MONITORING AND MAINTENANCE OF BREAKWATERS WHICH PROTECT PORT ENTRANCES

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ABSTRACT

While ports are gateways to the country's transport networks, breakwaters protect port entrance channels, into and out of the ports (Figure 1). The entrances to most of the ports in South Africa are protected by rubble mound breakwaters which have dolos armouring. These require regular monitoring and maintenance, especially in the light of predicted sea level rise and extreme sea conditions caused by global warming. TNPA, the local Port Authority, has commissioned the CSIR to annually monitor the main breakwaters of the SA ports to ensure they remain in good condition. This paper presents a brief description of the performance of the dolos breakwaters in South Africa, and the field monitoring techniques used to record the annual damage to the armouring. Examples are also given of recent storm damage and typical repairs carried out.

INTRODUCTION

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 their maintenance and for keeping the ports functioning. Depending on the severity of the wave attack, the breakwater armouring will deteriorate in time if not properly maintained. As is the case with road pavements, 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.

Figure 1: Breakwater Protecting the Entrance of the Port of East London

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. Breakwater monitoring also offers the potential for increasing the understanding of failure mechanisms associated with rubble-mound structures which are difficult to simulate accurately by way of physical model tests.

The eight ports, where the breakwaters are monitored, are spread out along the east and south coasts of South Africa, from Richards Bay in the north-east to Cape Town and Saldanha Bay in the south-west, as shown in Figure 2. All but one of these ports are protected by rubble mound breakwaters, which are covered with dolos armour units. The Port of

Saldanha Bay, lies in a large natural bay, and is protected by an artificial spending beach breakwater across the original northern entrance to the bay.

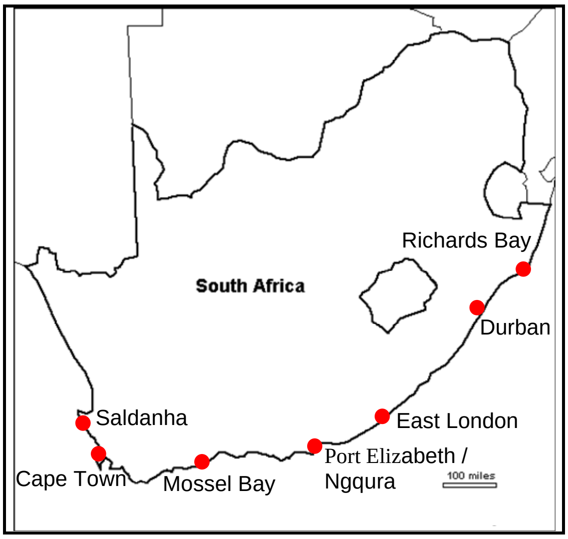


Figure 2: Location of South African ports with large breakwaters

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 ports are therefore limited by the local water depth. 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 required to intercept the littoral drift which is predominantly from south to north. Table 1 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.

Table 1: General statistics of Breakwaters at Southern African ports

Port	Year	Length	No Dolos	Size	Damage	Max Dam.
Cape Town	1988	500m	2865	25t	3,7%	6,6%
Mossel Bay	1995	200m	1213	7,5t	0,4%	0,9%
Port Elizabeth	1978	370m	3750	10t	4%	11,3%
Ngqura	2005	2750m	20818	30t	1,1%	5,4%
East London	1965	600m	3458	18t	32,5%	73.8%
Durban (pre-upgrade)	1985	585m	2126	20t	9,8%	32%
Richards Bay North	1976	600m	6771	5t & 15t	4,4%	13,3%
Richards Bay South	1975	1400m	6244	20t & 30t	3.7%	8,7%

Richards Bay has two dolos breakwaters, a shorter straight breakwater on the northern side and a longer curved breakwater on the southern side. The Durban entrance channel is currently being deepened and widened, and the breakwaters strengthened. East London, the only river port, has the oldest dolos breakwater structure which still has the original dolosse designed by Mr E Merrifield, the port engineer and inventor of the Dolos, 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. The new Port of Ngqura (Figure 3) has the longest outer breakwater, in South Africa, at 2,75km, with 21000 30t dolosse and a caisson at the head.

Figure 3: Dolos breakwaters at the Port of Ngqura

MONITORING METHODS

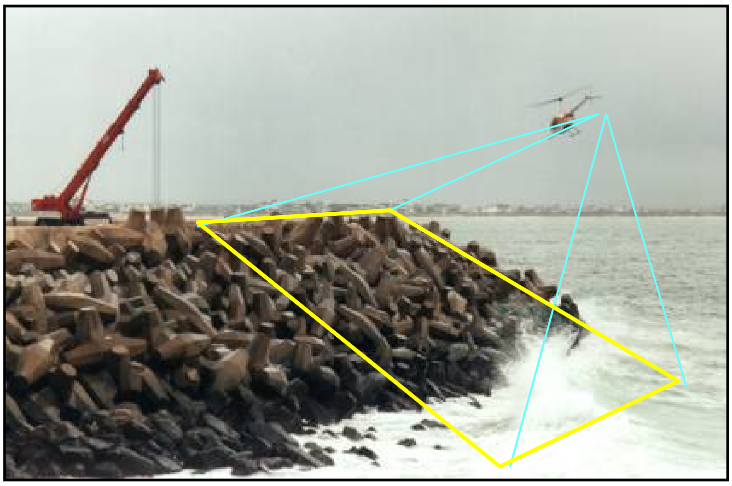
Most of the breakwater monitoring methods, used by the CSIR, are listed briefly below, together with descriptions of their usefulness and applicability. Detailed descriptions of these methods are available in various reports (CSIR, 1988a and Kluger, 1982).

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, is not very quantitative in the degree of damage and is not suitable for monitoring the entire slope.

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.

Photographic monitoring 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 involves the use of overlay or flicker techniques to check damage, is described below. The photographs may be taken from a boat (horizontal view), or crane or aircraft (vertical view), whichever is available. The helicopter (Figure 4) 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.

Figure 4: GPS Positioned Helicopter used for Photographic Monitoring



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 by tache or GPS (Figure 5). The size of the ball which must obviously be kept constant from one survey to the next is normally around r = 1,14 $V^{1/3}$/sin45 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 rock and dolos profiles.

Figure 5: Crane and Ball Survey of Breakwater Profiles

Seismic, sidescan sonar and multibeam 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.

Laser Scanning or tacheometric survey methods may be used to accurately monitor positions and levels of 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.

Other forms of monitoring which are complimentary to the breakwater monitoring techniques presented above, and which can be linked to the damage analysis, are:
wave recording (by wave buoy – wave 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) to check porosity
monitoring of concrete decay (possible alkali aggregate reaction)
monitoring of cracks in capping slab (linked to settlement)

ANALYSIS OF MONITORING DATA

Only the **photographic monitoring** will be described further, 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 electronically use the overlay (or flicker) technique to quickly compare respective photographs to detect individual armour unit movements of less than 0,5 m.

Both annual and cumulative damage are given in the monitoring reports, which is then linked to prevailing sea conditions during the monitoring period. 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, is 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. Monitoring results have shown that unrepaired localized damage causes an increase in the rate of damage in that localized 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.

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, design, 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.

The most important use of monitoring results, however, is for the 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 port entrance, and in the importance of the port 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 (in 4m water depth), 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 started. Both breakwaters are approximately 40 years old.

Calibration of site-specific model tests relies on heavily prototype monitoring results - the Port of Richards Bay breakwaters, have been monitored by various techniques since completion in 1976, but regularly since 1987 using photographic surveys from a mobile crane and then from a helicopter. 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 Hmo = 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.

BREAKWATER REPAIRS AT THE PORT OF RICHARDS BAY

The Port of Richards Bay 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 6), constructed between 1973 and 1976, which stretches for approximately 1,4km, almost perpendicular to the coastline. The original armouring on this breakwater consists mainly of 20t dolosse on both sides of the trunk, 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.

Figure 6: South Breakwater at the Port of Richards Bay

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 damage was undertaken by Zwamborn in 1988 (CSIR, 1988b) which led 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 repairs required the casting of 1 000 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.

The original breakwater construction used a total of 13 400 20t dolosse on the trunk, and 2200 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 was located on the trunk with 17% dolosse displaced or broken. 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.

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 Hmo. Storm wave set-up and low atmospheric pressure associated with these storms also had the effect of raising the water level, thereby increasing 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.

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 was specially designed to fit onto the 6,7m wide mass-concrete capping.

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 (1 001 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. A portal crane was used to handle the dolosse from the casting yard onto the stockpile and from there onto the trailers.

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 safely be placed from the present position of the crane. The limiting operating conditions for the crane were wind speeds of 50kph or swell heights above 2m.

DAMAGE TO FORESHORE PROTECTION ALONG N2 IN PORT ELIZABETH

Figure 7 and 8: Severe Wave Overtopping causing Flooding

During a severe storm in August 2008, with wave heights exceeding 4m (recorded off Ngqura), extensive damage was caused to the shore protection along the N2 Freeway in Port Elizabeth. The storm coincided with a spring high tide, which increased the wave overtopping, causing undermining of the railway line and closure of the freeway from flooding and rocks washed onto the tarmac (Figures 7, 8 and 9). Note the water pushing up through the storm water drains (Figure 8). The road was cleared within a day, but the railway took longer to reinstate, with the dumping of additional large rock shore protection.

Figure 9: Damage to the Railway Line

As with the dolos on breakwaters which protect port entrances, rock or dolos armouring along the shoreline, which protect coastal infrastructure, such as roads, railways and buildings, should be monitored and maintained to ensure that they remain in good condition. Proper design and regular monitoring and maintenance are ultimately more economical than the cost of closure and cost of the repair of major damage (Figure 10).

CONCLUSIONS

Breakwater monitoring in general, at South African ports and coastal protection structures has been successfully used as a useful tool 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 to optimize performance.

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. Since the early 1990s, many projects involving breakwater repairs and new breakwater design have been carried out 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 ensure that they continue to perform well into the future, despite the threat of sea level rise and possibly worsening sea conditions. This should help to prevent costly failures, such as that seen in Figure 10.

Figure 10: Breakwater Failure due to Focusing of Strom Waves

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