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ICE 05

Monitoring and Maintenance of Coastal Structures

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Introduction

Most coastal structures built in a dynamic marine environment will require regular monitoring and possible maintenance, especially after severe storm events. The type of structure, the quality of the design and construction and the stability of the foundation and surrounding coastline will determine the extent and frequency of this monitoring and maintenance. Coastal structures, and breakwaters in particular, protected by concrete armouring require special attention due to the importance of interlocking between the units and the effect of damage to individual units. Gradual deterioration can often pass unnoticed until weak areas give way to major damage, which might require extensive repairs. Early detection of deterioration such as displaced or broken 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.

Advances in Monitoring Methods

The latest innovation is the use of digital image technology and aerial monitoring. Equally important, however, are innovations in the monitoring of structures below water. With the latest advances in side-scan and multi-beam echo sounding instrumentation, coastal engineers are able to get a clearer picture of the performance of the whole armour slope. It is also important to monitor the interaction between the seabed and the toe of the structure, and link this to the changes in near-shore bathymetric profiles.

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 previous papers (Phelp, ICCE 1994). Although most of the coastal structures in South Africa are protected by Dolosse, these methods are also applicable to other types of armouring, including rock and single layer concrete armour.

Visual inspections are useful for checking specific damage and to give an overall impression, but cannot be used to compare progressive damage over time.

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. Valuable information can also be obtained from photographs taken during extreme sea conditions. Remotely controlled digital cameras are relatively inexpensive and are ideal for this purpose (Phelp, COPEDEC 1999 and ICCE 2002).

Diver inspections (Figure 1) are an extension of visual inspections to below water, provided visibility is good, however position fixing is more difficult and the survey more time consuming.

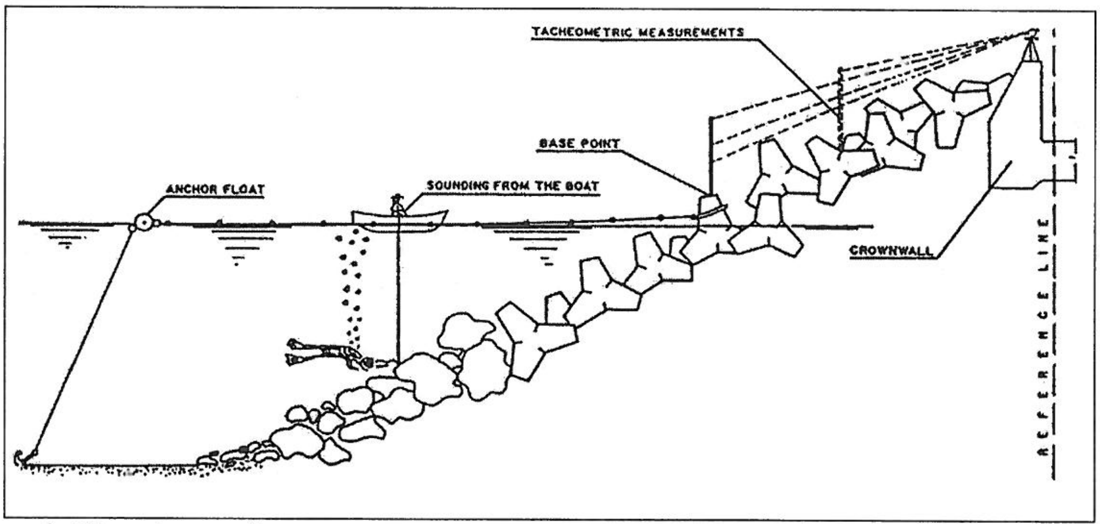

Figure 1 Diver Inspections Source CSIR

Crane and ball surveys (Figure 2) are used to monitor the breakwater profile (above and below water) at predefined intervals (normally 1.5 D_n to 2 D_n, where the equivalent cube diameter $D_n = V^{1/3}$ and V is the individual armour unit volume). A mobile crane is used to position the ball, and the coordinates are recorded by a leveling staff or DGPS mounted on the crane. The size of the ball which must obviously be kept constant from one survey to the next is $d = 1.14\ V^{1/3}/\sin 45°$ where d is the ball diameter (for Dolosse this equates to $d \sim 0.8\ D_n$ which is slightly larger than $d = 0.5\ D_{n50}$ for rock armour). During construction of a breakwater, crane and ball surveys are essential to monitor the as-built rock and armour unit profiles.

The measurement of cross-section profiles (in both model and prototype scale), gives another useful indication of damage. This is especially the case for checking underwater damage, where concentrations of breakage (prototype) and settlement of armour units will result in a local lowering of the profile. It is also important to measure the condition of the rock toe and the possibility of erosion of sediment along the breakwater. This was the main contributing factor to the damage on the south breakwater at the port of Richards Bay (Pillay, ICCE 1998). During the model tests carried out for the Richards Bay breakwater repairs, the erosion of the toe was accurately modelled, including the pre-settlement of the repair Dolosse into the sand.

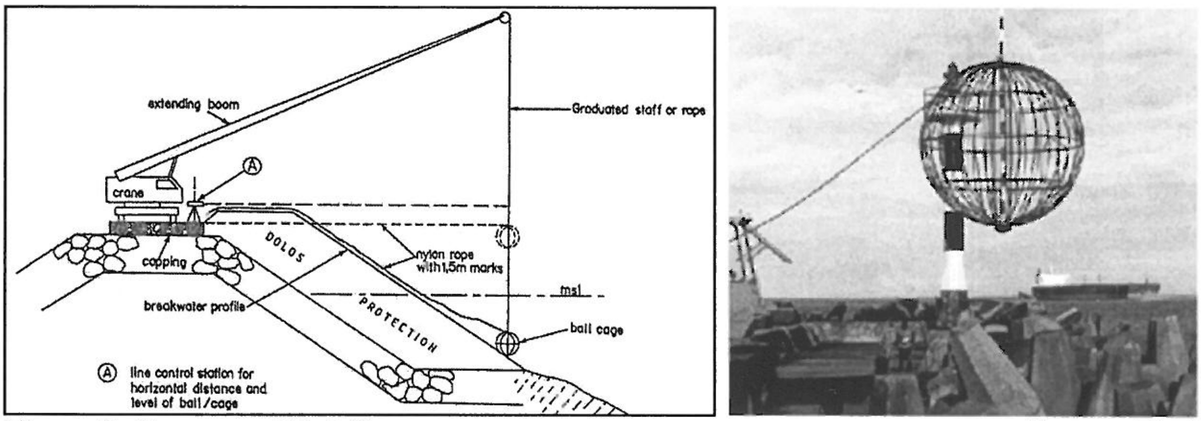

Figure 2 Crane and Ball Survey Source Phelp

\# **Seismic, sidescan sonar, swath and bathymetric surveys** (Figure 3) should 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 images below were obtained using a Reson Seabat 8050 Multi-beam Echo Sounder.

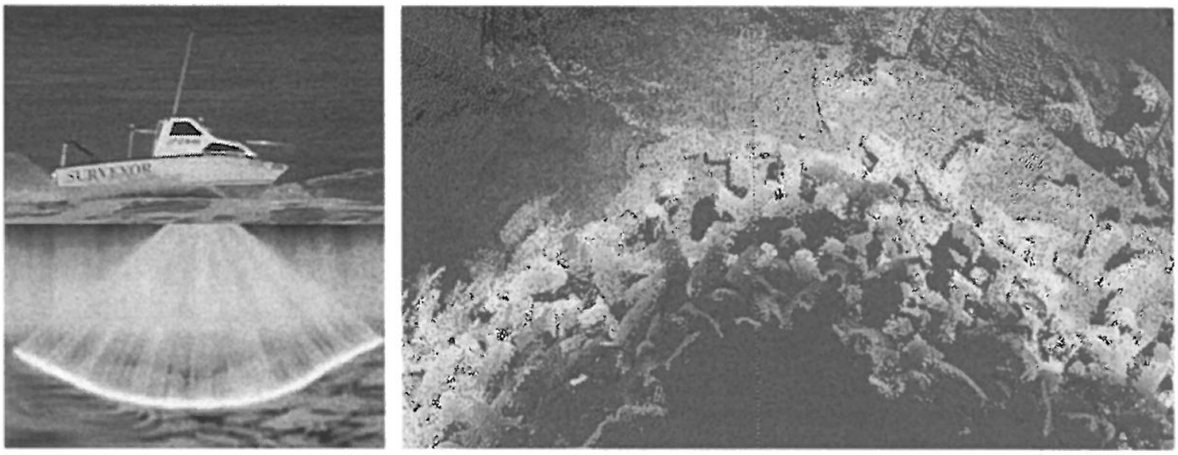

Figure 3 Multi-beam Swath Survey Source CSIR, Quincy 6042 Image Processing

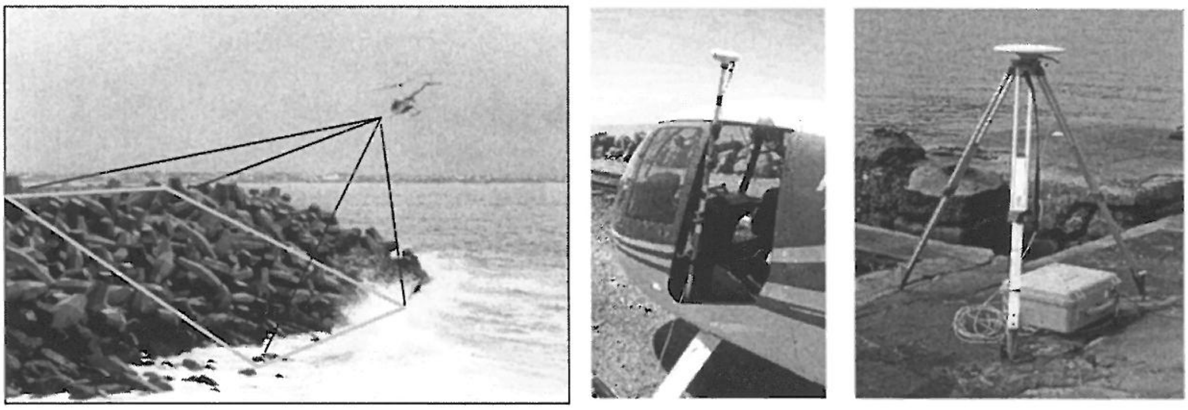

Figure 4 Photographic Survey Source Phelp

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 images taken before and after the monitoring period (usually annually) and adding the new damage to the previous cumulative damage per station. Provided the camera position and lens are kept constant for consecutive surveys, it is possible to use the flicker technique to quickly compare respective images to detect individual armour unit movements of less than 0.1 D_n.

The visible damage can be categorized into three degrees of armour unit movement (A) < 0.2 D_n, (B) 0.2 D_n to D_n and (C) > D_n, (D) unit breakage and (E) disappearance (loss) of the unit from the visible slope. The recording of small movements (A) gives an indication of settlement and shake down, while intermediate movements (B) give an indication of the armour stability under storm wave attack – but only movements larger than D_n (C) are considered as damage. Once a unit is displaced by more than $D_{n,}$ it is deemed to have moved from its design position and is no longer able to interlock with adjacent units. The damage per photographic monitoring station, which normally cover 20 m to 25 m of breakwater length (approximately 10 $D_{n)}$, are expressed as percentages, which are calculated by adding (C) + (D) + (E) and dividing by the total number of units per station (N). The movement of pieces of armour units, which have already broken are also monitored, but do not contribute further to the damage calculation. In the same way, the smaller unit movements (A) and (B) are recorded for information purposes, but do not contribute to the damage total. The movement history of a particular units is also tracked, so that the cumulative movement can be measured. Once this cumulative movement reaches more than D_n (C), it is then added to the damage total. In the case of rock, D_{n50} is used.

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 unit movements (C), in the damage criteria. This theory corresponds with the definition of damage of unit in scaled model tests, where movements more than the height of the armour unit are generally recorded as damage (together with an observation of the number of rocking units, to represent unit breakage without displacement). Model damage analysis is discussed in more detail in the next section. When prototype damage is repaired with new armour units, the cumulative damage is reduced by the number of new units placed, where they actually replace the damaged or lost units (Figure 5).

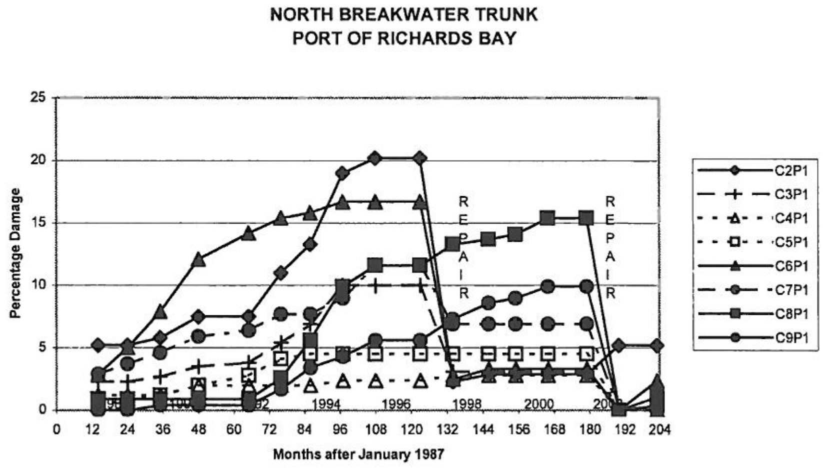

Figure 5 Rate of Damage Plot – percentages per station Source Phelp

Graphs (such as those shown in Figure 5) can also be plotted showing the rate of increase of damage per station which highlights those areas of the breakwater which may need urgent repairs. Figure 5 also shows the results of repairs to these stations. Wave data from wave buoys off each harbour breakwater, covering the monitoring period, are analyzed and included in the monitoring report so that annual damage can be linked to the prevailing sea conditions or significant storm events (Figure 6). Figure 6 shows the number of damaged Dolosse on the whole trunk of the Cape Town breakwater, out of a total of 2440 Dolosse (this gives an average of 1.8% damage for the 500m long trunk section). The "shake down' damage, after construction in 1988 was 18 damaged units (just over 0.7%), which resulted from a 1:15 year storm.

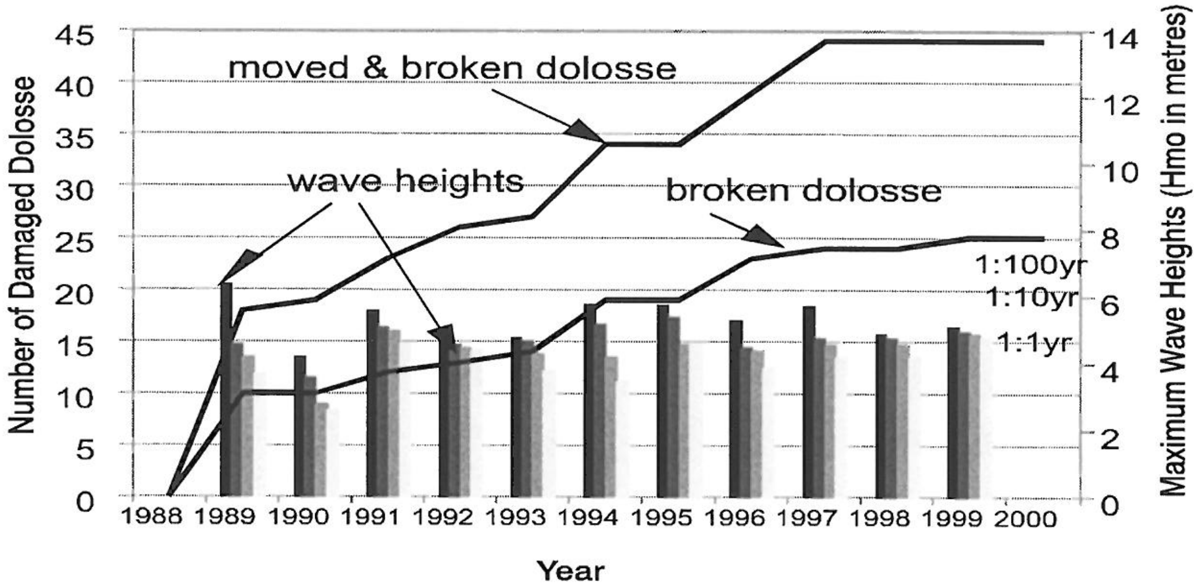

Figure 6 Rate of Damage Plot – total number of damaged units Source Phelp

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 and deterioration
\# 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.

Correlation Between Model, Prototype Monitoring and Performance:

It is important to standardize the methods of accounting for damage and coastal structure performance. There must also be a link between the small-scale damage recorded in physical model tests, and the corresponding damage and performance of prototype structures. The design of coastal structures is mostly based on the results of model tests, which need to be calibrated to prototype conditions. The use of digital image analysis has made it possible to maintain the same quantification of the detail at the different scales. The results of many repeated model tests have also been used to derive empirical formulae, which are used to give a first estimation of the design of the structure. Site-specific model studies are then used to fine-tune the design, but the hydraulic behaviour of the model breakwater needs to be carefully understood and interpreted to represent the designed performance of the prototype breakwater.

Structural integrity is traditionally assessed through observation of the movement of the model armour units, which is then used to quantify the damage under given design conditions. In the model it is necessary to estimate the number of units, which would have broken, by monitoring small unit displacements and the number of rocking units. The definition of damage for a model structure (a Dolos breakwater, for example) was originally defined as the number of Dolosse that have been displaced more than the height of a unit ($\sim 2D_n$), plus the number of Dolosse that have been rocking for more than two thirds of the duration of the test (for Dolosse $D_n \sim 0.6$ H).

In the model, the initial shake-down settlement of the model units, which occurs only after the model is filled with water and waves are generated, is normally small ($<0.3\ D_n$), and contributes little to the damage total, but can be easily detected by digital analysis. Although the pre-test condition of the structure is always recorded, for ease of analysis, the base-line image from which the larger movements are recorded (by the digital "flicker technique") is taken after shake-down settlement is complete. Using the old manual comparison of photographs, it is difficult to quantify this shake-down, but in prototype, small shake-down displacements on a newly constructed breakwater can result in high stresses and broken units, which add to the damage total. This was observed in Cape Town (Phelp, ICCE 1994) and in Richards Bay (Pillay, ICCE 1998).

It is important to carry out base-line monitoring before shake-down occurs, so that initial damage can be recorded. This was done at the port of Cape Town, where there was a near design storm soon after construction. This resulted in damage, including shake-down damage (C), (D) and (E), which was over twice the normal annual damage. Prototype shake-down (settling-in) occurs during and soon after each unit is placed, so that by the time construction of the whole slope is complete, the as-built monitoring records the position of the already partially settled breakwater. Further small movements are then less than those recorded in the model, but it is likely that some of the initial shake-down will result in breakage due to a build-up of static stresses. This is often missed in prototype monitoring, because the as-built photographic record (against which future damage is measured) are normally only taken some time after construction of the whole slope is complete. By this time the armour units have been subjected to continuous wave forces, and have become well interlocked. Despite this, the small movements of armour units (A) and (B) contribute to nearly half the total number of displaced units.

Flicker Optics

The Flicker Technique 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.

For analysis the images need the following manipulation to overcome certain variables:

Translation, rotation, scaling and warping to allow for errors in the 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 armour 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.

Through the above method, minute armour movements can be recorded and categorized (Phelp, COPEDEC 1999), but the dilemma is still how to determine what contribution these tiny movements should make towards the determination of damage in physical models. Historically, the damage calculation from the monitoring of prototype Dolos breakwaters (in SA) involves the summation of the number of units displaced more than D_n and the number of broken units. This is normally divided by the total number of units per photo station to give a percentage damage. To comply with a standard description of damage, this can be represented as the average damage number N_0, by dividing the station damage total (not expressed as a percentage) by the number of D_n lengths per photo station length.

From extensive tests carried out on Dolosse, the CSIR has found that the percentage of rocking units was roughly equal to the percentage of units displaced over a distance equal to one Dolos height (Phelp, ICCE 1994 and Zwamborn, COPEDEC 1995). This implies that prototype damage can be up to 2 or more times the number of units displaced by more than the height of a unit (or 1.7 D_n for Dolosse, assuming that the model accurately simulates the same number of rocking units as would be found in prototype, and that rocking prototype units will break). With the improved methods of monitoring model unit displacement (Phelp et al, COPEDEC 1999), the damage can be calculated by adding ratios of the different displacement bins. For example:
The damage to the south breakwater at the Port of Richards Bay was calibrated from model to prototype, by taking 40% of the displacements between D_n and 1.7 D_n, plus all the displacements greater than 1.7 D_n (Phelp et al, ICCE 1994), ie. Damage model = (displacements >1.7 D_n) + 0.4 (D_n <displacements <1.7 D_n). One needs to remember that displacements < D_n recorded in the model are considered as pre-test shake-down, and do not contribute to the damage total.
The damage to the main breakwater recorded at the Port of Cape Town was calibrated from model to prototype, by taking the number of units displaced more than D_n (drop tests showed that single movements of up to D_n did not necessarily result in breakage, plus those units rocking for more than 2/3 of the test duration. This resulted in a conservative estimation of damage of between 2% and 3% for 1:100 year design conditions, whereas the average cumulative damage recorded in prototype, under sea conditions close to the design conditions, was in the order of 1.9%
For the recently completed model tests conducted for the proposed Coega harbour, on the east coast of South Africa, the damage definition was conservatively defined as the displacements greater than 1.7 D_n plus 50% of the units which were displaced between D_n and 1.7 D_n, disregarding movements less than D_n (Holtzhausen, ICCE 2000).
ie. Damage model = (displacements >1.7 D_n) + 0.5 (D_n < displacements < 1.7 D_n).

Digital Image Techniques and Armour Tracking Procedure

The image-flickering technique has provided much more information on Dolos movements than was the case with the visual comparison of two corresponding photographs. Movements as small as 0.05 D_n could clearly be identified. Especially at the start of a model test, a lot of small movements related to settlement of Dolos units (shake-down settlement), make the interpretation of the flicker results difficult. Software has been developed that allows for the marking of Dolos movements by drawing lines over the images that are selected for comparison. The idea is to draw a line from the original position of a Dolos to its position after displacement. This provides the necessary information to produce displacement vector statistics. Displacement results can also be presented graphically in a displacement plots as shown in Figure 7 below.

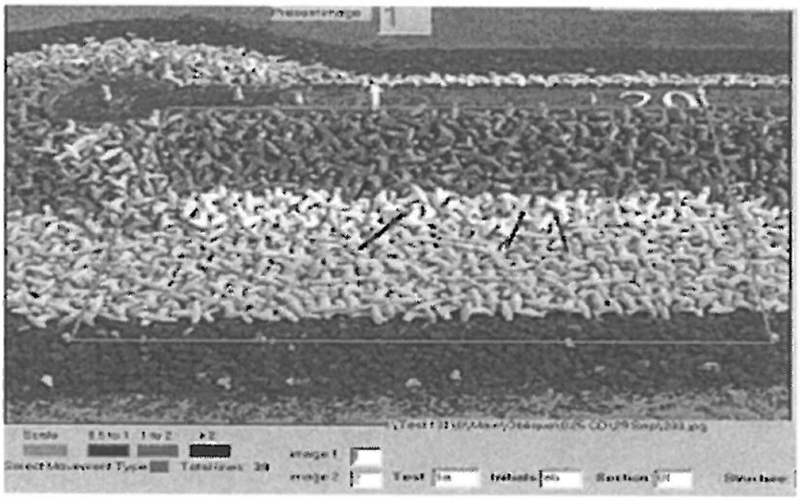

Figure 7 Displacement Plot Image Source CSIR

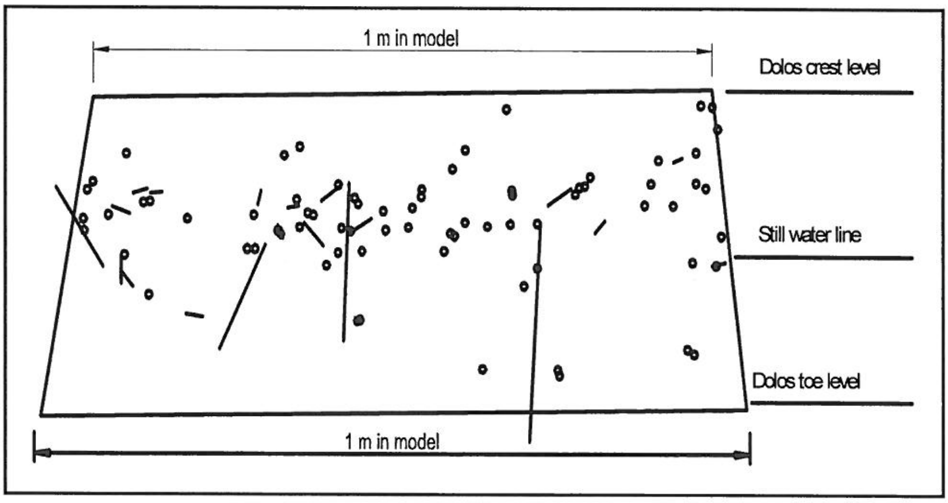

Figure 7 Displacement Plot AutoCAD Overlay Source CSIR

Since the shake-down movements were of little significance to real damage, it was decided to only mark movements > D_n. Software was development so that, by the end of the tests, analyses could be done with minimum effort in a user-friendly graphic environment. Once all the significant movements between two images have been drawn, a file save command writes all the lines to disk and prints a hardcopy of the displacements to a printer (as shown above). Small movements (< D_n) are marked with a circle, and displacements > D_n with a displacement line (indicating the actual path of a displaced Dolos). Using different colours for each of the wave conditions in a test, all the displacements recorded during the course of a test are shown in one displacement diagram. The displacement diagrams are written to a CAD DXF file format for further manipulation with CAD compatible software.

This idea is now also being applied to prototype breakwater monitoring results. So instead of averaging the percentage of damaged units over the photo station (normally 25m in length), the record of the individual damaged unit is stored together with its x and y coordinate. This means that the photographs need to be coordinated by using an overlay digital terrain model grid, so that the centre of each armour unit has a unique grid reference. It is preferable to use a real ground coordinate system, so that movements of the armour units can be linked to the grid system originally used for placing the prototype armour units during construction. (as described in Pillay, ICCE 1998). The crane used for construction is normally fitted with accurate DGPS, for placing each unit on a pre-determined grid, which is calculated from design packing density.

Once each unit has been coordinated, the cumulative damage can be referenced in time and space. This is an improvement on the present assessment of prototype damage for each 25m photo station, where percentage damage is averaged over the whole station. This definition of damage (N_O) should be applied to both model and prototype breakwaters, so that more direct comparisons of damage can be made. The effect with which the different sizes of armour units, and sizes of the photographic sections used for the analysis, would have on the values of N_O, still needs to be checked. Damage contours can also be drawn to highlight clusters of higher damage where the interlock of adjacent units has been lost, and the breakwater armour is vulnerable to further damage by storm waves focusing their energy into the "hole". Digitized archives of historical damage are now also being re-processed and coordinated, which should highlight further information about the location and progression of prototype damage.

The Use of Monitoring to Optimize Maintenance Works

In the case of major damage or part failures it is obvious that repair work should be undertaken as soon as possible. However, in many instances breakwater damage is gradual and it is often difficult to determine when the structure's safety is impaired. Regular maintenance or annual small-scale repairs are difficult and relatively expensive due to plant mobilization costs. The tendency is therefore to allow for a relatively large degree of damage to develop before major rehabilitation works are undertaken. In this regard, the need for regular breakwater monitoring cannot be overstressed. Much attention has been given to the economical optimization of new breakwater designs, but there is little information available on prototype performance and optimum maintenance/rehabilitation of breakwaters or coastal structures.

Based on examples from European harbour breakwaters (Zwamborn, COPEDEC 1995), it was concluded that breakwater stability reaches critical stage when crest failure occurs and/or armour failure exceeding, at least 30%, occurs. Experience of breakwater damage in the USA, although limited, has shown that repairs seem to vary from regular 3 to 5 year maintenance of rock jetties, and to allow for a fairly large percentage of damage to occur for concrete armour unit protected structures before major maintenance is undertaken. The Corps of Engineers has also adopted a rating system to decide on priorities based on the structure's stability and functionality. In Israel, experience indicates that breakwaters with damage to the armouring of 20% to 30%, although still functional, are at relative risk to localized failures which could endanger the stability or the crest wall. Localized repair work was only carried out as an emergency measure. When damage exceeds 30%, a properly designed and model tested rehabilitation scheme is strongly recommended.

In South Africa, guidelines have been developed for Dolosse, where maintenance is required when damage approaches 15%. Some preventative maintenance can however be advantageous, such as the removal and/or replacement of broken pieces, provided that surrounding Dolosse are not disturbed. In the past, regular maintenance was done in most South African ports and several breakwaters were equipped with dedicated cranes for this maintenance work. A more recent approach has been to allow a fairly high degree of damage to develop (about 30%), which is continually checked by detailed monitoring, before designing and construction proper maintenance works aimed at low future maintenance. Figure 8 shows an example of a station on the Cape Town spur breakwater, with 30% damage. Most of this damage was located along the water line and on the right hand side of the station. Planning for repairs to this area of the breakwater are already underway.

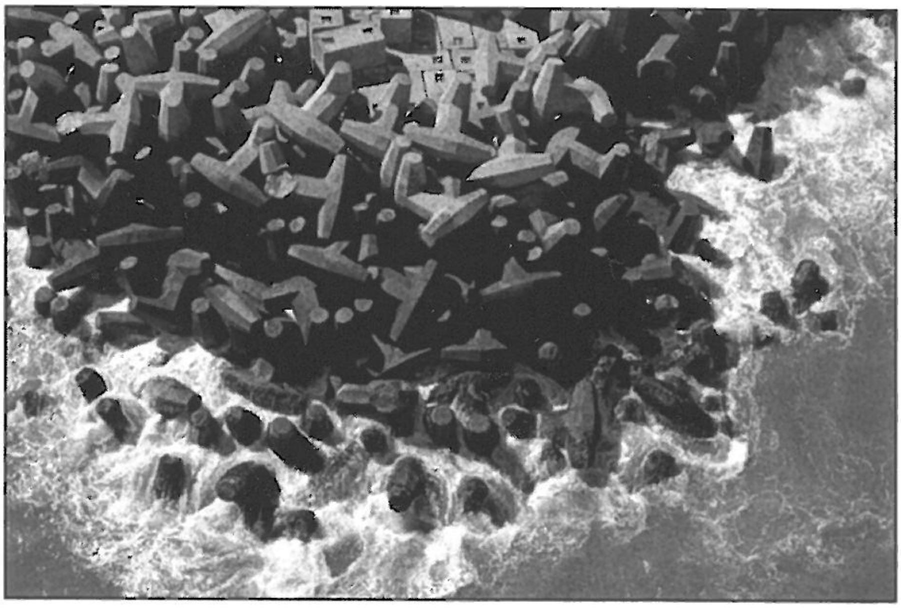

Figure 8 Cape Town Breakwater Spur – showing 30% damage Source Phelp

A lot depends on the availability of spare armour units and plant to carry out the repairs. Monitoring can be used to track the rate of damage and give early warning of potential weak spots, which might require more urgent repairs. Different armouring will require different damage interpretation and maintenance methods, especially taking into account the differences between single and double-layered concrete armour systems.

Case Studies in South Africa

The CSIR has been involved in the design and annual monitoring of coastal structures in South Africa for the last 40 years. Since the invention of the Dolos concrete armour unit in the late 1960's, up to the recent modeling and monitoring of Core-loc and Accropode breakwaters, annual data has been collected and compared to the designed performance. Optimized repairs have been carried out on coastal structures and breakwaters using Dolosse, Accropode, Core-loc, Tetrapode, Toskane, concrete blocks and rock, and aerial monitoring has been used to track the performance of both the repaired and un-repaired areas (Phelp, ICCE 1994).

The eight harbours, where the breakwaters are regularly 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. 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. 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.

Monitoring has provided much insight and information: To determine what contribution rocking and small Dolos movements (model breakwater) would contribute to breakage, it is important to study the relationship between displacement and breakage in prototype. Using the results of annual photographic monitoring of the Dolos breakwater at the Port of Cape Town, of all visible Dolos movements, recorded to within ±0.05 D_n. Of the 330 units which visibly moved, Table 1 shows the distribution of the size of movements recorded.

Table 1 Distribution of Dolos Movements Source Phelp

Movement	less than 0.2 D_n	between 0.2 D_n and D_n	above D_n
Percentage	47%	29%	14%

Slightly more than half the prototype damage could be attributed to Dolos movements (> D_n) and nearly half to breakage. The damage totals, above, include the initial shake-down settlement, when a large percentage of the total recorded smaller displacements occurred. More than half of the breakages, which have occurred during the first ten years of the life of the breakwater, occurred during the shake-down. After shake-down, just over half of the recorded movements, were new movements while just less than half had moved before. Monitoring results have also shown that Dolosse can withstand considerable movement without breakage. Table 2 gives an example of the size of all movements monitored where Dolosse did not break.

Table 2 Distribution of Dolos Movements without Breakage Source Phelp

Movement	< D_n	> D_n
Percentage	76%	14%

Towards an International Standard and Guidelines

Because scale modeling and monitoring are carried out all over the world, under different specifications, there is a need to standardize the methods of recording damage, both in small scale and in prototype. It is likely that there will be unique methods needed for the different types of structure and concrete armouring. The interpretation of the recorded damage must also be linked to the wave conditions experienced by the structure. A PIANC working group WG39: Breakwater Monitoring, was set up to draft international guidelines, and it is hoped that this paper will stimulate participation in efforts to this end. It is important that new structures be monitored both during and after construction, as part of the contractual specification. This will enhance our knowledge and improve design.

Acknowledgements

The Author would like to thank the South African National Ports Authority for its support, over many years. Without this, the prototype monitoring data would not have been collected.

Summary

This paper presented the need for the monitoring of breakwaters and coastal structures, to help understand the performance of prototype armouring. The different types of monitoring and were discussed. In an attempt to link the results of physical modeling to prototype performance, formulae were given to correlate the interpretation of damage (movement) of model armour units, with the movement and breakage of concrete units in the field. Most of the monitoring and modeling of breakwaters carried out in South Africa involves the use of Dolos armouring; and as such the correlations were only given for Dolosse. The use of generic terms, such as D_n, have however been used to make the analysis more universally comparable to other types and size of concrete armour units. The correlation for Dolosse is given below, which disregards all model unit movements less than D_n. The applicability of this correlation for other concrete armour units and rock protection still needs to be investigated further.

Damage in model scale = (all displacements $>1.7\ D_n$) + 0.4 ($D_n <$displacements $<1.7\ D_n$)

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