Wave parameters influence on breakwater stability

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Abstract. This research paper experimentally explored the wave parameters effects on the breakwater armour layer stability. Breakwater stability mainly depends on the armour layer that guards the inner layers against the wave attack and the wave condition affects the breakwater stability. The wave height, length and steepness effect were investigated during the test program. Different formulas were available in the literature to predict the breakwater stability. The laboratory results were thus employed to assess the applicability of existing design equations. Experimental results showed that under normal wave condition (Hs) the breakwater was stable, whereas under storm condition (Hs of 1.2 designed wave height) the roundhead reached the failure state. The results approved the impact of wave parameters on the breakwater stability and damage progression. Results revealed that the existing design formulas underestimate the structure stability.

1. Introduction

Breakwater as a coastal protection structure is frequently applied to protect the coastal area. The wave attack produces forces on the breakwaters due to the associated phenomena as breaking, reflection, refraction and resulting rip currents. The breakwater work is to dissipate the wave energy. Therefore, the resulted forces have a great impact on the stability of the breakwater armour layer. Breakwaters are always designed applying empirical formulas to determine the armour stone size, weight, density and/or breakwater slope with regarding to the wave conditions.

It is commonly agreed that any breakwater structure should be tested before construction using a physical modeling tool in order to examine its stability. The reliability of the rubble-mound type is governed by the weight and interlocking nature of the armour unit's material and the cross section of the structure. Mostly the conventional and low crested structures are composed of armour layers of different units, bedding layer of different smaller material and toe protection. The breakwater is usually built with different material size, larger material facing the wave attack to smaller material in the core. Consequently, investigating the design may result in reducing the construction costs, the size and reducing the weight of the armour units.

The armour layer stability was the focus of different researches, e.g. [1-9]. Mase et al. [10] investigated the effects of wave attack, wave breaking and wave steepness on the stability of the wave dissipating blocks. Van Gent and van der Werf [6] argued that the wave steepness, width, and thickness of the toe appear to affect the toe damage. Accordingly, these parameters need to be considered during the design process to derive accurate predictions of the damage to the toe structure. Kramer [11] believed that under slightly oblique waves, low crested structures could be exposed to be damaged. The stability of the rock armour layer with wave attack was recently investigated by [12 and 13].
The wave attack and overtopping may cause unit movement of the armour and bedding. This phenomenon is known as the hydraulic instability. The movements can take the form of rocking, displacement of units out of the armour units. Hanzawa et al. [14] reported that the larger the wave steepness, the larger the stability which is the opposite tendency of [1]. The stability number is depending on wave steepness in a direct relation, [10].

The hydraulic design of the breakwater is mainly based on the wave conditions. The structure stability depends on the allowable damage for the different breakwater layers and on the material used for the armour, the core, bedding and toe layers. The damage percentage for rock structures are defined according to [15] as "the normalized eroded volume in an active volume from the middle of the crest to one Hs below still water level". A statically stable structure has stability number, $N_s$, between 1 and 4. The damage in terms of displaced units is generally given as the relative displacement, $D$, [16] defined as the proportion of displaced units relative to the total number of units, or preferably, to the number of units within a specific zone around still water level (SWL).

Structure stability depends on the surrounding seabed, structural outer shape, characteristics of materials, and hydrodynamic parameters. Consequently, it was concluded that, the necessary armour rock size is in general influenced by the acceptable damage level and physical characteristics such as structural parameters, materials and hydrodynamics [11]. Helgason and Burcharth [3] proved that the effect of rock density is correctly described by traditional stability formulae for rock armour in case of structure slopes 1:2 and most likely for flatter slopes.

According to vidal et. al. [17], the stability number for non-over topped structures is 1.4 and for structures with the crest at the still-water level is 1.6. They also defined the initiation of damage, $S$ in range of 0.5 to 1.5, for $2.01 < (R_c/D_{n50}) < 2.41$, where $R_c$ is the free board and $D_{n50}$ is the nominal diameter of the armour units.

Many researches and design equations are available in the literature. The wave condition is the most important factor affects the breakwater stability. The accuracy and reliability of the existing equations is very essential as it has a great effect on the construction cost. The present laboratory experiments aimed to test the stone armour layers and their hydraulic stability under different wave conditions including the tide. The effect of the wave height, length and the wave steepness were assessed. The experiments results were employed to benchmark of the available existing designing formulas.

2. Material and Methods

A physical model was constructed at the Hydraulics Research Institute (HRI) of the National Water Research Center (NWRC), Egypt, to achieve the objective of this research. The model construction and setup are depicted in Figure 1. The wave basin of an area of 34.0-m x 31.0-m was equipped with a wave generating system capable of producing regular and irregular waves up to 15.0 cm wave height. The wave board was provided with active reflection compensation. This means that the motion of the wave board compensates for the waves reflected by the structure and preventing them to re-reflect at the wave board and propagate towards the model. A spending beach was placed around the basin boundaries to dissipate the transmitted waves. Moreover, the wave basin in front of the wave generator has slope of 1:10 to damp the waves.

![Figure 1. Model construction and setup.](image-url)
The breakwater was constructed from stone layers, with a side slope of 1:2. It had a crest level of +15 cm and a toe level of -26 cm. Specifications of the considered layers are given in table 1. The armour material was placed directly on the top of the under-layer material of different breakwater sections randomly.

| Breakwater Layers    | Model | Weight (gm) | Density (t/m³) |
|----------------------|-------|-------------|----------------|
| Armour (stones)      |       | 178 – 356   | 2.3            |
| Under layer (stones) |       | 15.0 - 37.0 | 2.4            |
| Toe (stones)         |       | 15.0 - 37.0 | 2.4            |
| Core (stones)        |       | 0.75 - 3.0  | 2.4            |
| Sea water            |       |             | 1.00           |

The considered armour layer is stone blocks. The armour layer weight was ranged from 178 gm to 356 gm in the model. Throughout this study, JONSWAP spectrum was applied in all tests with 1000 wave. The bed was leveled to produce the required bed in front of the breakwater with a slope of 1:50, along with a water depth in front of the breakwater 25.75 cm. Wave conditions were measured in the deep water and in front of the structure toe. The significant wave height in this test ranged from 4 to 12 cm with a peak wave period varies between $T_p = 0.9$ and $1.56$ s perpendicular to the breakwater, table 2.

| No. | Significant Wave Height (cm) | Peak Period $T_p$ (s) |
|-----|------------------------------|-----------------------|
| Test 1 | 4.0                          | 0.90                  |
| Test 2 | 6.0                          | 1.10                  |
| Test 3 | 8.0                          | 1.27                  |
| Test 4 | 10.0                         | 1.42                  |
| Test 5 | 12.0                         | 1.56                  |

Wave height meters (WHM) that were designed for dynamic fluid level measurements, were used to measure the incident wave heights in these experiments. The obtained time series at the toe were used for the analysis. The resulted damage due to wave attacks were recorded utilizing digital overlay photos during each test. The rocked units and moved stones that were displaced more than one-unit diameter, ($N_{od}$) were counted.

The characteristics of damage in this research was based on the eroded cross-section area, $A_e$, around sea water level (swl) as introduced by [18-20]. Where the eroded area was defined as ($S = A_e/D_{n50}$) for trunk damage.

Different design equations for breakwater stability were deduced for rock armour units, the results were used to assess their applicability. Van Der Meer [21] introduced the following formula for surging wave to compute the breakwater stability of stone material with considering the breaking condition.

$$\frac{H_s}{\Delta D_{n50}} = 1.0 p^{-0.13} \left( \sqrt{\cot \alpha} \frac{S}{N} \right)^{0.5} \epsilon_m^p$$  \hspace{1cm} (1)

Where $H_s$ is the significant wave height, $\Delta$ is the relative armour density, $D_{n50}$ is the nominal diameter of the armour units, $p$ is the breakwater permeability, $\alpha$ is the breakwater slope, $S$ is the damage level, $N$ is the number of waves, and $\epsilon_m$ is the wave steepness based on mean wave period.

Vidal et. al. [22] proposed a general equation for designing the breakwater stability of different sections. They introduced reduction factors for the different sections. The general equation with factors for the front trunk and head is presented as:
\[ N_s = 1.831 - 0.245 \left( \frac{R_c}{D_{n50}} \right) + 0.0119 \left( \frac{R_c}{D_{n50}} \right)^2 \]  

(2)

Where \( N_s \) is the stability number, and \( R_c \) is the free board.

Van Gent et al. [23] developed an equation to predict the stone armour stability. They considered the structure porosity and wave period. However, they disregarded the breaking condition.

\[ \frac{H_s}{\Delta D_{n50}} = 1.75 \cot (\alpha)^{0.5} \left( 1 + \frac{D_{n50-core}}{D_{n50}} \right) \left( \frac{S}{\sqrt{N}} \right)^{1/5} \]  

(3)

In which \( D_{n50-core} \) is the nominal diameter of the core units.

The breakwater was divided into zones to observe the damage, the number of armour layer stones was identified in each zone. The armour layer stability was investigated under different wave conditions representing calm and storm conditions, Figure 2. Stone movements and overtopping were monitored by photos and videos employing a digital camera in addition to visual inspections. The armour layer and toe were reconstructed after each test. The wave condition during the performed tests was recorded. The incident wave heights were measured using the WHM in the deep water and in front of the breakwater as shown in Figure 2. The breakwater stability was evaluated with respect to the designed conditions and allowable damages, for this breakwater the allowable damages percentage of \( S = 0-5\% \) along with stability \( N_s \) of 1.50.

![Figure 2. Model during operation.](image)

3. Results and Discussions

The changes to the armour layer due to the wave attack was examined in this study, where the stone movement was recorded using a precise digital video camera. After each test the moved armour units and rocked units were counted before reforming the armour layer for the next run. The damage was recorded as in table 3, and percentage damage was then computed applying guideline of [16]. The initiation of damage, \( S \) condition equals 2-3 (equal to damage \% 0-5) which corresponding to a little movement and displaced stones in a section according to [24], while failure status occurs with movement of stones at \( S = 8 \).

| Run | \( H_s \) (cm) | Head section | Trunk Section |
|-----|----------------|--------------|--------------|
|     | No. of stones moved or rocked | % damage | No. of stones moved or rocked | % damage |
| 1   | 4               | 0            | 0.00         | 0.00        |
| 2   | 6               | 0            | 0.00         | 0.00        |
| 3   | 8               | 1            | 0.52         | 1.00        |
| 4   | 10              | 1            | 0.52         | 2.00        |
| 5   | 12              | 4            | 2.05         | 9.00        |

Table 3. Recorded damage.
Referring to Figures 3 and 4, the damage level and progression were increased with increasing the water height for both the head and trunk sections. Figure 4 shows direct relation between the stability number and the damage percentage, which confirms the results of [25]. In Figure 3, the percentage damage was directly proportional to the relative wave height. Moreover, the damage level for the head section was higher for $N_s$ of more than 1.5 and the damage progression was also higher for a head section than the trunk. Moreover, Figure 3 demonstrates that the different breakwater sections are stable under severe wave conditions, only the head section face failure stage at $N_s$ of 2.4.

**Figure 3.a.** Damage level.

**Figure 3.b.** Damage progression.

**Figure 4.** Damage progression versus stability number.
It is worthy to mention that the stability of the breakwater was higher than the designed stability, as the breakwater was designed for a stability number of 1.5 with initial damage of two stones moving. This result agreed well with the previous studies. The head of the breakwater was much vulnerable due to the curvature and it was the least stable part especially in the case of emerged breakwaters, [22 and 24], where the interlocking was much less than other parts. The toe and bedding layers were stable under different wave attack.

![Figure 5. Effect of Wave Length.](image)

The wave length and the damage percentage are depicted in Figure 5. According to this figure, for long waves the damage was higher than short waves where little damage occurred. Figure 5 illustrates that with short wave attack slight damage occurred for both the head and trunk sections. It is also observed that with long waves the damage takes place at the head section. It is worthy to be noted that armour units interlocking improved and increased with shortest wave duration, while decreased with longer ones and they showed a high-performance consistency with the argument of [25].

Figure 6 presents the impact of wave steepness on the breakwater stability, they were inversely proportional, high stability corresponds to short wave steepness until wave steepness reached 0.034 then the relation became direct, having the same trend proposed by [24].

![Figure 6. Effect of wave steepness.](image)

The present experimental results were employed to evaluate and benchmark some of existing design formulas for the rock armour layer. The formulas of [22] and [24] produced the same trend for both the head and trunk sections, Figures 7 and 8 respectively. The design equations underestimated the stability of the breakwater for the trunk and the head section. Equation of [22] produced consistent results with the current experiments for the breakwater stability. Whilst, it was not sensitive to wave condition and it mainly was sensitive to the stone diameter and free board.
The discrepancy between the observed and calculated values may be due to the methodology in definition or calculation of damages. Although the design equations gave the same trends, but they underestimated the breakwater stability for the considered case. This confirmed that the actual stability was usually much higher than the designed ones, [24]. Also, the conclusion of [26] noted that the measured stability numbers and predicted are not the same.

4. Conclusions

The breakwater stability under wave attack was experimentally investigated throughout this research. The effect of the wave parameters was analyzed and graphically presented. The laboratory data were employed to evaluate the existing design equations. The damage in the breakwater was occurred when the breakwater was exposed to wave storm with failure in head section. While the trunk was stable under all wave conditions. The results agree well and support the previous investigations. According to the experimental results, the following conclusions could be drawn:

- The damage level increased for long waves than shorter waves with a direct relationship.
- The wave steepness had a clear impact on the breakwater stability for both the trunk and head section
- The breakwater stability was found to be higher than the designed, which increasing the construction costs.
- The percentage damage of the armour layer for the rounded head is higher than for the trunk. It was found to be 2.05% while for the trunk section was found to be 0.64% with the severe wave condition of Hs = 12 cm.
Comparison between the present damage results and those calculated by the existing formulas, revealed that they underestimated the stability and they were in a good estimation for occurring damage.

Vidal's equation was only sensitive for free board and nominal diameter and did not represent the stability under the different wave attack conditions.

According to the study results, further investigations are needed as follows:

- More research investigation is needed tackling the breakwater design to develop more accurate design equation that gives the accurate required armour units specifications for cost reduction.
- Development is needed to adjust the existing equations to match with the real estimate of the breakwater function which is the breaking state.
- Monitoring of existing breakwater could improve the existing design concepts and formulas by two-way approach.
- Physical modeling is still essential in the coastal structure to resolve the uncertainty in the designing formula especially the stability part. More efforts are required in this issue to reduce the overall cost, such as the development of the mathematical model that is able to execute stability tests.

5. Notation

The following symbols were used in this paper

| Symbol   | Description                                      | Unit |
|----------|--------------------------------------------------|------|
| A_e      | Eroded area                                      | m²   |
| D_{n50}  | Nominal diameter of the armour units             | m    |
| D_{n50-core} | Nominal diameter of the core units             | m    |
| H_d      | Wave height in deep water                        | m    |
| H_s      | Significant wave height                          | m    |
| N        | Number of waves                                  | -    |
| N_s      | Stability number                                 | -    |
| N_{OD}   | Damage number                                    | -    |
| P        | Breakwater permeability                          | m/s  |
| R_c      | Free board                                       | m    |
| S        | Damage level                                     | %    |
| T_p      | Peak period                                      | s    |
| α        | Breakwater slope                                 | -    |
| Δ        | Relative armour density                          | -    |
| Ƹ_m     | Wave steepness based on mean wave period         | -    |

6. References

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