POLITICAL STUDIES OF THE 6TH INTERNATIONAL CONGRESS ON THE APPLICATION OF PHYSICAL MODELLING IN COASTAL AND PORT ENGINEERING AND SCIENCE (COASTLAB16)

Ottawa, Canada, May 10-13, 2016

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RICHARDS BAY SOUTH BREAKWATER ROUNDHEAD PHYSICAL MODEL STUDY

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ABSTRACT

The results of three dimensional (3D) physical model tests performed to determine the most suitable maintenance repair strategy for the Port of Richards Bay south breakwater roundhead are presented. The south breakwater roundhead was severely damaged by a major storm which occurred during spring high tide in March 2007. Since then careful attention has been placed on the movement of the broken dolosse, especially on the roundhead during annual photographic surveys. The recent hydrographic and topographic survey of the breakwater was carried out in October 2014 which provided information for the physical model investigation.

The physical model study was carried out at the coastal and hydraulics laboratory of the Council for Scientific and Industrial Research (CSIR) at Stellenbosch. The repair options compared in the small scale physical model tests evaluates repairing the slope with existing 30 tonne dolos armour units, repairing by with existing dolosse and chaining them in clusters of three with UHMWPE rope as added support, a new design of the roundhead with antifer cubes, a new design of the roundhead with cubipod or a new design of the roundhead with two caisson. This paper presents the results of only the results from the physical model tests and provides options to be further investigated.

KEYWORDS: Dolos, roundhead, chained dolos, breakwater, Richards Bay,

1 INTRODUCTION

The Port of Richards Bay, located on the East Coast of South Africa (Figure 1), was constructed during the 1970s, initially to accommodate a coal terminal (NRIIO, 1974). After several expansions this port has become the largest in South Africa in terms of cargo volumes (Zwamborn, 1976).

Two rubble mound breakwaters protect the deep-water entrance and create a sheltered area for safe navigation of vessels and a calm inner harbour for port operations. The breakwater structures were completed in 1976. The breakwaters were designed for a storm with a significant wave height of 7.8 m (in 14 m water depth).

Since 1976 the breakwaters have withstood several major storms, including cyclones with significant wave heights close to the design storm wave height, which has caused significant damage to the dolos armour layers (Theron, 2011). To restore the original functional conditions, two major repair works were carried out in 1987 on the south breakwater trunk and in 1996 on the north breakwater (CSIR, 2014).

The armouring of the north breakwater consists of a double layer of 5 tonne dolosse on the trunk and root. The head was originally constructed with 15 tonne dolosse but was repaired with a double layer of 20 tonne dolosse with a double row of 30 tonne dolosse placed in front of the toe of the roundhead. The armouring of the south breakwater comprises a double layer of 5 tonne dolosse on the root, 20 tonne dolosse on the trunk and 30 tonne dolosse on the head. The head of the breakwater is protected with three layers of 30 tonne dolos units.

A severe storm in April 2007 caused further damage to the breakwaters, especially at the head of the south breakwater. The wave height recorded was 8.5 m. The damage level established following a survey performed in May 2007 concluded that the south breakwater’s roundhead was in a state of near failure and urgent repairs were required (CSIR, 2007). Other sections of the breakwater were also damaged but required no urgent repairs. Since then, temporary measures have been adopted to avoid the spread of the damage along the breakwaters while new permanent repairs are planned. These involved the placement of spare 30 tonne dolosse onto the damaged roundhead by land based equipment.

Together with TRANSNET engineers, the CSIR began investigations into testing different repair options based on
existing equipment and spare dolos units available at the port. At present the equipment available to the repair to the roundhead is limited to a load to a land based repair. The repair alternatives are evaluated in this study. The antifer cubes and cubipod units do not have a size restriction. Therefore heavier units can be manufactured without changing the stability of the unit compared to dolos units. However, dolos have a size limitation because of its slenderness, presently dolos heavier than 30-tonne fracture easily and should be recognised. The model tests were carried out at a scale of 1:75 based on the Froude Law.

1.1 Objective of the study

The objective of this study was to consider repair options for the roundhead of the south breakwater.

A comparison of the hydraulic stability of the various repair options are listed below:

A) Repair the slope with 30 tonne dolos units using the existing design;
B) 30 tonne dolos units joined together in cluster of three (using ultra high molecular weight polyetherlyne UHMWPE rope);
C) Repair with 65 tonne antifer cubes;
D) Repair the slope with 65 tonne cubipod units; and
E) Place two caissons in front of the breakwater and extend the roundhead towards the caisson.

A bathymetric survey provided sufficient information about the current state of the sea bottom in the surroundings of the south breakwater. The multi-beam survey data were processed and a map with the depth-contour lines was drawn, with spot heights, see Figure 2. The levels seen on the chart are referenced in metres (m) to chart datum (CD).

![Figure 1. Location of the Port of Richards Bay, South Africa (Google Earth, 2015).](image)

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![Figure 2. LIDAR and multibeam soundings of the south breakwater roundhead.](image)

Figure 2. LIDAR and multibeam soundings of the south breakwater roundhead.
1.2 Model Tests

The irregular wave field was described with a JONSWAP spectrum and used as the input signal for wave generation. The water level and wave parameters, which were calibrated in the physical model study represent conditions expected along the South African coastline (Rossouw and Rossouw, 1999) and (Theron, 2011), are summarized in Table 1.

<table>
<thead>
<tr>
<th>Test runs</th>
<th>Return period (yr)</th>
<th>Hmo (m)</th>
<th>Tp (s)</th>
<th>Water level at Structure (m MSL)</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>1</td>
<td>4</td>
<td>12</td>
<td>0</td>
<td>2600</td>
</tr>
<tr>
<td>Test 2</td>
<td>1</td>
<td>4</td>
<td>12</td>
<td>0</td>
<td>2600</td>
</tr>
<tr>
<td>Test 3</td>
<td>5</td>
<td>4</td>
<td>16</td>
<td>0</td>
<td>2500</td>
</tr>
<tr>
<td>Test 4</td>
<td>20</td>
<td>6</td>
<td>14</td>
<td>0</td>
<td>2500</td>
</tr>
<tr>
<td>Test 5</td>
<td>20</td>
<td>6</td>
<td>16</td>
<td>+5</td>
<td>2500</td>
</tr>
<tr>
<td>Test 6</td>
<td>50</td>
<td>8</td>
<td>16</td>
<td>+5</td>
<td>2500</td>
</tr>
<tr>
<td>Test 7</td>
<td>50</td>
<td>8</td>
<td>16</td>
<td>+5</td>
<td>2500</td>
</tr>
<tr>
<td>Test 8</td>
<td>100</td>
<td>10</td>
<td>16</td>
<td>+5</td>
<td>2500</td>
</tr>
<tr>
<td>Test 9</td>
<td>100+20%</td>
<td>12</td>
<td>16</td>
<td>+5</td>
<td>2500</td>
</tr>
</tbody>
</table>

The breakwater was built following the conventional prototype construction process: The core material, underlayer and toe protection were placed sequentially without compaction and within the limits marked for each layer of the design template. This procedure replicates the high porosity obtained in the actual construction (Burcharth, 1999).

The existing armour layer (30 tonne dolosse) contained large quantities of both broken and displaced dolosse. Available scale dolos units and stones were used to build this layer of the model. To simulate the effect of the broken pieces, stones of about half the dolos weight were placed between the non-broken dolos units. As a result, no broken model dolos units were used for the construction of the model.

The transitional slope of 1:15 begins at distance 4.5 m built in the basin to connect the deep water with shallower water wave transformation close to the roundhead. Thereafter, the bathymetry was scaled and constructed along the next 20 m of the basin. The last 3 m were used to construct a gravel beach that absorbed the remaining wave energy. A sketch of the seabed profile in relation to the model basin floor is presented in Figure 3.

![Figure 3: Seabed section profile and location of breakwater in the basin.](image)

After the seabed was constructed and the wave calibration exercise completed, the breakwater section was constructed with dolos armour following a sequential process of assessment of the five options for repair. The images of the roundhead are shown in Figure 4 (label A to E).
The roundhead was constructed with three layers of 30 tonne dolosse for option A. The 30 tonne units extended from the roundhead landwards for 100 m (prototype) after which 20 tonne units were used. The trunk section was made up of 20 tonne dolosse and continued to the root of the breakwater. The test section constructed in the model only represented 350 m of the breakwater starting at the roundhead progressing towards the root. The breakwater in prototype extends further to a length of 1400 m. The roundhead was tested with nine wave conditions then repaired with option B to E repeating the conditions listed in Table 1. Each armour unit was tested considering two water levels (low and high astronomical tide) and nine different wave conditions, which correspond to the design storms for different return periods indicated in Table 1.
The test series was carried out to replicate the as-built structure and simulate the present damage observed on the prototype roundhead. Figure 5 shows the breakwater roundhead and portion of the trunk during a test. Figure 6 presents the plan view sketch indicating the camera station locations as well as the wave probe locations.

The location of the six cameras shown in Figure 6 was used to take photographs before and after each test. The displacement of armour units were then tracked and recorded using the armour track software. Before and after each test, pictures were taken to be compared using the software. In this way the movements of the armour units within the corresponding reference area were distinguished and quantified to establish the stability of the structure (Phelp and Tulsi, 2006).
1.3 TEST RESULTS

The damage progression recorded at the six camera stations is presented in Figures 7 to 12. The repair alternatives consisted of covering the damaged structure with new concrete armour units. Five repair alternatives were investigated, such being using the available 30 tonne dolos on site representing a repair to as built design (Option A), or using the existing 30 tonne dolos in cluster of three by attaching UHMWPE (Option B), 65 tonne antifer cubes (Option D), 65 tonne cubipod units (Option C) and two 29 000 tonne caissons (Option E).

During the five experimental options, the damage was concentrated along the water line with the exception of the caisson where scour around the bed of the caisson occurred. The displacements were mainly caused by wave breaking and turbulent eddies on the leeward side of the roundhead. At the roundhead of the breakwater, the incident wave diverts to the seaward and leeward trunk, traversing along creating instabilities to the armour units.

During the tests waves overtop the breakwater impacting the lee side close to the water line. This impact exerts a force on the units that is directed down the leeward slope and adds to the turbulent forces of the waves propagating by diffraction around the head. These forces are only counteracted by friction between armour units. Therefore, the units at this particular location are less stable due to the relationship of test to number of displacements seen in Station 1 (Figure 7) and Station 6 (Figure 12).

Figure 7 shows the comparison of the damage progression of the five options tested at station 1 over the nine Test conditions. Option A (30 tonne dolosse) had the highest amount of displacements whereas option B to E results were minimal. The lowest displacements at this trunk section were during the cubipod roundhead option (C).

![Figure 7: Camera station 1 damage progression for the five alternatives with image location 200 m -300 m seaward](image)
The 30 tonne dolosse at station 2 (50m section before the roundhead) followed a similar pattern as Station 1, however the dolos units showed good stability with antifer cubes at the roundhead (Option D) as opposed to chained dolos units (Option B) or even cubipod (Option C) units.

Station 3 was repaired with option B (chained clusters of three dolos units), option C (65 tonne cubipod units), option D (65 tonne antifer cubes), option E (two 29 000 tonne caissons).

Options C, D and E were a complete removal of existing dolos units and replaced with new armour units transitioned
to the existing dolos along the trunk of the breakwater. These repair options are seen as positive for the roundhead as displacements after nine Test conditions show no movement at this location (Figure 9).

![Camera Station 4 (Roundhead leeward)](image)

**Figure 10:** Camera station 4 damage progressions for the five alternatives with image location roundhead lee side

The results from station 4 are similar to that of station 3 as seen in Figure 10. However, the displacement progression for option A is much higher indicating damage will become more severe.

![Camera Station 5 (Location 300 m to 350 m Leeward side)](image)

**Figure 11:** Camera station 5 damage progressions for the five alternatives with image location 300 m – 350 m Lee side

Station 5 dolos units along the leeward trunk of the breakwater depicts displacement of dolos units when the roundhead
is repaired for option C, D and E. Option A show the result if 30 tonne dolos units are used to repair the roundhead. However, the chained dolos units (option B) result in lower displacements other than options for this station, seen in Figure 10. This can be attributed to higher overtopping and more turbulence created as waves diffract around the roundhead by the other options.

Figure 12: Camera station 6 damage progressions for the five alternatives with image location 200 m – 300 m Leeward side

When looking at the different repair options the antifer cubes, cubipod and caisson would be more stable than the 30 tonne dolos units at the roundhead. This is explained by the different resistance mechanisms of these units in comparison to the dolos. The antifer cube, cubipod and caisson unit withstands the wave loads and water flow mainly due to its mass, whilst dolosse resists movement by the interlocking between units. However wave overtopping and turbulence by eddies is not favourable as wave energy is transferred along to breakwater to weaker trunk sections past the repaired section.

2 CONCLUSIONS

The main failure mechanism of the five repair alternatives is the displacement of units along the water line. The damage was concentrated along the water line, mainly 200 m seaward and leeward of the roundhead. In the design of the roundhead armour units, the stability formulae applied are the same as for the trunk. The placement of units at the roundhead is more complicated than other sections of the breakwater because of the convex shape of this section. Therefore, the specified packing densities are not that easy to achieve during construction of the repair works, even though a regular grid is used to assist the placement of units, the wave climate may not be favourable.

2.1 Dolos repair alternative with no change in original design (Option A)

To ensure the stability of the roundhead, it should be constructed with dolos units almost twice as heavy as the dolosse placed at the trunk. However, in the actual roundhead construction, the placed dolosse are just 1.5 times heavier than the units at the trunk, resulting possibly in more damage to the roundhead. Although there are many records of broken dolosse at the roundhead, this is not the main structural failure mechanism. However, the broken pieces should be taken into account in future storms because they can act as projectiles and increase the future damage of the structure.

At the roundhead the dolosse are less interlocked due to the convex shape of this section. Therefore, the armour layer will be more vulnerable to wave action, and care needs to be taken during placement. This means that the unit size is limited to avoid too much breakage of units.
2.2 30 Tonne chained / tied (UHMWPE rope) dolos repair alternative (Option B)

At the roundhead the 30 tonne dolos chained / tied in a cluster placement is more complex than dolos alone and due to the convex shape of this section it will require very skilled contractors. Therefore, the appropriate interlocking between units is more difficult to achieve. This may lead to a less stable armour layer; however it has not been tested before in reality as slope support but rather as toe support.

Since the chain is fastened to the dolos units it may result in structure failure of units by the chain / UHMWPE ropes creating additional load forces between individual units. Further investigations are necessary.

It has been noticed that the chains keep the units interlocked with existing dolosse resulting in very limited movement. However, at the roundhead due to placement difficulties and wave conditions, their performance is still to be tested.

2.3 Antifer cube repair alternative (Option D)

The antifer cube size has been determined using Chegini formula (Chegini et al., 2005). The formula includes larger number of relevant parameters to estimate the unit size. As a result the same armour unit size can be used for the whole structure.

The antifer cubes are randomly placed at the roundhead. This placement is not as difficult as for the interlocking units because it requires fewer placement specifications to be met. Therefore, due to the wave conditions expected at Richards Bay this repair alternative is possible. However, the required packing density is difficult to achieve due to the convex shape of the roundhead, which may lead to a more vulnerable structure.

The largest wave overtopping was noticed while testing with antifer cubes placed at the roundhead. This resulted in more frequent waves overtopping onto the leeward slope protected with dolos units (station 5 and station 6). If this option is to be selected in reality the antifer cubes should be extended further down the leeward section of the breakwater to limit further damage.

A new toe protection would have to be built in front of the first row of antifer cubes to ensure their stability. This may increase the total constructions costs of the repair alternative which needs to be further investigated, especially due to the fact that a crane with a longer reach will be required or to carry out the construction using a floating barge.

From the point of view of unit stability, massive armour units such as antifer cubes are not size limited. Therefore, the construction of 65 tonne antifer cube with a density of 2400 kg/m³ is possible for a low maintenance option, which would constitute a stable repair option for the roundhead only. This may have to continue further depending on the interlocking on the seaward and leeward slopes.

2.4 Cubipod repair alternative (Option C)

The cubipod units were compared to antifer cubes option for the study to limit overtopping. The cubipod performed slightly better than antifer cubes. The repair option is coupled with a redesign of the roundhead and extension of new armour units down the seaward and leeward trunk. This however, should be considered when costing the repair with Option D and E. A further cost analysis should be carried out to determine the most feasible option.

From the damage observed during the tests, the critical area located between 100 and 150 degrees from the incident wave direction should be redesigned to reduce its damage.

2.5 Caisson roundhead repair alternative (Option E)

Similar to option C, D the caisson head would require a redesign and additional expense for the repair. The caisson head showed similar overtopping volumes and displacement to existing dolos along the trunk that were not affected before option C, D and E. A cost analysis should be carried out to investigate the viability of this option.

In conclusion, the repair options most favourable in the short term are to simply repair the dolos slope with additional units and after storms monitor and repair the damaged sections. This option can be reinforced by creating clusters of three units and chaining of units by using UHMWPE rope slings to secure dolosse from being displaced. This can help in limiting initial rocking as well as allowing multiply units to withstand storms rather than individual units. However, limited prototype information is available for this option and should be investigated further. If funding is available a possible solution is to redesign the breakwater with the heavier alternative armour unit to reduce further maintenance costs.

ACKNOWLEDGEMENT

This study was financed by TRANSNET National Port Authority for the Port of Richards Bay. This support is gratefully acknowledged. The study formed part of a knowledge and skills transfer between CSIR and Port of Richards Bay engineering team whom are acknowledged for their participation in the field investigation and model study.
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