CHAPTER 109

RESULTS OF EXTENSIVE FIELD MONITORING OF DOLOS BREAKWATERS

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ABSTRACT

The entrances to most of the ports in South Africa are protected by rubble mound breakwaters which have dolos armouring. As part of their maintenance programme, Portnet, the local Port Authority, has commissioned the CSIR to annually monitor the main breakwaters. A minimum of five years of photographic and other monitoring data have now been accumulated. This paper presents a brief description of the dolos breakwaters in South Africa, and the field monitoring techniques used to record the annual damage to the armouring. The results and analysis of the photographic monitoring are given in more detail. The application of these results are also presented, and some exciting new developments in breakwater monitoring are discussed.

INTRODUCTION

The conclusions of the report of the PIANC Working Group no. 12 on the Analyses of Rubble Mound Breakwaters, (PIANC, 1992), stated:

> **'Finally, it is worth repeating that the experience of this working group has shown again, as others have found before us, that there is a great need for more detailed monitoring of existing rubble mound breakwaters including records of the wave conditions to which they are subjected in service. Collection and publication of data on this subject would greatly assist the advancement of engineering knowledge.'**

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The long-term stability of, and the intermittent storm damage to rubble-mound breakwaters are of considerable interest to the designers, builders and authorities responsible for maintenance. Depending on the severity of the wave attack, the breakwater armouring will deteriorate in time if not properly maintained. Gradual deterioration can often pass unnoticed until weak areas give way to major damage. Early detection of deterioration such as displaced, broken or lost armour units is therefore essential.

Annual monitoring of a breakwater provides an early warning system to identify any weak spots in the armouring which can then be repaired before the overall stability of the breakwater is threatened. The accumulation of data on damage which can be linked to the prevailing sea conditions during the monitoring period can also be used to improve breakwater design techniques and calibrate the design formulae which are mostly based on the results of hydraulic model tests. Breakwater monitoring also offers the potential for increasing our understanding of failure mechanisms associated with rubble-mound structures which are difficult to simulate accurately by way of physical model tests.

DESCRIPTION OF BREAKWATERS

The seven harbours, where the breakwaters are monitored, are spread out along the east and south coast of South Africa, from Richards Bay in the north-east to Cape Town and Saldanha Bay in the south-west, as shown in Figure 1. All but one of these ports are protected by rubble mound breakwaters, which are covered with dolos armour units. Saldanha Bay, which is also monitored on an annual basis, lies in a large natural bay, and is protected by an artificial spending beach breakwater across the entrance to the bay.

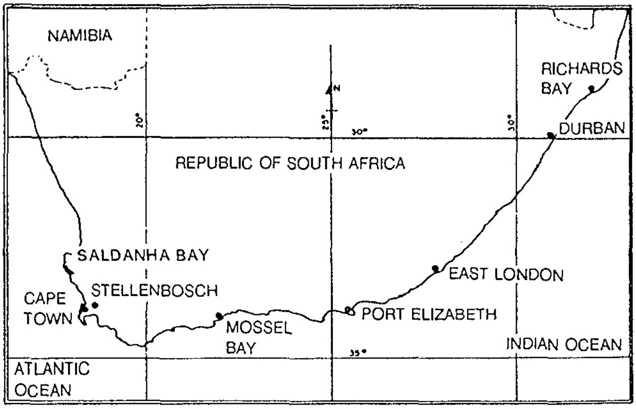


Figure 1. Location of Breakwaters

The main dolos breakwaters lie on the southern sides of the port entrance channels and the water depths at the toe of the breakwaters vary between 3 m and 15 m. The extreme wave conditions at most of the harbours are therefore depth limited. At the east coast ports the breakwaters have a dual function of reducing wave heights and preventing siltation in the entrance channels. At these ports maintenance dredging is necessary to intercept the littoral drift which is predominantly from south to north. Table I summarises the details of each of the dolos breakwaters (CSIR, 1981). The calculation of percentage damage, as given in the table, is described later in this paper.

Richards Bay has two dolos breakwaters, a shorter straight breakwater on the northern side and a longer curved breakwater on the southern side. East London, the only river port, is the oldest dolos structure which still has the original dolosse designed by Mr E Merrifield, the port engineer, in 1964. The main reason for the very high percentage damage to armouring on this breakwater, is that the dolosse were placed directly over randomly placed 35 ton blockwork. In some areas, there is only the blockwork left to protect the concrete mass-capping. Although the original breakwater was founded in 10 m water depth, a sand-bank, of 5 m depth, has formed just off-shore, which gives added protection from severe wave attack.

At the commencement of the regular monitoring programme for Portnet in 1989, a base-line damage status had to be calculated for those breakwaters which were already extensively damaged (specifically East London and Mossel Bay). This was done using a combination of visual inspection (of broken dolosse) and crane and ball survey. Cross-sectional plots compared the difference between the original as-built profiles and the existing profiles, and percentage damage was based on section areas.

Harbour	Length	No Dolosse	Year constructed	Monitored Years	Dolos size	Waiste ratio	Design Hs	Max % Damage	Average Damage
Richards Bay North	600 m	1000 (Head) 8800 (Trunk)	1973-1975	1987-1994	15t 5t	0,33 0,33	7,9 m	17% 16 %	8,5% 6,5 %
Richards Bay South	1400 m	2200(Head) 13400(Trunk	1973-1976	1979-1994	30t 20t	0,36 0,33	7,9 m	10% 17%	3,9% 7,5%
Durban	585 m	2100	1982-1987	1989-1994	20 t	0,33	6,5 m	20 %	6,1 %
East London	600 m	2000	1964	1987-1994	18 t	0,34	8,5 m	71 %	39 %
Port Elizabeth	370 m	4600 (outer) 3700 (inner)	1978	1988-1994	10 t	0,31	6,4 m	7,5% 4,3%	3,4% 2,7%
Mossel Bay	200 m	2400 (outer) 1900 (inner)	1967-1969	1987-1994	5,4t 2,7t	0,33	5,2 m	37 % 1,3%	28 % 1,1%
Cape Town	500 m	2900	1988	1989-1994	25 t	0,355	7,5 m	16 %	2,6 %

Table I. Summary of Breakwater Damage

MONITORING METHODS

Most of the breakwater monitoring methods, used by the CSIR in South Africa, are listed briefly below, together with descriptions of their usefulness and applicability. Detailed descriptions of these methods are available in various reports (CSIR, 1988a and Kluger, 1982).

- **Visual inspections** are useful for checking specific damage. The number of broken units per section of breakwater, and the type of break (important for structural analysis of armour units) can be checked visually but this is more time consuming than photographic methods and is not suitable for monitoring the entire slope. More broken units can usually be located using the visual method, and it is therefore useful at the start of a monitoring programme to get the base-line damage figures.

- **Close up photography** merely records the results of visual inspection and is useful for checking detailed progress of localised damage such as cracks in the mass capping. Camera type and position should be kept constant for good comparisons of subsequent photographs. Valuable information can also be obtained from photographs taken during extreme sea conditions. Areas of focused wave action can often be identified in this way, and related to the resulting damage to the breakwater. Aerial photography is normally not possible during storm events, but photographs, taken from the closest possible safe vantage point, have proven to be very useful.

- **Diver inspections** are just an extension of visual inspections to below water, provided visibility is good. Recording can be done by video or still photography but position fixing is more difficult and the whole operation more time consuming. This type of monitoring is normally only done if damage is already indicated by other methods such as crane and ball surveys.

- **Photographic surveys** from fixed positions to produce overlapping photographs covering the entire above-water condition of the breakwater (viewed at low spring tide) are the most useful and cost effective methods of breakwater monitoring. This method which involves the use of overlay techniques to check damage, should not be confused with photogrammetric survey methods, described below. The photographs may be taken from a boat (horizontal view), or crane or aircraft (vertical view), whichever is available. The helicopter was found to be most suitable, in that it could hover (wait for wave drawdown) and move quickly between monitoring stations. Position fixing of the helicopter is normally done by the use of Differential GPS, which is accurate to within 1m. The height can be set to suit the camera lens being used (the greater the height, the better the accuracy, but once chosen, the equipment should be standardised for subsequent surveys). For South Africa's dolos breakwaters the above method was found to be generally adequate for monitoring the above-water damage to the armour units. A new development, however, is to substitute the helicopter photographs with video, which is equivalent to taking 25 images per second (at the TV frame rate of 25 Hz for the PAL standard).

- **Photogrammetric surveys** can also be done from a crane or aircraft, although position fixing of the camera is more critical and accurate benchmarks are required to properly reference each section of breakwater being stereographically photographed. This method is time consuming and expensive and is only used where very accurate three-dimensional recording of armour unit positions are required. This method is more applicable to the monitoring of small armour units or rock where the individual movements are more difficult to identify. As with the photographic surveys, a spring low tide and good wave drawdown are essential to get maximum exposure of the breakwater slope.

- **Crane and ball surveys** are used to monitor the breakwater profile (above and below water) at predefined intervals. A mobile crane is normally used to position the ball, and the level of the ball is measured from a theodolite station on the breakwater. The size of the ball which must obviously be kept constant from one survey to the next is normally around $r = 1{,}14\ V^{1/3}/\sin 45^\circ$ where r is the ball radius and V is the dolos volume. The above survey method was found to be the most successful in recording underwater damage, but the reach of the crane could be a limiting factor in the seaward extent of the survey. During construction of the breakwater, this method is essential to monitor the as-built rock and dolos profiles.

- **Seismic, sidescan sonar and bathymetric surveys** can be used to supplement the crane and ball survey by extending the monitoring seaward. Seismic profiling can even be used to check the profile of the original breakwater which may now be buried by sand. This detail is very important for the design of breakwater repairs including the toe berm. The survey equipment can be operated from either a crane or boat depending on the sea conditions adjacent to the breakwater. Provided visibility is good, any unusual features indicated by the above methods can be investigated by divers.

- **Standard tacheometric survey** methods may be used to accurately monitor levels of predetermined positions on the capping slab and specific armour units to identify general deterioration by settlement of the entire structure. Cracks in the capping slabs usually indicate settlement.

This method can be used to obtain cross section profiles by pre-marking (studs or drill holes) and surveying points up and down the breakwater slope. This survey data should be referenced to a stable benchmark located on shore.

Although a number of different breakwater monitoring methods have been listed above, not all these surveys, except possibly the photographic survey, need to be done on an annual basis. It is, however important that 'base-line' surveys using each of the different methods, listed above, are done as soon as possible after construction of the breakwater to provide a reference level to compare future damage against.

Other forms of monitoring which are complimentary to the breakwater monitoring techniques presented above, are:

- wave recording (by wave buoy - height, period and direction)
- bathymetric surveys around the breakwater to monitor toe erosion
- sediment sampling adjacent to the breakwater to check grain size
- water/sediment movement through the breakwater (dye tests)
- monitoring of concrete decay (possible alkali aggregate reaction)
- monitoring of cracks in capping slab (linked to settlement)

The results of these surveys are then linked to the breakwater damage analysis.

ANALYSIS OF MONITORING DATA

Only the photographic survey will be described here, but the analysis principles are the same for the other methods of breakwater monitoring listed above. With the aim of the monitoring being the assessment of the deterioration of the breakwaters, the cumulative damage per monitoring station is calculated by comparing photographs taken before and after the monitoring period (usually annual) and adding the new damage to the previous cumulative damage per station. Provided the camera position and type of lens are kept constant for consecutive surveys, it is possible to use the overlay (or stereo-comparator) technique to quickly compare respective photographs to detect individual armour unit movements of less than 0,5 m. New, digital image analysis techniques are presently being investigated, and are presented later in this paper.

Both annual and cumulative damage are given in the monitoring reports. The visible damage has been categorised into three degrees of dolos movement (A) < 0,5 m, (B) 0,5 - 1,5 m and (C) > 1,5 m, (D) dolos breakage and (E) disappearance (loss) of the dolos from the visible slope. The damage per monitoring station, which normally cover 20 m to 25 m of breakwater length, are expressed as percentages, which are calculated by adding (C) + (D) + (E) and dividing by the total number of dolosse per station (N).

The movement of pieces of dolosse, which have already broken are also monitored, but do not contribute further to the damage calculation. In the same way, the smaller dolos movements (A) and (B) are recorded for information purposes, but do not contribute to the damage total. The movement history of a particular dolos is also tracked, so that the cumulative movement can be measured. Once this cumulative movement reaches more than 1,5 m (C), or h/2 where h is the height of a dolos, it is then added to the damage total. Although some experts only consider prototype dolos breakage as 'damage', it was found that once a dolos had moved more than half its length (h/2), the gap left by this movement often resulted in focused wave action, which in turn resulted in further damage (movement or breakage), especially under severe wave conditions. Monitoring results have shown that unrepaired localised damage causes an increase in the rate of damage in that localised area.

Because the main purpose of breakwater monitoring is to warn of potential failure areas which need to be maintained, it was decided to include these dolos movements (C), in the damage criteria given in the table. This theory is also more in line with the definition of damage of dolosse in scaled model tests, where movements more than h are generally recorded as damage (together with an observation of the number of rocking dolosse, to represent dolos breakage without displacement). The broken dolosse have however been listed separately to allow further analysis of damage, using dolos breakage as the only criteria.

It is recommended that the moved, broken or lost units be highlighted on the photographs which should be included in the monitoring report for easy reference. Weak areas or 'holes' in the armouring, which are more easily identified from photographs than in prototype, should also be highlighted to assist maintenance planning. When a hole is repaired with new units, the cumulative damage is reduced by the number of new units placed (n), but when the new units are just added to the slope and are not particularly filling any 'holes', only the total number of units per section (N) are increased.

The results of annual monitoring exercises at each port have been presented in reports issued to the port authority. The monitoring report also includes a brief description of the survey methods used, including camera details, and position and heights of camera stations to ensure continuity and ease of comparison for future monitoring. The wave data from wave buoys off each harbour, covering the monitoring period, are analyzed and included in each report so that annual damage can be linked to the prevailing sea conditions or significant storm events. Graphs are also plotted showing the rate of increase of damage per station which highlights those areas of the breakwater which may need urgent repairs.

APPLICATION OF RESULTS

The results of these breakwater monitoring surveys have been found to be vitally important for a better understanding of, design of, and appropriate maintenance planning of dolos structures. Prototype monitoring results are presently being used for both structural (Zwamborn and Phelp 1989) and hydraulic damage analysis. The ultimate objective is to have sufficient prototype breakwater data (of dolos structures in this case), to combine with the recorded wave conditions, to create a basis for validating design formulae which are, thus far, predominantly based entirely on the results of small scale model tests.

Some of the uses to which these results have been applied in South Africa, include the following:

■ **Planning of breakwater maintenance** - On-going maintenance is carried out on those breakwaters with permanently mounted breakwater cranes (Durban and East London have hammerhead cranes mounted on rails along the length of the mass-capping). At these ports it is economically feasible to carry out spot repairs, as needed and indicated by monitoring surveys. Gaps in the armouring are filled, and the percentage damage is kept low. For this purpose, a stockpile of spare dolosse is required at the root of the breakwater, within reach of the crane. As explained above, the damage at the East London breakwater was already high before the monitoring programme was started.

At other breakwaters, without permanent cranes, or spare dolosse, it is more feasible to let the damage rise to higher levels, before the planning of more major repairs. This critical level of damage depends on the importance of the breakwater in protecting the harbour entrance, and in the importance of the harbour itself. At Richards Bay, a major exporting port, planning for repairs to the southern breakwater commenced when the percentage damage per station exceeded 15 per cent. While at Mossel Bay, a small fishing harbour with a shallow water breakwater (-4 m), the maximum percentage damage per station was allowed to rise above 30 per cent before temporary repairs were done, and major repairs planned. As for East London, the damage to the Mossel Bay breakwater was already high when detailed monitoring commenced. Both dolos breakwaters are approximately 30 years old.

■ **Age of breakwater vs damage (history of damage after construction)** - The Durban and Cape Town harbour breakwaters, which have been carefully monitored since construction, have shown that the initial 'settling in' of dolosse during the first major storm event, can result in more than double the normal annual damage. The rate of damage at any station, after initial settling-in, is generally related to the cumulative damage total at that station; this tended to increase after 20 per cent.

The damage history of the Port of Cape Town breakwater is shown in Figure 2, below. This graph is based on 6 years of monitoring data on the breakwater trunk, which consists of approximately 2 400 25 ton dolosse over a length of 500 m. The cumulative damage (movement and breakage, and breakage only) is plotted as a line graph against the left Y-axis, whilst the four worst storms (during the annual monitoring period) are plotted as bar graphs against the right Y-axis. The 1989 survey showed very high 'settling in' damage.

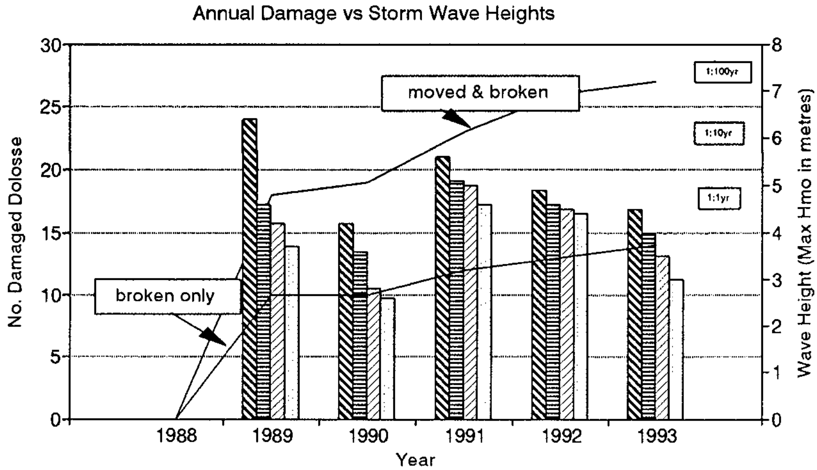


Figure 2. Damage History of Port of Cape Town Breakwater

■ **Ratio of dolos movement vs breakage** - All visible dolos movements (above water) were recorded to within an accuracy of 0,1 m by the photographic survey method. Of all the recorded movements:

52 per cent were less than 0,5 m,
32 per cent were between 0,5 m and 1,5 m, and
16 per cent were above 1,5 m

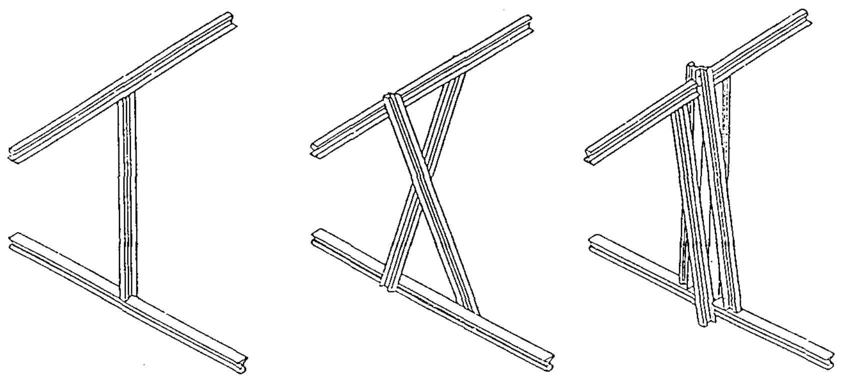
In this case, 1,5 m is approximately h/2 where h is the height of a 25 ton dolos. This means that on average, only 16 per cent of all recorded dolos movements contribute to the recorded damage total. After the initial 'settling in' of the breakwater after construction, which normally involves a high percentage of small movements, approximately 55 per cent of the recorded movements, were new movements while 45 per cent had moved before. Besides rocking units, many dolosse move, or are displaced more than once, before becoming stable.

Based on a sample of 233 events (dolos movements including breakage), recorded on the Table Bay breakwater over a 5 year period:

75 per cent moved (without breakage) less than h/2, and
15 per cent moved more than h/2 (also without breakage).
10 per cent of all the movements resulted in breakage.

Fewer than half the dolosse which moved more than h/2, actually broke, while some dolosse were seen to rotate up to 270° without breaking. Breakage of dolosse which had moved less than h/2, were usually the result of either rocking, impact from other dolosse or cold joints.

- **Effect of rail reinforcing in dolosse** - The results of swing tests (with yield cushions) on 9 t dolosse using rail reinforcing (Zwamborn and Phelp, 1989) compared well with the results of monitoring the 25 t rail reinforced units which were used to repair the Cape Town breakwater (Zwamborn, Claassens and Van Tonder, 1990). The three types of rail reinforcement tested are shown in Figure 3. The test results showed that X-type rail reinforced dolosse could withstand approximately double the fall height, compared to unreinforced dolosse. A near design storm which occurred in July 1989, resulted in damage (as monitored photographically), of the same order as that predicted by the swing tests and hydraulic model tests, thereby validating the design.



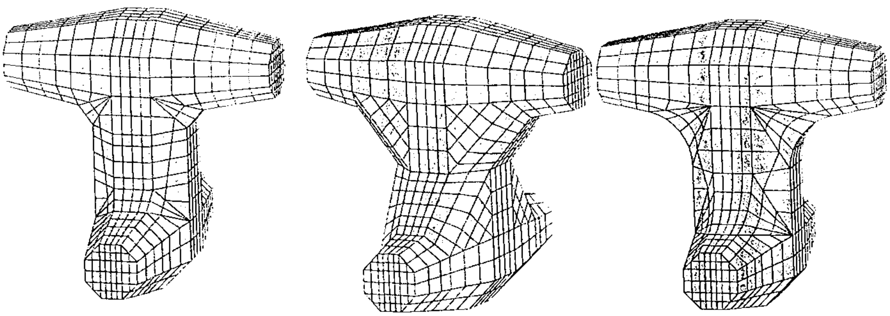
Single rail (43kg/m) X-type rail Double-V type rail

Figure 3: Types of Rail Reinforcement

Prototype reinforced units were observed to have moved more than h/2 without breakage, and many of those units which did break, were still held together by the rail reinforcing, and thus continued to be functional in providing protection to the breakwater. Monitoring surveys of Cape Town breakwater revealed that rail reinforcing reduces both shank and fluke failure, but was not effective in reducing torsional failure (especially the double-V type, Figure 3). Torsional loading of reinforced dolosse tended to shatter concrete on the shank of the dolos, leaving the rails exposed. However, this is not considered too significant, because torsional failures constituted only 11 per cent of all observed dolos breakage (based on a sample of 357 broken dolosse).

■ **Improvement of dolos shape to reduce breakage** - As part of the breakwater monitoring exercises done in South Africa, a detailed study has been made of the number and type of broken dolos armour units, with a view to improving the shape to reduce breakage (Luger, 1993).

An analysis of these prototype dolos breakages has identified the fluke-shank intersection of the dolos as a region of structural weakness. Over 80 per cent of the dolosse breakages were found to originate from this point. Finite element analysis has been used in an attempt to improve the stress distribution in the dolos by modifying the dolos shape in the region of the fluke-shank intersection. Three of the shapes which have been analyzed are shown in Figure 4. This work is aimed at developing a dolos shape which is structurally superior to the existing shape, without significantly reducing the excellent hydraulic stability of the existing shape. The improved shape should be suitable for use on new projects as well as for the repair of existing breakwaters.



Existing chamfer   Maximum chamfer   Large curved fillet

Figure 4: Evolution of Improved Dolos Shape

The continued monitoring of breakwaters where improved armour units are used will provide valuable data to determine the improved performance of the prototype units and confirm the theoretical advantages. The curved filleted dolos (Figure 4) are presently being used in the repair of existing breakwaters at Richards Bay and Mossel Bay, and in coastal protection works in Table Bay near the entrance to the Port of Cape Town. One advantage of using the improved dolosse for the repair of older dolos structures, is that there is still good interlocking between the new and old shaped units of the same weight.

■ **Effect of dolos size and waist ratio** - As a general rule, it was found that a larger waist ratio reduces the percentage of shank failure but increases the percentage of fluke failure. Independent of the waist ratio, the introduction of even the smallest fillet, reduces breakage at the fluke/shank intersection. This was observed on some of the older breakwaters which have both dolosse with no fillet and dolosse with small rounded fillets and the original chamfer (SPM,1984).

No relation could be found between breakwater damage and dolos size. It is the author's opinion however that dolosse, being slender units, are not suitable for deep water applications, and become structurally unstable above 35 ton to 40 ton, even with higher waist ratios. In South Africa, where most of the breakwaters lie in relatively shallow water, the dolos is still considered to be the most suitable armour unit.

■ **Calibration of site-specific model tests** - The Port of Richards Bay breakwaters, have been monitored by various techniques since completion in 1976, but regularly since 1987 using photographic survey from a mobile crane. The results of these surveys indicated that it was necessary to consider doing repairs to the 20 ton dolosse on the trunk of the south breakwater (CSIR, 1988b). Both 3D basin and 2D flume scale model tests were undertaken in 1991 to optimise the proposed breakwater repairs and check the effect of sand trap dredging adjacent to the breakwater (CSIR, 1992).

Because the breakwaters had already experienced storms with wave heights in excess of the 1:50 year design wave height of H_{mo} = 7,9 m, it was decided to calibrate the 'design damage' in the model to equate the existing prototype damage. Each test consisted of a sequence of wave height steps from 2,5 m to 8,5 m in increments of 1,5 m, run for an equivalent of six hours (prototype) each. The model damage was determined using the photographic survey method to record dolos movements. These dolos movements were divided into the number of movements less than the height of a dolos (<h) and the number of movements greater than the height of a dolos (>h). The calibration factor 0,4 (<h) + (>h) was found to give the best model approximation of prototype damage. Figure 5 shows the prototype and calibrated model damage for monitoring stations 5 to 17, which were spaced 25 m apart.

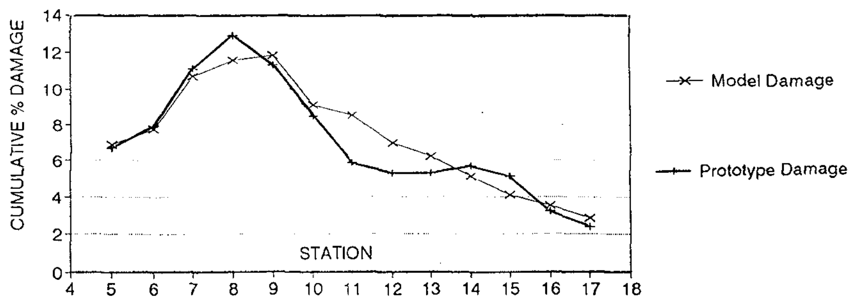


Figure 5: Prototype versus Calibrated Model Damage

By applying the same calibration factor to the model tests of different repair options, the expected design damage could be determined and the most effective repair option chosen.

Figure 5 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 6). 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 (CSIR, 1992).

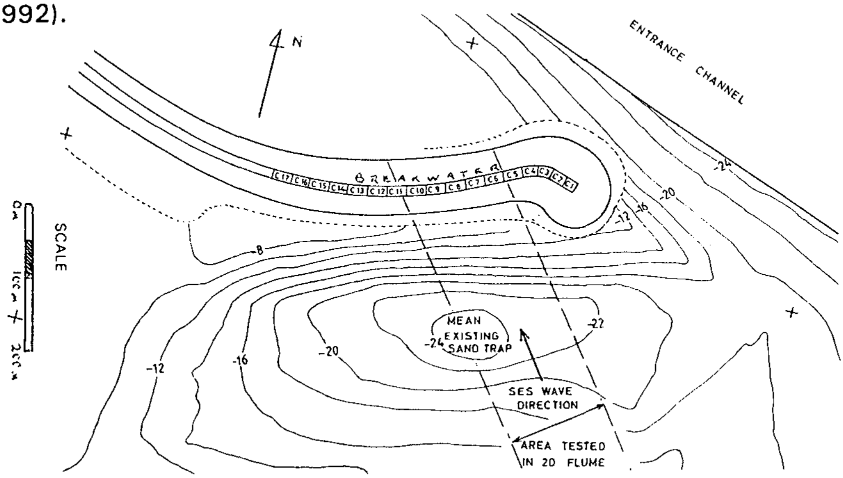


Figure 6: Mean Existing Sand Trap

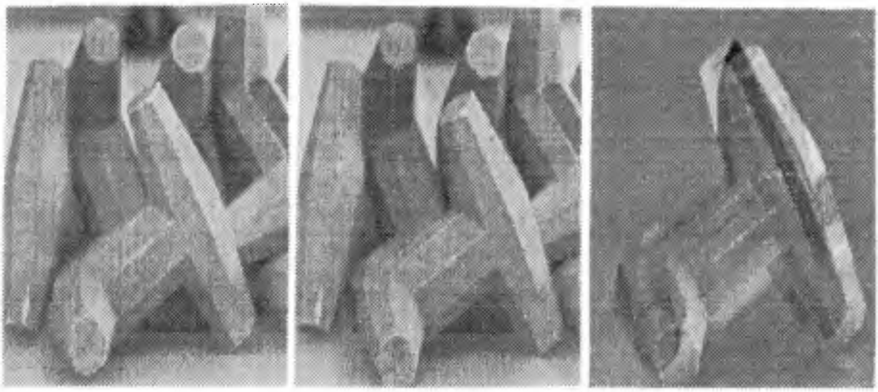
FUTURE DEVELOPMENTS

Future developments, in the field of breakwater monitoring, include improved correlation of damage with wave data, and video scanning for digital analysis, storage and presentation of monitoring results. The former involves the installation of directional wave recorders off the breakwaters. A brief description of the latter follows below:

A disadvantage of the photographic monitoring technique which is presented above, is the tedious manual comparison of photographs, even if the overlay or stereo comparator are used, to identify dolos movement and breakage. A recent new development is the replacement of the photograph of the breakwater by a digital image, captured by video recording or a live video camera signal. Flicker Optics[1] is a digital image processing technique which is then used to interlace, in real time, the image with a preview of the same breakwater station before the damage occurred. Any changes are then detected as a stroboscopic flashing of just that portion of the screen where the change has taken place.

A dynagram (Figure 7) is then generated by simply subtracting the video image in which movement has been detected, from the initial or reference video image. The dolos that has moved shows up clearly while the background, which has not changed, is almost featureless. Three main areas of application of the above technique are as follows:

- Digitizing of archived photographic records (via CCD camera and frame grabbing card) for re-analysis and inclusion in a database.
- Aerial monitoring of prototype breakwater using video camera.
- Real time monitoring of scale model tests on breakwaters.



Reference Image Later image Dynagram

Figure 7. Digital Image Processing

Direct image subtraction assumes an invariant image geometry, illumination and reflectance. Initial testing of this new monitoring technique was carried out under ideal conditions, achievable in the laboratory at small scale. By real time video monitoring, even the small 'settling in' movements of the scaled dolosse were detected. For analysis of the photographic and prototype video record, however, the images need the following manipulation to overcome certain variables:

- Translation, rotation, scaling and warping to allow for errors in camera position (even with DGPS position fixing).
- Contrast stretching and histogram equalisation to allow for changes in illumination (sun and shadow) during consecutive surveys.
- Spatial intensity gradient image formats and edge detection techniques to allow for surface variation such as sea growth.

Advantages of digital images, include the ability to store only the necessary data (ie dolos movements and breakage), for the database and later presentation of survey results. By using a screen overlay grid and the cursor to scale known positions on the image, the dolos movements can be quantified. this information is then added to the data base.

CONCLUSION

Breakwater monitoring in general, at South African ports and photographic monitoring in particular, have been successfully used as useful tools to identify damage, provide an early warning system (giving time for model tests of the repairs to be carried out) and assist in the planning of maintenance.

In this paper, the various methods of breakwater monitoring were covered and the use of monitoring results to calibrate model test results and improve repair designs were presented. Three projects involving two breakwater repairs and one new breakwater, soon to be undertaken, have been designed using mathematical and physical model tests, aided directly by the results of prototype breakwater monitoring. Ongoing monitoring of these structures will prove the performance of their design and of improvements made to the shape of the dolosse which are to be used.

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