BREAKWATER REPAIR:
MONITORING, MODELLING, AND CONSTRUCTION

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Abstract

*The trunk section of the **south breakwater**, at the entrance to the **Port of Richards Bay**, has suffered some damage since its construction which was completed in 1976. This paper briefly discusses the changes in the design conditions as a result of sand-trap dredging off the breakwater, the annual photographic monitoring results showing the excessive rates of damage, and the model testing of various repair options, using 20t and 30t dolosse. Both 2D flume and 3D basin model tests were carried out at various scales, with fixed and movable bed models. Finally the construction of the optimal repair, carried out in 1997/98, using a heavy duty mobile crane (with 48m boom reach) and DGPS positioning, is described.*

Introduction

The Port of Richards Bay, on the east coast of South Africa, has two dolos breakwaters, a shorter straight breakwater on the northern side of the harbour entrance channel and a longer curved breakwater on the southern side. The south breakwater consists of an "S" shaped rubble mound structure (Figure 1), constructed between 1973 and 1976, which stretches for approximately 1km, almost perpendicular to the coastline. The original armouring on this breakwater consists mainly of 20t dolosse on both sides of the trunk (Figure 2), but includes 30t dolosse on the roundhead. The south breakwater forms the main protection of the Richards Bay harbour entrance channel, against dominant southerly storms and the nett littoral drift, which is from south to north.

Annual photographic monitoring of the south breakwater has shown a gradual increase in damage to localised areas on the southern side of the trunk, despite spot repairs using 20t dolosse, carried out by Portnet in 1985. A detailed evaluation of the

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damage was undertaken by Zwamborn in 1988 (CSIR, 1988) which lead Portnet to commission the CSIR in 1991 to carry out investigatory model tests in an existing 3D 1:100 scale model of the entrance to the Port of Richards Bay. These tests were to check different repair options, taking into account the position of a dredged sand-trap along the seaward side of the breakwater. The original idea was to use 20t and 30t dolosse, available from a stockpile of spare dolosse at the root of the south breakwater.

Figure 1: Aerial View of South Breakwater

Due to delays in the commissioning of a suitable crane, and the use of most of the spare dolosse on repairs to the north breakwater head (Phelp, 1996), the construction of the repairs to the south breakwater were delayed until 1997/98. This also required the casting of 1000 additional 30t dolosse. Between 1991 and 1996, additional 2D flume tests were carried out at a 1:40 scale to check the stability of the rock toe of the repair slope. These tests were carried out with a movable (sand) bed to model the effects of toe scour. Before the commencement of the repair work it was found that, due to a gap in the dredging programme, there was a buildup of sand along the breakwater toe. Final model tests were therefor carried out to re-check the toe stability at this shallower depth.

Monitoring Results

The crane/helicopter photographic survey method (Phelp, 1994) has been used to annually monitor the breakwater since 1979 on an ad-hoc basis, but regularly since 1987, and crane and ball profiling surveys have been carried out since 1981. The photographic survey stations are spaced at 25m, and the ball profiles at 5m intervals. Figure 2 shows the position of the survey stations and Figure 3 the rate of damage increase since 1987.

The original breakwater construction used a total of 13 400 20t dolosse on the trunk, and 2 200 30t dolosse on the roundhead, which amounts to approximately 10 dolosse per metre of breakwater. The original depth at the head was -18m and -14m along the outer curve of the trunk. The worst damage prior to the repair, located at station C8, was 17% dolosse displaced or broken (Figure 2).

Ad-hoc spot repair work was carried out in this area in 1985, when 52 new 20t dolossse were placed. Although this showed a significant improvement in the measured profiles, the photo survey showed that half of these dolosse were broken and/or lost by 1987. This type of spot repair, which was not model tested, with non-reinforced dolosse in a single layer not interlocking with the surrounding dolosse, proved to be ineffective.
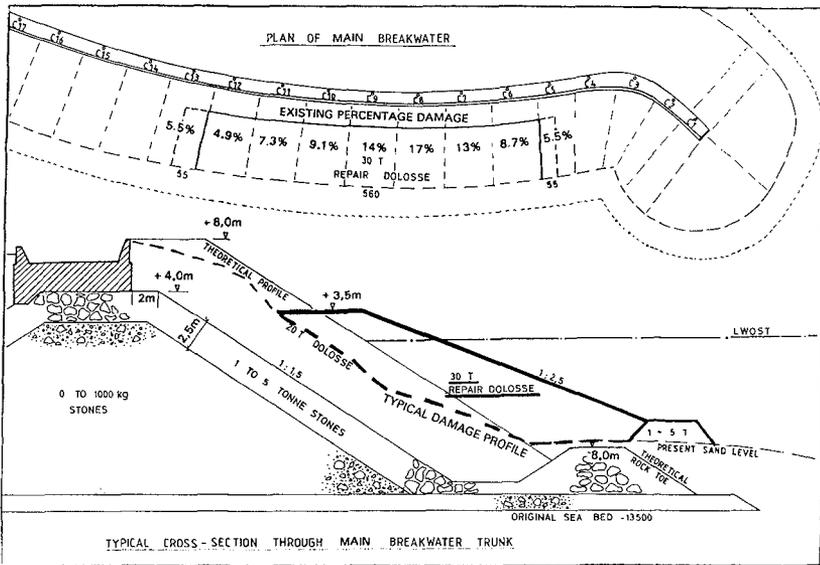

Figure 2: Plan View of South Breakwater and Cross-Section through trunk.

Factors Contributing to the High Damage

The occurrence of low pressure cyclonic storms (cyclones Demoina and Emboa in 1984) subjected the breakwater to wave heights exceeding the 7,9m 1:50 year design H_{mo}. Storm wave set-up and low atmospheric pressure associated with these storms also had the effect of raising the water level, thereby raising the depth limited wave heights reaching the breakwater. There have also been a number of lesser, but still powerful storms with wave heights in excess of 6m - the latest being experienced in 1990. The rates of damage are shown in Figure 3 for the worst stations on the trunk section.

A nett littoral drift of up to 800 000m^3 northwards has necessitated the dredging of a sand-trap against the outside of the south breakwater. Bathymetric surveys carried out regularly by Portnet in the sand-trap area have shown that dredging has taken place

much closer to the breakwater than originally anticipated (up to 60m closer). The depth of the sand-trap has reached -24m and the side slope as steep as 1:4,7. Figure 4 shows the dredger and Figure 5 the average position and sections through the sand-trap.
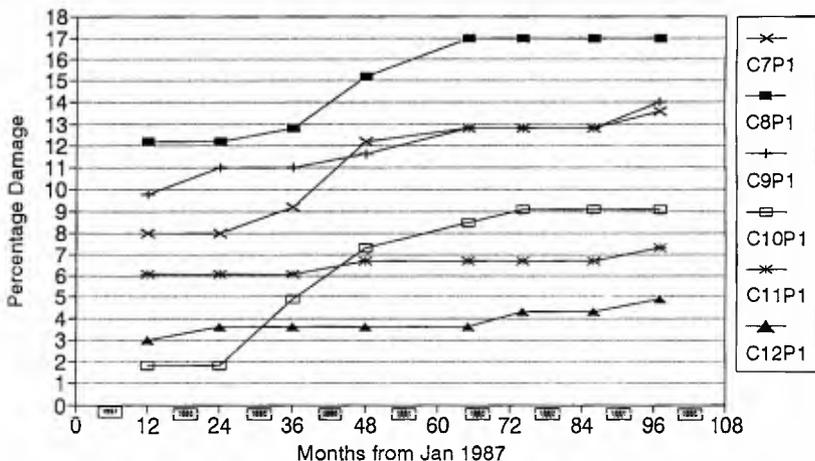

Figure 3: Rates of Damage to Worst Stations since 1987

Besides the deeper trap and steep side slopes, there has also been scour at the toe of the original breakwater (seismic surveys carried out by CSIR in 1993 confirmed the toe erosion (CSIR,1994)). The damage profile along the breakwater (shown in Figure 2) matched the plan of the sand-trap, with the highest damage area aligning with the deepest parts of the trap. The 3D basin model tests, which modelled various trap layouts, confirmed that the sand-trap allowed higher depth limited waves to reach the breakwater.

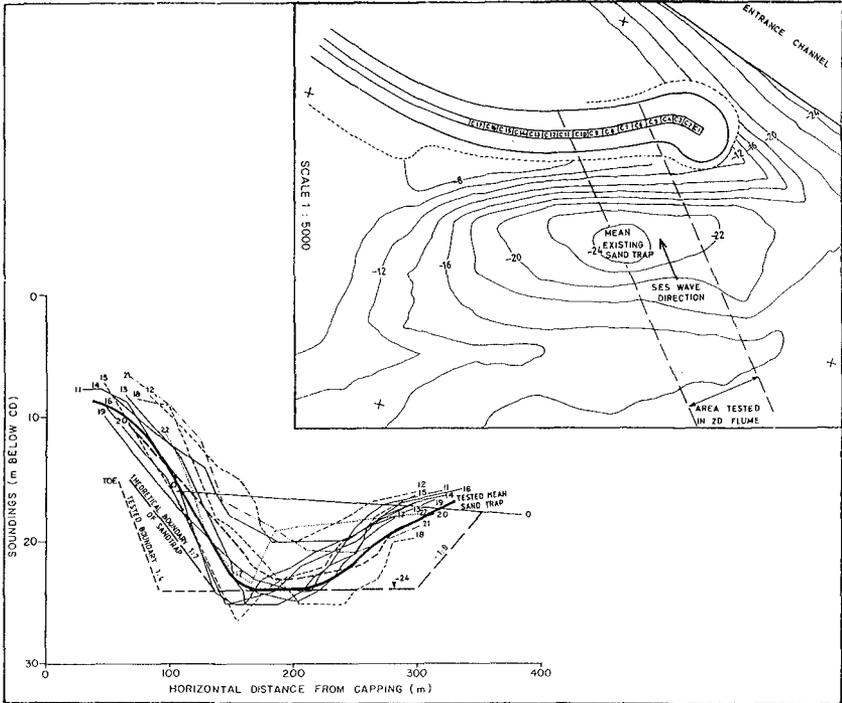Figure 4 : Portnet Dredger Trail Dredging in the Sand-trap

Figure 5: Plan and Cross-Sections showing Average Sand-trap Position.

Constraints to the Repair Design

Model tests were carried out in an existing 3D model of Richards Bay, to save both time and costs. This original model was built at a scale of **1:100** and covered the harbour entrance and part of the inner channel. The model test options were also originally restricted to using available 20t and 30t dolosse from a stockpile near the southern breakwater. A number of repair options were tested using either the 20t or 30t dolosse, with different repair slopes between 1:1,5 and 1:2,5, both with and without a rock toe.

The removal of rubble and pre-repair slope preparation was limited due to poor underwater visibility and rough sea conditions normally experienced along the outer breakwater. Contour plots of the outer slope, drawn from crane and ball profile surveys, were used to locate damage cusps below water and guide the filling of these holes at the toe of the armour slope. A double layer repair slope was then designed to cover the worst damaged areas. The top and sides of the repair are then tied into the original breakwater slope by tapering the repair. The width of the repair was limited to 40m from the splash wall, which was the limit for the boom of the crane lifting a 30t dolos. This mobile crane (Figure 10) was specially designed to fit onto the 6,7m wide mass-concrete capping.

Choice of Model Scale

The scale of 1:100 used for the tests gives a Reynolds number of approximately 1×10^4, which is just within the minimum range recommended by Van der Meer (Van der Meer, 1988). Some scale effects were expected, but have been found to make the model results more conservative. The scale effects, being similar for all the test runs, allowed for comparisons to be made between the repair options tested. The calibration test showed that the hind-cast of the damage which occurred in the cyclonic storms of 1984, is in qualitative agreement with the observed prototype damage confirming the validity of the physical model. Details of the chosen repair section were confirmed at larger scales (1:63) in a 3m wide flume with a fixed bed and at 1:40 in a 2m wide flume with a movable bed. Figure 5 shows the section through the sand-trap and breakwater which was modelled in the 2D flume tests.

Wave Generation and Measurement

Up to 14 standard wire resistance wave probes were used which were coupled so that measurements could be carried out over prescribed areas. A hinged paddle wave generator bank for the 3D tests was 30m long situated approximately 30m seawards of the breakwater (representing 3km by 3km in prototype). Based on a review of existing wave data and analysis of the cyclonic storm data as recorded by a waverider buoy off the breakwater, the following **main test conditions** were chosen:
- Wave direction, harbour entrance area (12s) **140°**
- Storm input, **Richards Bay Spectrum**, $\gamma = 2,74$ with the following 1.5 m steps $H_{mo} = $ **2.5, 4, 5.5, 7, 8.5 m** with wave periods $T_p = $ **12 s to 16s**. This is above the design wave height of 7,9 m and cyclone wave recording of 8,4 m.
- Water level MHWS = **+2,0 m CD** which resulted in the highest damage.

The above conditions were considered applicable to reproduce the damage on the breakwater which has been subjected to a minimum of one 1:1 year storms ($H_{mo}>5m$) per year, three 1:10 year storms ($H_{mo}>6m$) and one storm exceeding a 1:50 year storm ($H_{mo}>7.9m$) during the lifetime of the breakwater.

Test Procedure

In order to calibrate the physical model, a calibration test was carried out in which the prototype damage resulting from the storm history was reproduced in the 3D model (Figure 6). A number of repair options were then investigated, starting with the simplest option, and extending the repair until a stable solution was found. Before each repair was constructed, the original damage was replicated in the model. The repaired breakwater was than exposed to the conditions described above.

After each test, the repair was removed and the original damage reconstructed, after which the next repair option was implemented. The optimum repair option chosen from the 3D tests was then reproduced at a larger scale in the 2D flume tests, initially with a fixed bed and then with a movable sand bed. These larger scale flume tests were used to give special attention to the ability of the breakwater to withstand some toe scour resulting from sand-trap dredging.
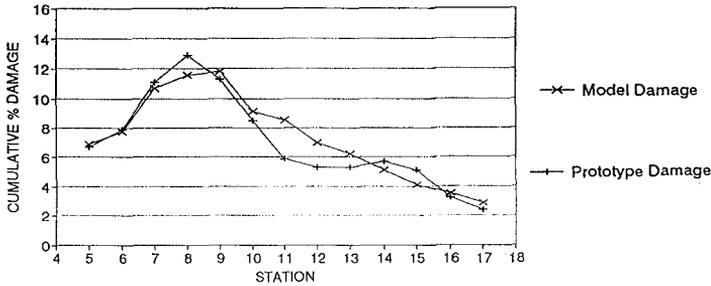
Figure 6: Prototype versus Calibrated Model Damage

Measurement of Damage

Prototype damage is assessed by counting the broken or lost dolos units and adding the units which have been displaced more than ½ h (dolos height). A number of swing tests were carried out on full-scale 9t dolosse to determine the degree of movement these dolosse could sustain without breakage (Zwamborn and Phelp, 1989). Based on the results of these tests it was recommended that all movements greater than half the height of a dolos be included as damage. This damage is then expressed as a percentage of the total number of dolos in a particular section of breakwater (Figures 2 and 3).

In the model, the number of dolos movements was determined by the digital analysis of video images taken before and after each run. In addition, the number of dolosse which were rocking was recorded visually and by cine camera during each test. However due to the difficulty in observing movements over the whole test area, it was decided to use the video measurement of small movements (< h), as an estimation of rocking dolosse. This was then calibrated against the recorded prototype damage to give a calibration factor of $0.4(<h) + (>h)$, which gave an accurate simulation of the prototype damage profile along the trunk of the breakwater between stations 5 and 17 (Figure 6).

Figure 6 also shows, both in model and prototype results, that the worst damage occurred between stations 7 and 9. Hydrographic surveys of the sand-trap between 1977 and 1991 have shown that, almost since completion of the breakwater, the deepest area of the sand-trap was located opposite stations 7 to 9 (Figure 5). This also coincided with the area where the sides of the sand-trap were steepest and closest to the toe of the breakwater. One model test which was carried out with a larger deeper sand-trap resulted in an increase in damage proportional to the extension of the sand-trap, which indicated that the increased breakwater damage could be linked to the sand-trap dredging.

Discussion on the Repair Strategy Followed

Static tests on dolosse have shown that a dolos can carry 4 to 6 times its own weight without breaking; this implies that a number of layers can be constructed without breakage under static load. Thus it was considered feasible to place a 1 to 2 layer thick 20t to 30t dolos strengthening layer, safely on top of the existing damaged 20t dolosse.

Although the quality of the underlying 20t dolosse is questionable, the dynamic loading over the past 20 years has caused the weaker dolosse to break, and careful placing of new dolosse should not result in significant further breakages, besides the initial "shake down damage". However, since most parts of the repair sections will consist of a number of already broken units, the repair itself was designed as well interlocked armour, finished to a uniform slope, which should be able to stand on its own. Although stresses cannot be modelled, extensive prototype observations and structural tests on full size dolosse support the above conclusions.

Repair Options Tested in 3D Basin

Comparative tests were first carried out using the same wave conditions and sand-trap configuration. Later tests included the option of extending and deepening the sand-trap. The **first repair option** tested involved covering only the worst stations (C7 and C8) with a double layer of 30t dolosse, with 20t dolosse on either side to tie into the existing slope. A total of 150 30t and 250 20t dolosse were used for repair option 1, placed at 1:1,5 slope with no rock toe. After this proved unsuccessful, **repair option 2** was tried, with 30t dolosse and a rock toe stretching from stations C5 to C12. A total of 504 dolosse were placed covering a distance of 165m. Although repair option 2 showed less damage, it was still unacceptably high. **Repair option 3** was similar to option 2 but with a flatter 1:2,5 slope from +3,5m. A total of 670 30t dolosse were used. This repair 1:2,5 slope option was repeated unsuccessfully with 950 20t dolosse and then with 785 30t dolosse but without a rock berm.

Repair Options Tested in 2D Flume

Repair option 3 was then repeated in a larger 1:63 scale 2D flume (3m wide). The effect of extending and deepening the sand-trap was also re-tested in the 2D flume. The latter test confirmed the relationship between high damage and the deepest part of the sand-trap (Figure 5). Because of the vulnerability of the breakwater toe to scour resulting from sand-trap dredging, it was decided to optimise the size and position of the rock toe by running some tests at an even larger 1:40 scale in a 2m movable bed flume. This was done to check stability of the toe at low tide, and its ability to accommodate settlement and erosion, but still maintain support for the bottom row of repair dolosse. The movement of the rock and change in profile of the toe were carefully monitored. These tests showed the need for the rock toe and first two rows of dolosse to be placed first, and allowed to settle, before the rest of the repair dolosse were placed.

Change in design conditions

After acceptance of the above repair design, a total of 1000 new 30t dolosse were cast near the root of the south breakwater (Figure 7). The start of construction of the repairs was however delayed for more than a year because the Portnet crane that was to be used for the repair at Richards Bay was unavailable. In this time there was substantial accretion, (of up to 3m) especially along the trunk of the breakwater (Figure 8). The breakwater repair section was again tested in the 2 D flume with the reduced depth. The depth at the toe at some sections was as shallow as -5m CD. During the re-testing of the

model it was found that the proposed rock toe was unstable, with the rocks being displaced into the dolos slope. The dolosse would have sustained more damage and become clogged (lower porosity) in such a scenario. Various options were then investigated to solve this problem, such as dredging a trench in front of the breakwater to lower the toe, or to use heavier rock (> 5t), or to do away with the rock altogether.
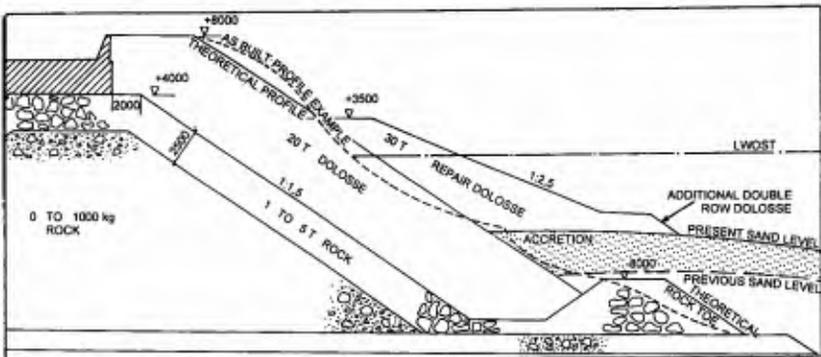

Figure 7: Casting Yard for New Dolosse

Figure 8: Final Repair Design Profile

Implementation of Model Test Results

A comparison of the damage at the end of each test run in the 3D basin showed that option 3, with the 30t repair dolosse at a flatter 1:2,5 slope was clearly the best option, although some "shake down" damage was expected from the repair settling into the existing dolosse, from the pre-settlement of the first rows of repair dolosse and from possible future toe scour. Research by the CSIR (Zwamborn and Phelp, 1989 and Luger, 1994) has shown that armour unit strength can be enhanced by rail reinforcing and by increasing the size of the dolos fillet between the fluke and shank. For this reason, the new dolos shape with large curved fillets was used and one third of the repair dolosse were rail reinforced for use in potentially high damage areas.

The solution that was eventually found to provide a stable repair at the shallower toe depth was to replace the rock toe with an additional three rows of "sacrificial" dolosse. There would ultimately thus be 5 rows of dolos lying on the accreted seabed. These dolos were allowed to pre-settle into the sand over a length of time, before placing the rest of the repair slope. In the model, the maximum settlement was recorded at 2-3m at the toe (Figure 9). It was also found that the dolos had to be placed at a packing density of 0,75 for the maximum pre-settlement to occur. The rest of the breakwater repair was then placed at a packing density of 0,85.

In reality the dolos would settle 2-3m or until they reached the previous rock toe, or the remnants thereof. The pre-settlement dolosse placed directly onto the sand were all to be rail reinforced for additional strength, and their settlement was monitored by ball surveys. Figure 9 gives a typical profile before and after placing the first 5 rows of dolosse, which shows the dolos 2m above the sand, indicating a settlement of about 2m. The results of the crane and ball survey were analysed and contours plotted of the data. These contours were then analysed and large holes were identified where additional dolosse were placed to ensure a smoother profile before placement of the new double layer repair. Each dolos was given a fixed co-ordinate (Figure 10), calculated to achieve the desired packing density and final repair profile.
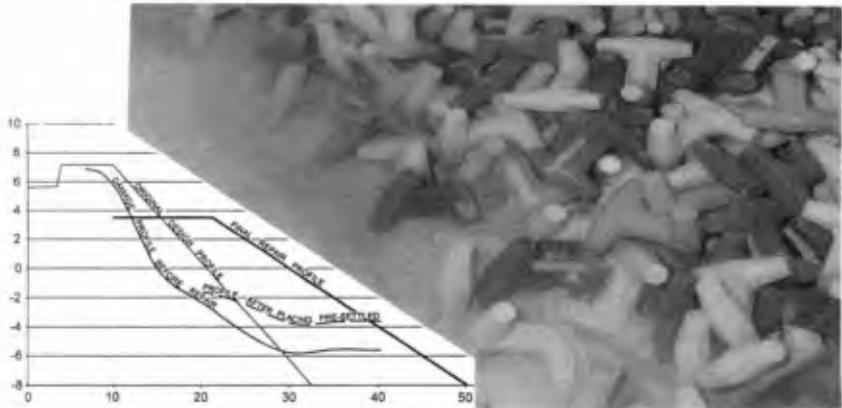

Figure 9: Pre-settlement of Toe Dolosse - Prototype and Model

Construction Methods

Based on the results of the model tests, only 30t dolosse were to be used for the repair. These dolosse were brought from the casting yard (1001 new 30t units) and old stockpile (37 old 20t and 88 old 30t units left over from the original breakwater construction) on the south side of the entrance channel directly onto the breakwater. Three double direction trailers were then used to transport the dolosse, but as these trailers could only pass when unloaded, it meant that only one 30t dolos could be brought onto the breakwater at any one time (Figure 11). A portal crane was used to handle the dolosse from the casting yard onto the stockplie and from there onto the trailers.

Initial crane and ball surveys were done with 5m profile intervals over the damaged areas. Repair dolos placing grids were then calculated and the pre-settlement dolosse were placed. Another ball survey was then carried out to check the pre-settlement, from which the final repair dolos placing grid could be re-calculated if necessary. The smoother the under-layer profile, the easier it was to set placing grids for uniform packing density.

The crane hook was fitted with a 15m sling (to ensure the hook and pulley remained out of the seawater), a quick release hook and a double cable sling. The double slings which support the dolosse were hand spliced (instead of swage joined) to allow easy removal of the slings once the dolos was in position. The quick release hook was hung from a swivel and fitted with two torque bars, which allowed easy rotation of the dolosse to ensure good interlocking. The torque bars were attached to 10mm nylon (light and water resistant) ropes, which were pulled perpendicularly from the mass capping to orientate the dolosse. The front row of toe dolosse were placed with the vertical fluke facing seawards.

It was found that to ensure correct packing density, the dolos placing must be kept as close as possible to the grid coordinates. The final orientation and positioning of the dolos is then done by eye to ensure good interlocking. Dolosse are placed with a minimum of three contact points to reduce the chance of rocking under wave action. After all the grid positions were full, it was found that up to 5% additional dolosse (using old 20t and 30t units from the stockpile) had to be placed "in holes" to ensure a well interlocked uniform profile. To identify these "holes" an aerial view of the slope was studied from a helicopter.

Figure 10: Pre-repair Contour Plot and Dolos Placing Grid

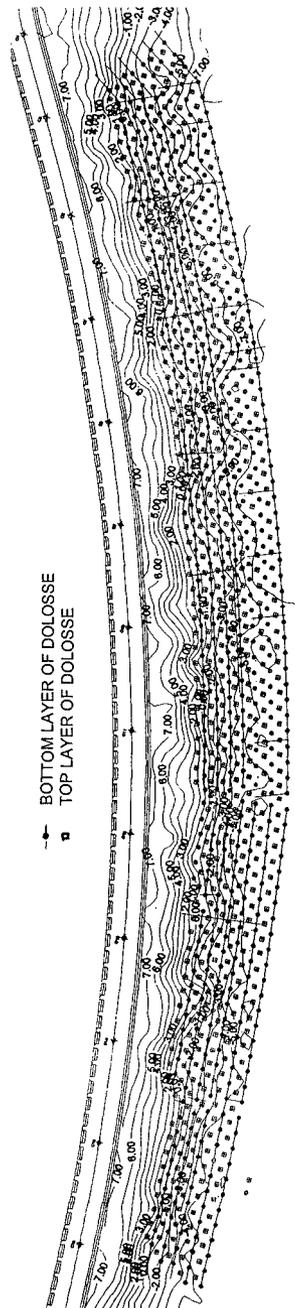BOTTOM LAYER OF DOLOSSE
TOP LAYER OF DOLOSSE

Figure 11: Portnet Crane Offloading Dolosse from Trailor

DGPS for Crane Positioning

For both the crane and ball surveys of the slope profiles, and the correct placing of the dolosse, there was a need to accurately position the hook of the crane. A differential GPS system was introduced using satellite positioning linked to a portable computer onboard the crane. The satellite receiver is positioned on top of the crane boom, directly above the position of the hook. The pre-determined positions are entered into AutoCAD software on the computer, and standard survey software enters the real time navigation parameters which indicate the position of the boom. By entering the standing position of the crane along the breakwater, the boom reach and safety circle can also be indicated on the screen. The crane operator can then immediately see which dolosse can be placed from the present position of the crane. The AutoCAD dolos placing grid is shown in Figure 10.

The positioning software includes the following useful features:
■ Zoom in and out, and centring the cranes position on the screen.
■ The entry of up to 20 predetermined crane standing positions on the breakwater, including facility to orientate and offset.
■ The entry of up to 1000 top and bottom layer dolosse, including an indication of size and numbering (colour options)

- The facility to import and do editing of an AutoCAD or other CAD drawing of the breakwater eg: the "as-built" layout.
- Indication and editing of the safe radius of the cranes reach.
- The input and storage of the placed positions of the dolosse.
- A backup system where the polar coordinates can be entered to position the crane, should the DGPS signal fail.

The dolosse were numbered as per their sequence of placement. A top layer dolos was always placed centred between 4 under-layer dolos. The sequence thus entailed the placing of alternate bottom and top rows of dolos, moving up the slope. The placing of the pre-settlement under-layer dolosse started at the root of the breakwater and progressed towards the head. The crane then returned to the root to place the rest of the repair dolosse after the lower dolosse had had a chance to settle. The end of the repair was always left tapered at 45° up the slope, thus ensuring no unstable units which might be displaced before the repair could be completed (during storm conditions or breaks in construction). The limiting operating conditions for the crane were wind speeds of 50kph or swell heights above 2m.

Figure 11: Successfully Completed South Breakwater Repair

Conclusions

Close cooperation was maintained between Portnet, the Client/Port Authority who also partook in the model tests and constructed the repairs, the CSIR Research Laboratory which undertakes the annual breakwater surveys and who carried out the model studies, and Entech Coastal Consulting Engineers who assisted with parts of the design and construction. This ensured problems encountered could be quickly investigated and amendments incorporated into the final design. The early warning provided by the annual breakwater monitoring also meant that there was sufficient time to carry out the model tests and come up with an optimum repair design.

The completed repair can be seen in Figure 12, which shows the uniform profile and good integration with the original structure. A final ball survey of the repair showed that for most profiles, there was a perfect match between the design and surveyed profile. This was achieved by accurate dolos placing with the aid of DGPS on the crane. This repair which was completed in June 1998, has already withstood two storms in excess of the 1:1yr design wave height above 4m. A photographic aerial survey done after these storms showed less than 1% damage resulting from the initial "shake down". Annual surveys will be continued, to monitor the performance of the new shaped 30t dolosse.

Acknowledgements

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