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CRABLOCK CONCRETE BREAKWATER ARMOUR UNIT
Development, Modelling and Application in Oman

D. Phelp[1], K. Tulsi[1], HE Abdulla Al Masaood[2] and Capt. M Eissa[2]

Abstract: During cyclone Gonu, a category 5 storm, which impacted the east coast of Oman in June 2007, a number of small craft harbours were severely damaged. Most of the breakwater structures were armoured with various sizes of rock protection. The Al Masaood Harbour near Dibba Al Fujeirah (north eastern UAE) suffered less damage due to the appropriate size of rocks on the breakwater. However to limit future damage due to possible increased storm activity, it was decided to armour the breakwater with CRABLOCK concrete armour units. This paper describes the development and use of CRABLOCK, which is similar to the Hexapod in shape (SPM, 2006). The results of physical model tests carried out at CSIR, in South Africa and also presented and discussed.

***Keywords**: Crablock, breakwater, armour unit, 2D and 3D physical model.*

INTRODUCTION

The CSIR was approached by Advanced Group of Companies (HE Abdulla Al Masaood) in 2008 to evaluate the hydraulic stability of a new concrete armour unit named CRABLOCK. The CRABLOCK, which has undergone a number of modifications, was used for armouring of the repairs and extension to the rock breakwater of the Al Masaood Harbour (see Figures 1 for the location and layout of the harbour). This harbour was one of the few small craft harbours in the Gulf of Oman which survived the severe storm of 2007, named Gonu. 2D and 3D physical model tests were carried out by CSIR, after the repairs, to check the stability of the new CRABLOCK.

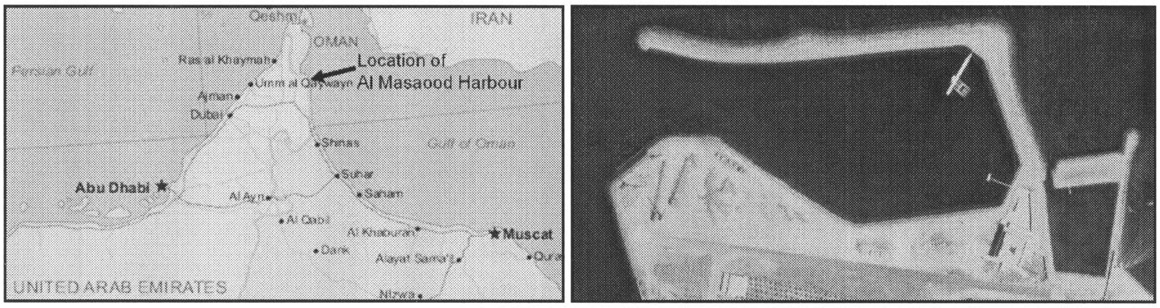

Fig. 1. Location and layout of Al Masaood Harbour in Fujeirah, on Gulf of Oman.

DESIGN WAVE CONDITIONS (CYCLONE GONU)

Gonu started as a tropical depression in the SE Indian Ocean on 2 June 2007 and grew to a category 5 storm off the east coast of Oman on 4 June with maximum sustained wind speeds of 120 knots. This was

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1 Coastal Engineer, CSIR, Box 320, Stellenbosch, 7599, South Africa, Email: dphelp@csir.co.za, ktulsi@csir.co.za
2 Managing Director, Al Masaood Advanced Group of Companies, Box 322, Abu Dhabi, UAE, Email: amvilla@emirates.net.ae and m.eissa@amsgroup.ae

the strongest tropical cyclone recorded in the Arabian Sea and was unique in its trajectory into the Gulf of Oman (Elderfield et al, 2008). By the time it had reached Muscat off the coast of Oman on 6 June, it had reduced to a category 2 storm with winds of 65 to 80 knots. The storm surge was estimated at 0.5m, with wave heights of 5m, and on top of this there was flash flooding caused by over 600mm of rainfall along the eastern coastline. Although Gonu occurred before the repairs to the Al Masaood breakwaters, the storm was used to define the wave heights for the model tests on the CRABLOCK. Wave heights of up to 6m were used for the 2D tests and up to 8m for the 3D tests on the breakwater roundhead.

DEVELOPMENT OF CRABLOCK UNIT SHAPE AND PLACEMENT

The CRABLOCK development followed the construction of the units on site at the Al Masaood harbour, and then the dry placement, in a regular pattern, on a mock rock slope, before placement in the water on the rock breakwater core (Figures 2, 3 and 4). The original idea of having two short stubs (Figure 2) was so that the units could lie flat on the rock slope and only interlock in the vertical direction. A later development was to lengthen the two stubs and interlock the units in both the horizontal and vertical directions (Figure 3). This improved the thickness, roughness and wave absorption of the armour layer.

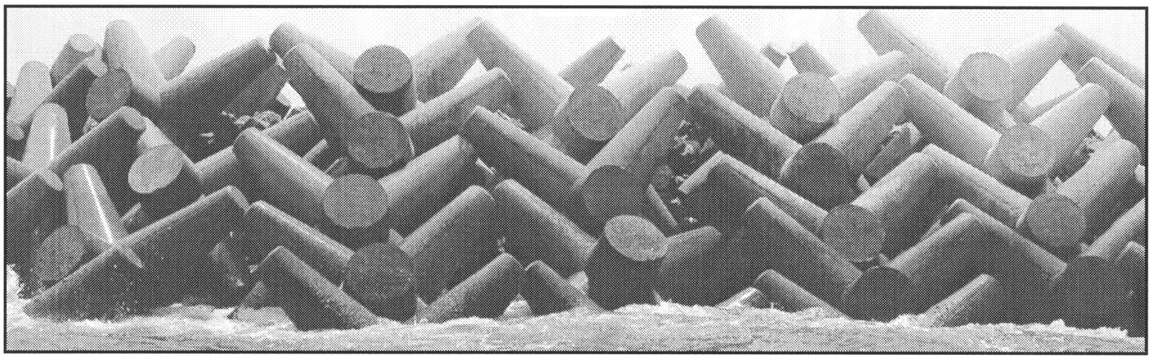

Fig. 2. Original CRABLOCK with four long flukes, two short stubs and loose placement.

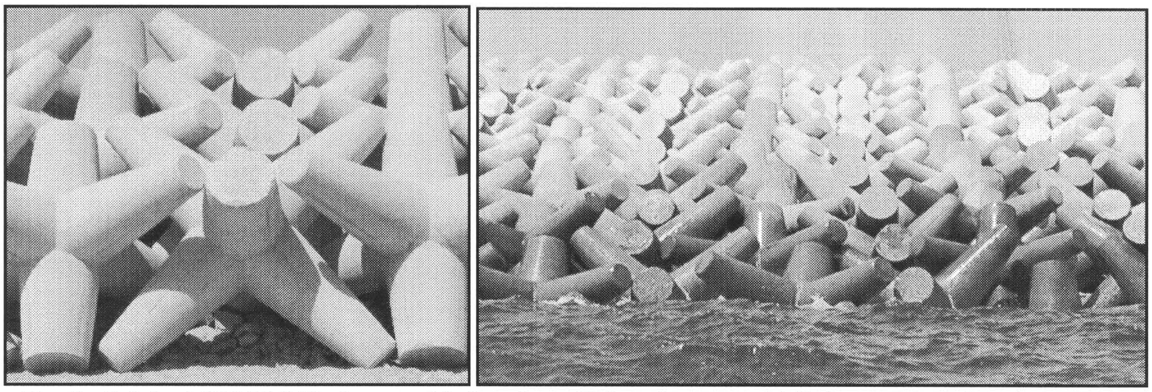

Fig. 3. Original CRABLOCK shape with four long flukes, longer mid-fluke and regular placement.

The final development of the CRABLOCK armour unit was to make it fully 3D symmetrical with all six flukes the same length (Figure 4). This created a less slender unit and allowed for tighter regular placement and also the option of random placement. Each successive change to the armour unit shape did not change the fact that the units were designed to be placed in single layers on top of the rock underlayer.

A later improvement was the addition of fillets (Figure 5) to reduce stress loads in the corners between the flukes, which did not affect the packing density. Storage and lifting of the units was also easier due to the symmetry of the final CRABLOCK unit, which meant that units did not have to be rotated before being placed. Single nylon slings were used to lift and place the units successfully (Figure 6).

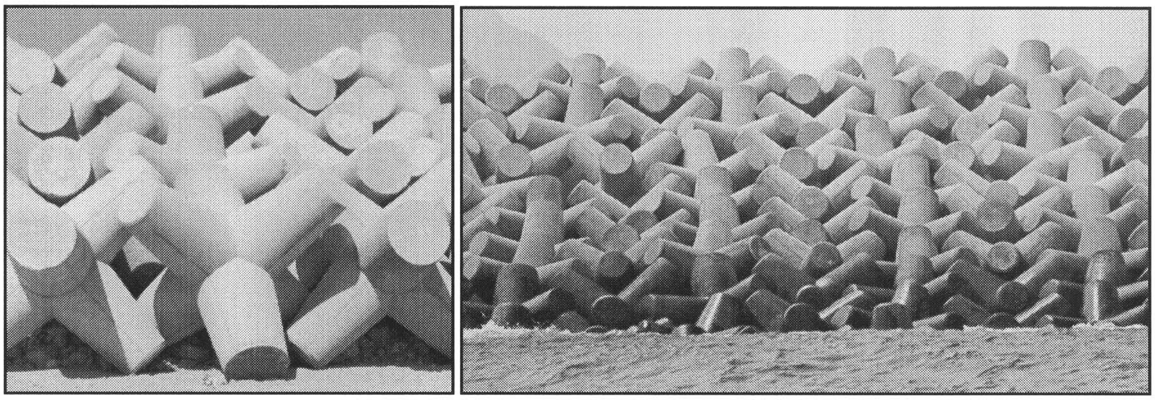

Fig. 4. 3D Symmetrical CRABLOCK with shorter flukes and tight regular placement.

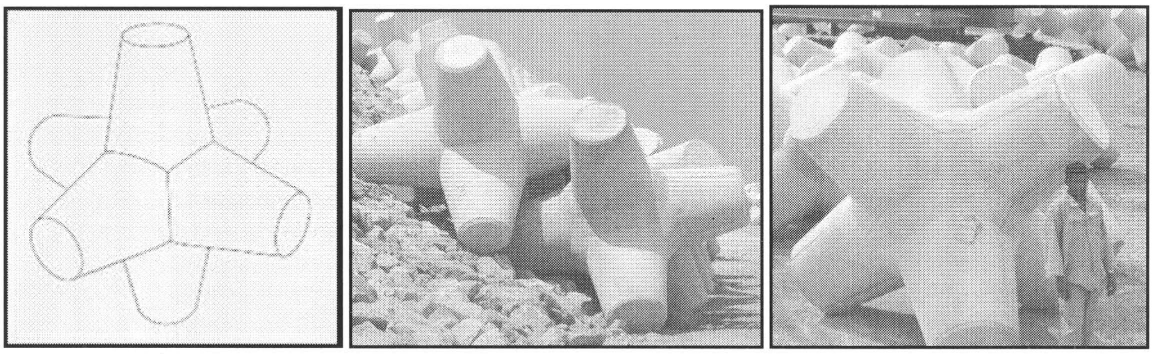

Fig. 5. Final CRABLOCK shape with 6 flukes of equal length, and the addition of fillets (right).

Before any units were placed in the water, the placement and packing densities were checked by placing the units in the dry, where the crane operators and divers could be trained. Wooden models of the units were also used for this purpose (Figure 6). All units placed below water were positioned by divers. At times of poor visibility, placing below water was delayed unit sea conditions improved.

Most of the CRABLOCK units placed on the Al Masaood harbour were placed in a regular pattern, with alternate adjacent units placed in opposing orientations. This created the tightest interlock between adjacent units. Packing densities of 1.1 (m^3 concrete per m^2 area or 27.5 units per $100m^2$) were achieved with spacing between the units being 0,71C horizontally and 0.57C vertically, where C is the height of the unit. On the roundheads where it was not possible to maintain a regular pattern, the placement was more random and the packing density lower. For random placement, the packing density achieved was

0.93 (m^3 concrete per m^2 area or 23.1 units per $100m^2$), with spacing of 0.8C horizontally and 0.6C vertically.

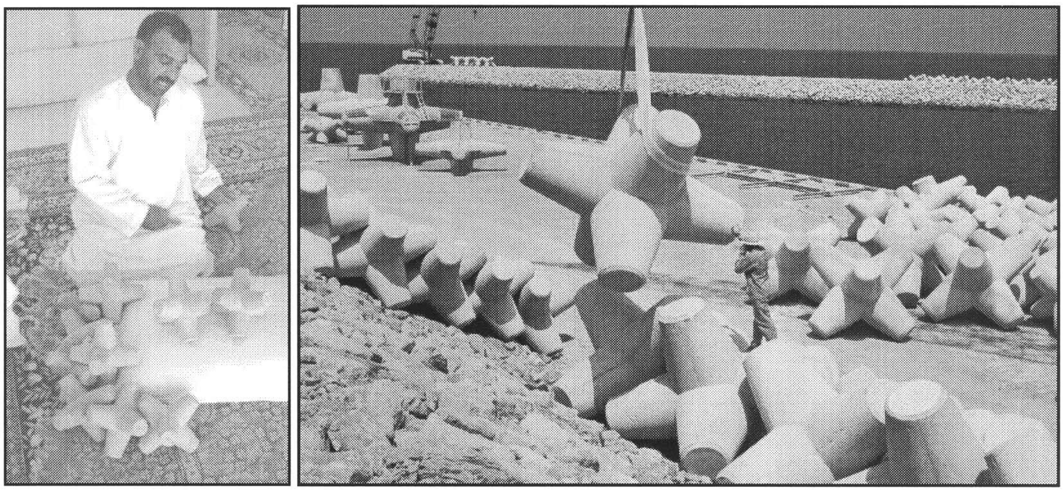

Fig. 6. Dry placement with wooden model units and on mock rock slopes.

The left side of Figure 7 shows the moulds and casting method used for the 10t CRABLOCK units, while the right side shows the semi-random dry placement of the roundhead. 15t CRABLOCK units were used on the prototype roundhead.

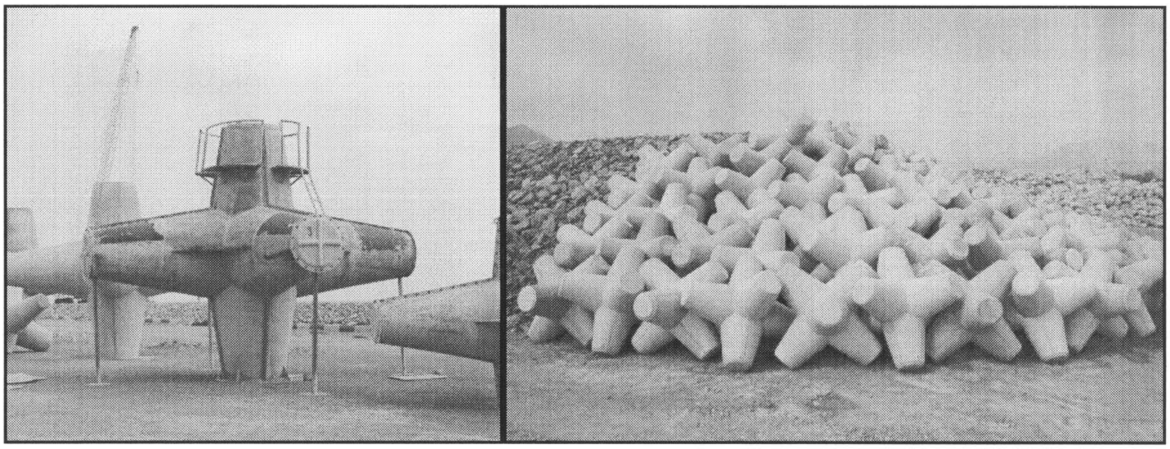

Fig. 7. Casting of the of armour units and dry placement trials of the breakwater roundhead.

2D FLUME PHYSICAL MODEL TESTS

Test Setup

A 0.75m wide and 30m long flume was used at a scale of 1:60 to test the hydraulic stability of a typical cross section of CRABLOCK armour units. The bathymetry used in the model was similar to that found off the prototype harbour with a foreshore slope of approximately 1:60. The slope of the rock and armour layer was 1:1.5 which is typical for most concrete armoured breakwaters, and is shown in Figure 8.

The depth at the toe was deeper than prototype at approximately -12m and the crest height was +11m (which was higher than the prototype breakwater, to prevent wave overtopping, which was not being investigated). A crown was made of 3t rock to support the top row of CRABLOCK units. The rock toe and filter layer consisted of 1t to 1.2t rock and the CRABLOCK units were the equivalent of 10t, which was the size of the repair units used on the prototype trunk sections. A total of 360 model units were used to cover the test section.

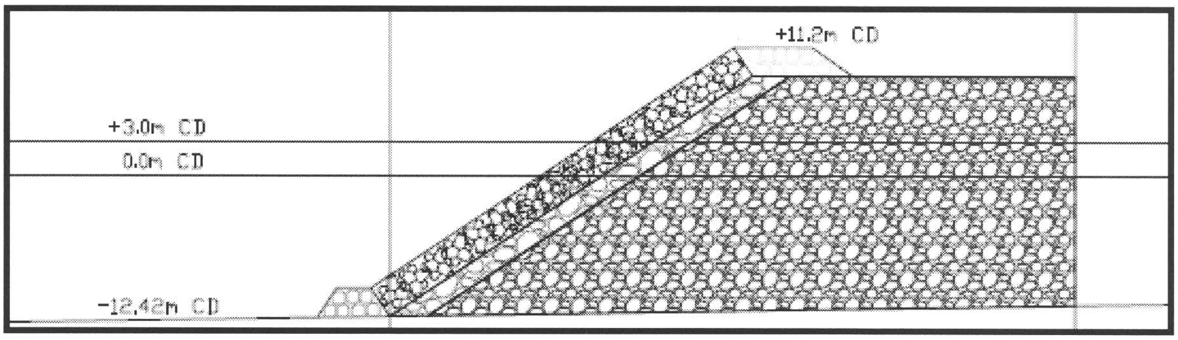

Fig. 8. Cross section used in the 2D flume tests.

Testing was initially carried out on the CRABLOCK with a uniform placement (two tests), and subsequently testing was repeated (six tests) with CRABLOCK with a random placement (Figure 9). A Jonswap wave spectrum was generated with wave heights increasing from 2m to 6m and wave periods from 8s to 16s. The water level was varied from 0m to +3m CD. All tests were carried out for test durations of 1000 waves.

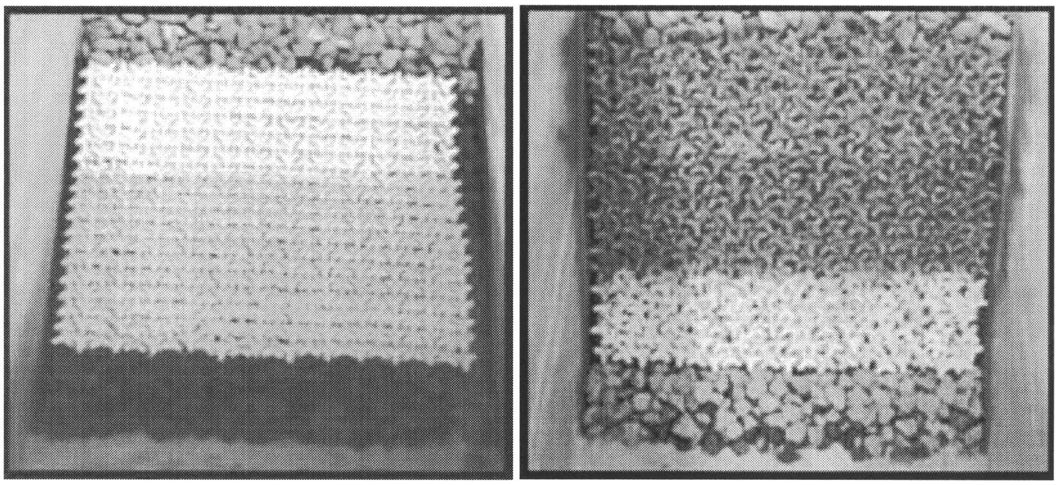

Fig. 9. Uniform and random placement of CRABLOCK in 2D flume.

Test Results

The model tests resulted in the larger waves breaking in the mid-slope, with little wave overtopping. Armour unit displacements were classified into 0.25C to 0.5C as settlement, 0.5C to 1C as rocking or potential damage and >1C as displacement damage. For the uniform placement there was little movement with wave heights up to 4m, and thereafter only minor damage occurred. Using the Hudson formulae, the stability coefficient for the uniform placement, with tight packing, was calculated at Kd = 14, although achieving this would depend on the uniform pattern also being achieved below water (as placed in the model tests). For the random placement, the stability coefficient reduced to Kd = 4 for the single layer system.

3D PHYSICAL MODEL TESTS ON BREAKWATER ROUNDHEAD

Test Setup

A 4m wide and 32m long quasi-3D flume was used at a scale of 1:60 to test the hydraulic stability of a typical trunk and breakwater roundhead of CRABLOCK armour units. The bathymetry was again similar to that found off the prototype roundhead with a foreshore slope of approximately 1:65. The slope of the rock and armour layer was 1:1.5 and the slope had about 9 rows of armour units from toe to crest.

The depth at the toe was approximately -5m CD and the crest height was +8m CD which were both similar to the prototype breakwater. A fixed capping was placed on top of the model breakwater to represent the road on top of the prototype breakwater, but no splash wall has been constructed (Figures 10 and 11). Once again, both uniform and random placement patterns were used. A total of ten tests were carried out for each packing pattern and armour size.

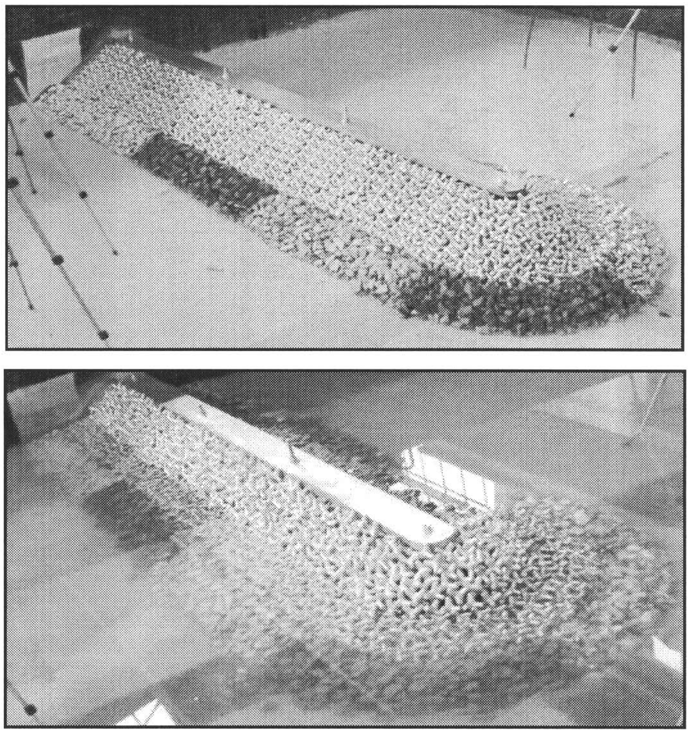

Fig. 10 Uniform and random placement of CRABLOCK roundhead in Quasi-3D flume.

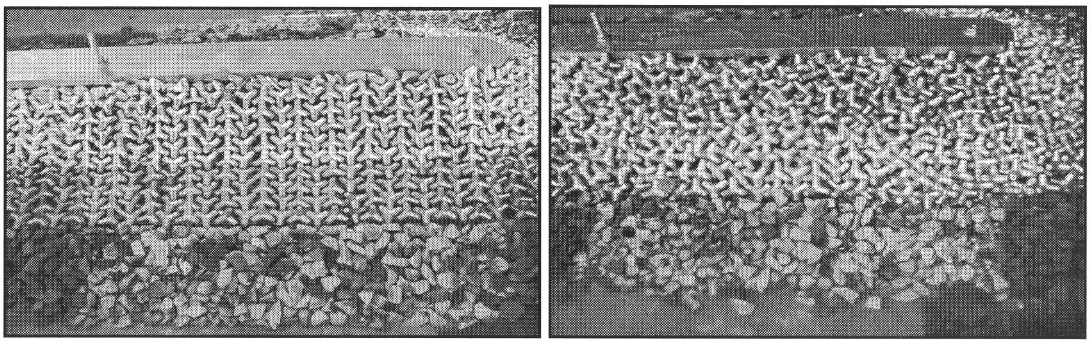

Fig. 11 Uniform and random placement of CRABLOCK roundhead.

Wave Generator and Wave Probes

The wave generator used in the quasi-3D flume comprises of a bank of eight paddles, manufactured by HR Wallingford, UK. The eight paddles generate a 4m wide wave across the width as seen in Figure 12. The paddle motion is of a rack and pinion type for shallow water wave generation. The wavemaker is capable of generating regular, irregular, long-crested, short crested waves. The paddle is also equipped with active wave reflection compensation (ARC).

The waves in the model were measured with capacitance probes coupled to an amplifier (Figure 12). As the water level varied around the probes, so did the capacitance reading. By calibration, these readings are converted to water level height measurements. By analysing the probe output, the capacitance data are converted to a time-series of the variation in the wave surface elevation, from which the wave parameters are calculated.

Two separate 3 probe arrays were used to measure the waves at the in front of the structure and near the wavemaker. The 3-probe arrays allow the extraction of the reflected wave component using the procedure described by Mansard and Funke (1980). The wave data was spectrally analysed by in-house software and the relevant parameters such as the significant wave height (Hmo) and peak period (Tp) and reflection coefficients were derived. Wave heights were increased from 2m to 8m with wave periods from 10s to 16s.

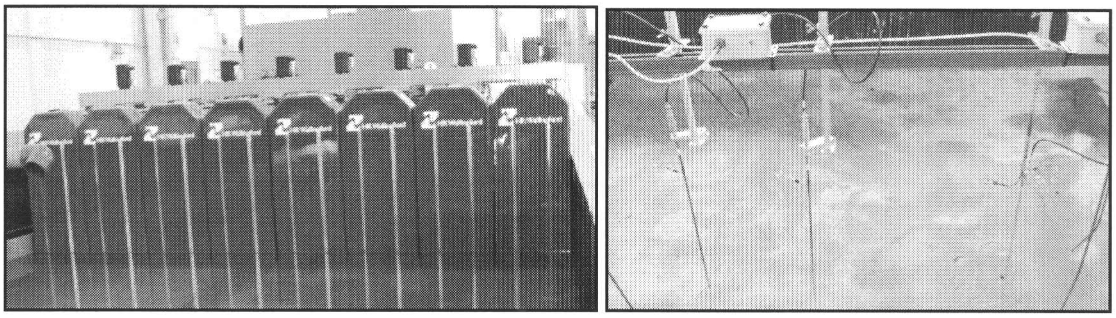

Fig. 12 Wave Generators and Capacitance Wave Probes.

The stability of the armour units was determined by comparing photographs taken before and after each test. Digital cameras were mounted at fixed positions with view angles perpendicular to the seaward slope. The areas of interest were the rock toe and the CRABLOCK slope. The stability of the slope of the structure was evaluated during the tests and by digital image analysis of the photographs taken. Figure 13 indicates the four camera stations.

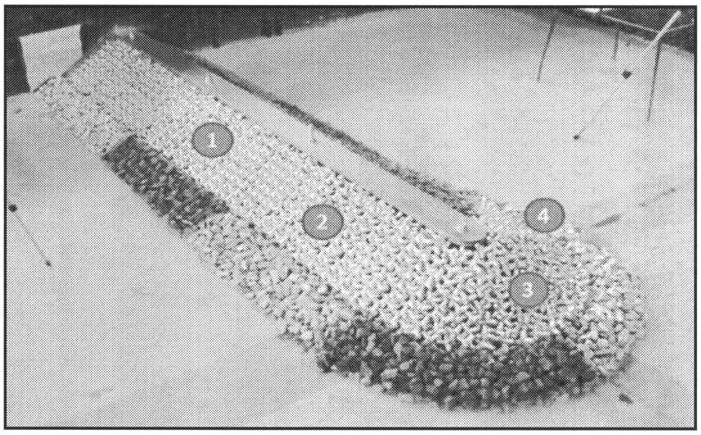

Fig. 13 Location of camera observation areas.

Stability Analysis

For stability analysis of the armour units, the armour track method was used as described by Phelp, D & Tulsi, K (2006). The two images were analysed using software developed by CSIR to assess the armour unit displacement that had occurred. These displacements were then scaled to a prototype scale by using a calibration image. The displacements are classified as for the 2D flume tests described above.

Rocking units might break and have to be added to the total damage. A formula to calculate the damage is presented in Phelp (2000), which used formula calibrated for the Dolosse. Since the CRABLOCK fluke shape is tapered, similar to those of the Dolos, this damage criteria will be used until prototype damage information on the CRABLOCK is available.

Test Results

Two alternative CRABLOCK sizes, namely 10t and 15t units were tested in the model and the stability was analysed for each. The 10t units had sharp intersections between the flukes whereas the 15t model units were made with the fillet, as shown on the right of Figure 5. The other alternatives tested mainly differed in the way the CRABLOCK armour units were placed on the slope. Once again, the units were either randomly or uniformly placed. Test 1 through to test 10 had the 15t units placed uniformly and test 11 through to test 20 had the 15t units orientated randomly within a uniform grid. Test 21 through to test 40 evaluated the stability of 10t units, carried out with ten tests of uniform placement and ten with random orientations. All tests were conducted for durations of 1000 waves. Water levels of 0m CD and +3m CD were also tested.

Severe wave overtopping was experienced with the 8m wave eights, and some overtopping with 6m waves. Figure 14 shows the wave overtopping for the 6m and 8m wave conditions.

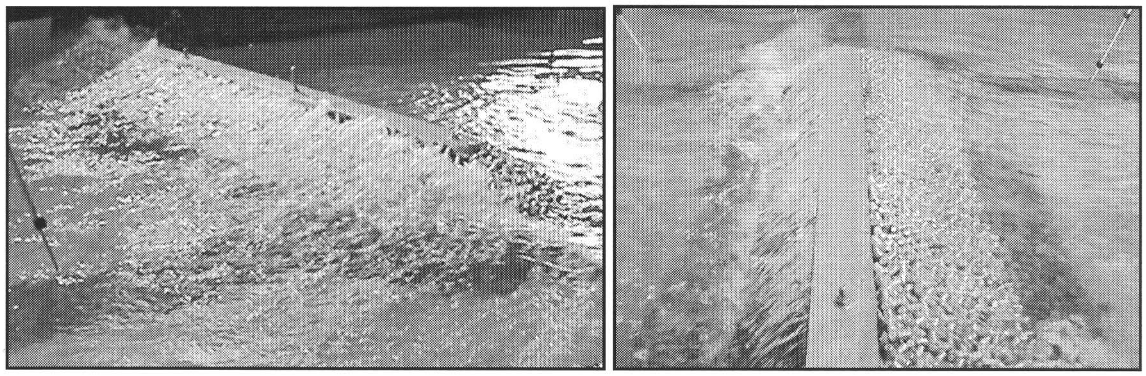

Fig. 14 Wave Overtopping for the 6m and 8m wave test conditions.

Tests 1 to 20 were with 15t units (1 to 10 uniform placement and 11 to 20 random placement), while Tests 21 to 40 were with 10t units (21 to 30 uniform placement and 31 to 40 random placement). The maximum displacement damage that occurred was 2.7 % along the trunk for random placement tests. For Test 1 to 30 the small displacement may be considered as initial settlement since the displacement damage ranged from 0.3% to 1.2%. Tests 30 to 40 were all carried out with random placement at high water (+3m CD) to assess the reserve stability of the units.

The range of displacement damage that occurred during these ten tests was in the order of 0.3% to 3.1%. This displacement indicates loss of an armour unit. Although a unit was displaced it did not result in total failure of the armoured slope rather it resulted in units shifting slightly to form a more interlocked slope to fill the void left by the displaced unit.

CONCLUSIONS

From the results of the tests described in this paper, the CRABLOCK armour unit performed satisfactorily for the wave conditions tested. Occasionally minor settlement and rocking occurred and can be considered as shake-down. In reality if rocking would continue, it may cause stresses on the flukes of the armour units, resulting in breakage. (Only displacement can be modelled in the laboratory as the units cannot break as in reality).

The results from the test indicate the most appropriate grid spacing of 0.71 x C for the horizontal and 0.57 x C for the vertical, which resulted in a 1.1 packing density.

The calculated Kd values for the 15t CRABLOCK with fillet with uniform placement along the trunk was 18, and on the roundhead 13.

The Kd values for the 10t CRABLOCK with uniform placement along the trunk was 16, and on the roundhead 12. The 10t CRABLOCK with random placement along the trunk had a Kd of 16, and on the roundhead a Kd of 12.

The physical model tests should only be used as indicative information to provide guidance for CRABLOCK armour units design. The stability of the prototype units should be verified with regular surveys of prototype structures that have been protected with this unit. Information on damage can only be verified over time with well documented prototype information on recorded offshore wave data and the damage of these units (how they break) after storm conditions. This information may then be compared to the movements recorded in the laboratory during the model testing.

However with the small chance of there being another Gonu tropical cyclone, creating waves in excess of 5m off the Fujeirah coast, in the Gulf of Oman, the Al Masaood harbour should not experience any significant damage to the new CRABLOC armour units. This is based on the model tests where the CRABLOCK units survived wave heights which were increased to 8m.

ACKNOWLEDGEMENTS

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