PROTOTYPE TESTS ON RIPRAP UNDER RANDOM WAVE ATTACK

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ABSTRACT

This paper describes the performance of test panels of riprap on an offshore island in the Wash estuary, UK, for the first 2½ years after their construction, by which time all but one had failed. It outlines the methods used in obtaining and analysing data on stone size, wind, tides and waves. The techniques used in surveying the test panels for damage and the reduction of the survey data to yield quantitative estimates of damage are described.

Comparisons are made between the damage to the riprap panels and what might have been estimated using laboratory data. Results do not support any scale effect causing riprap sized on laboratory data to be larger than necessary, and this conclusion is supported by the outcome of model tests carried out retrospectively by the Hydraulics Research Station (now HRS Ltd) at Wallingford, UK.

Slope protection is sensitive not only to wave height and stone size but also to construction methods and, bearing in mind possible departures from the desired specification, a cautious approach to the design of riprap protection is advisable.

1. INTRODUCTION

1.1 Use of Riprap for Slope Protection

In the context of this Report riprap is a graded quarry-stone layer on the sloping surface of an embankment protecting it from erosion by the action of wind generated waves. To prevent leaching of the embankment material through the riprap layer, one or more sub-layers (Filter layers) of smaller graded stone may be necessary. This method of slope protection is an alternative to continuous paving, interlocking slabs or precast concrete armour units. Because the cost of the slope protection can be a significant proportion of the total cost of a project, the reliability of available design information is important.

1.2 Limitations of Model Testing

Most design methods for riprap are based on results of hydraulic model tests, and their validity depends on the reproduction of all the characteristics of the prototype. It is seldom possible to meet this requirement fully, and errors arising from such limitations are referred to here as 'model effects'. The behaviour of riprap under wave attack depends on so many factors that some model effects are almost certain to be present (e.g. it is very difficult to ensure that the stone shape used in the prototype is reproduced in a model).

Even if the model accurately resembles the prototype, the forces are not necessarily reproduced exactly to scale, because all the

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requirements for dynamic similarity can not be met. Errors arising from this difficulty depend on the scale of the model, and are therefore known as 'scale effects'. Scale effects in laboratory tests of riprap were highlighted by work in the USA(1) which suggested that the use of small scale models could result in costly overdesign.

1.3 Background to the Study

Many of the early investigations into the behaviour of riprap and other forms of slope protection were based on model tests using regular waves. In that type of test, a significant 'model effect' is inevitable as real waves are irregular in height, frequency and direction. One of the first attempts to relate results of tests using regular waves to those using irregular waves is described in a U.K. Construction Industry Research and Information Association (CIRIA, formerly CERA) publication(2) on laboratory tests sponsored at the U.K. Hydraulics Research Station (HRS).

Research on the subject continued at HRS, in collaboration with CIRIA, with paddle-generated irregular waves, culminating in the publication of CIRIA Report 61 in 1976.(3). This comprehensive Report reviewed current practice under the headings of wave prediction, design procedure, design wave height, size, grade and shape of riprap, placing and thickness, filter design and run-up. Design curves and procedures based on these new measurements were presented.

1.4 The need for Field Tests

An important conclusion reached in CIRIA Report 61 was that, contrary to the American findings, no allowance for scale effects could be recommended when using these laboratory results with irregular waves for riprap design. The implication of this conclusion is demonstrated by reference to a possible Wash water storage Scheme(4) where riprap slope protection for bunded reservoirs in an intertidal zone was estimated to cost £38 m (1975 prices), about 65% of the total reservoir cost. Allowance for scale effects to reduce the size of riprap would have reduced the costs by about 30%.

With this in mind, field tests were proposed as the best method of establishing whether or not scale effects are indeed significant. An opportunity to carry out such tests arose during the construction of an offshore trial embankment in the Wash estuary, which formed part of the study of the feasibility of the water Storage Scheme.

2. OBJECTIVES AND SCOPE

The principal objective of the field trials was to compare observed behaviour at full scale with results predicted from small scale laboratory tests: hence to establish whether scale effects are significant and the scope, if any, for reducing costs of slope protection.

The field tests also provided a valuable opportunity to study practical aspects of handling and placing riprap, of checking the grading of both riprap and filter layers and of surveying the extent of the damage.

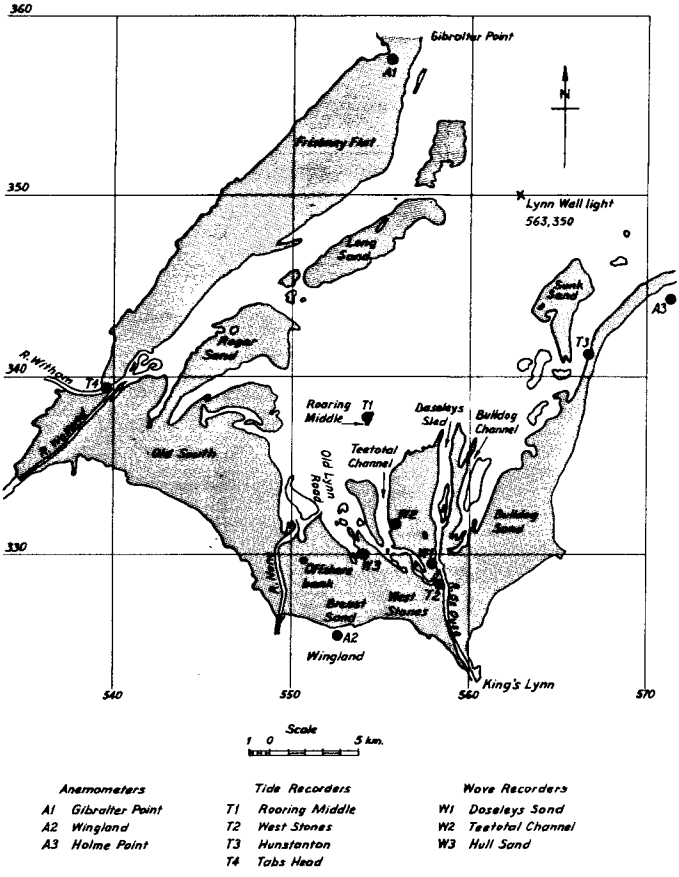

FIG. 1. LOCATION OF EXPERIMENTAL SITE AND DATA AQUISITION STATIONS.

The field study has since been rounded off by retrospective model tests, in which the test panels and wave and tide conditions that actually caused the main damage were reproduced at laboratory scale.

This paper concentrates on the field trials, but quotes the conclusions of the retrospective model tests. Details of these studies have recently been published[5],[6] and a further report[7] by CIRIA reviews both the laboratory and field tests.

3. DESCRIPTION OF THE FIELD TRIALS

3.1 Design of the Test Panels

The site in the Wash estuary is shown in Figure 1. The main trial embankment was circular in plan (Figure 2) and was constructed from hydraulically placed sand fill to a height of about 15 m above the sea bed. The large tidal range of the site (about 8 m at spring tides) was such that the foreshore was dry for about half the tidal cycle but some part of the lower half of the slopes was exposed to wave action for the other half of the cycle. The outside face of the main embankment was protected by heavy riprap (designated HRR) which was designed to withstand severe wave attack whether or not scale effects existed.

Four special riprap test panels were constructed, each 6 m wide and approximately 26.5 m long, on top of the main surface protection. Design of these panels was difficult because, for positive results, measurable damage (and perhaps failure) was desirable within a reasonable time scale. In view of the uncertainties over scale effects and in forecasting wave action, a range of sizes was selected so that the smallest riprap would almost certainly fail within a year or two with lesser damage (or none) expected to occur on the largest size. A fifth test section was selected from the adjacent permanent slope protection (HRR) which was also monitored.

3.2 Riprap grading

The specification called for riprap with the grading characteristics shown in Table 1, each size having a median diameter within a stated band, no stones exceeding a particular size, shape being such that the longest dimension was not more than three times the shortest dimension, and the small end of the grading defined by a minimum figure for the lower percentile (D_{15}).

TABLE 1 DIMENSIONS OF RIPRAP AND FILTER LAYERS

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5 (HRR)
RIPRAP					
Specified D_{100}	300-375	450-525	600-675	825-900	-
Specified D_{15}	155-190	225-270	310-355	425-460	-
Specified D_{50}	200-250	300-350	400-450	550-600	650-850
Measured D_{50}(mm)	230	400	500	560	660
Layer thickness, t (mm)	440	480	570	760	1320*
t/D_{50}	1.92	1.21	1.14	1.35	2.0*
FILTER LAYER					
D_{50}(mm)	40	40	40	40	40
Layer thickness (mm)	380	380	390	430	300*+

*design values
+also 200-mm layer of fine filter underneath.

It will be appreciated that checking the grading of riprap is not easy. Sieving is out of the question, yet, in most laboratory researches at small scale materials have been defined by sieve size. Samples in the field have to be treated as individual stones, most of which are so heavy that mechanical handling is needed. This not only poses problems on site, it also means that it is impracticable to expect a quarry to select and deliver riprap complying with a close specification.

After delivery of the material to the offshore bank site, a representative sample (about 15%) of the three smaller sizes was taken. Samples were also taken from Panels 4 and the HRR, although these samples were a smaller percentage of the total volume of stone delivered in these sizes. Every effort was made to ensure that the samples were representative of the bulk of material, but the procedure was necessarily subjective.

The material in each sample was graded by weighing on a spring balance while for every fifth stone in each sample three orthogonal dimensions were measured. The methods of weighing and measuring are described in reference 4.

The mass grading curves obtained were converted to dimensional grading curves (figure 3) using the relationship suggested in Reference 3:

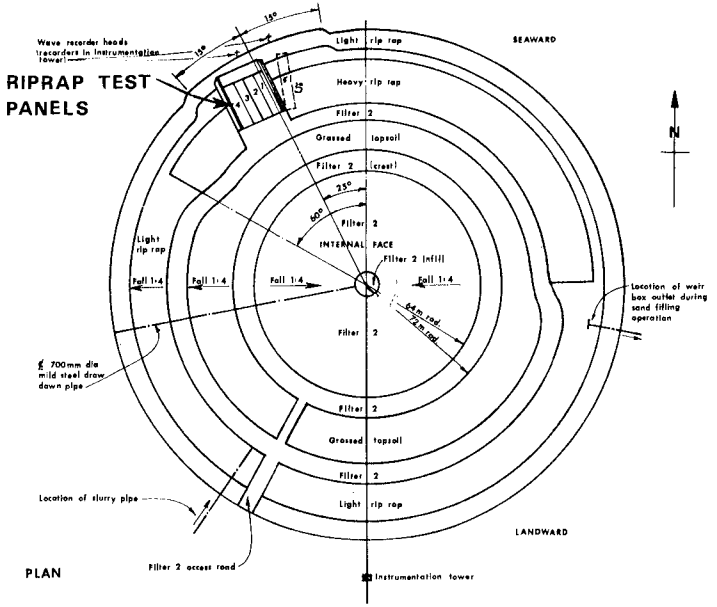

FIG. 2. LOCATION OF TEST PANELS ON OFFSHORE BANK.

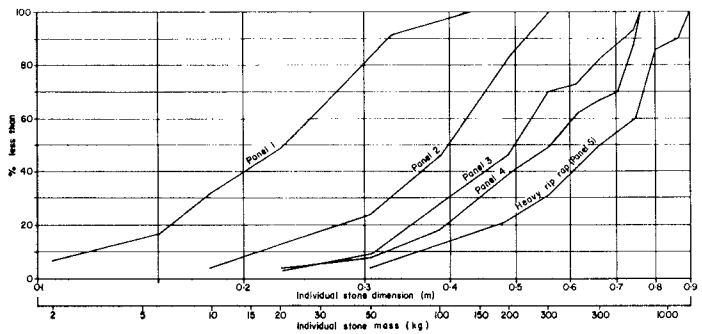

FIG. 3. GRADING CURVES FOR RIP RAP.

$$M = 0.65 \rho D_s^3$$

which is based on conversion of sieve gradings, where D_s is sieve size, to individual stone mass, M. This relationship was implicit in the original specification of the riprap grading. The conversion showed that the materials for Panels 2 and 3 were outside the tolerance specified, being somewhat oversize.

3.3 Construction

The first stage of constructing the four test panels was to blind the selected area of main riprap protection with a layer of filter material to ensure that no settlement of the test panels would occur through the filling of voids beneath them. A fabric sandwich, consisting of two layers of a non-woven sand-tight fabric separated by a sheet of PVC, was placed on the blinded surface to make the test panel foundation impervious, in an attempt to match the previous laboratory arrangement. A layer of filter was placed over the fabric on which the stone forming the test panels was laid, with the panel containing the smallest stone (Panel 1) at the eastern edge of the test area, each panel being flanked on its western edge by the panel containing the next larger size of stone. The location and arrangement of the panels on the embankment is shown in Figure 2, and a longitudinal section through one of the panels is shown in Figure 4.

Proposals for strengthening the edges of the panels, so that if one panel failed completely the adjacent panel would not be weakened were considered. However, any method of edge strengthening would then form an upstanding edge, which could cause undesirable wave reflections interfering with the performance of the riprap or could itself be washed away. Bearing in mind the cost and uncertain performance of any such arrangement, no special edge treatment was incorporated.

The area of the main bank protection selected as Panel 5 lay immediately to the east of the special test section. No special provisions were made in placing this riprap or in placing the two filter layers separating the permanent riprap from the sandfill of the embankment.

The stone was imported by sea from quarries in Belgium. It was then brought from offshore stockpiles by barge and placed direct in position by floating crane using a 4 tonne cactus grab.

Segregation is a problem with riprap and is made worse by multiple handling, as necessarily occurred with the construction techniques employed offshore in the Wash. It also increases with widely graded stone. Despite efforts on site to control the work so as to minimise segregation generally, and particularly in the test panels, it was not practicable to correct segregation other than marginally once it occurred.

For the test panels, control of the placing operation was strict and the quality of the finished slope protection is probably better than would normally be found using this method of placing. Nevertheless,

visual inspection revealed that the riprap surface was rough and fairly open, with occasional holes through which the surface of the filter layer could be seen, this being particularly noticeable on Panel 4. The mean thicknesses of the riprap are listed in Table 1 which also shows that in all panels except Panel 1 the relative layer thickness ratio, t/D_{50}, was less than 2.0, the value recommended on the basis of laboratory research.

Three factors tended to reduce the relative layer thickness below the intended value:

1. Penetration of the riprap into the filter layer material.
2. Loss of material in transport and handling, which could not be made good at the time.
3. Because the stone tended to be oversized, the given coverage in terms of mass per unit area yielded a lower ratio of t/D_{50}.

The derivation of mean layer thickness is not always defined in earlier work but the problems of controlling this parameter are considered in Reference 5. Discrepancies must be expected in difficult field conditions.

3.4 Data Collection

There were two principle components of data collection: wave climate and damage to riprap. Measurement and analysis of wave action was a major task and only an outline of the methods adopted can be presented here (details are given in reference 5).

Waves were measured by two pressure transducer wave recorders mounted near the seabed in front of the trial panels, and data on wave heights and periods were obtained at approximately hourly intervals through the high tide period under control from a lunar clock. Water levels were measured continuously in order to identify the level at which wave attack was concentrated. The direction of wave attack was deduced from wind data obtained from an anemometer set up on the coast, about 1.5 km away.

Damage to the riprap panels was measured at regular intervals so that it could be related to the wave action. The method of surveying damage was based on the procedure used previously in the laboratory, and involved measuring profiles along the riprap surface in relation to a fixed framework.

Five survey lines for each panel were fixed by stretching piano wire tagged at the required intervals, from a frame at the toe of the panels to a pulley fixed to a second frame at the top of the panels. The level at each plan position was obtained by measuring down from the tags on the piano wire, using a vertical scale fitted with a spirit level and having a hemispherical foot. The diameter of the hemisphere was equal to half the average of the specified median stone size limits of the panel being surveyed, and thus a different foot was required for each panel.

In addition to the levelling survey, each panel was photographed from a fixed point whenever a survey visit was made.

A total of 17 surveys were carried out over the 2½ years period of study.

3.5 Damage Analysis

The survey data were analysed by computer to give a quantitative description of the damage sustained by each panel and a surface profile plot of each line surveyed.

The definition of damage was that used in the HRS laboratory studies reported by CIRIA(3) : the volume removed, expressed as an equivalent number of D_{50} - size spherical stones for a $9D_{50}$ width of panel, considering only downward movements of the surveyed profiles (reductions in thickness). In the laboratory tests, these movements occurred in a fairly well-defined area about the still-water level. Positive movements (accretion of displaced stone) generally occurring in the region below the eroded area were ignored, since these are not of interest when considering the ability of the riprap layer to withstand damage (Figure 5).

The volumes of material eroded from each panel since the beginning of the study, and also since the previous survey, were obtained by differencing the relevant profiles. The eroded volumes were then converted to the mass of stone removed and then to the equivalent number of D_{50} size spheres over a 9 D_{50} width.

Some statistical analysis of the individual survey measurements was made to give measures of the mean movement of the surface in each section, the roughness of the surface, and changes in individual measurements between surveys.

4. RESULTS

4.1 Wave events and General Damage History

It was unfortunate that large waves (H_S just over 1 m) occurred with high water levels very early in the project, during the gale lasting from 16 to 18 November 1975, within days of laying the test riprap. The main effect was the total failure of Panel 1 (Figure 6). The riprap and the underlying filter were completely washed away from the central section of the panel, part being deposited in the lower section of the panel and part being completely lost. The upper limit of damage, about 6 m from the top of the panel, was marked by a near vertical face exposing the riprap and filter layers. The failure of Panel 1 had been expected to occur during the course of the first winter, but the occurrence of a severe storm so early meant that no results on progressive damage were available for this panel.

Erosion damage on Panel 2 was also serious on this occasion, being assessed at 112 D_{50} stones. Damage was concentrated on the side

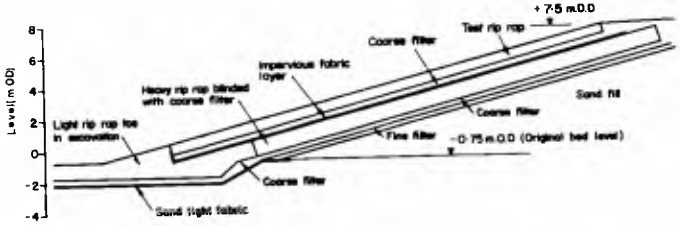

FIG. 4. SECTION THROUGH TEST PANEL.

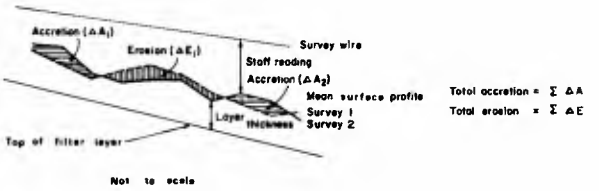

FIG. 5. ILLUSTRATION OF DAMAGE ANALYSIS.

FIG. 6. FAILURE OF PANEL 1, NOVEMBER 1975.

closest to Panel 1, and a considerable part was undoubtedly because of the loss of edge support resulting from the total loss of riprap and underlying filter from the central part of Panel 1. Table 2 lists the survey dates and the damage status.

During December 1975 three wave events were recorded, one of which included waves with H_S nearly 0.9 m. The two most severe events occurred with winds orthogonal to the panels, but tide levels were in general low at the time and so there was little additional damage to the panels. The next severe gale occurred on 3 January 1976, when winds of up to 40 m/s (90 mile/h) were recorded. Waves on this occasion were not very large, partly because the wind did not reach its peak until some time after high water and partly because it was blowing from the west with a very restricted fetch. Tide levels were high, however, and waves at high water were large enough to cause further erosion at the top of Panel 1, as filter material was washed out from the foot of the vertical cliff marking the upper limit of earlier damage. Over the next week, this caused the area of Panel 2 affected by loss of edge support to extend up the slope.

Three events with waves of about 0.75 m occurred between mid-January and mid-February 1976. Only the first event was with winds directly in line with the test panels, the second and third events being with winds from the east and northeast respectively. However, damage to Panel 3 and 4 as well as further damage to Panel 2 was noted.

The period to April 1977 covering the next winter, was relatively calm: the maximum significant wave height recorded was 0.83 m, but on this occasion the wind was further from the northeast (70° from orthogonal). Only minor drainage was observed, comparable to the probable maximum error in measuring damage, so was not significant.

Data collection in the Spring of 1977 was marred by the loss of wave records from 19 March to 8 May, a period when northerly and north-easterly winds were dominant. However, hindcasting of wave events demonstrated that particularly severe wave attacks (H_S = 1.4 m) occurred immediately after surveys on 5/6 April. Waves were directly orthogonal to the bank and, being the severest to date, some damage was to be expected to most of the panels, although no further survey was carried out until August 1977.

Immediately following the August survey there was further severe wave action (4 days with H_S up to 1 m at high tide). Winds were primarily from the north east, though they backed to north north west and resulted in the total failure of Panel 2 (see table 2, survey on 12.10.77) and further damage to Panels 3, 4 and 5.

One further event, with waves nearly 1.0 m high, was recorded in December 1977, but the wind was from the west and no damage was observed.

Waves recorded in the event of 11/12 January 1978, the third winter of observation, when winds were from the north, were far in

Table 2. Comparison of surveyed and calculated damage (No. of D_{50} stones.)

Panel No.	Survey Date	Since previous survey		Since initial survey	
		Surveyed damage	Calculated damage	Surveyed damage	Calculated damage (See note 1)
1	19.11.75	839	313	839	313
E=39 (See	14.5.76	329	241	1075	554
note 2)	12.10.77	108	F(See note 3)	1170	F
2	19.11.75	83	32	83	32
	3.12.75	10	5	73	37
(E=26)	18.12.75	17	12	74	49
	15.1.76	47	6	95	55
	17.2.76	29	8	103	63
	2.3.76	16	0	108	63
	18.3.76	38	0	93	63
	31.3.76	40	0	117	63
	13.5.76	5	9	92	72
	16.8.77	48	(71)	139	(143)
	12.10.77	121	37	231	(180)
	9.3.78		F		F
3	3.12.75	3	0	3	0
(E=21)	18.12.75	3	2	1	2
	15.1.76	9	0	2	2
	29.1.76	12	0	5	2
	17.2.76	24	0	18	2
	2.3.76	3	0	9	2
	18.3.76	2	0	7	2
	29.4.76	12	0	8	2
	14.5.76	3	0	4	2
	6.12.76	12	0	10	2
	5.4.77	4	3	5	5
	15.8.77	16	(23)	7	(28)
	11.10.77	16	11	18	(39)
	9.3.78	231	137	236	(176)
4	2.12.75	10	0	10	0
(E=17)	16.1.76	5	0	9	0
	17.2.76	18	0	33	0
	13.5.76	2	0	24	0
	6.12.76	19	0	32	0
	5.4.77	12	0	9	0
	15.8.77	18	(14)	20	(14)
	11.10.77	19	5	35	(19)
	9.3.78	162	63	188	(82)
5(HRR)	16.1.76	16	0	16	0
(E=12)	2.3.76	6	0	19	0
	13.5.76	6	0	14	0
	7.12.76	13	0	25	0
	6.4.77	4	0	20	0
	15.8.77	11	(4)	28	(4)
	11.10.77	8	1	27	(5)
	9.3.78	12	31	27	(36)

Notes:

1. Sum of calculated damage between surveys.
2. E is probable maximum error in calculated damage.
3. F indicates damage beyond range measured in the laboratory

Bracketed values derived from data which includes hindcast wave conditions.

excess of the previous maximum (H_S = 2 m) and resulted in the total failure of Panels 3 and 4 (Figure 7) (see Table 2, survey of 9.3.78). Panel 5, the permanent riprap, suffered very little damage. This was a very rare combination of wave attack and high tide: the tide level exceeded the calamitous 1953 storm surge in fact.

4.2 Damage calculated from Laboratory results

Results of the laboratory study[3] were used with the recorded wave data to hindcast the damage sustained by the test panels. The method used is a variation of that set out as Method 2 in CIRIA report 61(3), making the appropriate allowance for the different water densities in the laboratory and fieldwork. The data contained in that Report were used to prepare Figure 8, in which damage is related to number of waves incident on the panel and the ratio H_S/D_{50}. The total damage expected was obtained by summing the damage arising from waves of each height, i.e. as if they were attacking an undamaged surface.

The laboratory work showed that a damage level of about 115 stones removed corresponds to the level of failure at which the filter layer could be touched with the survey probe. However, the differences between field and laboratory conditions (Section 3.1) reduce the significance of this value. The lower ratio of thickness to stone size used on the test panels suggests that failure might occur with fewer stones being removed. On the other hand, varying water levels would cause damage over a larger area than in the laboratory tests, suggesting that a greater level of damage could be tolerated before local failure is reached.

4.3 Comparison between measured and hindcast damage

Table 2 summarises the comparison between damage to the test panels as measured by field surveys and that hindcast on the basis of laboratory tests. The general impression is that measured damage is rather greater than that calculated except in the case of panel 5, where measured and calculated damage are comparable (but small in absolute terms and only of the order of possible survey error).

In interpretting the results of this comparison, it should be remembered that the conditions of the field study inevitably differed from those in the previous generalised, somewhat idealised, laboratory research in the following respects:

1. The presence of tides causing the water level to vary continuously from below to about three quarters of the way up the test panels.

2. The variability of the wave events.

3. The sequential action of waves at different elevations and with differing heights.

4. The range of directions from which the waves approached the test panels.

FIG. 7. FAILURE OF PANELS 3 AND 4, JANUARY 1978.

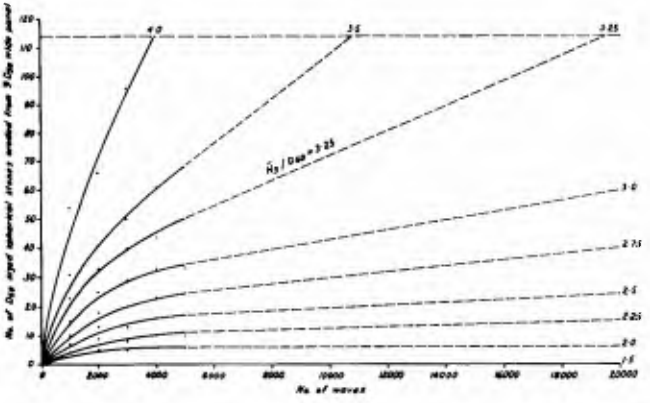

FIG. 8. DAMAGE FROM WAVE ATTACK, BASED ON HRS RESULTS (REF. 3)

5. The very large number of waves involved.

6. A different ratio of filter-size to riprap size.

7. The thickness of the panels ($2D_{50}$ in the laboratory work: but considerably less than that in Panels 2, 3 and 4 in the field trials).

8. Different methods of placing the riprap, involving some degree of segregation and differing bulk density of the finished layer.

9. Problems of measuring stone size and differences in the grading and shape of the riprap.

10. The very different sizes of the stone in the laboratory and site situation and the consequential scale effects.

Some or all of these differences between field and laboratory conditions undoubtedly account for discrepancy between observed and calculated damage, based on scaling up the laboratory work, and could perhaps obscure scale effects if they existed. Nevertheless, the clear conclusion is that using laboratory research results for riprap design, omitting any allowance for scale effects, does not result in an over-conservative design.

4.4 Retrospective Model Tests

The overall impression was that agreement between earlier laboratory tests and field trials was fair and that there was no evidence of major scale effects. Nevertheless, further evidence was sought from specific model tests in which the conditions actually observed during the field trials were reproduced as far as possible. These retrospective model tests were undertaken by HRS in 1981 and results have now been published(6). These small scale (1:17) laboratory tests satisfactorily reproduced the damage behaviour observed in the field tests, thus adding weight to the conclusion on the absence of significant scale effects.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Evidence for Scale Effects

In general, the amount of damage sustained by the test panels was slightly greater than that calculated from laboratory research results. The exception was Panel 5 which, in the most severe event, suffered slightly less damage than predicted, though the difference is within the survey and other tolerances. The discrepancies between observed and hindcast damage can be explained by inevitable differences between laboratory and field conditions. Retrospective model tests in which the field conditions were more realistically represented than in previous basic research showed good agreement between model and full scale results.

This study has thus not confirmed the CERC findings(1) concerning scale effects, namely that small scale model results tend to overestimate the size of riprap needed to provide protection against waves of a particular height.

5.2 Practical Aspects of Riprap Design and Construction

The field trials, which were undertaken under close supervision, demonstrated the problems of laying riprap to meet specified gradings, mean size and layer thickness.

Procedures developed for monitoring and analysing progressive damage to riprap involved considerable effort but were successful and are recommended for any future full scale study.

Whilst the general guidelines for riprap design given in CIRIA report 61 have been validated by results of field tests, gaps remain in our knowledge of the behaviour of riprap. These include the effect of varying water level, the effect of oblique attack, the influence of non-uniformity arising from segregation of graded stone, the importance of layer thickness and grading of both filter layer and of the riprap itself, and the modes of progressive failure resulting from locally damaged areas.

5.3 Recommendation for Design

Results of small scale hydraulic model tests on riprap should be adopted without making allowance for "scale effects" which might justify smaller sizes. If model tests are not conducted specifically for the slope protection in question, then the design procedures given in CIRIA report 61 are recommended.

Designers should be aware of the practical difficulties in meeting specifications for riprap. If the consequences of damage to riprap are not acceptable than a cautious approach to design should be adopted.

6. ACKNOWLEDGEMENT

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