SOHAR BREAKWATERS – COST BASED RISK ASSESSMENT

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ABSTRACT

The Port of Sohar (Oman) is protected by two breakwaters which were damaged during the 2007 tropical cyclone Gonu. Extensive surveys were carried out in the past to determine the extent of the damage and studies were made for repair and upgrade designs. However, the costs for the proposed repairs showed so large that in 2016 repairs still had not been carried out.

When asked for its opinion, Royal HaskoningDHV advised the port that in the decision making process to repair the breakwaters an important item was overlooked, i.e. that also the repaired breakwaters would have a certain risk to be damaged. Consequently, the repair should only be made in case the benefits from the repair (reduction of risk) would outweigh the costs for such repair.

Following these observations, Royal HaskoningDHV was requested to quantify this in a cost based risk assessment. An important element in this quantification was finding a relationship between the damage to the concrete armour units (predominantly showing settlement) and the occurring wave conditions. Such relationship was established based on the model tests carried out in the past and relates the number of settling armour units (N_{od}) to the incident wave conditions (H_{m0}, T_p), the packing density of the armour units (ϕ) and the number of waves in a storm (N_w). Using this established relationship the present and future risk of the breakwaters could be quantified, taking into account the probability of the occurring wave conditions. The approach to the cost based risk assessment, the damage function and the results of the analysis are presented below.

1 SOHAR BREAKWATERS – HISTORY

1.1 The Port of Sohar

The Port of Sohar is located in the North of Oman, some 250 km south of the Strait of Hormuz (Figure 1).

Figure 1 The Port of Sohar, Oman (situation in 2007)

Construction of the port commenced in 2000 and the breakwaters were completed in 2002. The breakwaters are built as rubble mound breakwaters provided with CORE-LOC™ armour units. Typical cross sections of the north and south breakwater are presented in Figure 2 and Figure 3. The north breakwater is provided with 1.6 m^3 CORE-LOC™ and the south breakwater with 3 m^3 CORE-LOC™.

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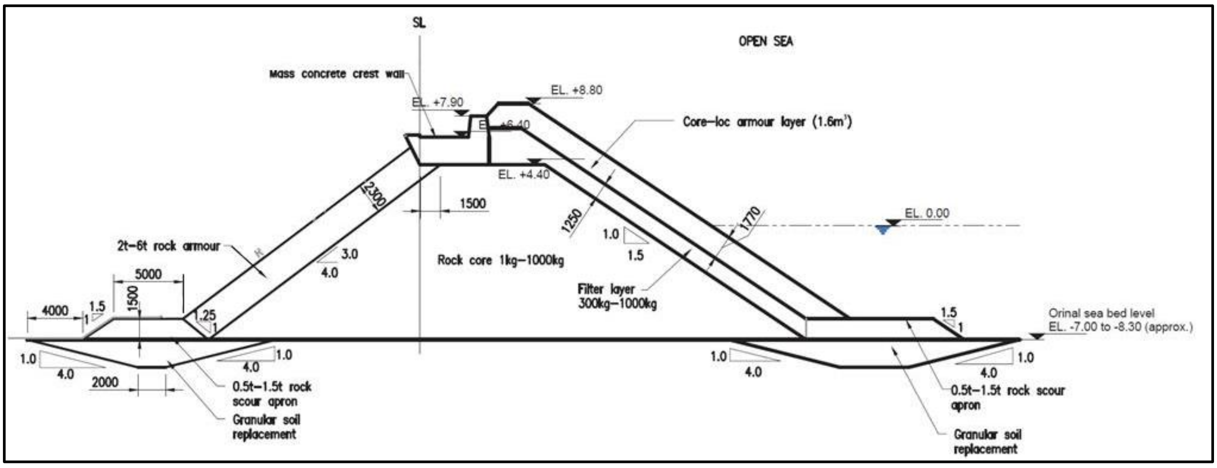


Figure 2 Sohar north breakwater (2007)

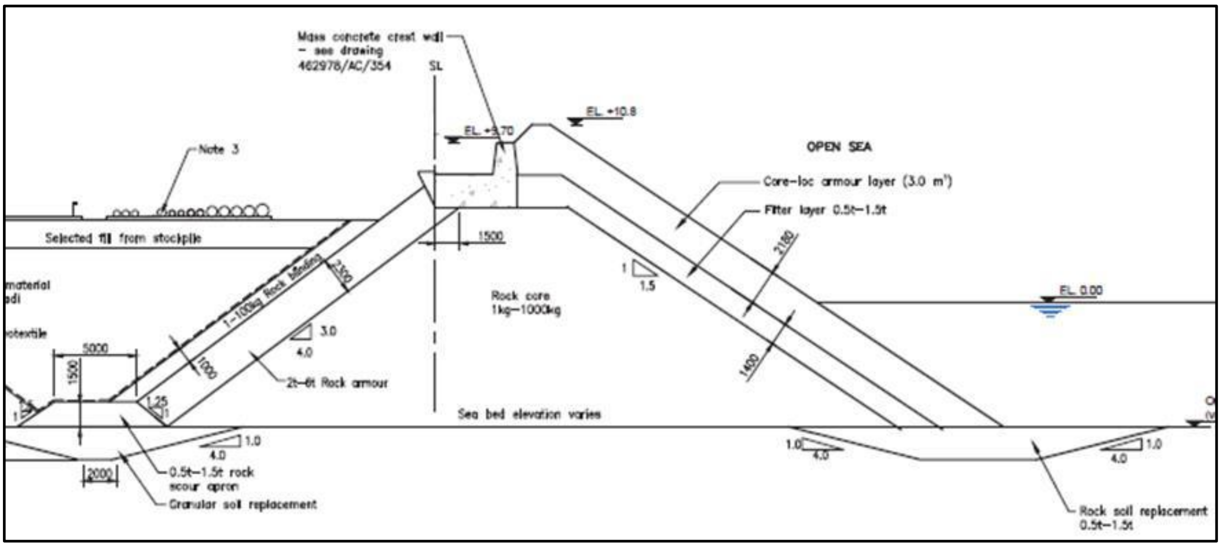


Figure 3 Sohar south breakwater (2007)

1.2 Tropical cyclone Gonu

In May 2007 tropical cyclone (TC) Gonu occurred on the Arabian Sea and was ultimately classified as a super cyclonic storm. Due to interaction with the dry Arabian Peninsula, TC Gonu decreased in intensity by the time it emerged in the Gulf of Oman and was degraded to a severe cyclonic storm and subsequently to a cyclonic storm on 7th of June just before it made landfall in Iran (Figure 4).

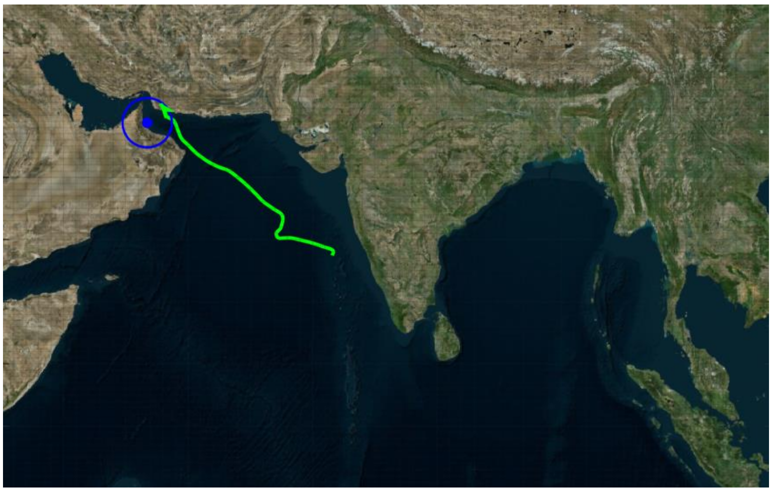


Figure 4 TC Gonu track, passing Sohar at 166 km distance (Source: Joint Typhoon Warning Centre)

1.3 Damage to the breakwaters

When TC Gonu passed the Port of Sohar, large waves hit the breakwaters resulting in large wave overtopping (Figure 5). Although no measured wave data are available during the passage of tropical cyclone Gonu, anecdotal evidence suggests that waves were up to 3-3.5 m in height lasting over a 48-hour period, with a wave period of about 7s (Ibn Khaldun-Halcrow, 2007).

Figure 5 Heavy wave attack and overtopping on the south breakwater during TC Gonu

A visual inspection of the breakwaters undertaken immediately after the passage of TC Gonu revealed the following damage to both the north and south breakwaters (Ibn Khaldun-Halcrow, 2007), (Baird, 2010):

- The inside roadway on the south breakwater (approximately between Ch. 1400-1900) was impacted by wave overtopping, with the platform corridor material, rock fill, and geotextile interlayer being displaced.
- Some of the pipelines on the inside of the south breakwater were displaced by rock fill moved during the storm. The inside face of the south breakwaters did not sustain any damage between Ch. 1900 and the roundhead.
- Several CORE-LOC^{TM} units were displaced on the south breakwater, mainly between Ch. 1800 and 2900.
- The filter/under layer became significantly exposed in certain areas, specifically between Ch. 2060 and 2130 on the south breakwater. In other areas, the damage was not quite as significant; however, there are “fault lines” or seams between sets of units where the filter layer is exposed.
- It appeared that there was some settling of CORE-LOC^{TM} units down the slope of the seaward side for both breakwaters.
- A few CORE-LOC^{TM} units were broken on both breakwaters.
- The dive inspection did not show any real displacement of units underwater, nor did it show any broken units, nor did it show any units being deposited at the toe of the structure.

1.4 Investigations 2007 - 2014

The damage inflicted on the breakwaters was such that extensive surveys, studies and investigations were performed in the years 2007 – 2014 to record the damage to the breakwaters in detail, explain why tropical cyclone Gonu had such large effect on the breakwaters and provide recommendations for repair.

It goes beyond the scope of this paper to reflect on all these studies, but to repair the breakwaters it was basically recommended to remove all CORE-LOC^{TM} armour units from the slopes of the north and south breakwater and replace them at a higher packing density (Halcrow Middle East LLC, 2014).

The cost implication of this recommendation was large. Cost estimates for repositioning of all CORE-LOC^{TM} units ran into millions of Omani Rial (OMR) and consequently these repairs were not immediately carried out.

1.5 New tender

As the costs for the recommended full repair are so large, Sohar Industrial Port Company in 2016 launched a new tender for consultancy services to upgrade the breakwaters, with the clear objective to optimize the costs for repair. The services were awarded to Royal HaskoningDHV, primarily as the proposed “cost based risk assessment” for the breakwaters aimed to identify whether the repairs recommended in the past could be justified from an economical point of view. The approach thereto and the outcome thereof are further discussed below.

2 METHODOLOGY TO THE COST BASED RISK ASSESSMENT

2.1 Repairs decision process

With the breakwaters clearly being damaged by TC Gonu it makes common sense to expect that there is a risk of further damages. The more important question is though whether this risk is small or large. In case of a small risk, one may decide to accept the risk. But in case the risk is (very) large, one would likely decide to repair the breakwater. Hence it is required to quantify the risk.

In order to quantify a risk there are two components to be addressed: the probability that an event happens and the consequences of that event. If an event is to happen frequently, one would like to see that (negative) consequences such as casualties, damages and economic loss due to such event are low or non-existent. High (negative) consequences are essentially never acceptable which in practical terms implies that the probability of occurrence of such event should be (very) small. So, assuming that the future damage risk of the current breakwaters can be quantified (being either high or low), the question remains: “when to decide to invest in a repair of the breakwaters?”

A repair of the breakwaters at this moment will require a substantial amount of money. But once the breakwaters have been repaired there will still be a risk that the repaired breakwaters could be damaged, even when there is a clear objective of the repair to reduce the remaining risk. Adopting that the investment in a repair should result in at least a reasonable reduction of the risk, it makes sense to do this repair only in case the present day repair costs are reasonably lower than the reduction in risk due to that repair. Assuming that the risk can be expressed in money (in this case OMR), the repairs would only be justified if:

Repair costs < Present risk – Future risk

2.2 Risk

2.2.1 Cost based risk

As discussed above a risk consists of two components: the probability of an event and the consequence of that event. Consequences of an event could be casualties, direct damages and indirect damages.

When looking at the TC Gonu type of environmental conditions (Figure 5) it is assessed that under extreme conditions no staff will be on or near the breakwaters and for the risk assessment of the breakwaters it will be assumed that the risk of casualties on the breakwaters will be extremely low. Hence loss of life or other casualties has NOT been taken into account in the risk assessment and breakwater repair decision process.

The risk assessment therewith becomes a cost based risk assessment in which the consequence of an event (like TC Gonu) is expressed in OMR. Based on this approach the risk is calculated as:

$$Risk_{OMR} = P_r\,(\text{event}) \times C_{OMR}\,(\text{event}) \quad (1)$$

Where the risk is expressed in OMR, P_r is the probability of occurrence of an event and C is the cost consequence of the event expressed in OMR.

The cost consequence of an event not only addresses the costs of damage to the breakwater itself (direct damage to the civil structure), but may also include the consequential damages. For instance in case the port or a terminal cannot be used for a certain period of time until repair has been carried out. It is assumed that these consequential damages can also be expressed in costs.

2.2.2 Proposed repairs and future risk

The studies that have been carried out in the past included different methods of repair. (Halcrow Middle East LLC, 2014) in particular mentions 3 methods:

- Base repair, i.e. rebuild the breakwater to the original design with a packing density of the armour units of $\phi = 0.57$.

- Repack all armour units above LAT to the latest recommended packing density of about ϕ = 0.63 (CLI, 2012).
- Repack the full existing slope to latest CLI packing density about ϕ = 0.63.

When such repairs are considered, the effect of such repairs on the future risk needs to be taken into account. Hence, also for these repairs a (future) risk assessment will be required.

2.2.3 Direct damage

To assess the risk, both the occurrence of an event and the consequence of an event need to be addressed. With respect to the latter, the consequences of TC Gonu in terms of direct damages to the breakwater can be summarized as follows (Baird, 2010):

- Displacement of CORE-LOC™ units along the slope of the breakwaters, resulting in “a higher than expected packing density in most areas on the underwater slope of the breakwaters” and “a general reduction in the packing density of CORE-LOC™ units on the above water breakwater slope” (Figure 6). Hence, the change in packing density is a consequence of the displacement of the armour units down the slope under the influence of incident wave conditions. This applies to both breakwaters (north and south).
- Another type of damage identified during the assessment relates to areas where the toe of the breakwater armour layer has been compromised. This deficiency exists at several locations on both the north and south breakwaters. This type of damage was observed in areas where it was apparent that there was a mass accumulation of units at the bottom of the slope.
- Approximately 35 broken CORE-LOC™ units were observed within the study area. Most of these remain within the interlocking grid and would only need to be replaced in areas where the repacking is required.
- The final type of damage or as-built non-conformance relates to armour units that were observed sitting on top of and outside of the interlocking grid.

Figure 6 Impression of (local) damages after TC Gonu
Left: north breakwater. Right: south breakwater

Further, (Baird, 2010) observes that the main cause of damage is formed by the wave and water level conditions that occurred during TC Gonu.

Based on the above it is concluded that the risk of damage to the breakwaters is dominated by the probability of wave and water level conditions to occur. The consequences of these events are predominantly driven by the displacement of armour units. The latter in turn are affected by the (as constructed) packing density of CORE-LOCTM units. Displacements of the armour units in turn result in higher packing density and accumulation of armour units under water, a reduction in packing density above water, as well as a higher probability that armour units hit each other and break.

For a proper risk assessment in relation to this type of damage it will be required that:

- A clear relationship is established between the wave and water level conditions and the displacements of armour units or changes in packing density.
- The damage level is defined e.g. in terms of number of displaced armour units, for both the present and the repaired breakwater condition.
- A proper joint probability assessment of wave and water level conditions has been carried out and is available.

2.2.4 Indirect damage

No indirect damages are reported by (Baird, 2010) nor by (Halcrow Middle East LLC, 2014). But most likely indirect damages are to be expected in case overtopping of the breakwater becomes too high. In such event the operations behind the breakwaters will be affected (e.g. shut-down). For the north breakwater the (future) container terminal operations might be under threat in such an event and for the south breakwater the pipelines and/or the inside revetment rock layers might be under threat in such a case. Overtopping and how it relates to the indirect damage has been addressed in the studies by Royal HaskoningDHV, but does not form part of the present paper.

3 THE DAMAGE MODEL

3.1 Damage development

As discussed above, for the risk assessment of the breakwaters a relationship between wave and water level conditions and displacement of armour units and/or packing density will be required. But such damage function is not a priori defined. This is illustrated by the (2012) design guideline for CORE-LOC™ (CLI, 2012), which applies the Hudson formula to determine the size of the armour unit:

$$\frac{H_S}{\Delta \cdot D_n} := \left(K_D \cdot \cot\alpha\right)^{\frac{1}{3}} \tag{2}$$

The ratio between design wave height H_s (m) and unit size D_n (m) and relative density Δ (-) is a fixed value based on slope gradient and stability coefficient K_d.

Hence, in case the incident waves increase beyond the design wave and the size of the CORE-LOC™ is fixed, there is no indication what is to be expected for the damage to the breakwaters.

But it is obvious that damage has been inflicted by TC Gonu and one may question whether damage will not develop further. As literature does not provide information on the damage development to be expected, results of the available 2-D model tests for the 2013 base and upgrade repair method of the Sohar breakwaters have been used to develop such damage function.

When looking at concrete armour units, the Rock Manual (CIRIA; CUR; CETMET, 2007) provides the following relationships between damage and incident wave conditions for cubes and Tetrapods in a double layer:

Type of armour	Design formula / relationship
Double layer of randomly placed **cubes**	$\frac{H_s}{\Delta D_n} = \left(6.7\frac{N_{od}^{0.4}}{N^{0.3}} + 1.0\right) s_{om}^{-0.1}$
Double layer of randomly placed **Tetrapods** (surging waves)	$\frac{H_s}{\Delta D_n} = \left(3.75\left(\frac{N_{od}}{\sqrt{N}}\right)^{0.5} + 0.85\right) s_{om}^{-0.2}$
Double layer of randomly placed **Tetrapods** (plunging waves)	$\frac{H_s}{\Delta D_n} = \left(8.6\left(\frac{N_{od}}{\sqrt{N}}\right)^{0.5} + 3.94\right) s_{om}^{0.2}$

Table 1: Relationships between damage and wave conditions for cubes & Tetrapods (CIRIA; CUR; CETMET, 2007)

From these formulae it follows that:

- The damage (N_{od} = number of displaced[4] armour units in a D_n wide strip of the breakwater) is non-linearly dependent on $H_s/\Delta D_n$.
- The damage is non-linearly dependent on the number of waves N.
- The damage is non-linearly affected by the steepness (s_{0m}) of the incident waves and thus dependent on the wave period (T_m).

[4] Displaced here actually should be read as "extracted" instead of "settled".

As these formulae do not only include the wave height, but also the wave period and the duration of the storm (i.e. number of waves), this type of formula has been taken as a starting point to develop a relationship between wave parameters and damage to the Sohar breakwaters, i.e.:

$$N_{od} := \left(\frac{\frac{H_s}{\Delta \cdot D_n}}{\alpha_1} \right)^{\alpha_2} \cdot s_{0p}^{\ \alpha_3} \cdot N_w^{\ \alpha_4} \tag{3}$$

where the coefficients α_1 to α_4 are to be determined. To do this, a decision must be made which damage parameter to select, where particularly the available 2-D model test reports (HR Wallingford, 2013) on the base repair and upgrade repair provide data on:

- Displaced armour units, within different categories of displacement[5]:
  - Category 1: $0.1{*}D_n$ < displacement < $0.5{*}D_n$
  - Category 2: $0.5{*}D_n$ < displacement < $1.0{*}D_n$
  - Category 3: displacement > $1.0{*}D_n$
- Rocking armour units.
- Extracted armour units.

Looking at the available model tests results, the amount of extracted units and rocking units showed to be so small that this data provide insufficient information to develop a clear dedicated damage function. Hence the number of displaced armour units has been taken as damage parameter.

To demonstrate the viability to select the number of displaced (settled) armour units as "damage parameter" in relation to the observed damages at the Port of Sohar, the following model of thought discusses the relations between packing density and armour unit displacements.

3.2 Relation between upslope and downslope packing densities

Assuming that no armour units are being extracted and that the units mostly displace downslope, the average packing density upslope (φ_1) is affected by the change in packing density downslope (φ_2) relative to an initial packing density (φ_0) and to the length of the (compacted) downslope L_2 relative to the total slope length L_0 (all based on continuity). Based on this approach the mean upslope packing density can be computed by the following relationship:

$$\phi_1(L_2, \phi_2) := \phi_2 + \frac{L_0}{L_0 - L_2} \cdot (\phi_0 - \phi_2) \tag{4}$$

Starting with L_0 = 100, L_2 can be interpreted as the percentage of the total slope (as L_0 = 100) having an increased packing density ϕ_2. Starting with ϕ_0 = 0.58 the effect of an increasing downslope packing ϕ_2 on the upslope packing density ϕ_1 is shown in Figure 7:

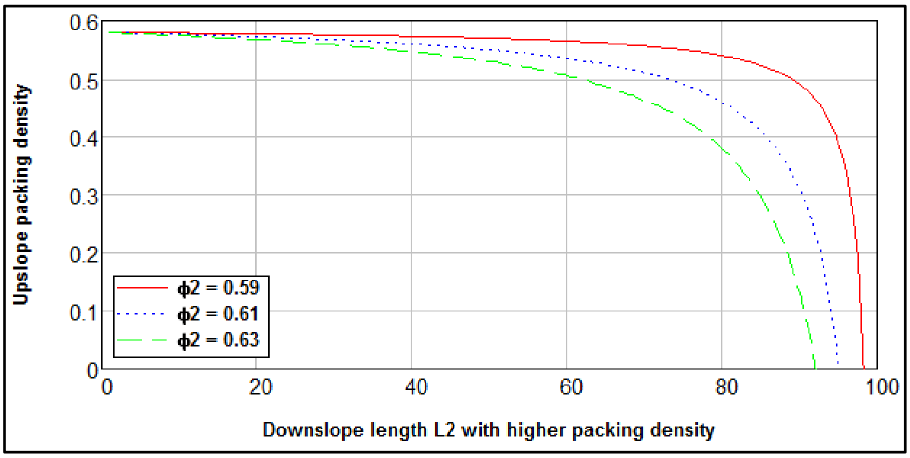


Figure 7: Theoretical effect of downslope packing density (ϕ_2) on upslope packing density (ϕ_1). Initial packing density is ϕ_0 = 0.58.

[5] Here displacement should be read as "settlement" instead of "extraction".

Figure 7 indicates that very low packing densities in the upslope region should result in case the packing density in the lower slope region increases AND in case the length of this part of the slope increases (meaning that more and more units have moved down the slope).

3.3 Packing density and armour unit displacements

By definition, the packing density can be calculated as:

$$\phi := \frac{D_n^{\ 2}}{D_h \cdot D_v} \tag{5}$$

Where D_h and D_v represent the horizontal and vertical placing distances of the armour units and D_n = $V^{1/3}$ where V represents the volume of an armour unit. Further using $D_v = D_h / 2$, this gives:

$$\phi := \frac{2 \cdot D_n^{\ 2}}{D_h^{\ 2}} \tag{6}$$

Given an aimed value for the packing density, the placing pattern D_v and D_h can be expressed in terms of D_n. This is shown below in Figure 8.

A packing density of ϕ = 0.57 would result in $D_h = 1.873*D_n$ and $D_v = 0.936*D_n$. It is to be observed though that in the observations on the displacement of CORE-LOC^{TM} units in the 2-D model tests, the minimum displacement considered is $0.1 \cdot D_n$ (lower limit Category 1 displacement). However, a change of +/- $0.1 \cdot D_n$ in above figure (around ϕ = 0.57) results in a variation in packing density of 0.52 to 0.63 (for D_h) and between 0.47 and 0.71 for D_v.

Hence, in case vertical displacements of $0.1 \cdot D_n$ result in compaction of the armour layer (typically under water) the packing density would increase theoretically to nearly 0.71. However, in case vertical displacements result in loosening of the armour layer (typically above water), the packing density may reduce to 0.47. Larger displacements obviously have an even larger impact on the packing density.

Albeit that this is a theoretical result and assumes that all (or many) armour units displace, the results are in fair agreement with the model tests and prototype observations. The warning is that the displacement of the armour units appears to have a large effect on the packing density. Many armour units showing even a small displacement may have a positive impact on the stability of the armour units when the amour layer compacts (lower part of the slope), but a negative impact when the armour layer loosens up (upper part of the slope). For larger displacement this effect becomes larger.

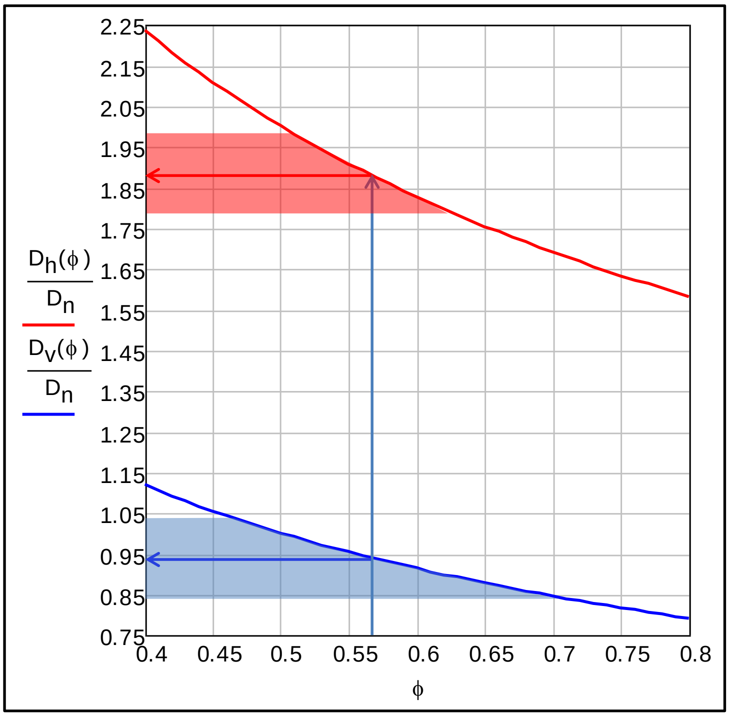


Figure 8: Effect of packing density on placing distances and vice versa

Using the above two theoretical models on the packing density, it is possible to couple downslope displacement of armour units (resulting in a compaction of the armour layer) with an upslope reduction in packing density, as shown in Figure 9.

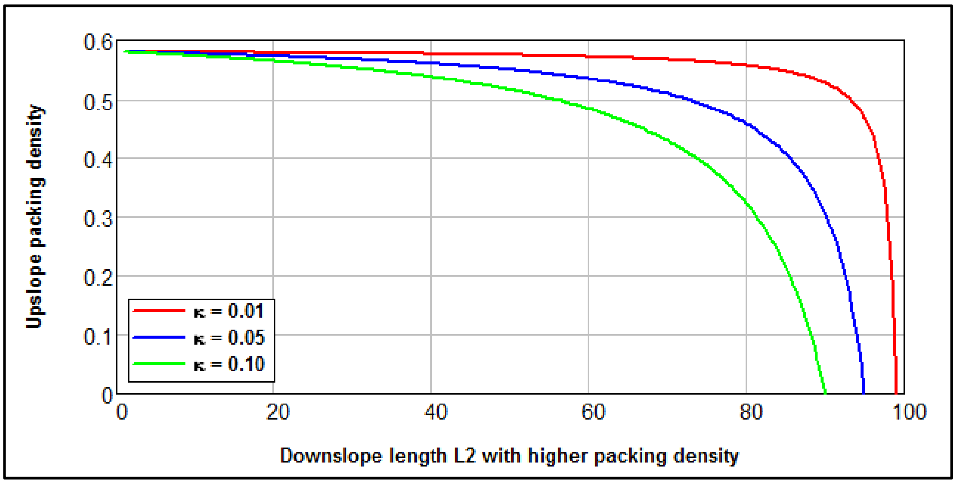


Figure 9: Effect of downslope displacements ($\Delta D_v = \kappa \cdot D_n$) on upslope reduction in packing density. Initial packing density is $\phi_0 = 0.58$.

Figure 9 demonstrates that, assuming a change in downslope packing density due to displacements of say $\kappa = 0.05*D_n$, the average upslope packing density reduces to about $\phi = 0.45$ in case 80% of the downslope armour is being compacted. When κ increases to $0.10*D_n$ such low upslope packing density is already reached when 2/3 of the total slope is compacted due to such displacements. Theoretically the upslope packing density only remains unaltered when there is no compaction (settlement) in the downslope area at all.

The conclusion to be drawn from this "model" is that even small displacements of many armour units (often interpreted as "initial settlement") may have a large effect on the packing density of the armour units in the upper regions of the slope. Hence, selecting displacements larger than $0.1 \cdot D_n$ (rather than $0.5 \cdot D_n$ or $1.0 \cdot D_n$) as damage parameter in the envisaged damage model makes sense.

Apart from this it may be questioned whether the classification of the displacements in the model tests (not addressing displacements less than $0.1D_n$) has been chosen wisely as smaller displacements may also result in reduced packing densities on the upper slope. Finally it may be questioned whether the common practise to neglect "initial settlement" as damage is justified. The above model suggests that any displacement after construction of the armour unit layer should be interpreted as damage.

3.4 Modified damage function

From the investigations into the damage of the Sohar breakwaters and above considerations it has become clear that the initial packing density of the CORE-LOC™ units affects the stability of the armour units. Therefore the <u>initial</u> (as-built) packing density (ϕ) preferably should be included in the damage function as well. This can be done in different ways, but as a lower packing density is assessed to affect the stability of the amour units in a negative way, the following basic relationship has been applied:

$$N_{od} := \left(\frac{\frac{H_s}{\Delta \cdot D_n}}{\alpha_1 \cdot \phi} \right)^{\alpha_2} \cdot s_{0p}{}^{\alpha_3} \cdot N_w{}^{\alpha_4} \tag{7}$$

where: N_{od} = Number of displaced (settled) CORE-LOC™ armour units in a strip D_n wide, accumulated during the test
H_s = H_{m0} = significant wave height
s_{0p} = Wave steepness = $H_{m0}/(gT_p^2/(2\pi)$
N_w = Number of waves
ϕ = Packing density at the start of the test
α_i = Coefficient (to be determined)

It is emphasized that the packing density is the <u>initial</u> packing density of the armour layer. The effect of reduced packing densities in the armour layer due to settlement in the layers is implicitly included in the results of the model tests themselves.

3.5 Final damage model

Taking equation (7) as a starting point, coefficients α_i were established by finding the fit resulting in the least squared error between calculated and observed N_{od} numbers. The best fitted results and coefficients are presented in Table 2:

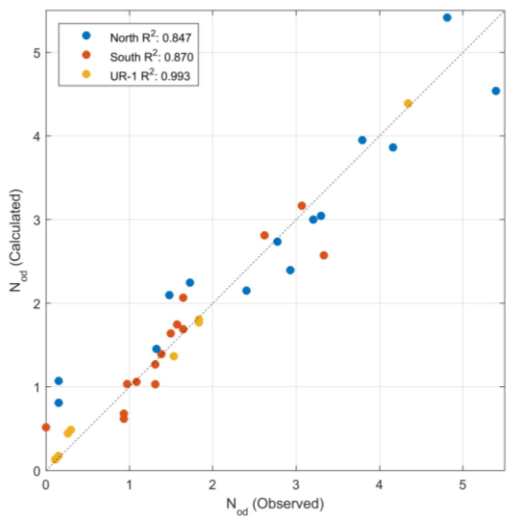
	α_1	α_2	α_3	
■ North breakwater (repair full slope)	5.0491	2.1309	-0.3671	
■ South breakwater (repair full slope)	5.4503	1.829	-0.2736	
■ South breakwater (repair above LAT)	7.7803	4.452	-0.8383	

Table 2: Best fit α coefficients for damage function

The result of the fitting analysis reveals that:

- There is a strong non-linear relation between N_{od} and H_{m0} ($\alpha_2 > 1$) which is in line with stability relationships for other armour units and rock.
- There is an inverse proportionality with s_{0p} ($\alpha_3 < 0$) indicating that lower steepness results in more damage. In turn this implies that longer waves (higher wave periods) result in more damage, which also is to be expected (based on experience).

The fitting procedure revealed that there was no clear relationship with the number of waves ($\alpha_4 = 0$), most likely since the number of waves in the model tests is more or less the same for all tests. Hence the number of waves is not included in the present damage function. From the figure included in Table 2 it can finally be observed that the resulting functions give a very reasonable prediction of the damage to be expected, but that there is still some scatter around the calculated values.

It is to be noted that, theoretically, this damage (or better: settlement) function could be applied to design CORE-LOC™ armour layers, however this is not advised and supported by the authors of this paper for the following arguments:

- Results and coefficients are based only on series of tests for this dedicated, single project.
- Results and coefficients are site dependent (e.g. affected by the specific particulars of the site like wave conditions and/or bathymetry and water level).
- It is unclear what damage number to use for "acceptable damage" or "failure".

Still, given the relationship found between damage and incident wave conditions, it seems worthwhile (in general) to carry out additional investigations into this "damage" function. Not only for the CORE-LOC™ armour unit, but also for other single layer armour units as it is expected that the found trend may apply to other armour units as well.

4 QUANTIFICATION OF THE COST BASED RISK ASSESSMENT

The cost based risk assessment for the CORE-LOC™ armour layer requires the probability of an event and the consequences of the event (damage) expressed in OMR. The probability of an event is dominated by the probability of occurrence of the wave conditions. The consequences are dominated by the expected damage to the CORE-LOC™ armour layer.

4.1 Wave conditions and probability

4.1.1 Nearshore wave statistics

The nearshore wave conditions at the locations of the north breakwater trunk and the south breakwater are presented in Figure 10 and Figure 11.

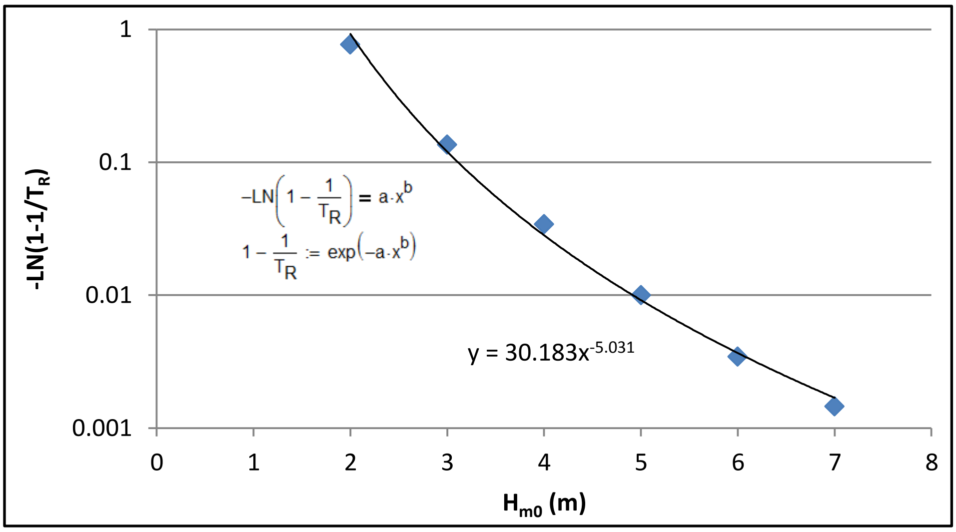


Figure 10 Non-exceedance probability function for the north breakwater. T_R = return period, H_{m0} = spectral significant wave height

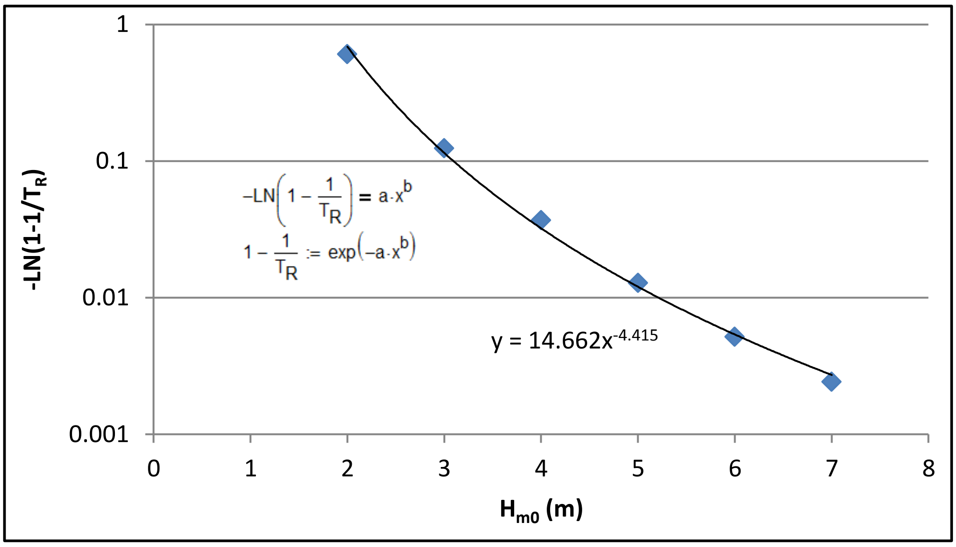


Figure 11 Non-exceedance probability function for the south breakwater. T_R = return period, H_{m0} = spectral significant wave height

The above probability functions represent the long term average probability on an annual basis. When the lifetime of the structure is to be included, the probability that a wave condition is NOT being exceeded in this lifetime $K(H_{m0})$ can be calculated by:

$$K(H_{m0}) = (F(H_{m0}))^{Nyrs} \quad (8)$$

where N_{yrs} is the lifetime of the breakwaters in years. The probability density function $k(H_{m0})$ is by definition the derivate of $K(H_{m0})$. An example of these functions is presented below for the south breakwater:

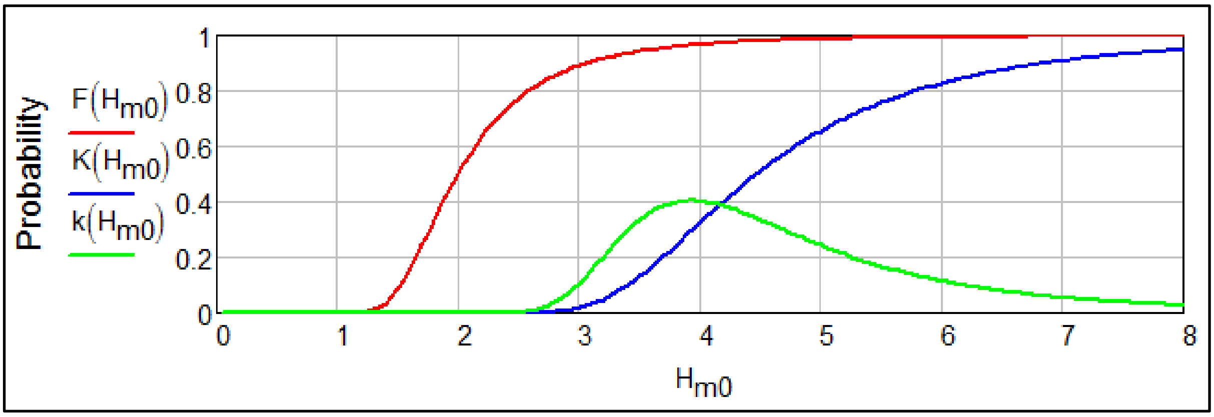


Figure 12 Probability functions for the south breakwater (similar for the north breakwater)

From Figure 12 it can be interpreted that the probability per year (■) that a wave height H_{m0} is smaller than 4m is 97% (hence a very small chance that it will be larger than 4m). But the probability that it will (always) be smaller than 4m during the (remaining) lifetime of the breakwater of 35 years (■) is 32% (hence a fairly large chance it will happen at least once in the lifetime that a wave height H_{m0} will be larger than 4m).

The probability density function (■) indicates that of the higher waves (H_{m0} > 2.5m) to occur during the remaining lifetime of the structure, most of these wave will be in the order of 4 m. The probability that these waves will reach wave heights in the order of 7 to 8 m is small.

4.1.2 Wave height – wave period relationships

The nearshore T_p~H_{m0} relationships as given in Table 3.

Location	T_p~H_{m0} relationship
North breakwater	$T_p(H_{m0}) := 5.9847 \cdot H_{m0}^{0.467}$
South breakwater	$T_p(H_{m0}) := 5.4788 \cdot H_{m0}^{0.4561}$

Table 3: Relationships between peak wave period T_p and near shore significant wave height H_{m0}

As the differences in coefficients at the two locations are small, also the differences in wave periods and wave steepness's between the two breakwaters are small.

4.2 Damage as function of wave height

Filling in the T_p~H_{m0} relationship in the damage function (7), the damage function becomes a function of H_{m0} only (for a fixed value of N), as shown in Figure 13. From this figure it can be observed that for a given wave height H_{m0} and more or less the same T_p (see Table 3) the north breakwater shows much more damage than the south breakwater. This is obvious since the CORE-LOC™ armour units on the north breakwater are smaller than those on the south breakwater. Apart from this, changing the packing density from ϕ = 0.57 (Base Repair) to ϕ = 0.63 (Upgrade Repair UR3) indeed reduces the damage to be expected, but not that much.

Also the south breakwater shows that a lower packing density (ϕ = 0.57, Base Repair) results in more damage than in case of a higher packing density (ϕ = 0.63 Upgrade Repair UR2). But more interesting to see is that the Upgrade Repair 1 (UR1, repacking above LAT with ϕ = 0.63) results in less damage compared to the Base Repair and UR2 in case the wave heights remain below about 6.5m. For wave heights larger than 6.5m the damage for UR1 will be larger than for Base Repair and UR2.

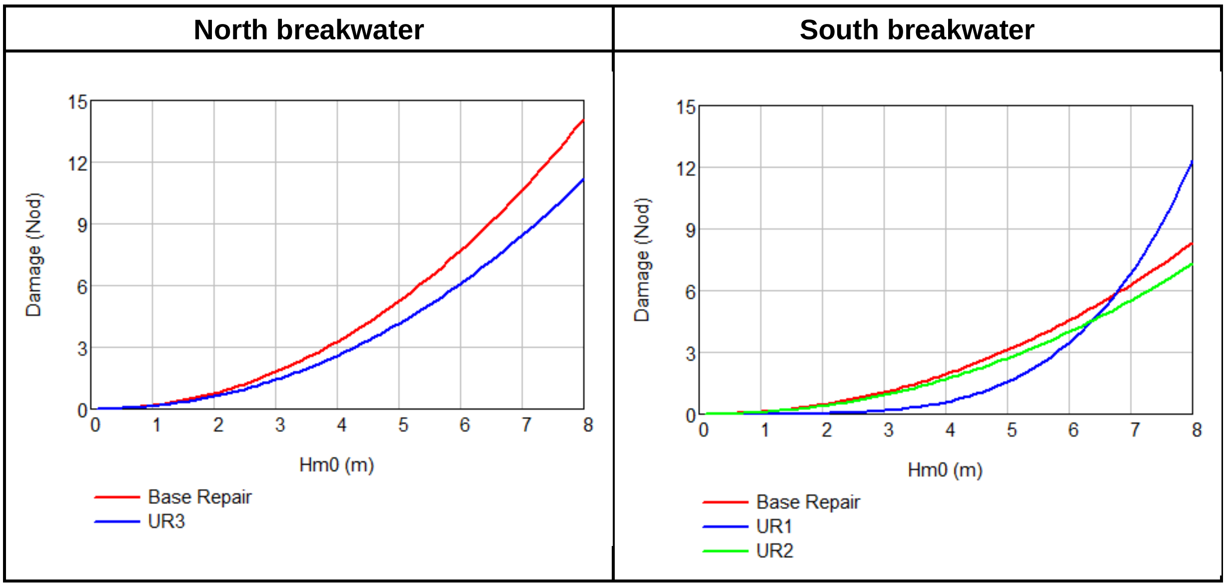


Figure 13 Damage as function of H_{m0} (Base repair: Φ=0.57 full slope, UR1: Φ=0.63 above LAT, UR2: Φ=0.63 full slope, UR3: Φ=0.63 full slope)

4.3 Development of damage cost functions

From the above it is clear that the physical damage, i.e. settlements expressed as N_{od} value, to be expected as function of the wave conditions can be calculated (Figure 13). However, for the cost based risk assessment this physical damage needs to be converted to damage costs.

The best guidance for the assessment of the damage costs being equivalent to the repair costs is provided by studies carried out between 2008 and 2014 (Halcrow Middle East LLC, 2014). These costs have been increased to a 2016 price level taking into account a 3% indexation (Table 4). It is noted that in the year 2016 one OMR equalled about 2.6 USD.

Repair method	North breakwater		South breakwater	
Repack CORE-LOC™ armour units	Full slope	Partial slope = 60% of full slope	Full slope	Partial slope = 60% of full slope
Base repair (ϕ = 0.57)	2480	-	3010	-
Upgrade repair (ϕ = 0.63)	2590	1760	3120	2045

Table 4: Costs for repair (OMR per running meter breakwater, 2016 price level) as input to cost based risk assessment

These repair costs typically apply for the condition of the breakwater as presently observed. However, it is to be expected that the repair costs will increase in case the damage to the breakwater CORE-LOCS™ would increase in case of future higher waves (H_{m0}), inflicting additional damage. As this damage is mostly correlated to the further displacement of armour units, for the cost based risk assessment it has been adopted that the direct damage costs increase proportionally with the damage assessment (N_{od}) relative to the present damage. The present damage is formed by the damage due to TC Gonu corresponding to an incident wave height of about H_{m0} = 3.8m. Combining the damage costs with the damage functions shown in Figure 13, the found damage cost functions are shown in Figure 14.

The damage cost functions demonstrate that, assuming the same wave height, the economic damage to the north breakwater will be larger than to the south breakwater. This is primarily driven by the higher physical damage (N_{od}) due to the smaller CORE-LOC™ armour unit. The damage costs will be higher for UR3 as the higher packing density requires more armour units to be placed.

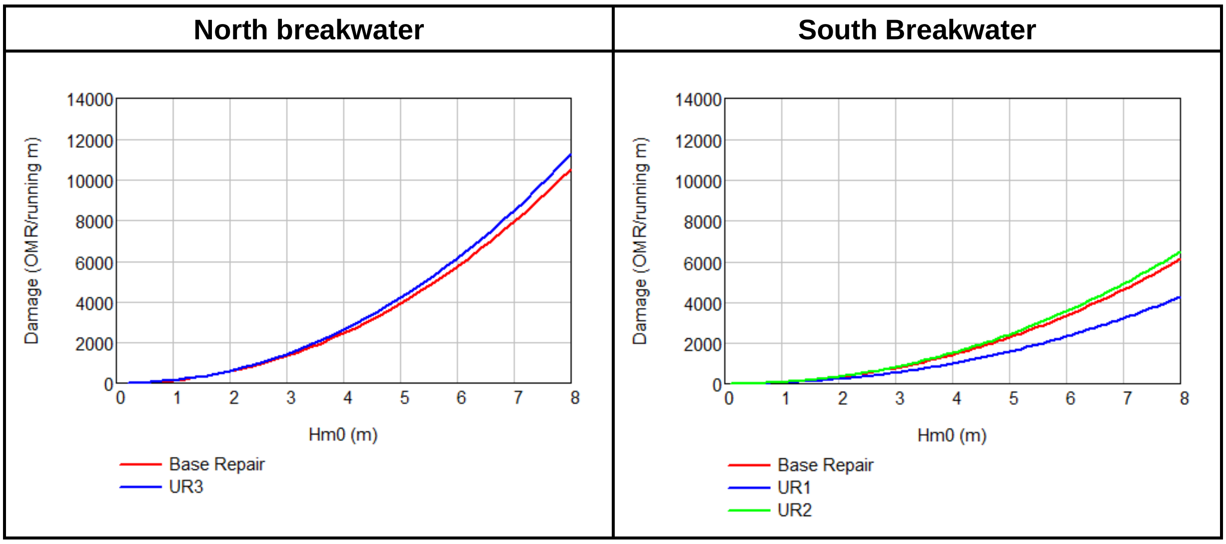


Figure 14 Damage costs as function of H_{m0}, 2016 price level. (Base repair: Φ=0.57 full slope, UR1: Φ=0.63 above LAT, UR2: Φ=0.63 full slope, UR3: Φ=0.63 full slope)

The same observation can be made for the south breakwater. The damage costs overall are smaller compared to the north breakwater due to the larger armour unit and next to that the variation in packing density affects the costs as well. As the UR1 repair only includes a repair above LAT, the damage costs are lower than for Base Repair and UR2.

When including the above indicated costs in the cost based risk assessment, these costs shall be interpreted as “loss of value” due to (future) damage to the repair alternative addressed, irrespective of the actual repair action. For example, in case a future damage would results in an assessed cost of 3000 OMR/running meter and this damage would not be repaired (for whatever reason), then still the damage = “loss of value” = 3000 OMR/running meter even though no money is spent on such repair.

The above costs reflect direct cost linked to the repair of the breakwater armour layers. As mentioned earlier, no indirect damages resulted from TC Gonu, hence it is assessed that the amount of indirect costs related to an armour repair of the settled armour units will be limited.

4.4 Cost based risk assessment

The final step in the cost based risk assessment is combining the occurrence of an event with the damage costs of such event. The procedure is demonstrated in Figure 15 below. The damage costs due to a wave of e.g. H_{m0} = 4.5m to the Base Repair of the south breakwater is multiplied with the probability (density) that this wave height will occur[6] once in the 35 year lifetime of the structure. This is repeated for all possible wave heights to occur. Adding all contributions results in a ***cumulative risk***, expressed in money (OMR).

[6] As damage increases for increasing wave height, the probability of occurrence in 35 years is to be used, not the probability of exceedance. Hence the probability density function $k(H_{m0})$ needs to be used.

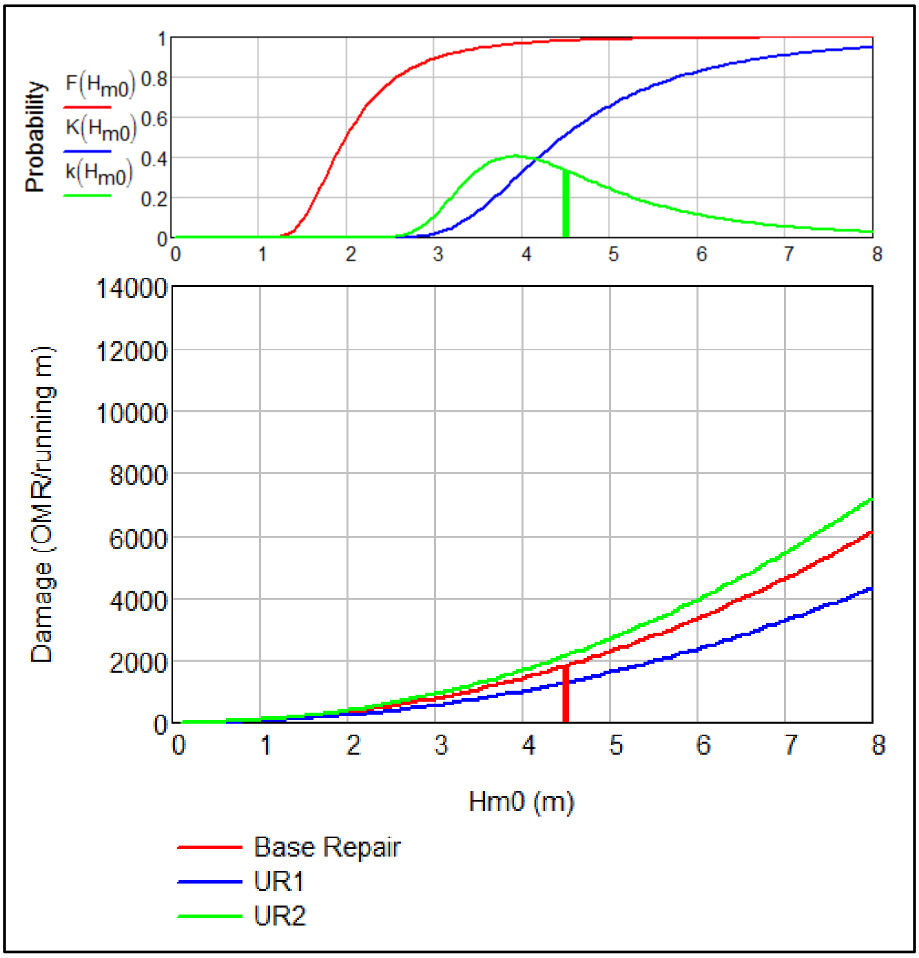


Figure 15 Procedure cost based risk assessment (2016 price level)

As the damage functions have been determined on the basis of the 2-D model tests, the risks typically apply to the repair solutions as included in the available Base Repair and Upgrade Repair model test reports. In short these can be summarized as:

- **No Repair**

  In case the present (damaged) breakwaters are not being repaired, the risk over the remaining lifetime of the breakwater needs to be added to the damage that has already been inflicted on the breakwater. The present damage cost results from the damage cost functions (for the Base Repair) using a wave as occurred during TC Gonu, which is in the order of H_{m0} = 3.7 to 3.8m. For the risk assessment in case of No Repair then only larger wave heights need to be taken into account based on the damage cost function for the Base Repair (original packing density).

- **Base Repair - repack full slope, ϕ = 0.57**

  This breakwater repair alternative particularly represents the original design (and original packing density) of the breakwaters. For the cost based risk assessment it is adopted that the damage development of this alternative is representative for the current breakwaters.

- **No Repair**

  In case the present (damaged) breakwaters are not being repaired, the risk over the remaining lifetime of the breakwater needs to be added to the damage that has already been inflicted on the breakwater. The present damage cost results from the damage cost functions (for the Base Repair) using a wave as occurred during TC Gonu, which is in the order of H_{m0} = 3.7 to 3.8m. For the risk assessment in case of No Repair then only larger wave heights need to be taken into account based on the damage cost function for the Base Repair (original packing density).

- **Repack full slope, ϕ ≈ 0.63**

  In this repair approach all armour units have to be removed and placed back with a higher packing density.

- **Repack above LAT, ϕ ≈ 0.63**

  In this repair all armour units have to be removed and placed back with a higher packing density, but “only” above LAT level.

The results of aforementioned costs based risk assessment are presented in Table 5.

Table 5: Accumulated economic risk for armour displacement (OMR per running metre breakwater) over 35 years lifetime of the breakwater. 2016 price level.

Note: Differences in risk (Δrisk) taken relative to the No Repair alternative

Option	North breakwater		South breakwater	
	Risk	ΔRisk	Risk	ΔRisk
No Repair	5,487	-	5,227	-
Repack full slope, ϕ = 0.57	3,776	-1,711	3,564	-1,663
Repack full slope, ϕ ≈ 0.63	3,122	-2,365	3,085	-2,142
Repack above LAT, ϕ ≈ 0.63	3,492	-1,995	4,059	-1,168

From Table 5 it can be observed that, as the breakwaters are already damaged, the economic risk itself is the highest for the damaged breakwater and all repair options result in a reduction of that risk. This is in line with the expectations. The biggest risk reductions are achieved when the armour units would be repacked with a density of 0.63 over the full length of the slopes of the north and south breakwater. In such event the risk reduction on the north breakwater is slightly higher (per running meter) than on the south breakwater. Whether the assessed reduction in risk justifies the investment in repair is discussed below.

4.5 Economic benefit of potential breakwater repair or upgrade

Using the cumulative economic risk values of Table 5 it is possible to quantitatively indicate whether a potential repair or upgrade of the damaged primary armour slopes of the north and south breakwater is beneficial from an economical point of view.

Thereto it is additionally required to incorporate the anticipated inflation over a period of 35 years (i.e. the remaining design life) and thereupon discount the inflated economic risk to a 2016 price level (i.e. incorporate an average interest rate over 35 years). When a long term inflation rate of 3% is chosen and an interest rate of 4%, the quantitative results presented in Table 6 show that:

- It is not beneficial to fully re-pack any of the two breakwaters with the originally applied packing density of 0.57 (i.e. Base Repair full slope): it would lead to a negative investment of about 3 million OMR for the south breakwater and of about 2.5 million OMR for the north breakwater, given the length of both breakwaters.
- Also upgrading the complete armour slope to a packing density of 0.63 (i.e. Upgrade Repair full slope) is economically not attractive: it would lead to a negative investment of about 2.7 million OMR for the south breakwater and of about 1.8 million OMR for the north breakwater.
- Upgrading the damaged breakwaters with a packing density of 0.63 at only that part of the primary armour slope which is located above LAT, gives in total the lowest negative investment: at the south breakwater a negative investment of about 2 million OMR is found, whereas upgrading the north breakwater leads to a negative investment of about 660,000 OMR; thus in total a negative result of 2.66 million OMR.

Design life = 35 years	Cumulated risk in design life [2016]	Cumulated risk discounted	Reduction in cumulated risk relative to 'No Repair'	Present day repair investment	Repair benefit in design life
South breakwater (OMR/m')					
Option:					
No repair	5227	3727	0	0	0
Base repair full slope (ϕ = 0.57)	3564	2541	1186	3010	**-1824**
Upgrade repair above LAT (ϕ = 0.63)	4059	2894	833	2045	**-1212**
Upgrade repair full slope (ϕ = 0.63)	3085	2200	1527	3120	**-1593**
North breakwater (OMR/m')					
Option:					
No repair	5487	3913	0	0	0
Base repair full slope (ϕ = 0.57)	3776	2693	1220	2480	**-1260**
Upgrade repair above LAT (ϕ = 0.63)	3492	2490	1423	1760	**-337**
Upgrade repair full slope (ϕ = 0.63)	3122	2226	1686	2590	**-904**

Table 6: Economic “benefit” (in OMR per running metre breakwater) of repairing or upgrading the ‘damaged’ breakwaters

4.6 Actual breakwater repair

Based on the above cost based risk assessment it has been concluded that the considered repair methods are not justified. The economic benefit of any of these considered options is less than the investment cost for present day repair. However, this does not imply that the breakwaters are not being repaired at all. As discussed and agreed with the owners of the port, it was decided to do so-called “no-regret” spot repairs at several isolated locations. These small scale repair actions do focus on areas along the slope above LAT level where the interlocking between adjacent armour units has disappeared completely and moreover the secondary armour stone at these spots is fully exposed beyond an agreed area (leading to a far too low local packing density).

5 CONCLUSIONS

From the early ages of the introduction of single layer armour units, breakwaters with these units, like the breakwaters for the Port of Sohar, are typically designed on the basis of the Hudson formula (2). Drawback of this formula is that it does not provide a relation between incident wave conditions and damage to the armour layer. Model tests performed to confirm such breakwater designs apply criteria like “no extractions” and “minimum rocking”. Model tests for the Port of Sohar confirmed that these criteria were being met.

Still, after the passage of TC Gonu, clear damages were inflicted on the breakwaters of the Port of Sohar, mostly in the form of displacement (settlement along the slope) of the concrete armour units. This shows that, apart from “extractions” and “rocking”, displacement of armour units is to be interpreted as damage. The displacement of the armour units on the breakwater of the Port of Sohar resulted in reduced packing densities above water and increased packing densities under water. Expectedly, the reduced packing densities above water may even form the onset to (higher risk of) extractions and rocking (Lem, Stive, & Gent, 2016).

The cost based risk assessment for the breakwater repair for the Port of Sohar confirms that the displacement of the armour units appears to have a large effect on the packing density of the armour layer. Many armour units showing even a small displacement may have a positive impact on the stability of the armour units when the amour layer compacts (lower part of the slope), but a negative impact when the armour layer loosens up (upper part of the slope). For larger displacement this effect becomes larger. The conclusion to be drawn from this is that even small displacements of many armour units (often interpreted as “initial settlement”) may have a large effect on the packing density of the armour units in the upper regions of the slope. Hence, it may be questioned whether the common practise to neglect "initial settlement" of armour units in terms of damage is justified. The present analysis suggests that any clear displacement i.e. settlement after construction of the armour unit layer should be interpreted as damage.

Taking this as a starting point and using available model test results, a relation was sought and found between the displacement of the armour units applied for the Sohar breakwaters (CORE-LOC^{TM}), the incident wave conditions, the size of the armour units and the packing density of the armour units. Theoretically, the resulting damage function (7) and coefficients (Table 2) can be applied to design CORE-LOC^{TM} armour layers, however this is not advised and supported by the authors of this paper (and likely not permitted by the licensee as well) for the following arguments:

- Results and coefficients are based only on series of tests for this dedicated, single project.
- Results and coefficients are site dependent (e.g. affected by the specific particulars of the site like wave conditions and/or bathymetry and water level).
- It is unclear what damage number to use for "acceptable damage" or "failure".

Still, given the damage function found it seems worthwhile (in general) to carry out additional investigations. Not only for the CORE-LOC^{TM} armour unit, but also for other single layer armour units as it is expected that the found trend applies to other single layer armour units as well. Once the damage function has been confirmed, it is anticipated that it can be applied to design single layer armour units, by taking appropriate damage i.e. settlement criteria, as a function of the incident wave conditions. By limiting the number of displacements (settlement) it is anticipated that implicitly other criteria like "extractions" and "rocking" will be met.

In the present analysis, dedicated to the Port of Sohar, the damage function has been used to assess the damage development for the (already) damaged breakwaters of the Port of Sohar and for a number of repair strategies. As the found damage function also predicts the damage development of the repaired breakwaters, the effectiveness of these repair options could be assessed in terms of (repair) cost versus benefit (reduction in economic risk). The outcome of the cost based risk assessment shows that the proposed (large scale) repairs are not economically justified. Instead the repairs presently in progress only address local spots on the breakwater slope above water where repairs are deemed necessary anyhow.

CORE-LOC^{TM}

In this document the name CORE-LOC^{TM} is used frequently. The concrete unit has been developed and patented by the US Army Corps of Engineers (USACE) in the mid 1990's, and is nowadays also licensed by Concrete Layer Innovations (CLI). Wherever "CORE-LOC" is written this should be read as "CORE-LOC^{TM} ".

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