# Riprap design for wind-wave attack

## Retrospective model tests of the measured damage to riprap panels on the offshore bank in the Wash

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## Preface

This report describes retrospective tests made of test riprap panels laid on the Wash trial bank. The model results are in substantial agreement with the field measured damage, and do not indicate a Reynolds scale effect. An extension of earlier tests at HRS on "Riprap design for windwave attack" confirms the finding of that report that no allowance can be recommended when transforming from small scale model tests to full scale. The results from identical repeat tests show a significant inherent variableness in the damage parameter.

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# 1 Introduction

Riprap in the context of this report is a graded quarrystone layer laid on the surface of an embankment to protect it from erosion by the action of wind generated waves. To prevent leaching of the embankment material through the riprap layer by wave induced movement one or more sub-layers, or filter layers, of smaller graded stone may be used. Where the wave heights are not excessive this method of slope protection is often an alternative to continuous paving, interlocking slabs or pre-cast concrete armour units. The relative cost of the slope protection can be a significant proportion of the total cost of a project and hence the reliability of the available design information or the data from model tests is crucial.

In 1962 the Civil Engineering Research Association (CERA) sponsored laboratory tests at the Hydraulic Research Station (HRS) which resulted in the publication of a report[1] giving design procedures for determining the riprap size required for given design wave conditions. This CERA work represents one of the first attempts to relate the results of tests using regular waves to those using irregular waves; in this case generated by wind.

Research on the subject continued at HRS, in collaboration with the Construction Industry Research and Information Association (CIRIA; the successor to CERA), using the then newly developed procedure of paddle generated irregular waves. This work culminated in the publication of the comprehensive CIRIA Report 61 in 1976.[2] This 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. A significant conclusion of this report was that no allowance for Reynolds scale effect could be recommended when using the data for full scale design.

In open boundary hydraulics research, phenomena primarily dependent on gravitational and inertial effects are modelled according to the Froudian laws. Secondary forces arise when water is the fluid in both prototype and model, because, for example, surface tension and fluid viscosity are not correctly modelled. Scale effects occur when these secondary forces become significant. For the present research, depending upon the mechanism for failure, lift and drag on individual stones could be dependent on Reynolds number, which is a measure of the relative importance of inertia and viscous forces. Thus at the low Reynolds number of a small scale laboratory study, the lift and drag forces may be larger than is the case under strict dynamic similarity and hence proportionately greater damage might occur on the model, than at full scale through this scale effect. This results in the scaled up riprap size being too large.

Reynolds number scale effects were claimed by Thomsen et al[3] although their evidence was not entirely convincing. They reviewed small scale and large scale research in the United States of America and concluded that only in the largest scale tests were results free from Reynolds scale effects. Indeed their data indicates that in the HRS tests, which covered a six fold variation in Reynolds number, there should be a 30% scale effect in the stability number, $N_{ZD}$, at near zero damage; an effect which should have been detectable but which was not found. The work of Thomsen et al suggests that the armour size at full scale designed for minimal or zero damage on the basis of the HRS tests could be up to 60% oversize. However, before this potential saving can be realized the conflict between the work of Thomsen et al and the HRS work must be resolved.

Tests at full scale, reproducing the conditions of the HRS study, were desirable but impracticable. No suitable site was readily available and financial considerations required that such an undertaking be made in conjunction with a constructional project to minimise mobilization and other costs. Such an opportunity arose in connection with the construction of an offshore trial embankment within the Wash estuary as part of the studies of water storage in the area. A number of test riprap panels were built on top of the main armour of the trial embankment and the ensuing damage by wave action monitored, together with measurements of the waves and the tides. Because the conditions were far removed from the original laboratory experiments particularly with the introduction of tides HRS agreed to perform retrospective tests as part of their basic research programme.

The research contract for the test panels in the Wash was placed by CIRIA with the Central Water Planning Unit and the work was carried out by the Unit's consultants, Binnie and Partners. This work covered the period from November 1975 to May 1976 and was reported in CIRIA Technical Note 84.[4] A subsequent research contract was placed by CIRIA directly with Binnie and Partners to extend the period of observations. This resulted in CIRIA Technical Note 101[5] which covers the 2½ year period, November 1975 to March 1978, by which time the test riprap panels had been destroyed.

This report summarises the field riprap measurements made in the Wash and describes the retrospective model tests made at HRS. Also presented are measurements made in a small programme of tests designed to extend the range of Reynolds number tested in the original CIRIA Report 61[2] and measurements from a series of tests to investigate the repeatability of identical tests.

## 2 Field measurements

CIRIA Technical Note 101[5] gives a complete description of the design, laying and subsequent measurements made of the damage to the riprap panels together with a detailed analysis of the measured data. The following is a summary of the main points pertinent to the retrospective model tests.

The location of the trial bank is within the Wash estuary and its principal dimensions are shown on figures 1 and 2 respectively. The trial bank is trapezoidal in section and circular in plan with a maximum crest elevation of 14m OD; the seabed elevation being −0.75m OD. The outer 1 on 4 slope is armoured up to the 7.5m OD level with riprap having a median stone size, $D_{50}$, of 0.66m over the seaward facing sector N60W to N90E and a $D_{50}$ size of 0.53m over the remainder.

Included in figure 1 is the location of wind, tide and wave recording equipment where data was recorded prior to the construction of the trial bank. On the basis of this data the test riprap panels 1-4 were laid facing N25°W, each 6.5m wide and extending up the slope from about 1m OD to 7.5m OD (figure 2). The underlying main riprap armour was blinded with coarse filter and then covered with an impervious fabric layer on which the filter and test riprap panels were laid. The impervious fabric layer provided an analogy with the earlier laboratory tests. A section through the test riprap panels is given in figure 3. At each side of the test area the main embankment armour was thickened to provide side support for the test riprap. The grading curves for the test riprap panels are show in figure 4. Panel 5 was an adjacent area of the main slope protection with the same orientation as the test riprap panels 1-4.

The riprap for both the trial bank and the test panels was transported by barge and then coaster from Belgium to a transhipment area within the Wash. The test riprap was brought by barge from the transhipment area and placed directly in position using a cactus grab having a capacity of about 2 tonnes. The upper 5m of the test slope was beyond the reach of the cactus grab and material for this area was stockpiled at the limit of the grab's reach and then dragged up into position using a hydraulic excavator. The multiple handling of the test riprap resulted in some segregation of the material; this was particularly noticeable in the central section of panel 1. A view of the newly completed four riprap panels is shown on Plate 1. A visual inspection of the finished panels showed the surface to be rough and fairly open with many holes through which the surface of the filter layer could be seen. This was very obvious for panel 3 which had the lowest relative thickness. The principal dimensions of the riprap and filter layers are given in Table 1.

Waves were measured at the site using two seabed mounted pressure sensing wave recorders located just seaward of the toe of the test panels. A programmed clock operated the recorders alternately to record four sets of wave data, over each high tide, in the form of an analogue signal on paper chart. The wave recorder switching sequence is shown on figure 5.

Recording of winds and tides continued at the locations shown in figure 1 during the test programme but in September 1977 the West Stones tide recorder was moved to the offshore trial bank.

The riprap surface was surveyed by measuring vertically down from a wire stretched up the slope between fixed frames. The wire was fixed to the frame at the toe of the slope and passed over a pulley on the frame at the top of the slope; a standard weight attached to the upper end of the wire giving the tension. The frames were drilled to ensure repeatable positioning of the lines and tags at regular intervals along the wires located the measurement points. For each panel five survey lines 0.75m apart were established with tag spacings along the lines of 0.25m for panels 1 and 2 and 0.5m for the remaining panels. The vertical distance of the riprap surface below the wire was measured using a scaled staff fitted with a spirit level. For each panel a different staff was used having a hemispherical foot, the diameter of which was related to the riprap size. Measurements were also made over an area of the larger trial embankment armour to the east of the test panels and designated panel 5.

The panels were completed in November 1975 and an initial survey was made of panels 1 and 2 on 6.11.75. Over the period 16/18.11.75 significant wave heights just over 1m were measured and during the survey visit on 19/20.11.75 the panel 1 was found to have failed. A large area of the riprap and the underlying filter had been completely removed. Also loss of side support from panel 1 to panel 2 resulted in some damage, probably by undermining, to panel 2. During this site visit all five panels were surveyed. Thereafter regular site visits were made to survey the panels and to collect other data. Table 12 of reference 5 presents a summary of all wave events, defined as $\bar{H}_3 > 0.5$m, that occurred until the final survey on 9.3.78 when panels

2, 3 and 4 were found to have been destroyed. This final loss of riprap is attributable to the major storm in January 1978 when a maximum significant wave height of 2.14m was recorded at a tidal level of 5.79m OD. Between the first storm in November 1975 and the storm in January 1978 significant wave heights in excess of 1m occurred on only two occasions. In one the maximum measured significant wave height was 1.01m and in the other the estimated significant wave height was 1.4m, based on measured wind data; both wave recorders being out of action at the time.

The different performance of panels 4 and 5 left an unresolved anomaly. Although the median stone size of the two panels were close together, 0.56m and 0.66m respectively, panel 4 was destroyed whereas panel 5 suffered only superficial damage. There were significant differences between panels 4 and 5 in the laying thickness and in the filter grading which may have had an influence on the different damage levels sustained.

## 3 Retrospective model tests

Table 12 of reference 5 tabulates all the wave events during the period November 1975 to March 1978 for which the measured or hindcast significant wave height exceeded 0.5m. There are 103 wave/tide events and clearly it was not practicable to reproduce all on the model. An examination of the wave/tide events and the measured damage suggested that the number of events could be reduced to 4; the first storm of November 1975, consisting of 3 wave/tide events, which severely damaged panel 1, and the severe storm of January 1978, consisting of 1 wave/tide event which in all probability severely damaged the remaining 3 test panels but not the main embankment armour, panel 5. The two storm events are subsequently referred to as storm 1 and storm 2 respectively. The provisional programme was to make a first test run of the two storm events and then to repeat it with additional wave/tide events if necessary.

**The model scale 3.1** A scale of 1:17 was chosen giving model $D_{50}$ stone sizes of 13mm for panel 1 and 39mm for panel 5. This covered the range of sizes used in the tests on which CIRIA Report 61[2] was based and ensured that the tests would be over a range of Reynolds number for which the work of Thomson et al predicts large Reynolds scale effects. Indeed the panel 1 size of 13mm is below the minimum size of 20mm in the CIRIA 61 tests thus giving even lower Reynolds numbers and hence the possibility of greater Reynolds scale effects.

**The physical model 3.2** The test riprap panels were laid out as shown in figure 6 in a 6m wide random wave flume. Riprap panels 1-4 were tested in the 4m wide section of the flume at an angle to the incident waves while riprap panel 5 was tested separately in the narrower 0.61m wide sub-flume. Testing panel 5 square on to the waves rather than at an angle would if anything give slightly increased damage on the model.

Plates 2 and 3 show the modelled panels 1-4 for the test runs 1 and 2 respectively. The scaled filter and riprap were laid on a wooden support frame, the sloping floor of which was stepped to accommodate the varying total thicknesses of the four panels. The edge supports to panels 1 and 4, which in the field consisted of a thickened layer of the main embankment armour, were incorporated in the support frame; no attempt being made to model the main embankment armour. The riprap panels were terminated at the lower end at about the 2m OD level.Wave heights below this level were not measured in the field because the pressure sensors were mounted about 1m above the seabed.

The model riprap was of crushed carboniferous limestone having a specific gravity of 2.70 and sieved in ¼ inch cuts from ¼ inch to 2 inch and then mixed by weight to give the grading curves shown on figure 4. Appendix 1 gives details of the stone shape analysis. The filter layer was sieved from smooth shingle from 2 – 6mm and from coarse sand from 0.2 – 2mm and mixed by weight to reproduce the field grading curve for the filter under panels 1-4. For panel 5, only the 2 – 6mm shingle was used for the filter.

For test run 1 the filter layer was laid dry, compacted and screeded but for test run 2 the material was laid damp, compacted and then screeded after the wave basin had been flooded and drained. This latter procedure was adopted because of a suspicion, during the first test run of settlement during the first wave/tide event. This suspicion was not confirmed by subsequent comparison of the damage measured for the two tests.

The model riprap was laid in such a way as to simulate some of the field procedures and a comparison of plates 1 and 2 indicates the degree of similarity produced for test run 1. Panels 2-4 show a reasonable similarity but panel 1 appears to lack sufficient fine material. The grading curve on figure 4 shows the tail of the curve at the ¼″ size with 7% less than this size. For test run 1 the grading was terminated at the ¼″ cut but for test run 2 an extra cut down to ⅛″ was added and the improvement in appearance can be seen by comparing plates 1 and 3.

Table A, below, shows the thickness of the modelled riprap panels achieved for the two test runs. For test run 1 the panels were all thicker

**Table A** Laying thicknesses of model riprap

| Panel | Scalar thickness required mm | Model thickness Test run 1 mm | Model thickness Test run 2 mm |
|---|---|---|---|
| 1 | 25.9 | 31.2 ± 3.4 | 26.4 ± 3.5 |
| 2 | 28.2 | 34.9 ± 4.5 | 34.8 ± 4.5 |
| 3 | 33.5 | 36.7 ± 3.8 | 41.9 ± 4.1 |
| 4 | 44.7 | 49.1 ± 3.8 | 46.9 ± 3.4 |

The layer thickness of panel 5 was not measured on either the field or the model. A thickness of $2D_{50}$ was specified for both

than required but more stringent laying control for test run 2 reduced at least panels 1 and 4 to values nearer the scalar values.

As with the field riprap the model panels 3 and 4 and to a lesser extent panel 2 had an open porous appearance with holes extending down to the filter layer in many places.

Panels 1-4 were set at an angle of 25° to the incident waves; this being a reasonable mean of the angle of approach of the highest waves in the two major storm events to be simulated. Shingle beaches on either side of the support structure ensured that no end distortion of the waves occurred.

### Instrumentation and analysis 3.3

#### The wave generator 3.3.1

The waves were generated by a piston type paddle which was servo controlled to follow in position the output from a signal generator. The random wave signal with the required spectral and statistical properties of wind waves was generated by an HRS spectrum synthesizer.[6,7,8]

Wave measurements 3.3.2 Wave measurements were made using twin wire resistance probes and a pressure tranducer interfaced with the HRS mini computer data acquisition and analysis system.[9] The twin wire wave probes, which measured the surface waves, were situated in the calibration channel and just seaward of panel 1. The pressure transducer, was mounted at the scalar height above the seabed adjacent to the twin wire wave probe in the calibration channel. There was no significant difference between the results for the two twin wire wave probes indicating that reflections from the embankment were not a significant problem. In all cases spectral analysis techniques were used.[10]. Throughout this report the transducer measurements are referred to as the seabed measurement.

Riprap surveys 3.3.3 The riprap surface was surveyed on fixed lines using vertically sliding rods mounted on a beam. The rods had hemispherical feet with a diameter equal to $D_{50}/2$. Each panel was surveyed along 5 lines downslope of a square, in plan, grid of 20, 30, 40 and 50mm for panels 1-4 respectively. Panel 5 was also surveyed using a 50mm square grid. For each test run the riprap panels were surveyed immediately after laying and the mean of the five downslope sections for each panel formed the base against which damage was calculated. Subsequent mean damaged sections were compared with the initial mean section and using only those points showing erosion, the eroded volume was calculated; the numerical result being expressed in terms of the number of equivalent spherical $D_{50}$ stones/$9D_{50}$ width of slope to be compatible with both the earlier CIRIA reports.[2,5].

Photography 3.3.4 A photographic record of the riprap panels was made during the two test runs with a permanently mounted camera set square on to the slope. This was generally operated before each test and after each wave/tide event but for the second test run and storm 2 a photograph was taken after each tidal step. Low angle front views were taken after construction and after each storm. For the second test run and again for storm 2 a video record was taken with a camera mounted high over the toe of the slope.

**The wave/tide event 3.4** As the wave flume used does not have pumping facilities each tide was reproduced as a stepped tide; each step lasting for 5 minutes on the model and with the appropriate wave height. Ideally the wave and tide data in table 12 of reference 5 should give four values of the tidal level and the wave parameters, $\overline{H}_3$ and $\overline{T}$. From these the tidal curve was drawn, transformed into the model stepped tide and the wave height for each step interpolated using the wind data. Unfortunately only one wave recorder was operating during storm 1 and the wave/tide events have been built up from two points rather than four, thus leading to some uncertainty.

Simulation of field waves 3.4.1 The field waves were measured using seabed mounted pressure transducers and recorded in analogue form on paper chart. Analysis of the analogue records was by the Tucker/Draper method yielding significant wave height, $\overline{H}_3$, and mean zero crossing wave period, $\overline{T}$, at the transducer. Transformation to surface values was achieved by applying gross correction factors based on the JONSWAP spectrum (supplied by HRS) to both parameters. The resulting values were used to compile table 12 of reference 5.

For the model study the field wave records were photographically enlarged and digitized; the digitizing interval being about 0.8 s. Spectral analysis of the digital record yielded the wave energy spectrum which was then corrected for the frequency response of the transducer. From the moments of the spectrum, $\bar{H}_3$ and $\bar{T}$ were calculated. The seabed spectrum was transformed to the surface using the standard equation

$$p = \frac{\varrho g a \cosh k (h-x)}{\cosh k h}$$

where

p is the pressure at depth x below the surface.

a is the wave amplitude.

h is the depth of water, seabed – MSL.

k is the wave number $2\pi/\lambda$.

$\lambda$ is the wavelength.

and x is the depth of the transducer below the surface. (h – x) is the height of the transducer above the seabed.

The surface spectrum thus produced was smoothed at the high frequency end and from the moments of the smoothed spectrum the surface wave parameters were calculated. Smoothing of the spectrum is necessary because at the higher frequencies noise becomes significant and coupled with very large transformation factors distorts the high frequency tail of the spectrum. Any aliasing errors in the high frequency tail of the spectrum due to the 0.8s sampling interval were eliminated by this smoothing.

The wave spectrum synthesizer was programmed to give the scaled field surface energy spectra and an extensive series of calibrations were made prior to the model tests. For the first test run the waves were biased to the surface wave parameters given in reference 5 but after a closer examination of the data the wave settings were biased towards the seabed measurements for the second test run. The measured wave heights and periods for both the field and model data are given in Table 2. Examples of the field and model seabed spectra are given in figure 7. The modelled wave/tide event for the severe storm of January 1978 is shown on figure 8.

The field waves obtained by the two analysis methods are shown in Table 2. The main feature is that the spectrally analysed data are consistently higher than those analysed by the Tucker-Draper method. The Tucker-Draper method gives a statistical estimate of $\bar{H}_3$ for a record which has a standard error dependent upon the number of waves in the record; in this case $\pm 8\%$. The pressure transducer frequency response function was applied as a gross parameter at the calculated zero crossing period of the record for the Tucker-Draper analysis. For the HRS spectral analysis the frequency response was included at the discrete frequencies of the spectrum. This means that the HRS corrected spectrum will give slightly higher waveheights than the corrected Tucker-Draper. In the spectral analysis procedures the parameter $\bar{H}_3$ is obtained from the standard equation $\bar{H}_3 = 4\sqrt{m_o}$ where $m_o$ is the total energy of the spectrum. The value of 4 applies strictly to narrow band spectra. There is increasing evidence that this value reduces with increasing spectral width and values as low as about 3.6 have been obtained. Measurements in the wave facilities at HRS using the Moskowitz and JONSWAP spectra indicate a value about 3.8. A similar value has been obtained from field recorded data at Perranporth. There is no generally agreed alternative value and 4.0 is used for consistancy.

### Summary of the test programme 3.5

**Panel 5 3.5.1** Panel 5 was built in the side flume, figure 6, and tested first using the four wave/tide events simulating the two major storms. This allowed a further check to be made on the wave calibrations prior to the tests on panels 1-4. Table 2 gives the measured wave parameters for each tide level tested. The riprap was surveyed after laying, after the first three wave/tide events simulating storm 1 and finally after storm 2. The volumes eroded, in terms of the number of equivalent $D_{50}$ stones/$9D_{50}$ width are given in table 3. Subsequently no further measurements were made on this panel although it was left in position for the two test runs made on panels 1-4. Some further minor erosion occurred on this slope during these runs but the filter layer remained substantially protected.

**Test run 1 3.5.2** Panels 1-4 were positioned in the main flume, figure 6, and tested using the four wave/tide events simulating the two major storms. Table 2 shows the measured wave parameters for each tidal step. After each wave/tide event a full survey of all the riprap panels was made. The eroded volumes are given in table 3. The panel 1 riprap was sufficiently eroded by storm 1 to allow exposure of a small area of the filter. The damage, however, was less than occurred on the field riprap for the same storm. After storm 2 the model panels 1-3 were eroded away to the support frame level over the upper part of the slope. Panel 4 would also have suffered more damage but for the large step in the support frame floor between panels 3 and 4 which allowed stone to become wedged in position and thus resist the eroding forces. Plates 4-6 show overhead views of the panels as constructed and after each major storm.

**Test run 2 3.5.3** The panels for the first test run were laid to the top of the support frame rather than the scalar upper level of 7.5m OD. but before storm 2 was run this was rectified.

As the result of the first test run the following changes were made before making a repeat test run:

1) The grading of riprap panel 1 was extended to include a finer fraction (see section 3.2).
2) Some wave heights were adjusted, generally higher, to give better correspondence between the model and field seabed measurements (see section 3.4.1).
3) The laying of the riprap panels was more carefully controlled to obtain better correspondence between the field and model laid thickness (see section 3.2).
4) The large step between panels 3 and 4 on the model support frame was filleted.

Panels 1-4 were reconstructed and retested incorporating the four modifications noted above. The measured wave parameters are given in table 2. A break in the central mini computer resulted in the loss of some wave data. The eroded volumes for each panel after each wave/tide event are given in table 3. Panel 1 was severely damaged after storm 1 with riprap and filter material eroded to the support structure floor. Some undermining of panel 2 also occurred adjacent to the eroded panel 1. After storm 2 the upper parts of panels 1-4 had all been completely washed away. Plates 7-11 show overhead views of the panels as constructed and after each wave/tide event.

### Description of damage 3.6

The following description is of the progressive damage observed during test run 2. Variations from this observed in test run 1 are noted.

During the wave/tide events of the storm 1 the riprap panel 1 was steadily eroded and moved downslope. This was facilitated by the tidal action which prevented the formation of the classic S shaped erosion/deposition profile. With the removal of a small area of riprap the filter became exposed and washed out down to the support structure floor. Removal of panel 1 material then continued both by the downslope process described above and also by undermining. The water washed up and across the denuded support structure to undermine the riprap above and to the side of the exposed slope by removing the exposed underlying filter. This process continued during storm 1 until the fully eroded area extended across panel 1 and just into the side of panel 2. Plate 12 shows an overall view of the four panels at this stage and plate 13 shows a close up of panel 1. The diagonal slope of the material at the lower boundary of the denuded area should be noted. It arose because exposure first began near the left hand side of panel 1 and progressed up and across slope. This resulted in a diagonal downflow of water from each receding wave and hence a greater concentration of downflowing water towards the left hand side. Thus more material was removed from this area. This basic process continued throughout the test and resulted in material from panels 2 3 and 4 moving across slope as well as downslope. The progression of the denuded area for the first eight tidal steps in the simulation of storm 2 are shown in plates 14(a-h). Initially with the lowest tidal level the denuded area extended towards the toe of the slope. With increasing tidal level the denuded area progressed up and across slope with more material being washed down to the lower areas of the slope and the scour hole partially filled. At the same time, due to the angled approach of the waves, there was a gradual movement of the filter material, and the smaller riprap across the slope onto panels 2 3 and 4. By the time high water was reached panel 2 and the upper part of panel 3 was substantially covered. Up to this point there was little surface erosion from panel 4. With the receding tide much of this material was removed, particularly from panels 3 and 4, and washed downslope. Plate 15 shows the riprap after storm 2.

In test run 1 the damage to panel 1 by storm 1 only reached down to the filter layer, which although partially exposed was not washed out. After storm 2 the damage to panels 1-3 was similar to that for test run 2. Panel 4 was only marginally damaged as a result of the riprap becoming wedged against the large step in the support structure floor, (plate 6). There was little surface erosion from panel 4.

In test run 1 water flowing off the left hand abutment of the support structure onto panel 1 accentuated the erosion of material at the interface of the abutment and panel 1. This run off was suppressed in test run 2 for storm 1 but there was still a tendency to greater erosion along this interface.

### Comparison of field and model results 3.7

Viewed overall there is a good correspondence between the model and field damage for test run 2 particularly when factors, to be discussed later, are taken into account.

Comparison of the results from the two test runs shows good repeatability for panels 2, 3 and 4 over storm 1. The differences for panel 1 and for panel 4 and storm 2 arise from the changes made after the first test run.

Damage volumes 3.7.1 The eroded volumes of material for each model riprap panel for each wave/tide event are given in Table 3. The field and model measured damage in columns 4-7 are based upon the surveys immediately preceding and following the appropriate storm. Thus a direct comparison between the field and model data is possible. There were no wave events on the field greater than 0.5m between the surveys spanning storm 1. The field surveys spanning storm 2 covered a period of about 5 months. Prior to storm 2 six storm events occurred and the maximum value of $\bar{H}_3$ in these was 0.98m. Subsequently there were four storm events in which a maximum $\bar{H}_3$ of 1.1m was recorded. However, examination of the preceding two years wave data and damage measurements suggests that these events would not have caused significant damage.

Where direct comparison is possible between the model and field measurements the model gives less damage except for panel 1 and storm 1 and panel 5 and storm 2.

Extent of damage 3.7.2 A comparison of level differences between surveys for corresponding events for the field measurements and for the model test run 2 is shown in figure 9. The comparison for panels 1 and 2 is based on surveys taken before and after storm 1 for both the field and model measurements. For panels 3 and 4 the field differences are based upon surveys after storm 1 and storm 2 whereas the model differences are based on the initial survey and that taken after storm 2. The level differences for panels 1, 3 and 4 show the erosion hole to be higher up the slope on the model than on the field. Indeed the upper part of the riprap panels was completely eroded on the model whereas on the field some material remained at the top of the riprap slope.

**Discussion of results 3.8** Variations between the results from test run 1 and test run 2 are explained by the changes made between the tests and noted in section 3.5.2 above.

Panel 1 3.8.1 The field and model measurements for panel 1 for storm 1 are the best data for model/field comparison because the field surveys were very close to the storm event and also because the panel 1 was largely uncontaminated by material from the other panels except towards the end of wave event 3 as panel 2 was undermined. Table 3 shows the erosion on the model to be 20% greater than on the field while figure 9 shows it to be higher up the slope. This difference can be explained as follows. An enlarged plot of figure 9 is shown on figure 10 for panel 1 only, with the model data for the first and second wave/tide events included. These latter show the initial formation of the scour hole lower downslope with some deposition near the toe of the modelled slope. In profile the scour hole after the first two wave/tide events is well within the final profile of the field measurements and since the peak tidal level of the third wave/tide event was slightly lower than the two preceding tides a final model scour hole approximating more closely to the field measurements was expected. This, however, was not the case and the reason for this lies in two further differences between the model and field slopes.

The field riprap panels were laid on an impermeable membrane covering the main embankment armour which had previously been blinded with fine material. When panel 1, and subsequently the remaining panels failed, the membrane was ripped away exposing the underlying riprap. Thus the wave run up and run down over the exposed area were influenced by both the surface roughness and permeability of the underlying riprap. On the model, however, the smooth floor of the model support structure, when exposed, allowed greater run up and hence greater damage to the upper part of the riprap slope by an undermining action. Run down on the model was also enhanced giving a more rapid removal downslope of the eroded material. This produced a build up of material on the lower part of the slope because the rate of deposition exceeded the rate of removal.

The model riprap panels were terminated at about the 2m OD level and no waves were run below a tidal level of 2.5m OD. Both these factors restricted the removal of material, particularly the filter material, from the lower part of the slope.

Had these factors been modelled it is thought that the model/field comparison for panel 1 over storm 1 would have been much closer.

Panel 2 3.8.2 The field measured levels of survey lines 1-3 of panel 2 prior to and after storm 1 are shown on figure 11. They show substantial damage along the line adjacent to panel 1, consistent with the removal of the panel 1. The lines 2 and 3 show only limited damage towards the lower part of the slope suggesting that the sideways undermining of panel 2 was limited.

Panel 2 on the model shows significantly less damage than the field panel over storm 1 (table 3). Some undermining occurred with the loss of side support from panel 1 but this was limited and did not extend to the survey lines. This loss of side support only occurred towards the end of the third wave/tide event of storm 1. Again it is thought that the presence of the smooth model support structure floor significantly affected the model performance. The scour hole in panel 1 developed during the test both upslope and diagonally upwards across the slope. Removal of substantial material from the upper part of panel 1 and its deposition on the lower part of the slope both slowed the spread of the scour hole across panel 1 and kept it at too high a level. In addition some of the larger undermined panel 2 stone was washed onto the panel 1 near the panel 1/2 interface thus inhibiting the undermining of panel 2. Had this not occurred the spread of the scour hole across panel 1 and into panel 2 would have been more rapid and at a lower level. This would have increased the duration of undermining and hence the damage to panel 2.

Panels 3 and 4 3.8.3 In both cases the damage on the model after storm 2 was less than on the field and was also higher up the slope, table 3 and figure 11. Undermining of both panels on the model began at the top of the slope and worked downslope with a considerable proportion of the undermined material being washed diagonally downslope onto the lower parts of panels 1 and 2; an action that was enhanced by the smooth exposed model underslope. The material deposited on panels 1 and 2 hindered further erosion of these panels and also impeded further undermining of panels 3 and 4. In addition the cross slope movement of the smaller material from panels 1 and 2 onto panels 3 and 4, due to the angled wave attack, hindered the surface erosion of panels 3 and 4. Prior to the deposition of material on panel 4 there was little evidence of surface erosion from this panel as Plates 14 show. In test run 1 where little undermining of panel 4 occurred there was similarly little surface erosion. Again it is thought that modelling the underslope conditions together with extending the tests to lower tidal levels would have ensured that the undermining action would have progressed at a lower level into panels 3 and 4 leaving some of the upper slope intact.

Panel 5 3.8.4 Damage to panel 5, the main embankment armour, was unaffected both in the field and on the model by any undermining action. The damage on the model and the field was similar.

**General summary of retrospective tests 3.9**

Overall the results of the second test run on panel 1-4 are in agreement with the damage measured in the field. Had the factors discussed in section 3.8 been modelled it is thought that the erosion of the model and field riprap panels 1-4 would have shown much closer agreement.

The model has shown that undermining, from the smaller sized panel 1 to the larger sized panel 4, is the principal cause of the failure of panel 4. Surface erosion from panel 4 did not contribute significantly to the failure of this panel. This result is surprising because it is generally held that layer thickness is an important parameter in the stability of riprap, and panel 4 was only 1.36 $D_{50}$ instead of the usually recommended $2D_{50}$. The failure of the larger riprap due to undermining illustrates the importance of control in the laying of riprap. Any weakness which gives rise to sufficient local damage could cause failure of the riprap by undermining by waves less than the design wave condition.

The retrospective tests described above were made to try and resolve the question as to whether a Reynolds scale effect exists in the results of small scale models (see section 1 above). On the basis of the work of Thomsen et al[3] the modelled panel 1 should show a scale effect of about 100% in the stability number at near zero damage; that is for the same wave conditions the erosion on the model should be substantially greater than that measured in the field. The model erosion is only 20% greater, but allowing for the excessive erosion to the upper part of the slope due to not modelling the underlying riprap this discrepancy should probably be much less. For panels 2-4 the model damage is less than that measured in the field. There is therefore no evidence from these retrospective tests to support the existence of a Reynolds scale effect in small scale model tests, at least down to the Reynolds Number of these tests ($6 \times 10^3$ to $1 \times 10^4$ based on the Thomsen et al definition of Reynolds number). The panel 5 result is perhaps the most significant result here. There was no undermining action on this panel and the field and model measured damage is both small and not significantly different.

# 4 Reynolds and model effects

During the course of this study the work of Torum et al[11] came to hand. In this they published the results of retrospective model tests of the Bilbao breakwater for which simultaneous records of waves and damage were available. This breakwater is armoured with 65T concrete blocks. They found the final damage to the model armour layer to be in fair agreement with the field measurements. In particular the model measured damage was in no case greater than that measured in the field; a finding which suggests that scale or model effects, if any, do not necessarily give conservative results. Limited information about the progress of the damage on the field precluded any conclusion being reached about the influence of scale and/or model effects on zero-damage stability. By model effects they mean a failure to correctly reproduce on the model all the field phenomena; for example stone grading, stone shape, wave climate etc. In addition they reassessed the work of Thomsen et al and others and concluded that the apparent Reynolds scale effect could possibly be explained in terms of a model effect or a wave period effect. There is thus some agreement between the work of Torum et al and HRS.

**Extension of CIRIA 61 tests 4.1** The retrospective tests on the Wash test riprap panels were concluded after test run 2. This decision was made because the undermining action leading to the failure of panels 2-4 masked the effect being sought, namely the scaling of the surface erosion of the riprap panels. The tests demonstrated the failure mode of the field test panels but while further refinements of the model might have improved the field and model comparisons they would not have given a definitive answer to the question of Reynolds scale effects on surface erosion. Instead it was decided to extend the range of the tests, on which reference 2 was based, to lower and higher Reynolds numbers.

This was done by taking one particular test run from the original series and making two models of it; one as small as practically possible and the other as large as possible within the limits of the wave flume facilities of H.R.S. Following the procedures used in the original work ensured that only the Reynolds number was changed between the three models. Table 4 shows the principal dimensions of the three series of tests.

The model results are plotted on figure 12 using the same plotting method as for the original work. The data shows no obvious trend with Reynolds number at near zero damage. At the lowest wave heights used, ie near zero damage, the model Reynold's numbers are $2.8 \times 10^3$ on the smallest model and $3.7 \times 10^4$ on the largest model which on the basis of the work of Thomsen et al should show at least an 80% Reynolds scale effect in the stability number at near zero damage between the smallest and largest model. This means that if, on figure 12, the results from the smallest model tend to zero damage at a value of $\bar{H}_3/D_{50}$ of say 1.0 then the results for the largest model should tend to zero damage at a value of $\bar{H}_3/D_{50}$ of 1.8. Manifestly this is not so. There is some indication that small models may underestimate the damage at high damage rates.

These additional tests suggest that Reynolds scale effects are not present in small scale models used to test riprap armoured embankments at low damage rates, at least down to model stone sizes of 10mm and model wave heights of 8mm.

**Repeatability of identical tests 4.2** For the extended CIRIA 61[2] tests described above the model riprap was laid using the procedures described in reference 2. However, because the riprap is a random mass of stone, characterised by a grading curve, it was anticipated that some variation might be expected even from identical tests. A series of five repeat tests were made on the smallest model, $D_{50}$ = 10mm, at a value of $\bar{H}_3$ of 30mm. After each test the riprap was stripped out, thoroughly mixed and relaid ensuring that the same volume of riprap just filled the test panel.

Use of the initial conditions setting on the HRS spectrum synthesizer ensured an identical random wave train for each test. The riprap was surveyed after each 1000 wave interval and each test was of 5000 waves duration.

The results, plotted on figure 13, show a significant difference between the test. The overall variation of $\overline{H}_3$ and $\overline{T}$ between the tests was less than 2% and 1% respectively and does not explain this difference. It is thought that the difference is related to the relative disposition of the larger stones in the grading, particularly in the erosion zone. These tend to shelter and support stone in their immediate vicinity particularly upslope. Two or more large stones close together can produce an arching effect in the intervening riprap which hinders erosion. Conversely, the removal of a large stone is often accompanied by a general local erosion of smaller stone.

These repeat tests were made at a waveheight which gave moderate damage rates. A comparison of test runs 1 and 2 for panel 2-4 and storm 1 suggests that at lower waveheights and hence lower damage rates the scatter of results from identical tests may be less.

This non repeatability of identical tests highlights an important effect, namely that a measurement of damage in the field or on a model is only an estimator of a parameter which has some statistical variability. It suggests that in any test programme allowance should be made for multiple repeat tests to establish mean damage levels with confidence limits so that the designer can design on a probabilistic basis.

## 5 Summary of findings

The retrospective model tests have reproduced within the variability of the phenomenon the damage measured in the field and shown that once the small riprap, panel 1, was destroyed in storm 1 the subsequent damage to the remaining panels was by progressive cross slope undermining. Surface erosion on panel 4 was small. Thus the failure in the field of panel 4, with only superficial damage to panel 5 in storm 2 is explained by the cross slope undermining of the riprap.

Where the measured erosion damage was not affected by undermining, ie panel 2 and storm 1, the model erosion damage was less than that measured in the field. For panel 5 the damage on the model and the field was similar. This result suggests that small scale models do not give conservative results and conflicts with the work of Thomsen et al[3] on the effect of Reynolds number near zero-damage.

The extension of the CIRIA 61[2] tests confirms the conclusions of that report that no Reynolds scale allowance can be made when designing full scale riprap from model tests.

Results from identical model tests show poor repeatability. There is thus an inherent variability in the damage parameter for both field and model measurements. Allowance should be made for this particularly when investigating small effects.

The inherent variability in the damage parameter suggests that *ad hoc model* testing of armoured slopes should include provision for repeat tests to establish the distribution of the damage parameter.

Careful control of the field laid riprap is necessary to avoid weak areas, as erosion of these may lead to more widespread damage due to undermining with waves less than the design wave.

The findings of this report refer specifically to the modelling and design of riprap armoured slopes. The work of Torum et al[11] suggests, however, that it may be of wider application.

## 6 Acknowledgements

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Figures 1-5 and Plate 1 are reproduced from reference 5 by kind permission of the Construction Industry Research and Information Association.

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## 7 References


1. BURGESS, J. S. and HICKS, P. H. Riprap protection for slopes under wave attack. Civil Engineering Research Association, Research Report 4, May 1966.
2. THOMPSON, D. M. and SHUTTLER, R. M. Design of riprap slope protection against wind-wave attack. CIRIA Report 61 December 1976.
3. THOMSEN, A. L., WOHLT, P. E. and HARRISON, A. S. Riprap stability on earth embankments tested in large and small scale wave tanks. U.S. Army Corps of Engineers, Coastal Engineering Research Centre, Tech Memo 37, June 1972.
4. YOUNG, R. M.:, ACKERS P. and THOMPSON, D. M. Riprap design for windwave attack: prototype tests on the offshore bank in the Wash Construction Industry Research and Information Association. CIRIA Technical Note 84, July 1977.
5. YOUNG, R. M., PITT, J. D., ACKERS, P. and THOMPSON, D. M. Riprap design for windwave attack: long term observations on the offshore bank in the Wash. Construction Industry Research and Information Association. CIRIA Technical Note 101 July 1980.
6. FRYER, D. K., GILBERT, J. and WILKIE, M. J. A wave spectrum synthesizer. Journal of Hydraulics Research, 11 (3), 1973.
7. DEPARTMENT OF THE ENVIRONMENT. Hydraulics Research 1972, H.M.S.O.
8. HYDRAULICS RESEARCH STATION. Wave spectrum synthesizer. Tech Memo 1/1972, June 1972.
9. DEPARTMENT OF THE ENVIRONMENT. Hydraulics Research 1978, HMSO.
10. MARNER, R. and GAN, L. H. H. Spectral analysis programs for use on the HRS data acquisition and analysis system. HRS computer unit, Report CR4. December 1979.
11. TORUM, A., MATHIESEN, B. and ESCUTIA, R. Scale and model effects in breakwater model tests 5th International Conference on Port and Ocean Engineering under Arctic Conditions, Trondheim, August 13-18, 1979.

## 8 Notation

| | |
|---|---|
| $a$ — | the wave amplitude |
| $h$ — | the water depth — seabed to mean sea level |
| $k$ — | the wave number — $2\pi/\lambda$ |
| $l_l$, $l_u$ — | the vertical lower and upper limit of erosion damage measured from SWL |
| $p$ — | the pressure at depth x below the surface |
| $x$ — | the depth of the pressure transducer below the surface |
| $D_{50}$ — | the median stone size of the riprap grading. This corresponds to $D^R{}_{50}$ in reference 2 |
| $D_u$,$D_I$,$D_L$ — | the upper, intermediate and lower orthogonal dimensions of the rectangular block enclosing a stone |
| $D_S$ — | the sieve size |
| $\overline{H}_3$ — | the significant wave height – determined from the moments of the spectrum |
| $M$ — | the mass of a stone |
| $N_{ZD}$ — | the zero damage stability number used by Thomsen et al in reference 3. This is a function of $\overline{H}_3/D_{50}$ for a given slope and armour |
| $N_\triangle$ — | the erosion volume expressed in terms of the number of equivalent spherical $D_{50}$ stones per 9 $D_{50}$ width of slope. The same definition as reference 2 |
| $R_e$ — | the Reynolds number – using the definition $R_e = g^{1/2}\overline{H}_3{}^{1/2} D_{50}/\nu$ as used by Thomsen et al in reference 3 |
| $\overline{T}$ — | the mean zero-crossing wave period – determined from the moments of the spectrum |
| $\varrho$ — | the mass density |
| $\nu$ — | the kinematic viscosity |

# Appendix

# Appendix 1

**Comparison of the model and field riprap.**

In both the field and model study representative samples of the riprap were taken and the individual stone measured to yield the mass, M, and the three orthogonal dimensions of the enclosing rectangular block, $D_u$, $D_I$ and $D_L$. In the case of the model riprap the samples were taken from known sieve cuts and hence, $D_S$, the sieve size was known. The following table compares the field and model riprap

| | | Model | Field |
|---|---|---|---|
| 1) | $D_u/D_L$ | 1.91 | 1.96 |
| 2) | $D_u/D_I$ | 1.33 | 1.24 |
| 3) | $D_I/D_L$ | 1.43 | 1.49 |
| 4) | $M/\varrho D^3_S$ | 0.55(A) | 0.65(B) |
| 5) | $M/\varrho D^3_I$ | 0.37 | 0.44 |
| 6) | $M/\varrho(D_I D_L)^{3/2}$ | 0.63 | 0.73 |
| 7) | $D_S/D_I$ | 0.88 | 0.88 |
| 8) | $D_S/\sqrt{D_I D_L}$ | 1.05 | 1.04 |

Notes

A This model value is identical to that measured in the earlier CIRIA 61 tests.

B No sieve sizes were measured on the field. This value was taken from reference 3 to obtain the stone mass to stone size conversion shown on the riprap grading curves.

Items 7 and 8 were calculated from items 4, 5 and 6.

Overall the agreement is fair. There is however an indication that the field riprap is slightly more bulky than that on the model. This arises because the crushed material used on the model tends to be wedge shaped whereas the field material, blasted from the quarry, tends to be cubical.

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## Tables

**Table 1** **Principal dimensions of field riprap and filter**

| Material | Riprap layer thickness (m) | Filter layer thickness (m) | $D_{50}$ (m) |
|---|---|---|---|
| Panel 1 | 0.44 | 0.38 | 0.23 |
| Panel 2 | 0.48 | 0.38 | 0.40 |
| Panel 3 | 0.57 | 0.39 | 0.50 |
| Panel 4 | 0.76 | 0.43 | 0.56 |
| Panel 5 | * | * | 0.66 |
| Filter | | | 0.04 |

* Not measured

**Table 2** **Calculated field wave parameters and measured model wave parameters**

| SPECTRUM | M.S.L | TEST ON PANEL 5 ONLY | | | | TEST RUN 1 | | | | TEST RUN 2 | | | | H.R.S. ANALYSIS | | | | CIRIA T.N.101 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | M.OD | SURFACE | | SEABED | | SURFACE | | SEABED | | SURFACE | | SEABED | | SURFACE | | SEABED | | SURFACE | |
| | | H | T | H | T | H | T | H | T | H | T | H | T | H | T | H | T | H | T |
| WA1A | 2.1 | 0.50 | 3.76 | 0.37 | 4.16 | | | | | | | | | | | | | | |
| | 2.7 | 0.79 | 3.62 | 0.52 | 4.07 | 0.66 | 3.64 | 0.44 | 4.09 | 0.66 | 3.69 | 0.43 | 4.16 | | | | | | |
| | 3.4 | 0.90 | 3.60 | 0.52 | 4.16 | 0.73 | 3.59 | 0.42 | 4.13 | 0.85 | 3.60 | 0.48 | 4.15 | | | | | | |
| | 3.9 | 0.91 | 3.70 | 0.49 | 4.32 | 0.77 | 3.56 | 0.39 | 4.20 | 0.91 | 3.69 | 0.48 | 4.26 | 0.85 | 3.73 | 0.48 | 3.98 | 0.76 | 3.8 |
| | 4.3 | 0.64 | 3.59 | 0.31 | 4.19 | 0.80 | 3.74 | 0.41 | 4.37 | 0.71 | 3.68 | 0.34 | 4.31 | | | | | | |
| WA1B | 4.6 | 0.69 | 3.68 | 0.33 | 4.28 | 0.63 | 3.64 | 0.29 | 4.24 | 0.82 | 3.71 | 0.38 | 4.33 | | | | | | |
| | 4.7 | 0.55 | 3.71 | 0.26 | 4.33 | 0.66 | 3.70 | 0.31 | 4.31 | 0.77 | 3.72 | 0.35 | 4.30 | | | | | | |
| | 4.6 | 0.71 | 4.14 | 0.40 | 4.86 | 0.78 | 3.96 | 0.42 | 4.82 | 0.91 | 4.16 | 0.52 | 4.83 | | | | | | |
| | 4.3 | 0.60 | 4.12 | 0.35 | 4.84 | 0.83 | 3.98 | 0.48 | 4.79 | 0.89 | 4.03 | 0.52 | 4.87 | | | | | | |
| | 4.0 | 0.83 | 3.97 | 0.49 | 4.72 | 0.72 | 3.94 | 0.44 | 4.68 | 1.00 | 3.93 | 0.59 | 4.77 | | | | | | |
| | 3.5 | 0.73 | 3.90 | 0.46 | 4.63 | 0.68 | 3.95 | 0.44 | 4.70 | 0.84 | 3.99 | 0.54 | 4.76 | 0.90 | 3.95 | 0.55 | 4.30 | 0.75 | 4.3 |
| | 3.1 | 0.57 | 3.88 | 0.38 | 4.54 | 0.76 | 4.03 | 0.54 | 4.76 | 0.64 | 3.93 | 0.43 | 4.71 | | | | | | |
| | 2.7 | 0.62 | 4.12 | 0.46 | 4.67 | 0.68 | 4.06 | 0.52 | 4.70 | 0.73 | 4.07 | 0.54 | 4.74 | | | | | | |
| | 2.1 | 0.61 | 4.13 | 0.49 | 4.66 | | | | | | | | | | | | | | |
| WA2A | 2.1 | 0.74 | 3.55 | 0.54 | 4.12 | | | | | | | | | | | | | | |
| | 2.6 | 0.72 | 3.53 | 0.47 | 4.04 | 0.52 | 3.81 | 0.37 | 4.36 | 0.67 | 3.47 | 0.43 | 4.03 | | | | | | |
| | 3.2 | 0.75 | 3.55 | 0.43 | 4.20 | 0.73 | 3.52 | 0.44 | 4.15 | 0.72 | 3.46 | 0.40 | 4.12 | | | | | | |
| | 3.7 | 0.72 | 3.46 | 0.37 | 4.19 | 0.75 | 3.55 | 0.41 | 4.23 | 0.73 | 3.45 | 0.36 | 4.20 | 0.71 | 3.66 | 0.42 | 4.03 | 0.68 | 3.9 |
| | 4.1 | 0.75 | 3.55 | 0.37 | 4.25 | 0.83 | 3.70 | 0.45 | 4.40 | 0.85 | 3.57 | 0.41 | 4.37 | | | | | | |
| | 4.4 | 0.73 | 3.58 | 0.34 | 4.37 | 0.87 | 3.65 | 0.44 | 4.45 | 1.01 | 3.63 | 0.48 | 4.45 | | | | | | |
| | 4.5 | 0.59 | 3.72 | 0.30 | 4.65 | 0.71 | 3.80 | 0.38 | 4.71 | 1.03 | 3.87 | 0.55 | 4.86 | | | | | | |
| WA2B | 4.3 | 0.71 | 4.05 | 0.42 | 4.92 | 0.93 | 3.78 | 0.52 | 4.74 | 1.11 | 3.86 | 0.61 | 4.80 | | | | | | |
| | 4.1 | 0.85 | 3.93 | 0.51 | 4.77 | 0.84 | 3.81 | 0.49 | 4.81 | 1.09 | 3.91 | 0.64 | 4.91 | | | | | | |
| | 3.7 | 0.68 | 3.91 | 0.42 | 4.75 | 0.90 | 3.84 | 0.55 | 4.74 | 0.87 | 3.81 | 0.51 | 4.70 | | | | | | |
| | 3.3 | 0.80 | 3.69 | 0.51 | 4.53 | 0.63 | 3.80 | 0.41 | 4.61 | 0.81 | 3.83 | 0.52 | 4.77 | 0.88 | 3.77 | 0.54 | 4.23 | 0.71 | 4.2 |
| | 2.9 | 0.51 | 4.06 | 0.36 | 4.71 | 0.71 | 3.74 | 0.48 | 4.53 | 0.76 | 3.80 | 0.50 | 4.70 | | | | | | |
| | 2.5 | 0.52 | 3.97 | 0.40 | 4.63 | 0.63 | 3.77 | 0.46 | 4.52 | 0.66 | 3.84 | 0.48 | 4.54 | | | | | | |
| | 2.1 | 0.65 | 4.04 | 0.53 | 4.68 | | | | | | | | | | | | | | |
| WA2C | 2.1 | 1.04 | 4.20 | 0.84 | 4.94 | | | | | | | | | | | | | | |
| | 2.6 | 1.14 | 4.13 | 0.86 | 5.00 | 1.15 | 4.18 | 0.92 | 5.06 | 1.10 | 4.10 | 0.84 | 4.97 | | | | | | |
| | 3.1 | 1.16 | 4.02 | 0.81 | 4.90 | 1.07 | 3.91 | 0.75 | 4.84 | 1.13 | 3.99 | 0.79 | 4.90 | | | | | | |
| | 3.6 | 1.14 | 3.94 | 0.73 | 4.89 | 1.15 | 4.12 | 0.77 | 5.09 | 1.19 | 4.06 | 0.79 | 5.05 | 1.16 | 4.11 | 0.78 | 4.31 | 1.03 | 4.4 |
| | 4.0 | 1.17 | 4.00 | 0.71 | 4.96 | 1.13 | 3.97 | 0.69 | 4.91 | 1.37 | 4.20 | 0.90 | 5.17 | | | | | | |
| | 4.2 | 1.15 | 4.00 | 0.68 | 4.96 | 1.18 | 4.11 | 0.71 | 5.02 | . | . | . | . | | | | | | |
| | 4.3 | 1.06 | 3.93 | 0.60 | 4.89 | 1.20 | 4.06 | 0.70 | 4.93 | . | . | . | . | | | | | | |
| WA2D | 4.2 | 1.16 | 4.21 | 0.74 | 5.38 | 1.04 | 4.50 | 0.68 | 5.44 | . | . | . | . | | | | | | |
| | 4.0 | 0.88 | 4.45 | 0.59 | 5.52 | 1.00 | 4.36 | 0.66 | 5.37 | . | . | 0.88 | 5.52 | | | | | | |
| | 3.6 | 0.87 | 4.41 | 0.61 | 5.45 | 0.95 | 4.32 | 0.67 | 5.30 | . | . | 0.91 | 5.52 | | | | | | |
| | 3.2 | 0.72 | 4.35 | 0.52 | 5.23 | 0.73 | 4.41 | 0.54 | 5.26 | . | . | 0.75 | 5.26 | 1.14 | 4.41 | 0.82 | 4.60 | 0.81 | 4.7 |
| | 2.9 | 0.61 | 4.54 | 0.46 | 5.36 | 0.82 | 4.32 | 0.62 | 5.15 | . | . | 0.63 | 5.33 | | | | | | |
| | 2.5 | 0.75 | 4.40 | 0.58 | 5.17 | 0.68 | 4.56 | 0.57 | 5.33 | . | . | 0.80 | 5.23 | | | | | | |
| | 2.1 | 0.89 | 4.40 | 0.72 | 5.14 | | | | | | | | | | | | | | |
| WA6A | 2.1 | 1.11 | 4.54 | 0.95 | 5.37 | | | | | | | | | | | | | | |
| | 2.6 | 1.31 | 4.52 | 1.07 | 5.56 | 1.37 | 4.55 | 1.07 | 5.50 | . | . | 1.08 | 5.53 | 1.21 | 4.51 | 0.99 | 4.61 | 1.06 | 5.4 |
| | 3.2 | 1.52 | 4.55 | 1.20 | 5.69 | 1.47 | 4.59 | 1.11 | 5.68 | . | . | 1.14 | 5.65 | | | | | | |
| WA6B | 3.7 | 1.63 | 4.57 | 1.22 | 5.80 | 1.60 | 4.76 | 1.18 | 6.04 | . | . | 1.19 | 5.96 | | | | | | |
| | 4.3 | 1.81 | 4.67 | 1.32 | 6.00 | 1.86 | 4.74 | 1.31 | 6.11 | . | . | 1.29 | 6.12 | 1.89 | 4.39 | 1.27 | 5.37 | 1.74 | 5.9 |
| | 4.8 | 1.93 | 4.83 | 1.38 | 6.23 | 1.84 | 4.83 | 1.26 | 6.21 | . | . | 1.37 | 6.37 | | | | | | |
| WA6C | 5.2 | 1.91 | 5.05 | 1.35 | 6.49 | 2.01 | 5.35 | 1.44 | 6.84 | . | . | 1.49 | 6.74 | | | | | | |
| | 5.7 | 2.12 | 5.18 | 1.52 | 6.79 | 2.19 | 5.21 | 1.53 | 6.91 | . | . | 1.51 | 7.03 | | | | | | |
| | 5.8 | 2.14 | 5.24 | 1.51 | 6.82 | 2.10 | 5.33 | 1.46 | 7.06 | . | . | 1.61 | 6.90 | 2.11 | 5.55 | 1.47 | 5.50 | 2.14 | 6.1 |
| | 5.5 | 1.90 | 5.26 | 1.37 | 6.69 | 1.73 | 5.33 | 1.27 | 7.08 | . | . | 1.35 | 6.60 | | | | | | |
| WA6D | 5.0 | 2.12 | 5.01 | 1.56 | 6.48 | 1.77 | 4.85 | 1.21 | 6.45 | . | . | 1.39 | 6.59 | | | | | | |
| | 4.3 | 1.13 | 4.91 | 0.84 | 6.29 | 1.11 | 4.78 | 0.78 | 6.26 | . | . | 1.33 | 6.33 | | | | | | |
| | 3.4 | 0.86 | 4.92 | 0.68 | 6.13 | 0.93 | 5.19 | 0.74 | 6.29 | . | . | 1.22 | 6.10 | 1.69 | 5.12 | 1.27 | 5.50 | 1.08 | 6.7 |
| | 2.5 | 1.10 | 4.67 | 0.92 | 5.77 | 0.85 | 4.96 | 0.70 | 6.04 | . | . | 0.99 | 5.63 | | | | | | |

## Table 3 Measured damage to the model riprap panels

| Panel | Storm 1 | | | | Storm 2 | |
|---|---|---|---|---|---|---|
| | Model wave/tide event 1 | 2 | 3 | Field | Model | Field |
| **Test Run 1** | | | | | | |
| 1 | 102 | 127 | 191 | 839 | | |
| 2 | 15.9 | 18.2 | 25.9 | 83* | 303 | |
| 3 | 11.2 | 8.5 | 11.4 | | 176 | 231 |
| 4 | 7.1 | 12.2 | 12.3 | | 35 | 162 |
| **Test Run 2** | | | | | | |
| 1 | 90 | 177 | 1064 | 839 | | |
| 2 | 13.6 | 14.1 | 26.6 | 83* | 333 | |
| 3 | 9.0 | 10.8 | 13.3 | | 179 | 231 |
| 4 | 7.4 | 10.4 | 13.9 | | 81 | 162 |
| **Panel 5** | | | | | | |
| 5 | | | 4.4 | | 12.5 | 12 |

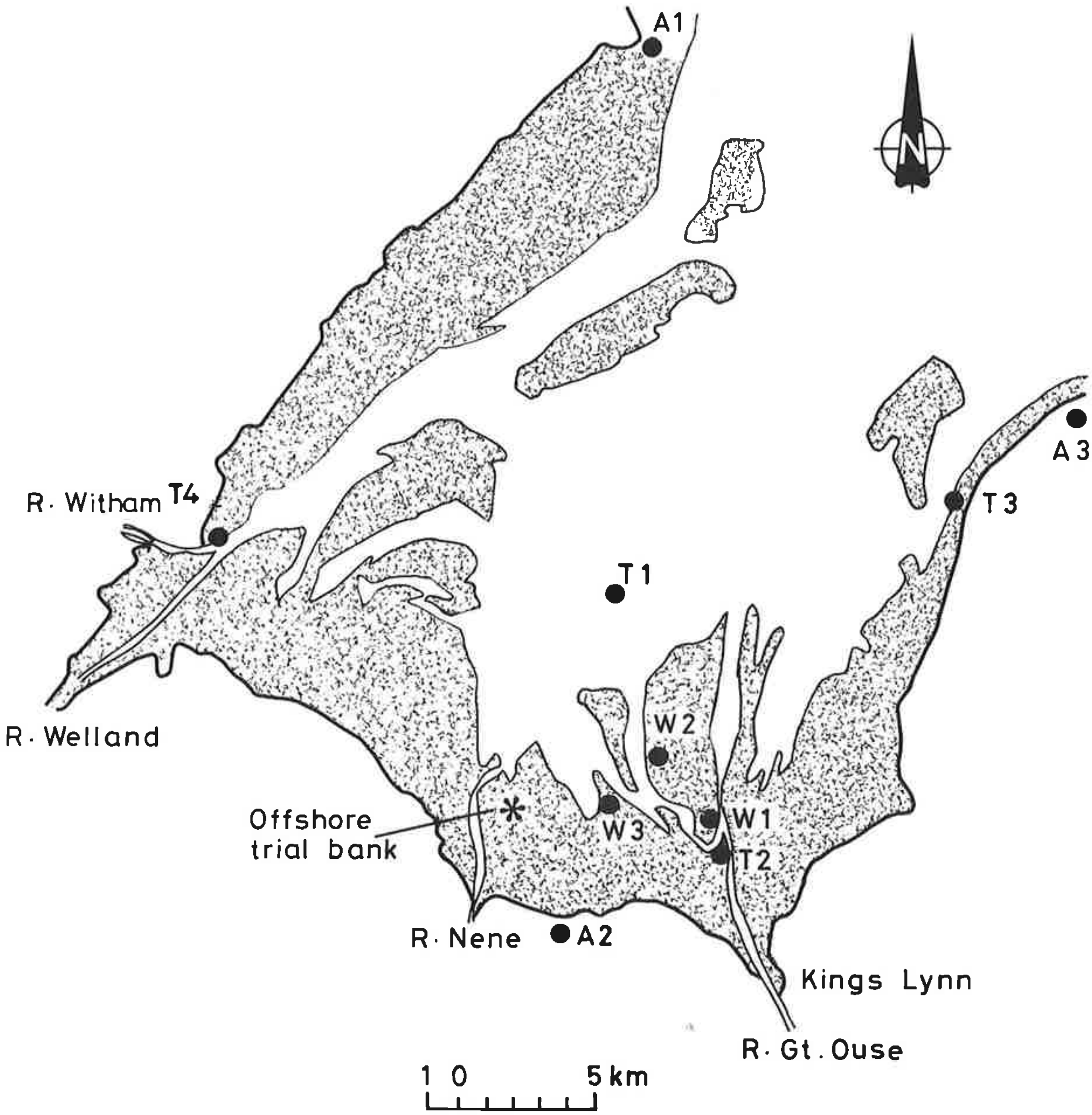
* Damage based on survey lines not affected by undermining

## Table 4 Principal dimensions for three Reynolds No tests

| | Small Model | Previous test | Large Model |
|---|---|---|---|
| h m | 0.305 | 0.61 | 1.50 |
| $D_{50}$, m | 0.010 | 0.020 | 0.049 |
| $\overline{T}$, s | 0.91 | 1.30 | 2.04 |
| $\overline{H}_3$, m | 0.008 – 0.035 | 0.037 – 0.066 | 0.059 – 0.162 |
| $R_e$ | $2.8 \times 10^3 - 5.8 \times 10^3$ | $1.2 \times 10^4 - 1.6 \times 10^4$ | $3.7 \times 10^4 - 6.2 \times 10^4$ |
| $2\pi D_{50}/g\overline{T}^2$ | 0.0076 | 0.0076 | 0.0076 |
| $2\pi h/g\overline{T}^2$ | 0.23 | 0.23 | 0.23 |

$R_e = g^{1/2}\,\overline{H}_3^{\,1/2}\,D_{50}/\nu$ (the formulation used by Thomsen et al)

**Figures**



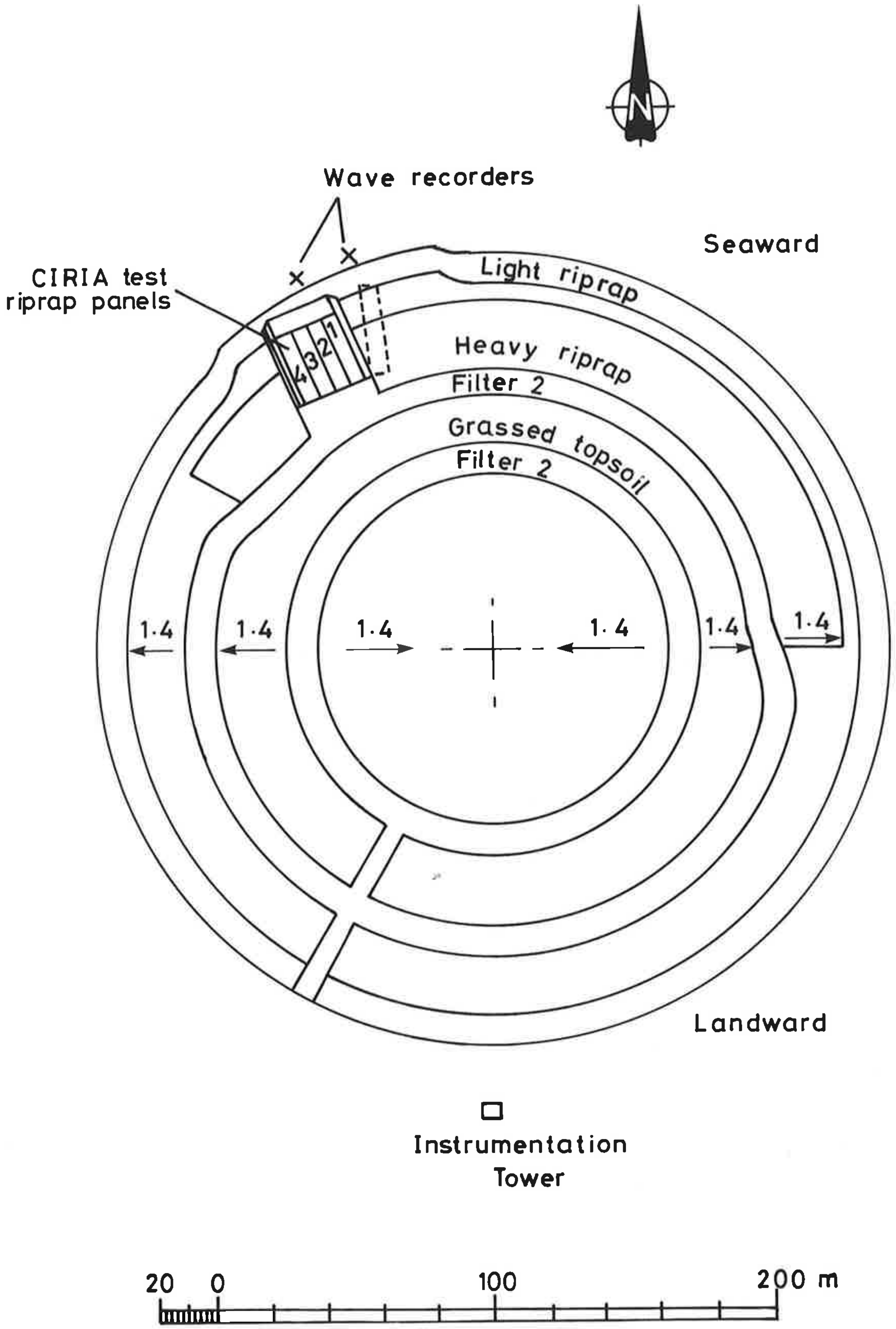

Anemometers
A1 Gibralter Point
A2 Wingland
A3 Holme Point

Tide Recorders
T1 Roaring Middle
T2 West stones
T3 Hunstanton
T4 Tabs Head

Wave Recorders
W1 Daseleys Sand
W2 Teetotal Channel
W3 Hull Sand

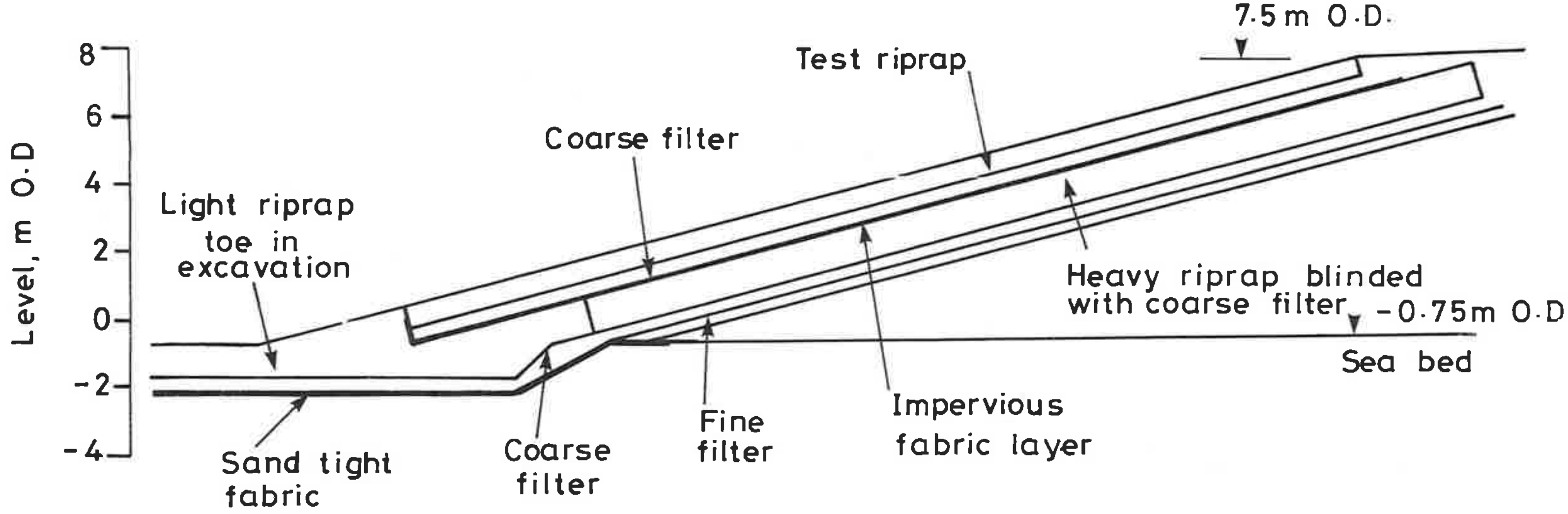
Location of trial bank and hydrographic measurements in the Wash

Fig 1



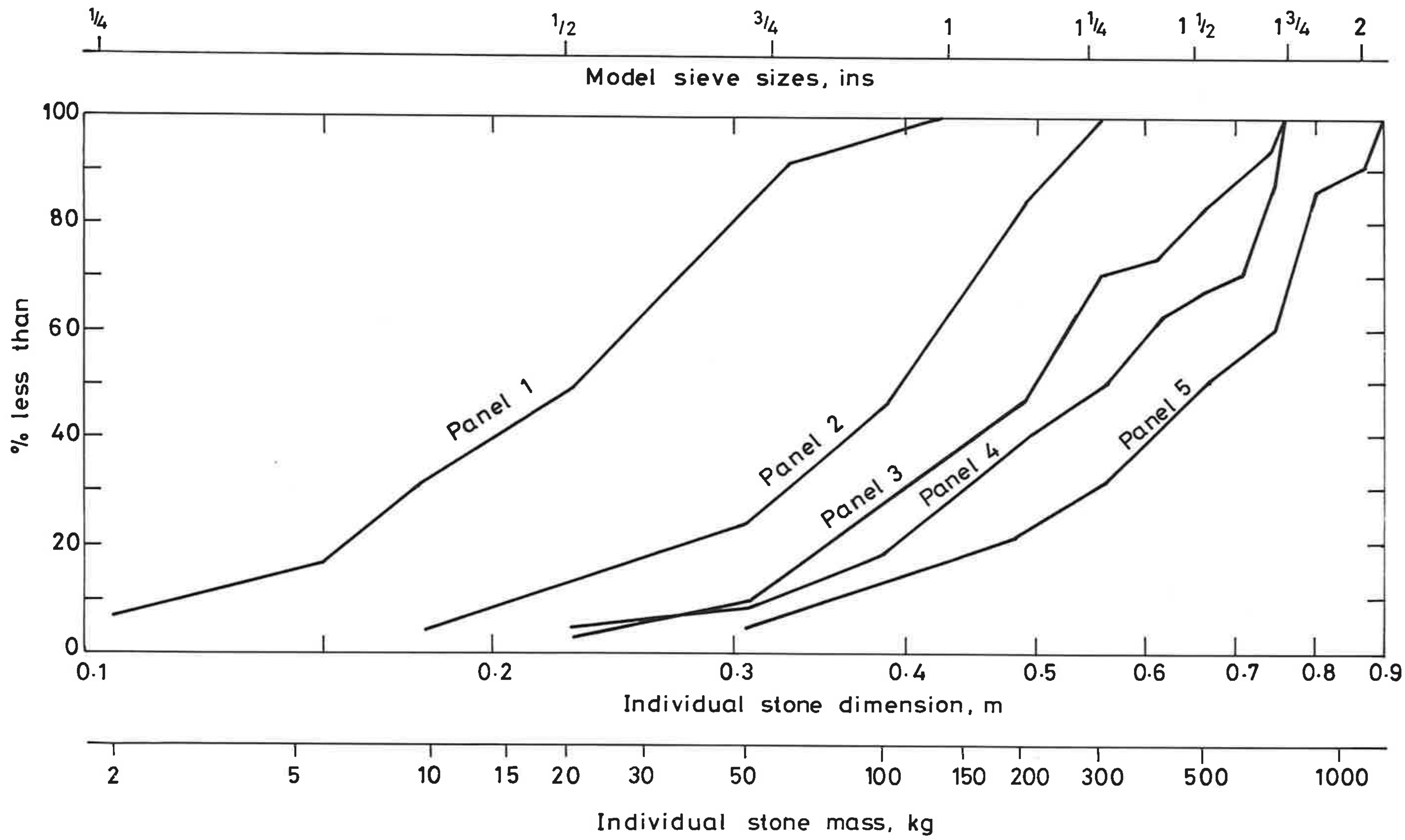

Offshore trial bank

Fig 2



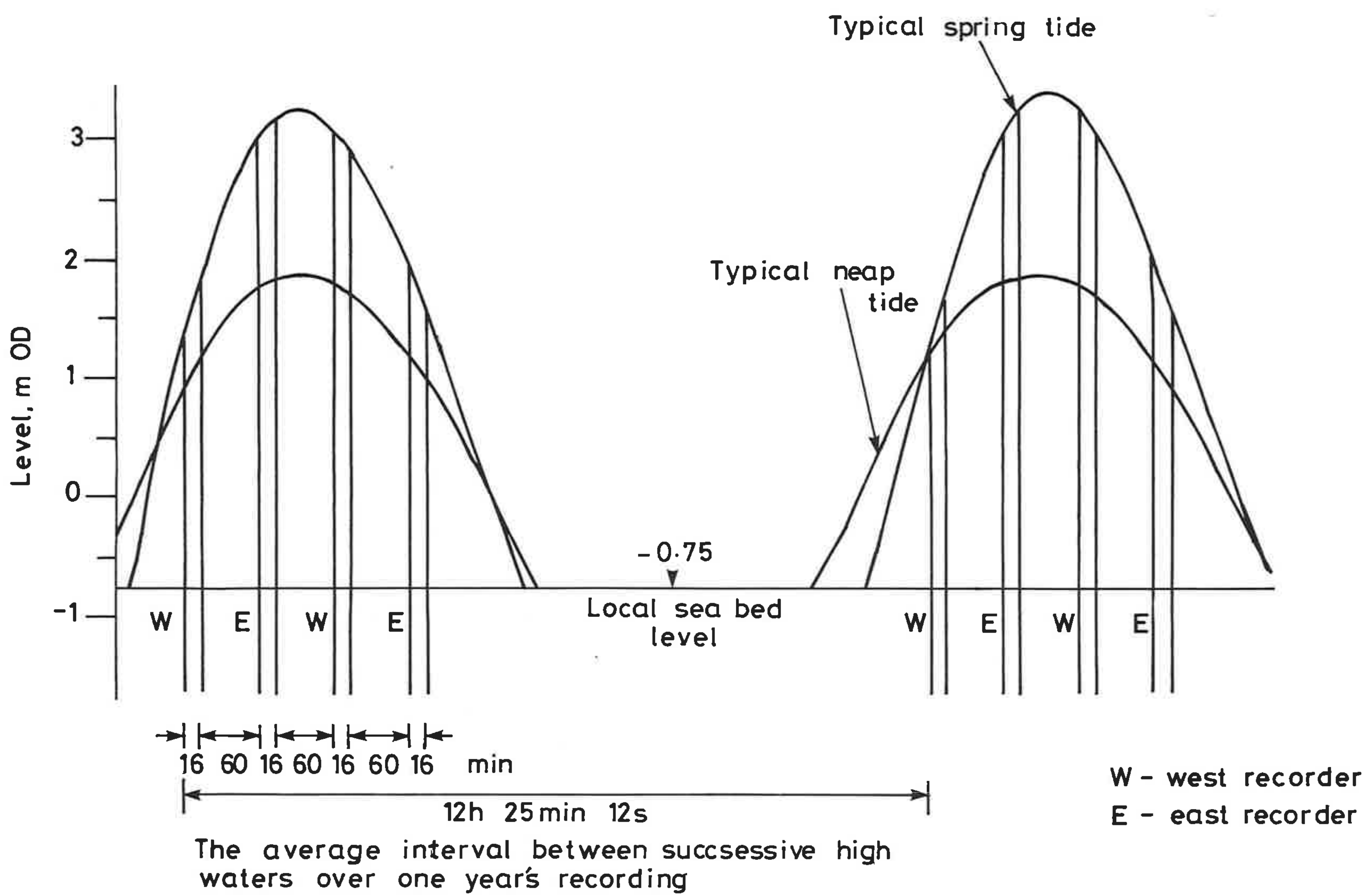

Section through test panel

Fig 3



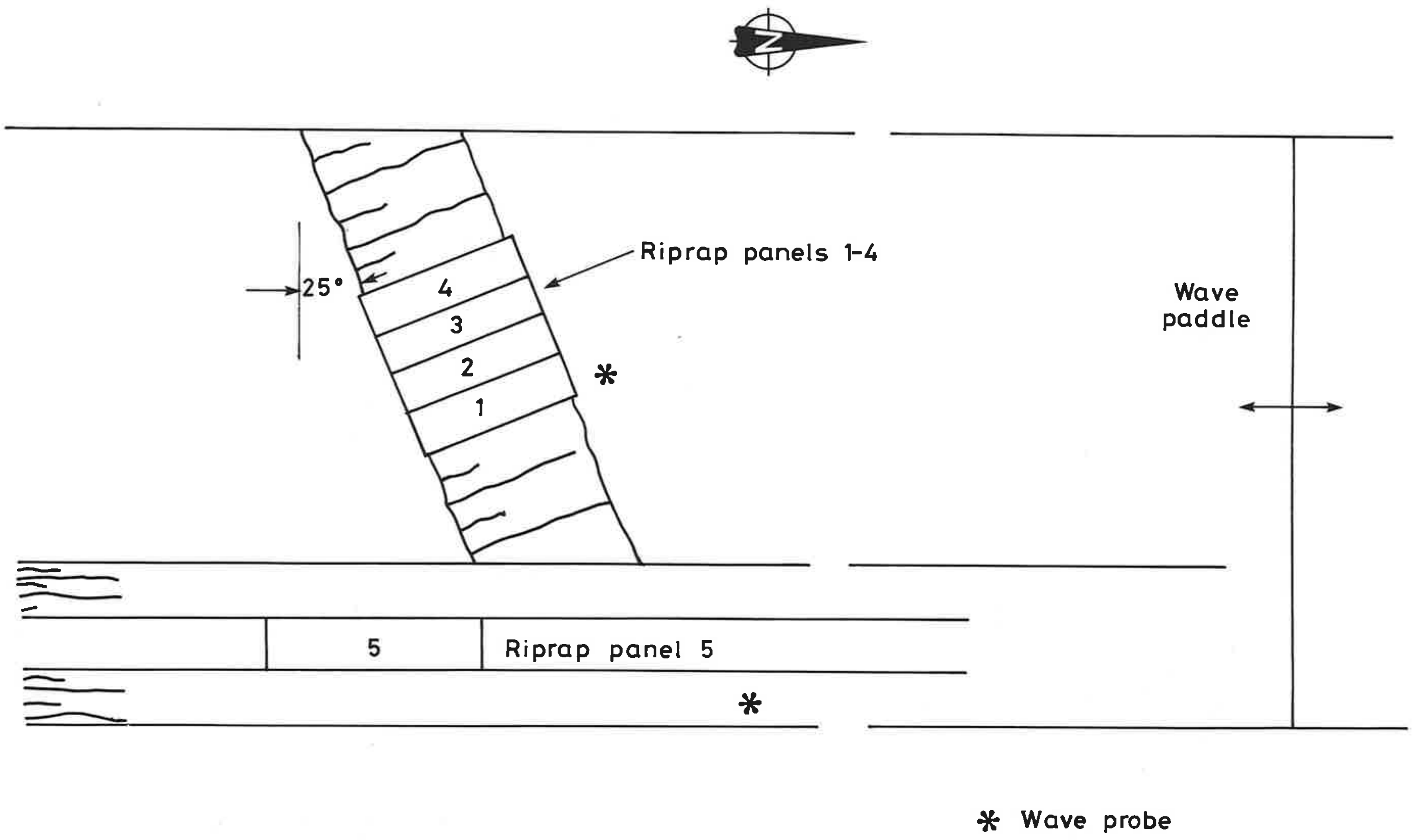

Grading curves for riprap

Fig 4



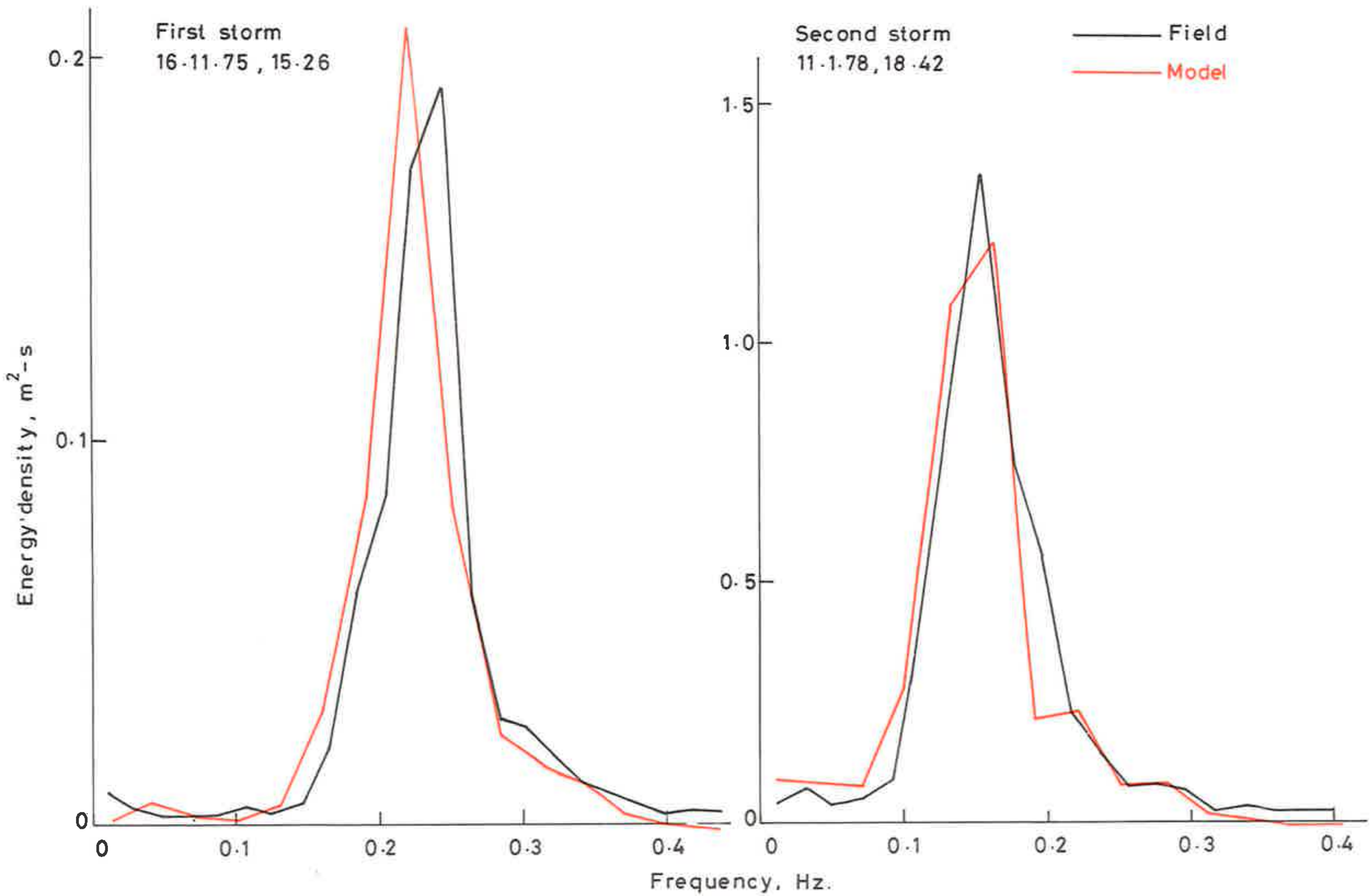

Wave recorder switching sequence

Fig 5



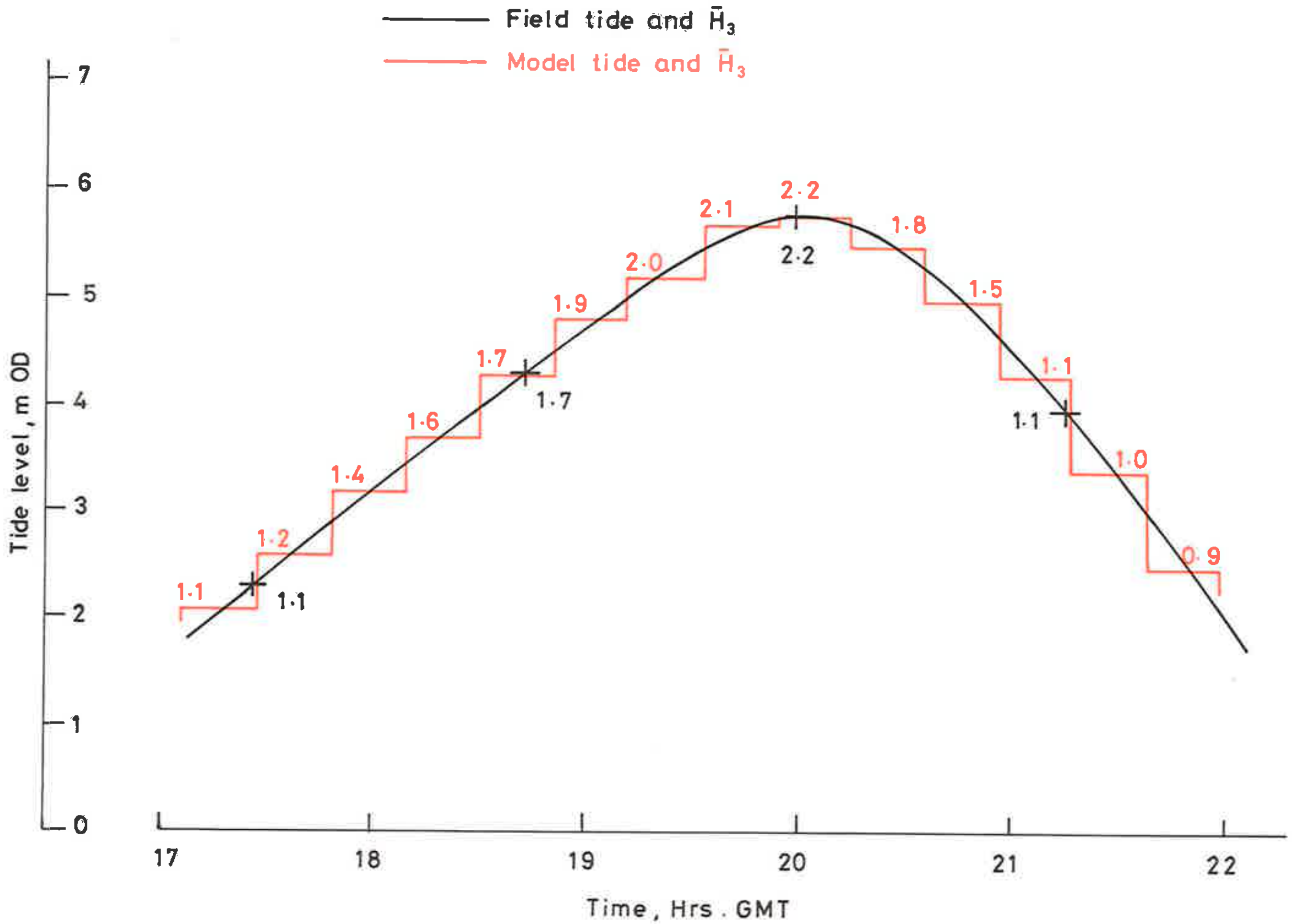

Layout of model in wave basin

Fig 6



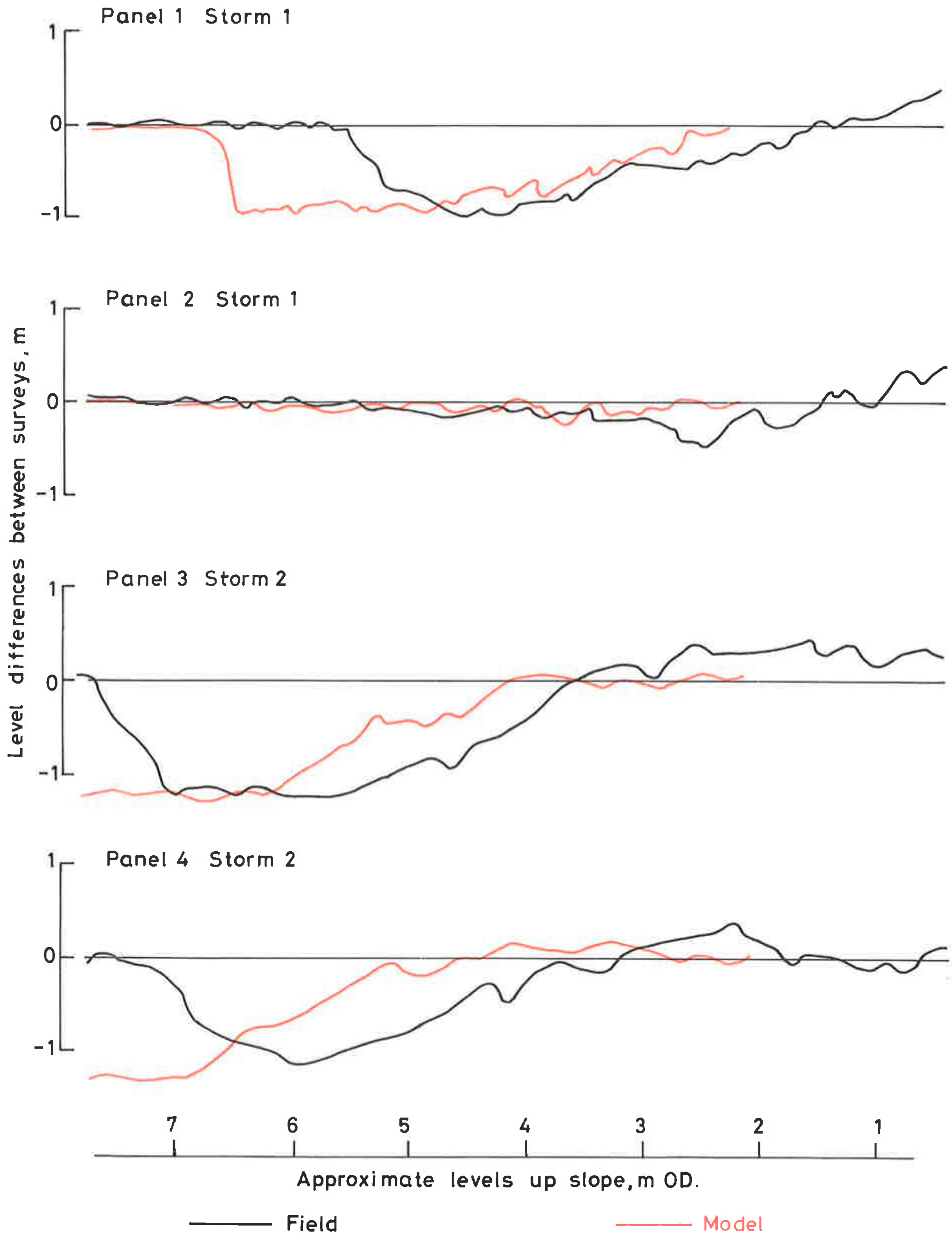

Examples of field and model sea bed spectra

Fig 7



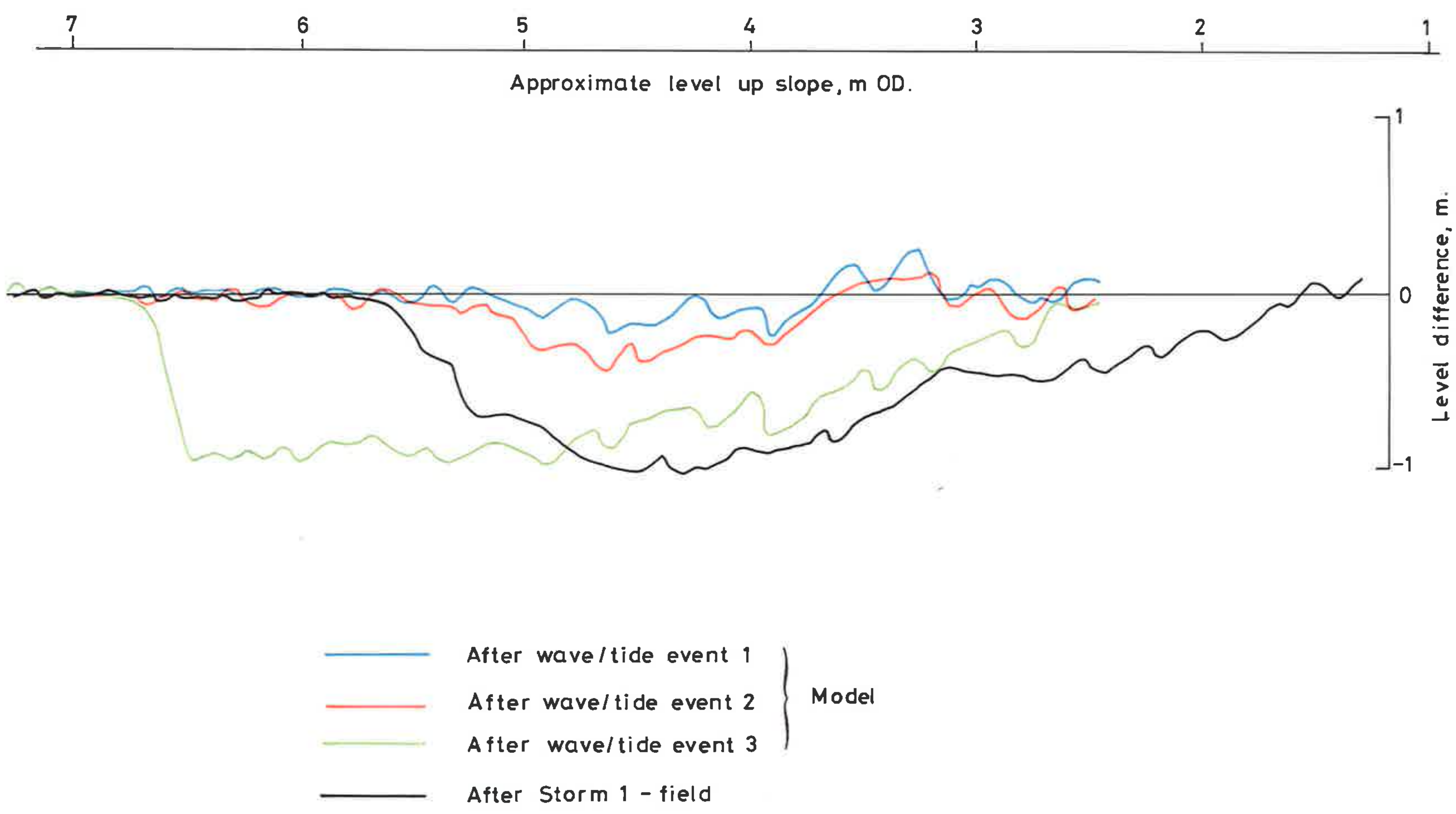

Wave/tide event for severe storm of January 1978

Fig 8



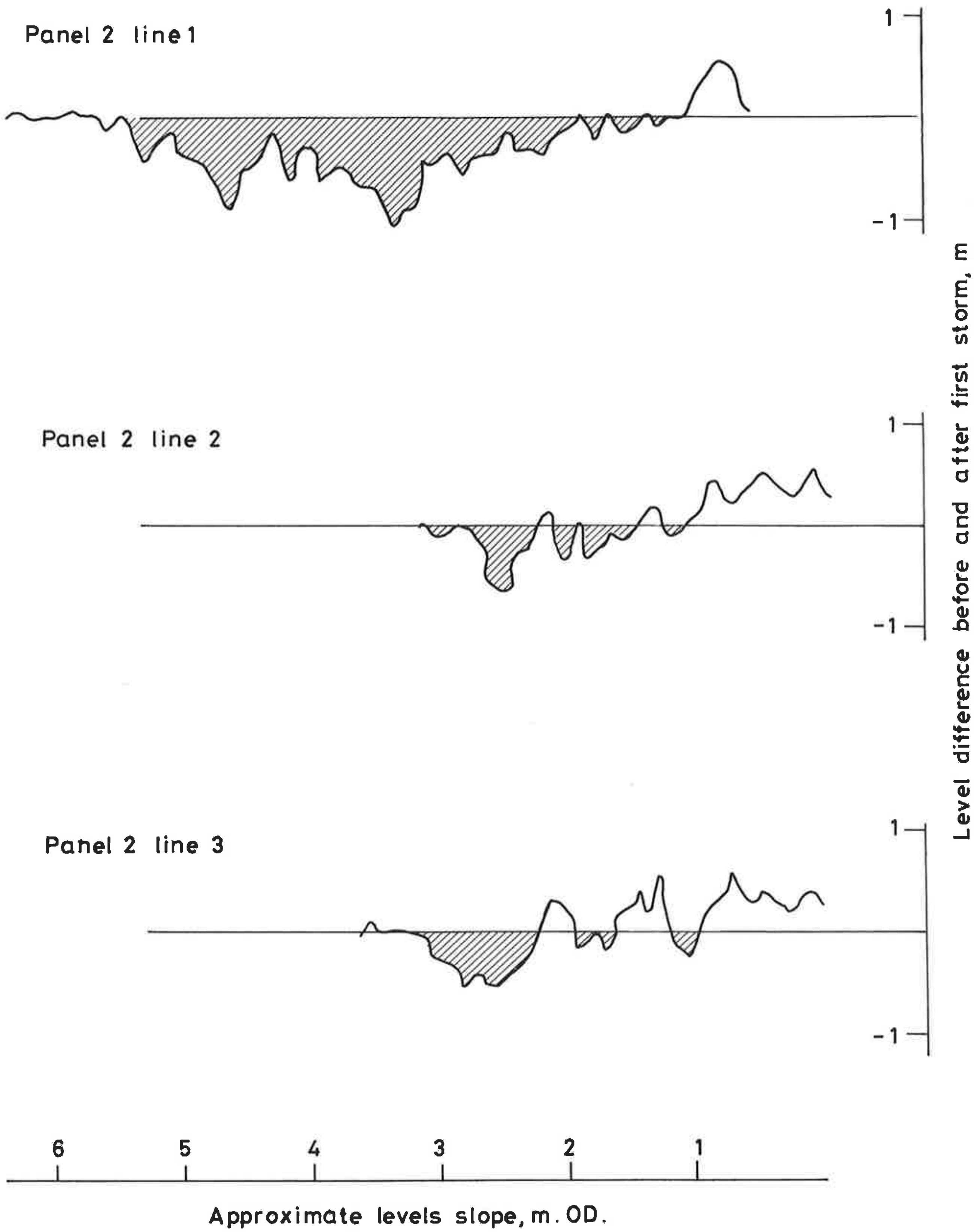

Comparison of level differences between surveys field and model

Fig 9



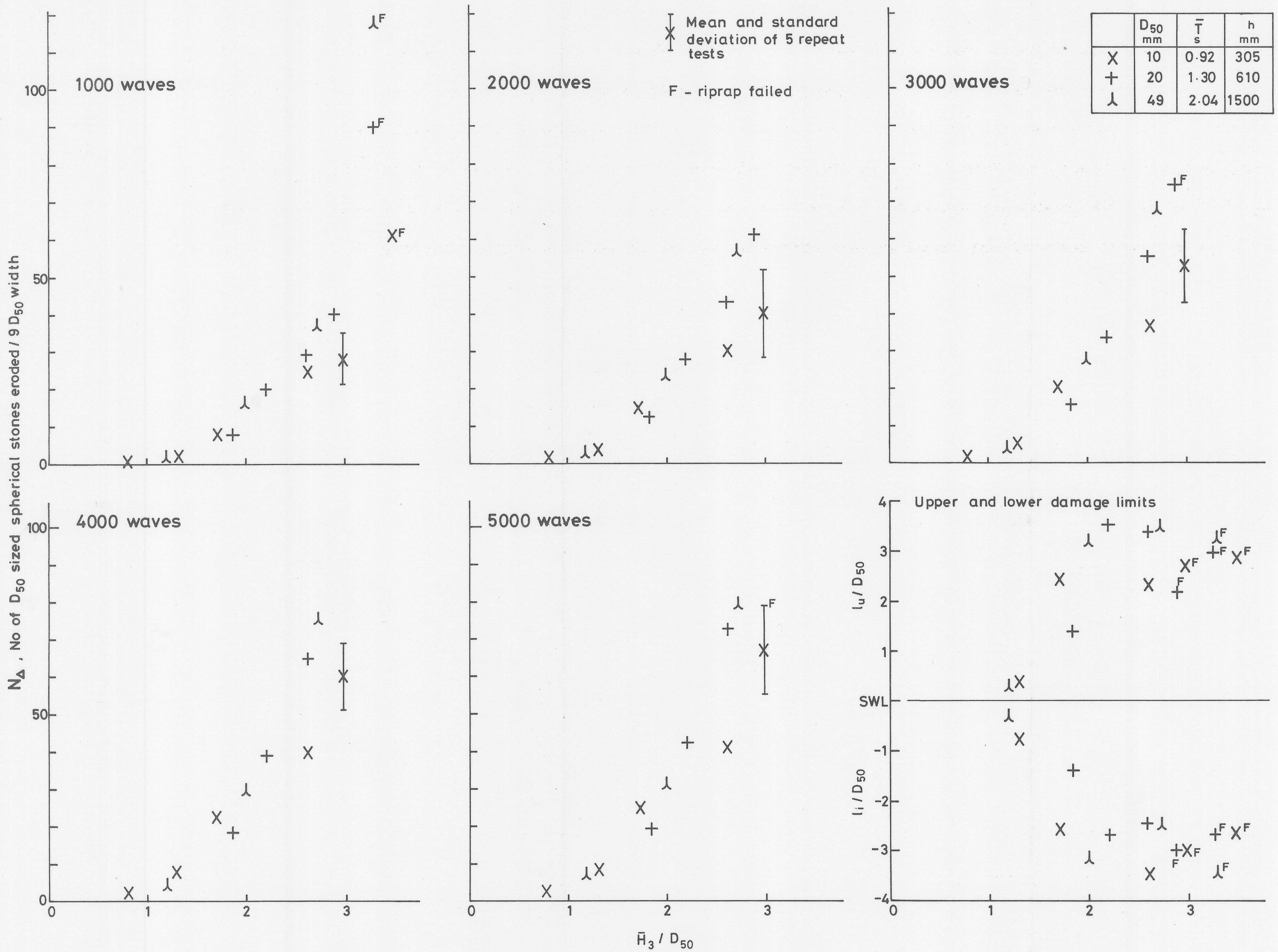

Level differences after each wave/tide event for storm 1 on panel 1

Fig 10




## Field sections on panel 2

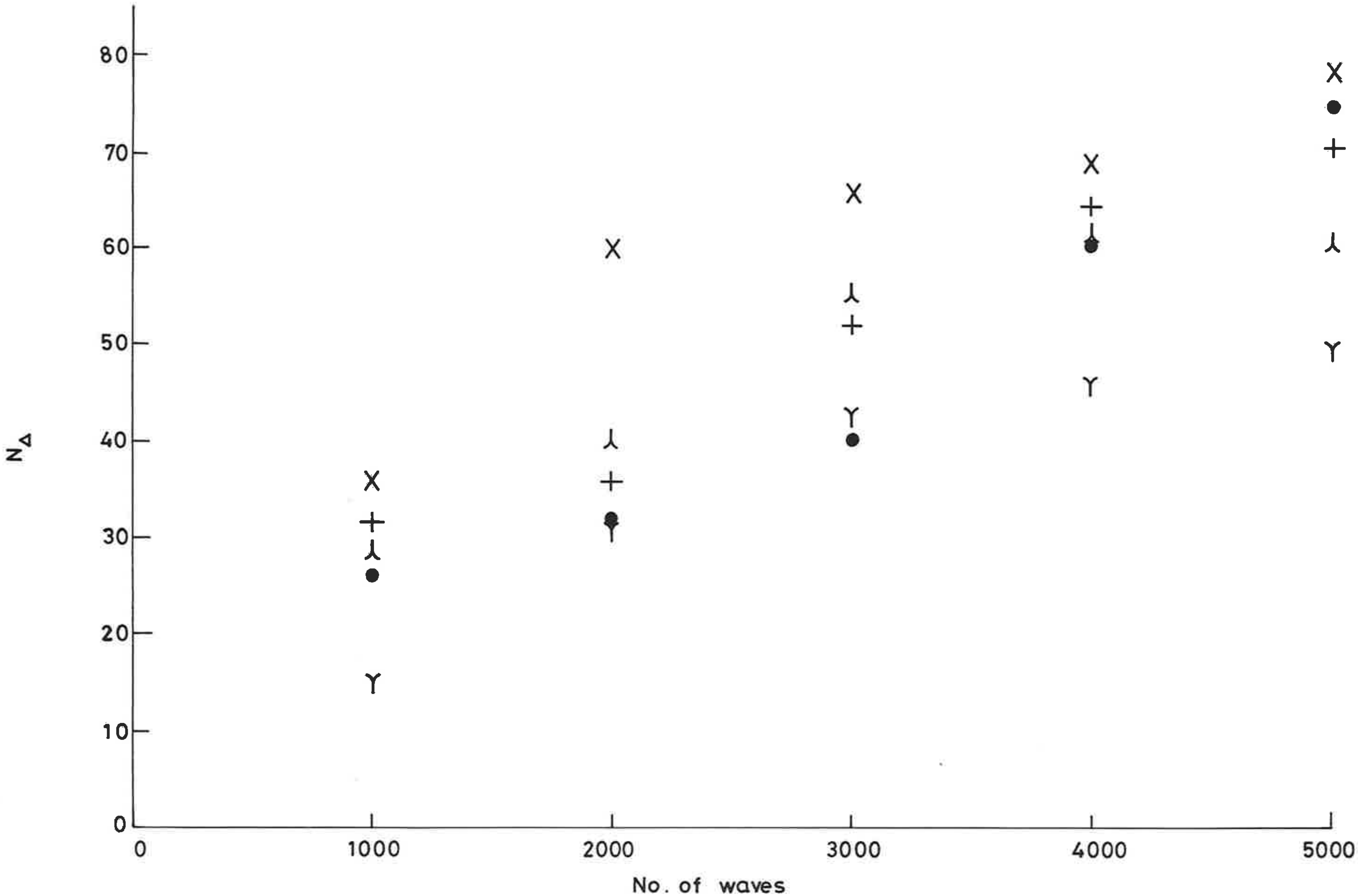
Fig 11




| | $D_{50}$ mm | $\bar{T}$ s | h mm |
|---|---|---|---|
| X | 10 | 0·92 | 305 |
| + | 20 | 1·30 | 610 |
| ⅄ | 49 | 2·04 | 1500 |

Results of extended CIRIA 61 tests

Fig 12




Repeat tests

Fig 13

# Plates

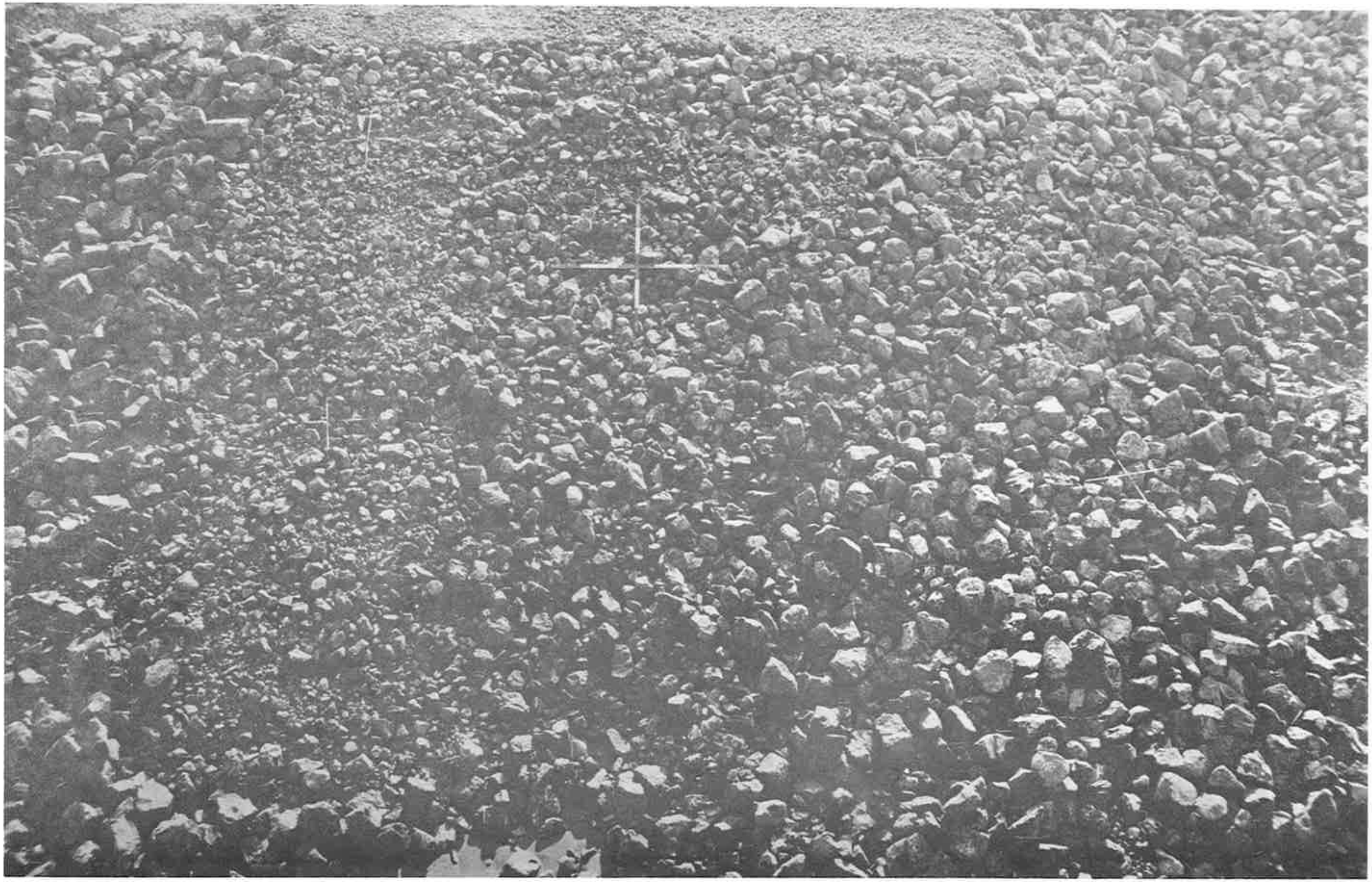


**Plate 1** **Field riprap panels 1-4**


**Plate 2** **Model riprap panels 1-4 — test run 1**

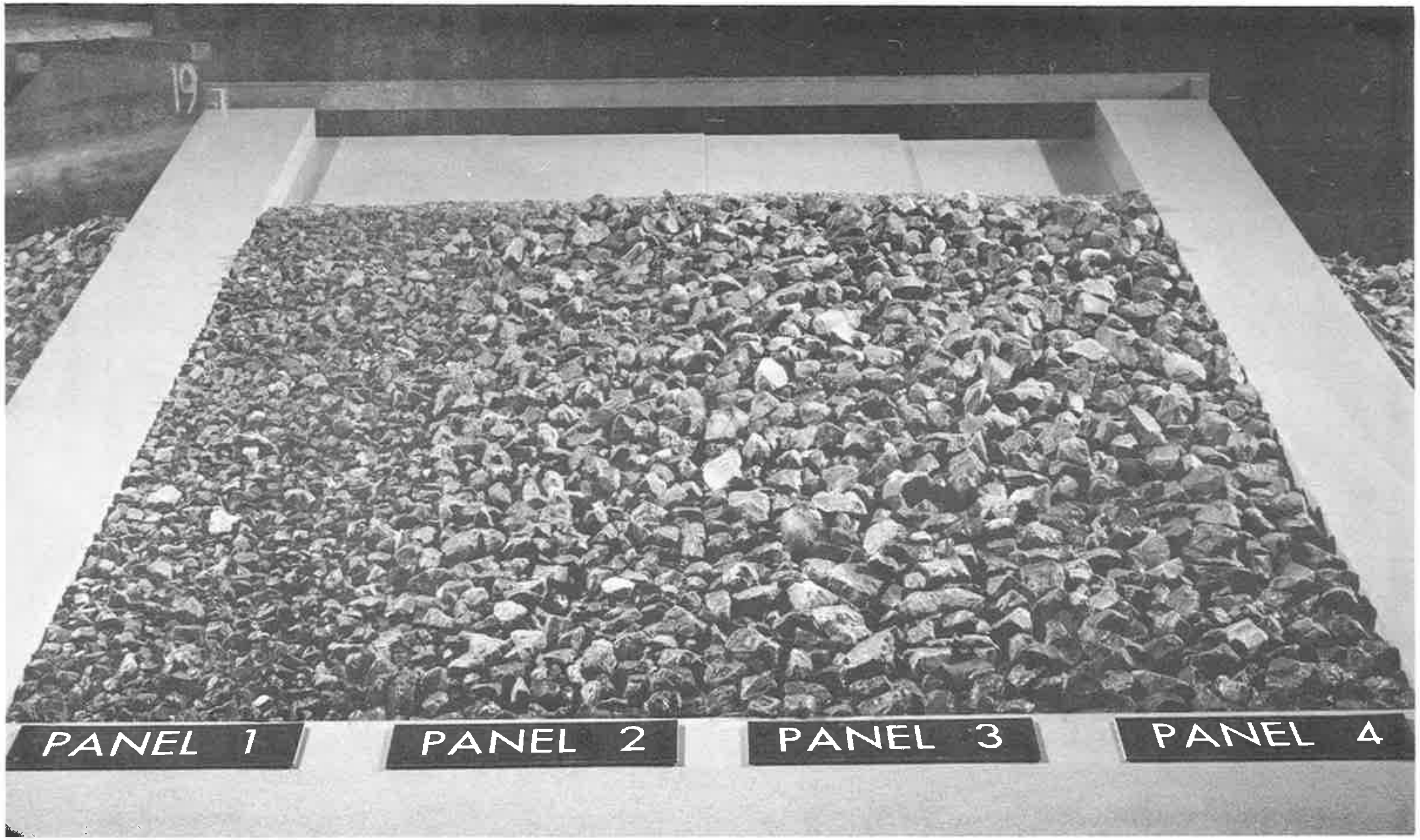



**Plate 3** **Model riprap panels 1-4 — test run 2**

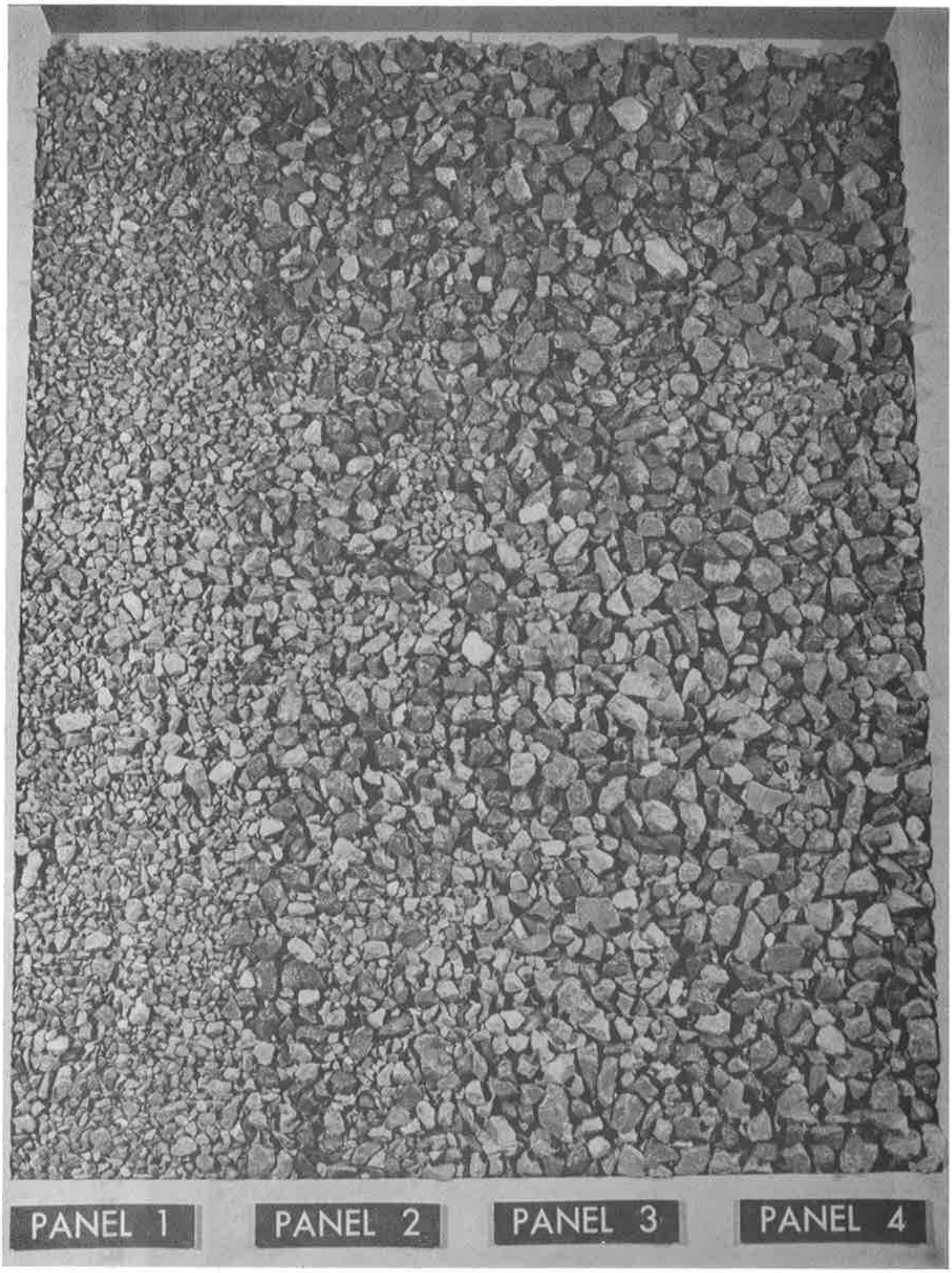



**Plate 4** Riprap prior to test run 1

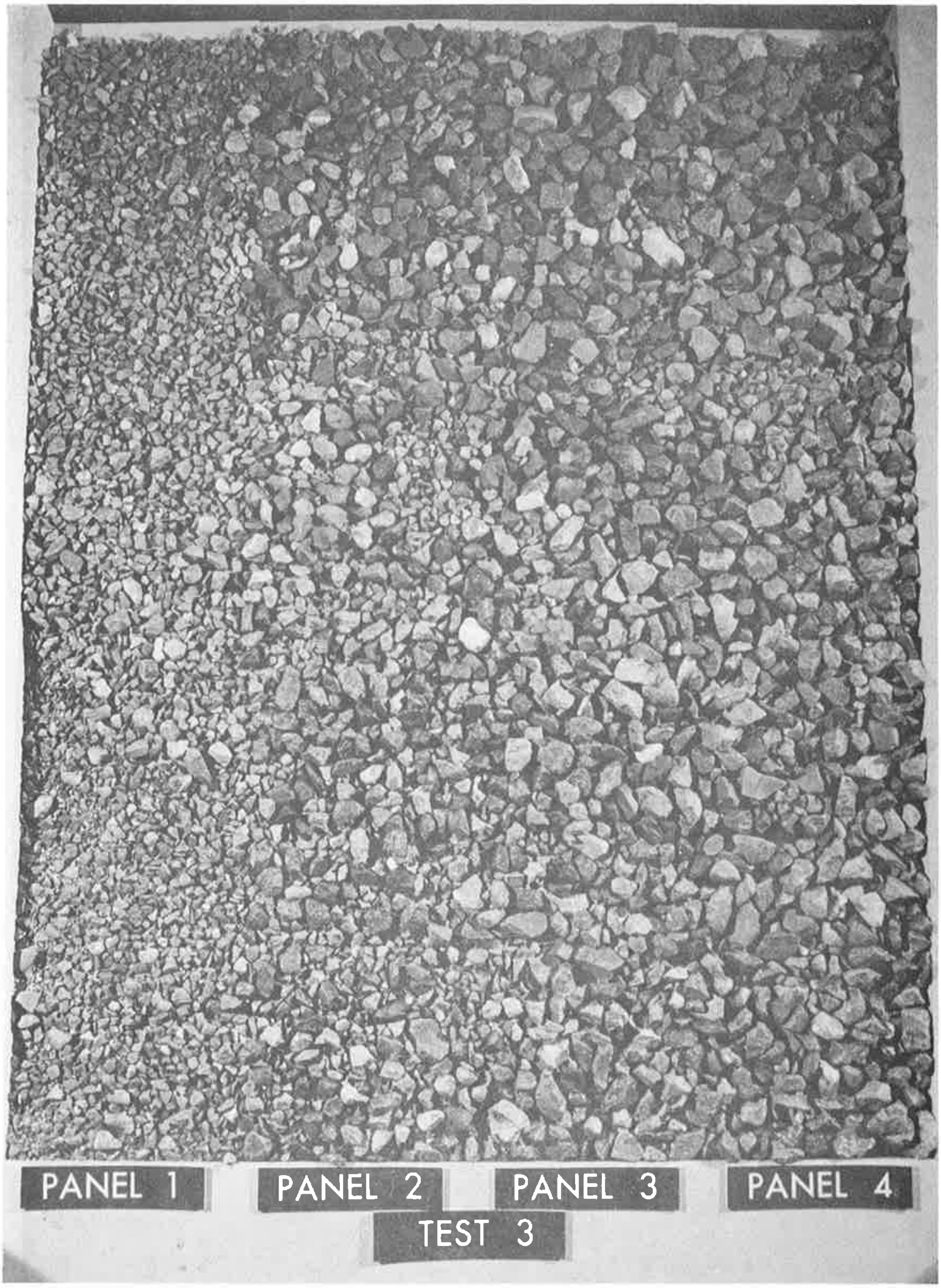



**Plate 5** Riprap after storm 1 — test run 1

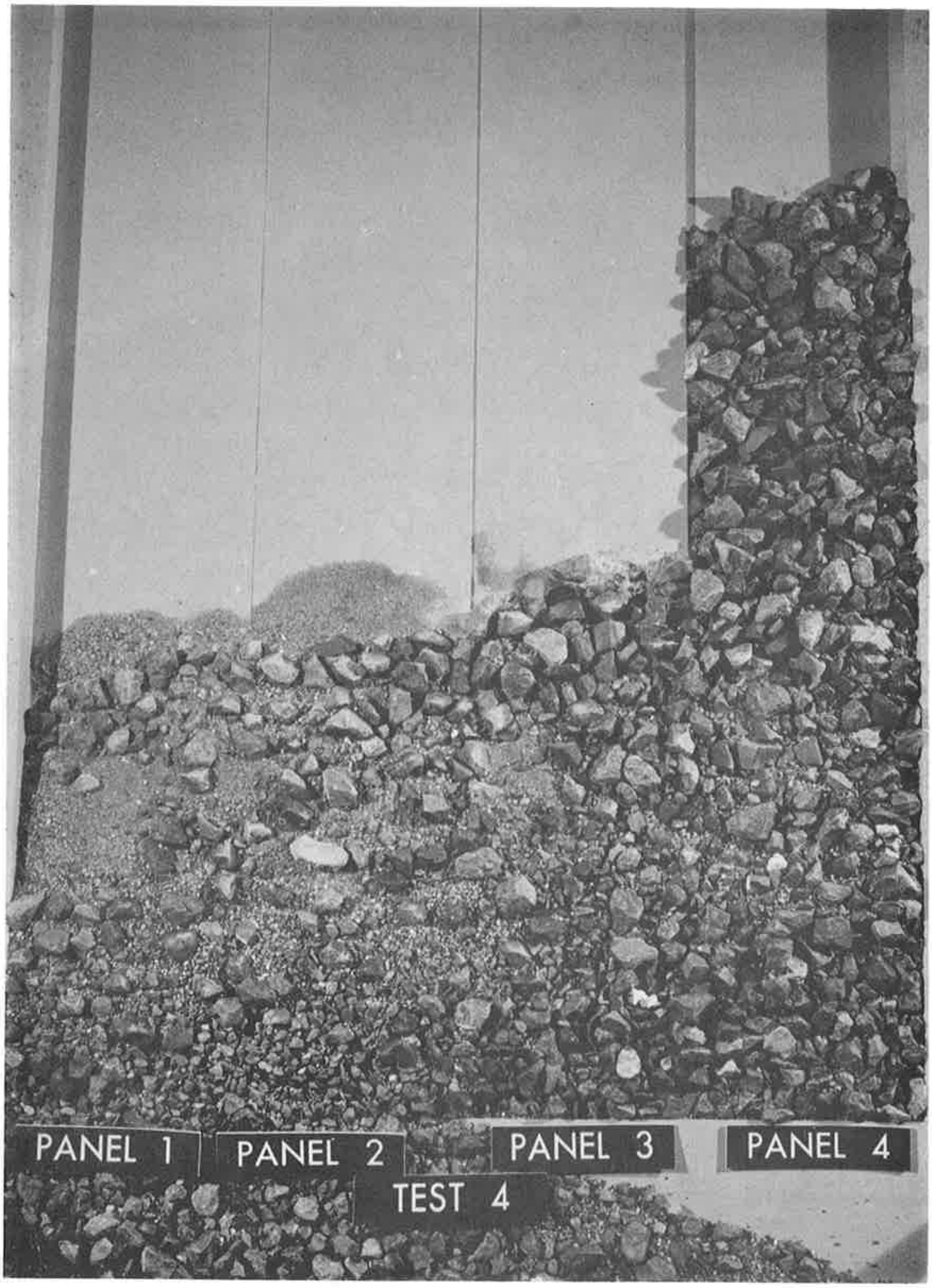



**Plate 6** Riprap after storm 2 — test run 1

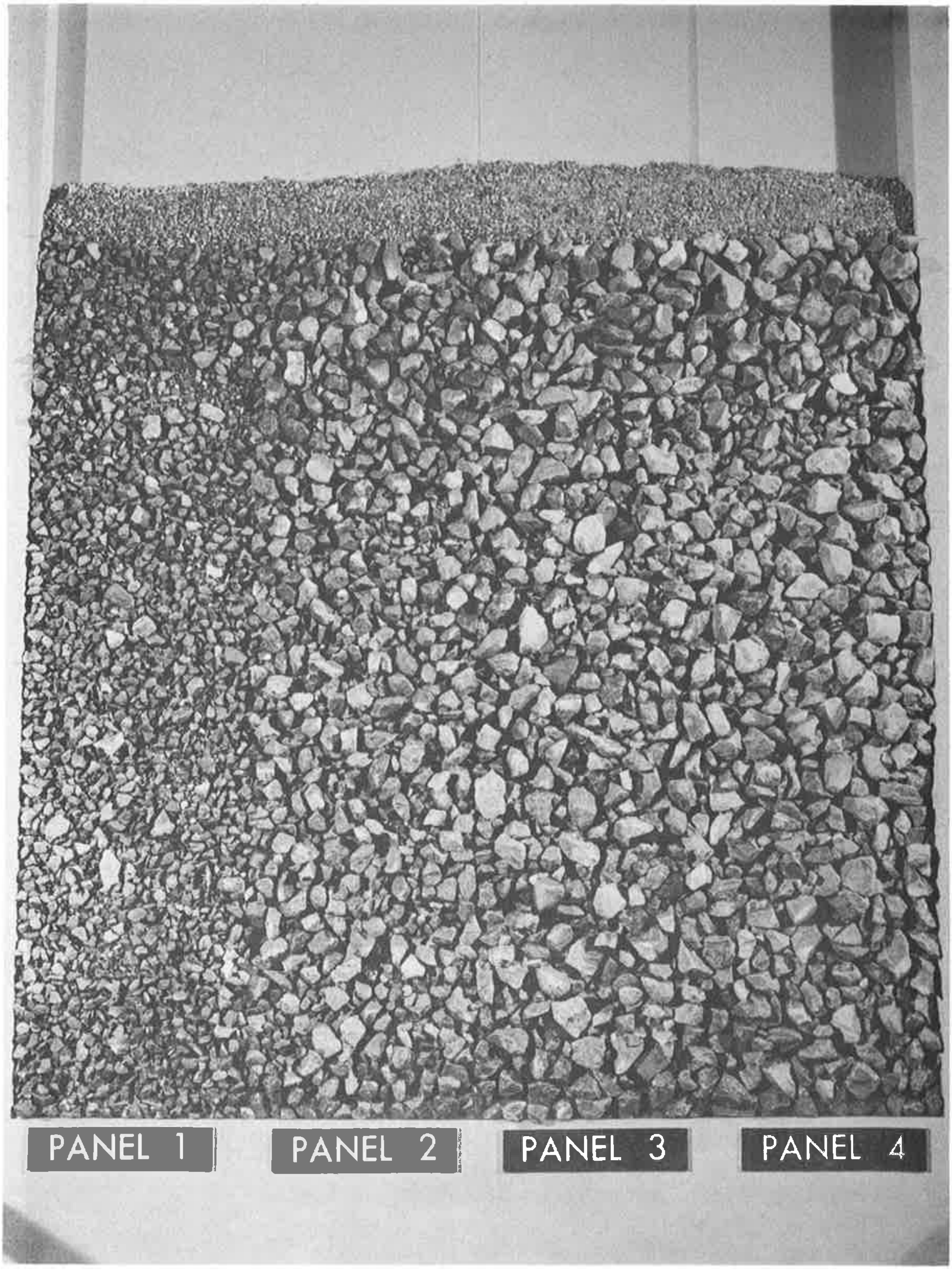



**Plate 7** Riprap prior to test run 2

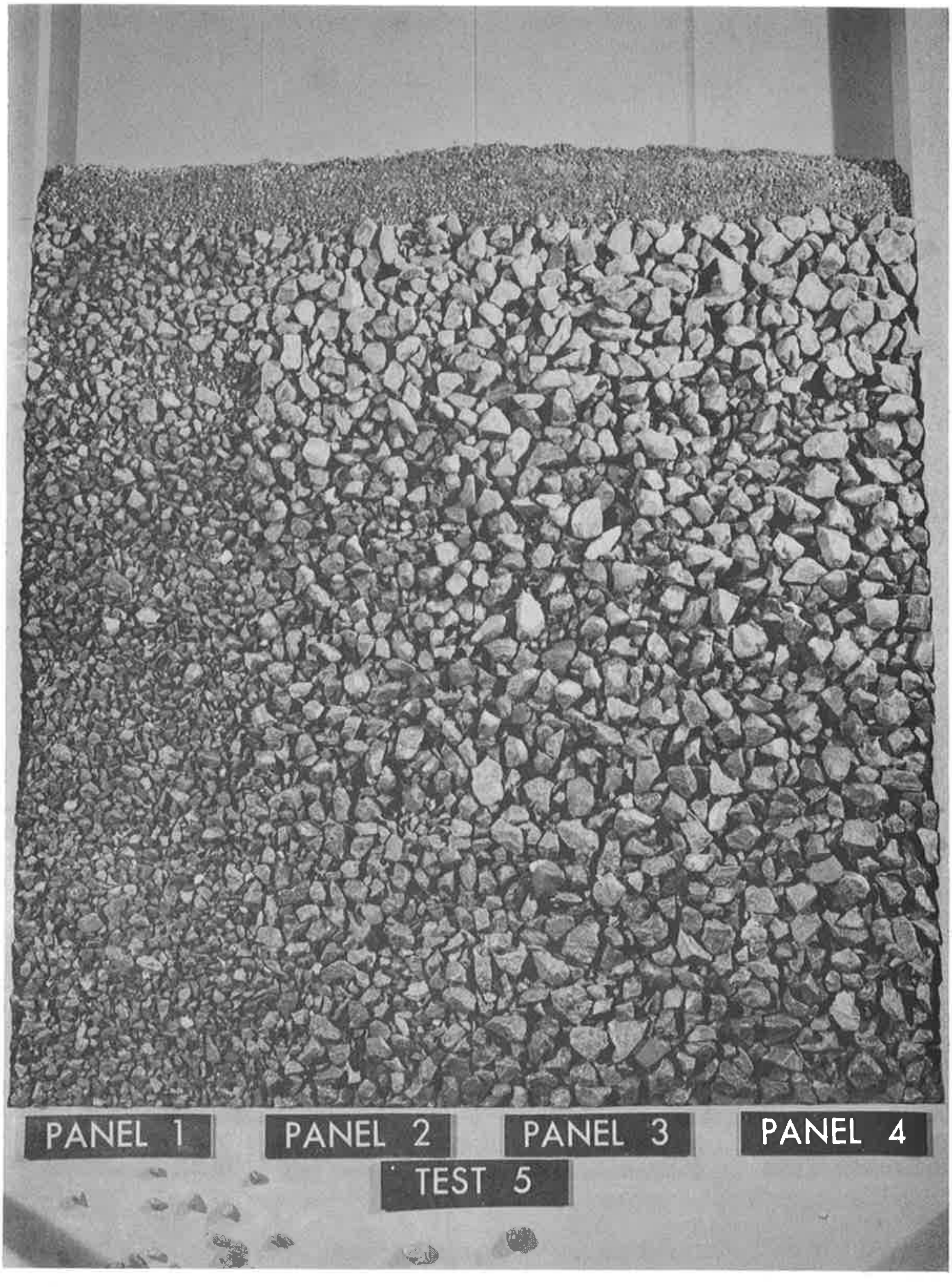



**Plate 8** Riprap after wave/tide event 1, storm 1 — test run 2


**Plate 9** Riprap after wave/tide event 2, storm 1 — test run 2

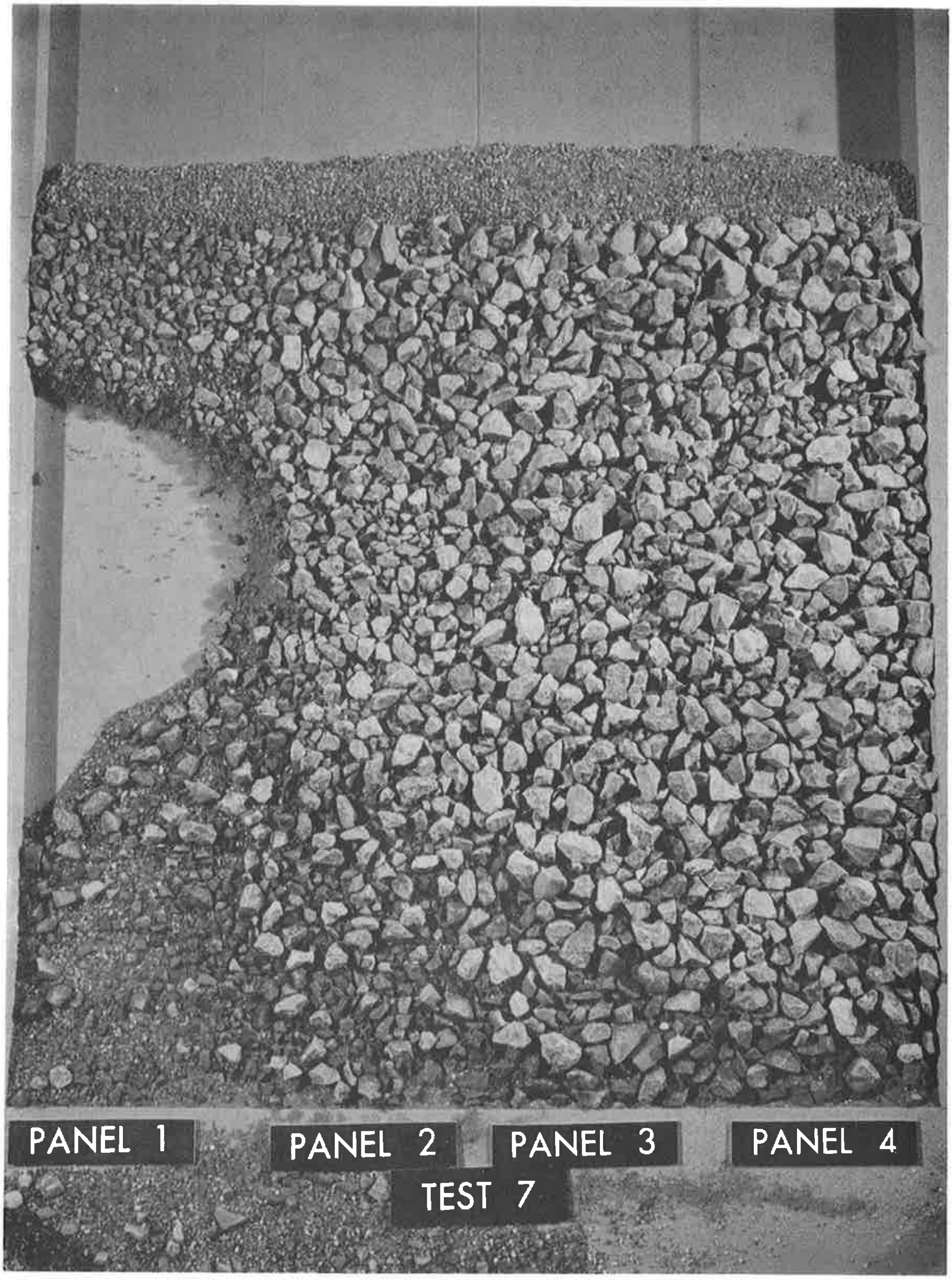



**Plate 10** **Riprap after storm 1 — test run 2**

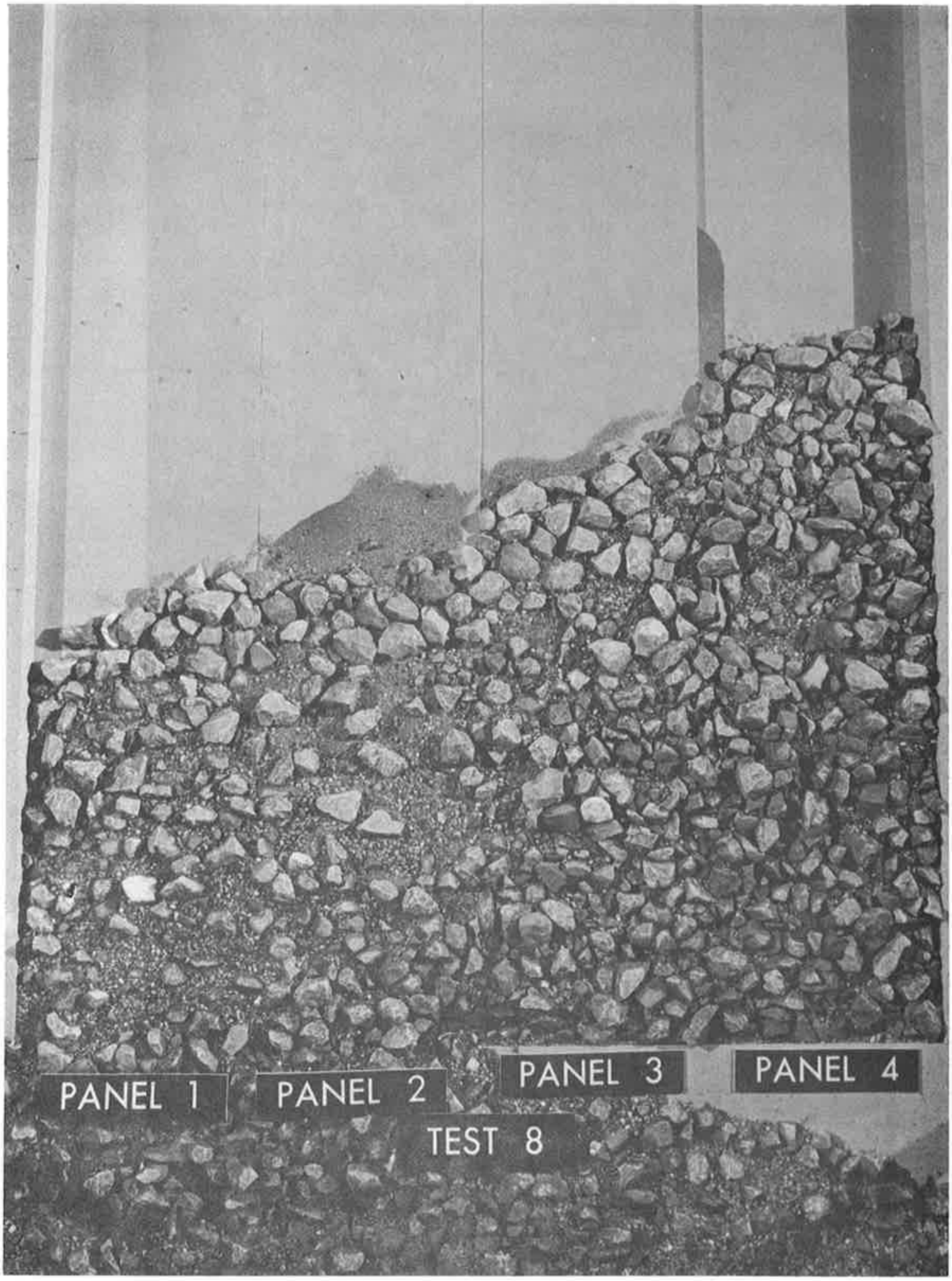



**Plate 11** Riprap after storm 2 — test run 2

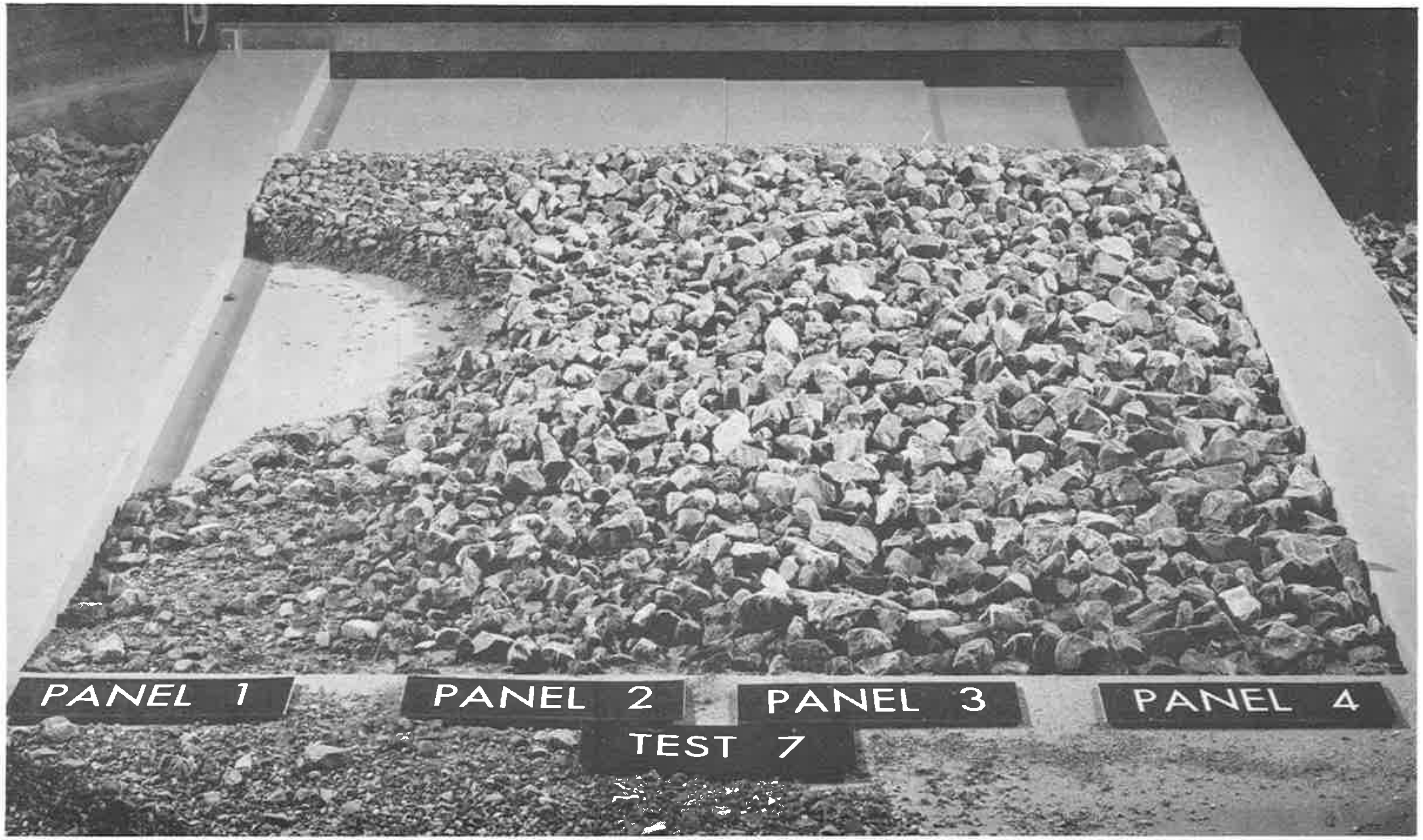



**Plate 12** Riprap panels 1-4 after storm 1 — test run 2

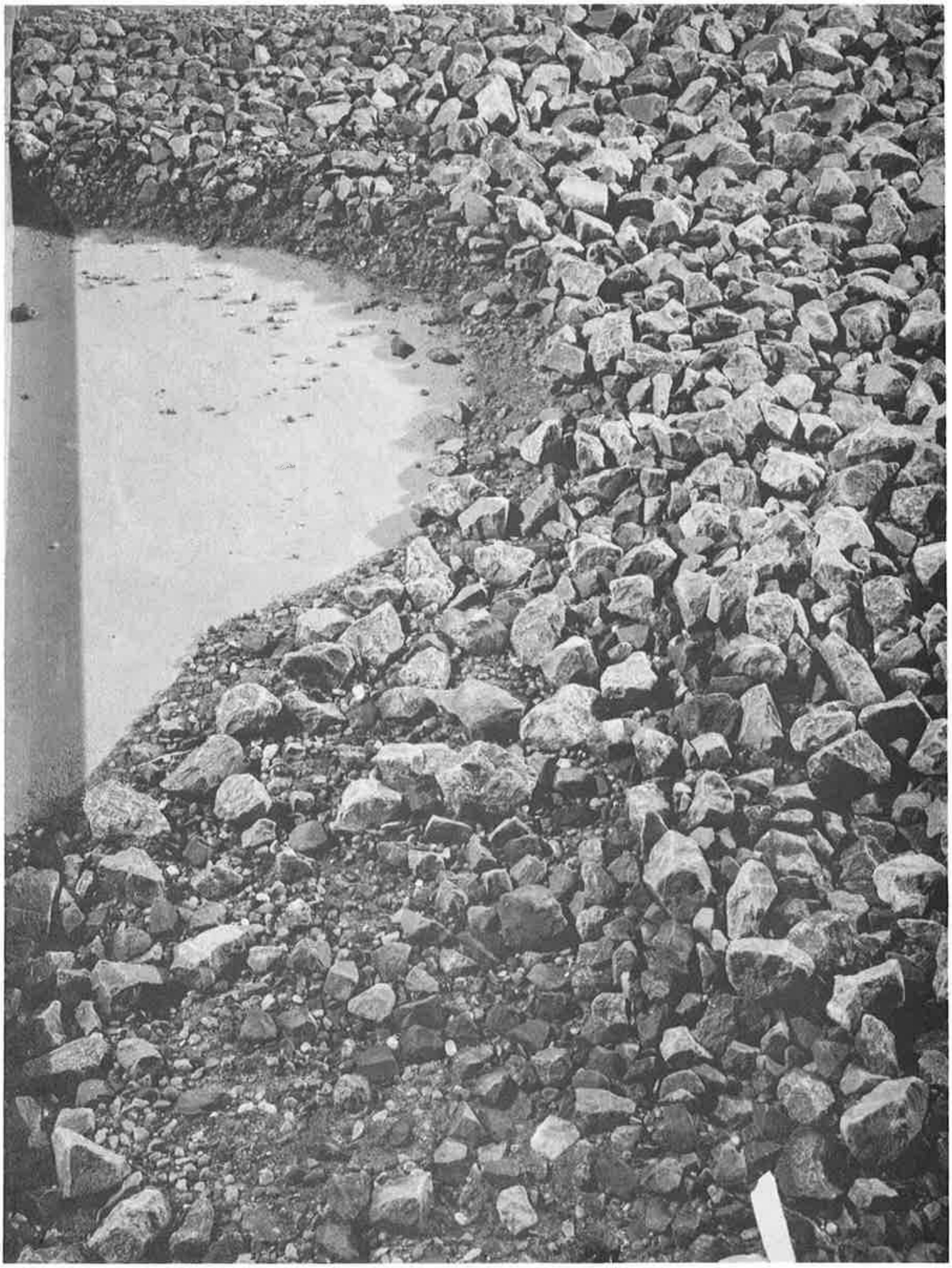


**Plate 13** **Riprap panel 1 after storm 1 — test run 2**

**Plate 14** **Progress of damage during storm 2 — test run 2**

**a) After tide step 1**

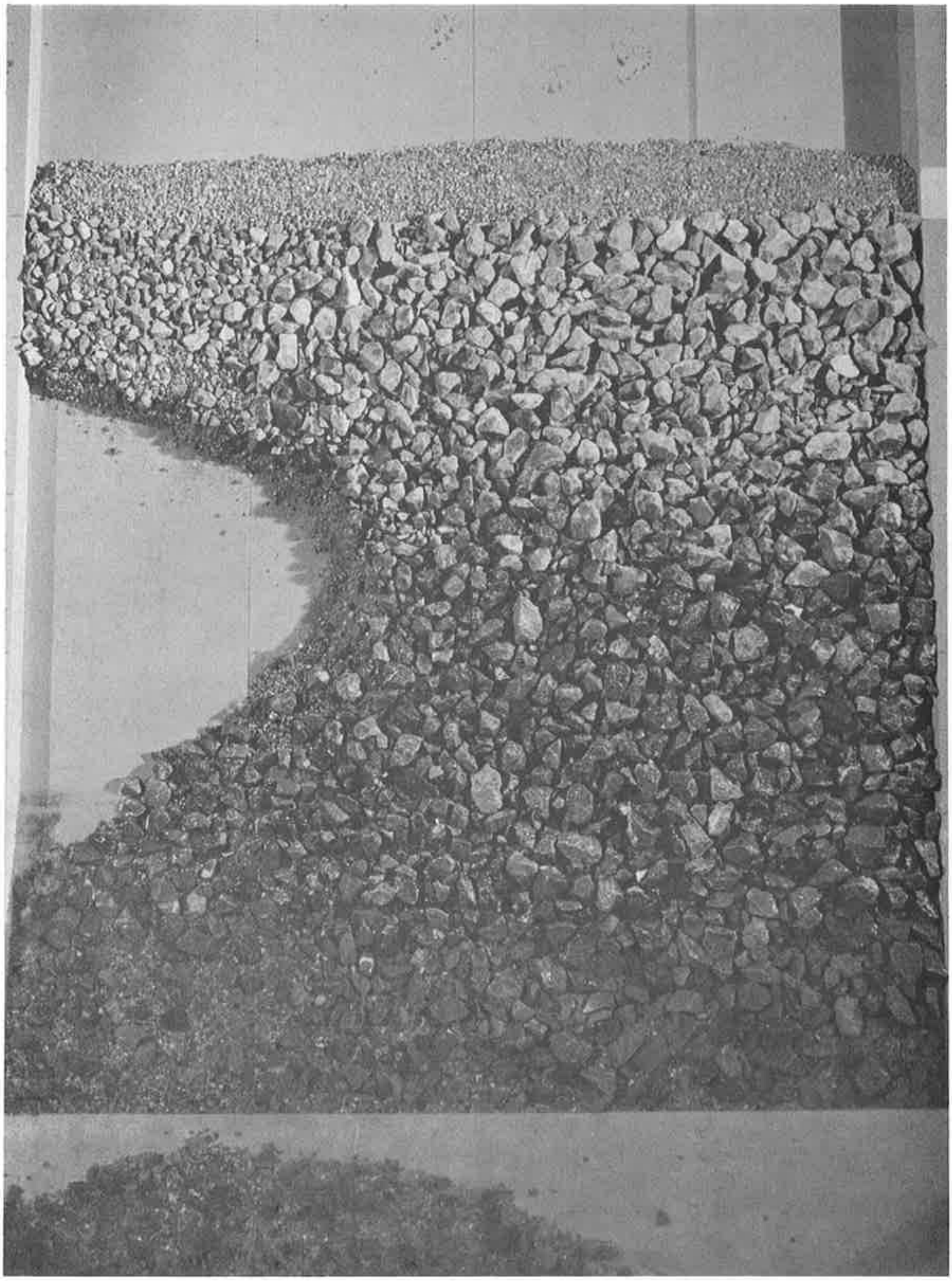


**Plate 14** **Progress of damage during storm 2 — test run 2**

**b) After tide step 2**

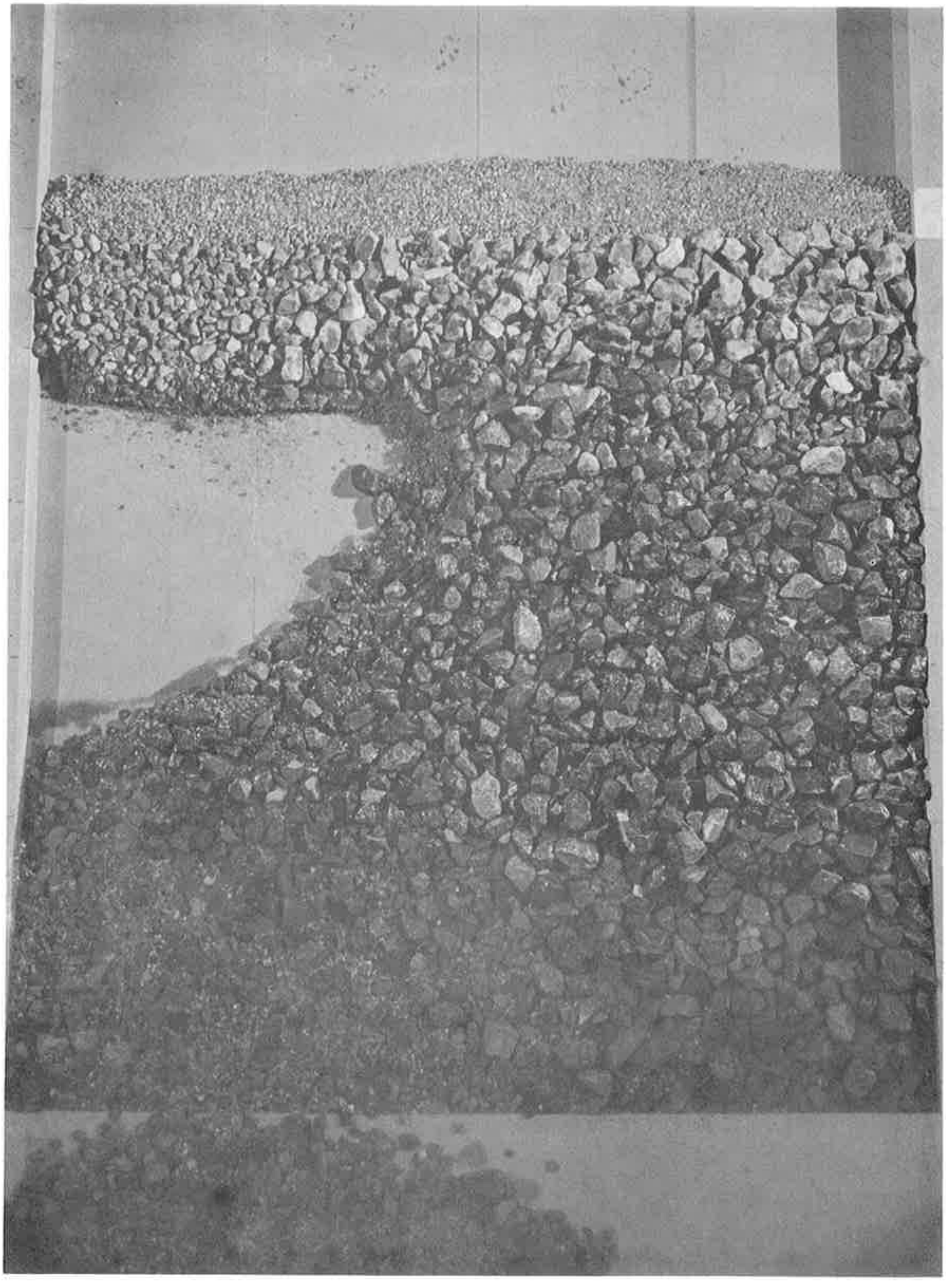


**Plate 14** **Progress of damage during storm 2 — test run 2**

**c) After tide step 3**

**Plate 14** **Progress of damage during storm 2 — test run 2**

**d) After tide step 4**

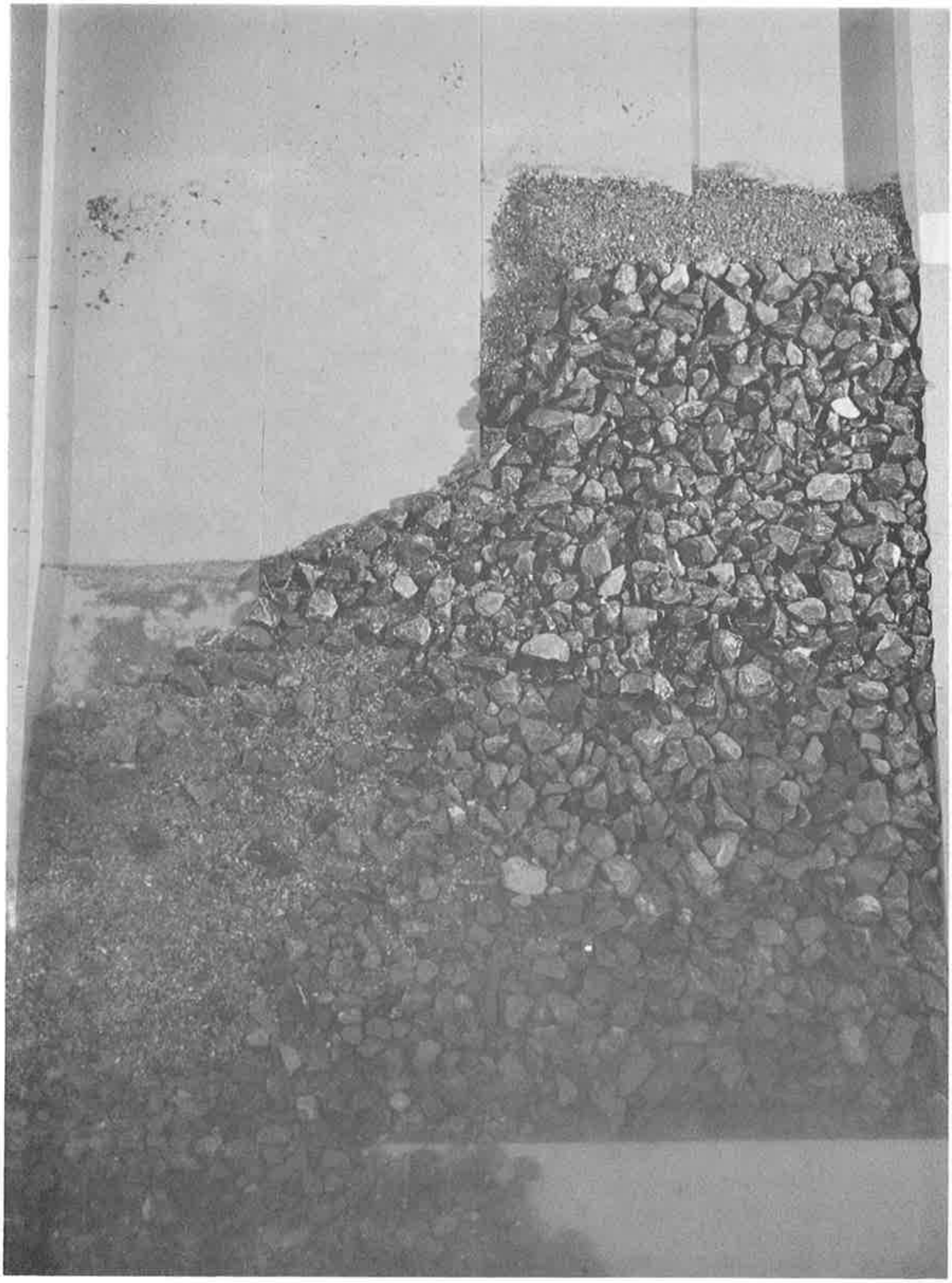


**Plate 14** **Progress of damage during storm 2 — test run 2**

**e) After tide step 5**

Plate 14 Progress of damage during storm 2 — test run 2

f) After tide step 6

**Plate 14** **Progress of damage during storm 2 — test run 2**

**f) After tide step 6**

**Plate 14** **Progress of damage during storm 2 — test run 2**

**g) After tide step 7**

**Plate 14** **Progress of damage during storm 2 — test run 2**

**h) After tide step 8**

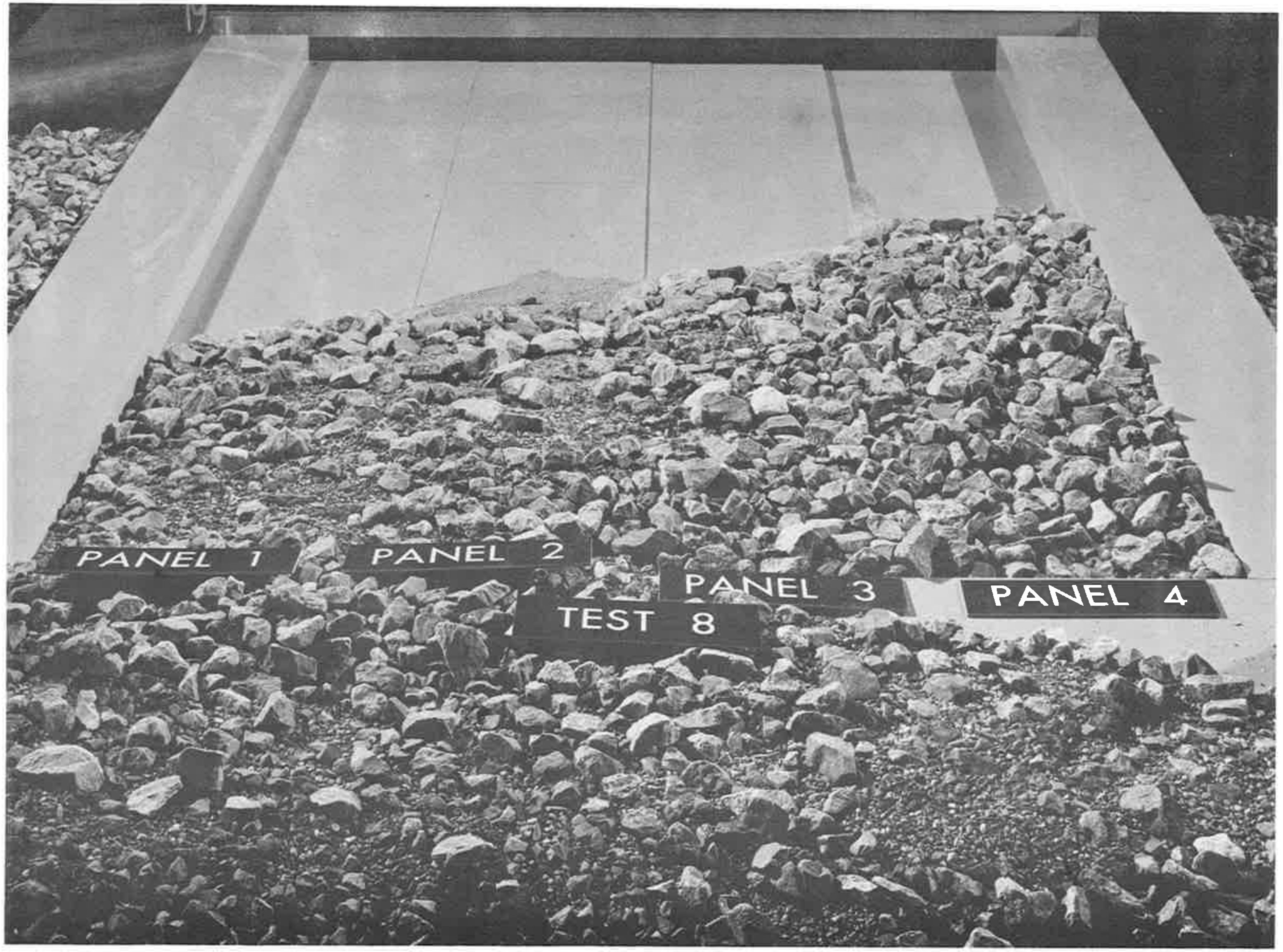



**Plate 15** Riprap after storm 2 — test run 2