect scaling of permeability is a function of the scale factor of the test such that it increases with increasing scale factor because of the size effect. Care must be taken to scale as nearly as possible this aspect of the breakwater for a model test. The generally accepted method of preventing viscous effects is to construct the breakwater such that the Reynolds number for the flow exceeds a certain value (typically 10^3 [12]). Recently Burcharth [3] has pointed out that this criterion is not satisfactory for two reasons. First of all, a single value of a Reynolds number cannot represent the complicated and unsteady flow which occurs in the prototype. Secondly, the permeability of prototype cores is very difficult to predict since the permeability is sensitive to small variations in grading and separation of the material when dumped. In general, the prototype flow field is poorly known.

In order to try to minimize this problem, more emphasis must be placed in examining the geotechnical stability of prototype breakwaters [1]. Correct scaling of this property can only be accomplished once tests of the permeability, flow and internal pressure in the prototype core are measured and understood. If this were done, correct viscous flow should be obtainable directly for model tests which use very large armour units. For those tests in which smaller armour units (i.e. high scale factor) are used, a solution may be to run an appropriate math model to determine the internal pressure field and, by adjusting the core permeability, calibrate the small-scale physical model to reproduce correctly the calculated internal pressure field [3]. This type of approach, although it is not ideal, should result in better model-prototype conformity.

The present tests have implications to the understanding of the behaviour and design of prototype breakwaters. First of all, the difference in the results clearly shows that the core plays an important role in the overall energy dissipating properties of a rubble-mound breakwater. Secondly, the tests show that the relative stability of the armour layer can be enhanced if the core is made more porous. If it were, it would assume a relatively higher percentage of the wave energy dissipated within the breakwater than a less porous core. This would decrease the amount of wave energy which would be dissipated in the armour layer and consequently make the armour layer more stable. Of course, this aspect would have to be incorporated into the design of the breakwater with due consideration to the geotechnical stability of the structure.

7.0 SUMMARY

Based on the results of the present tests, it is clear that incorrect viscous flow in the core can influence the hydraulic and structural stability of the breakwater. Care must be taken, therefore, to scale this viscous flow as correctly as possible. If this is done, model tests of the stability of rubble-mound breakwaters would be more reliable since they would then be relatively unbiased by viscous effects.

8.0 ACKNOWLEDGEMENTS

The authors would like to thank George Ashe for overseeing the construction of the breakwaters and for technical assistance during the tests, and to Rob Bowen for making the strength-reduced armour units.

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