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Arthur de Graauw

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The long-term failure of rubble mound breakwaters

1 - Rubble mound breakwaters

Figure 1

The Kissamos breakwater (Crete) is a typical example of a rubble mound breakwater. This particular structure has been preserved from wave attack due to tectonic uplift (Flemming, 1981). However, most ancient breakwaters were destroyed by wave action and their remains are found under water as “submerged breakwaters”.

Picture from Hariclia Hampsa’s PhD thesis, 2006.

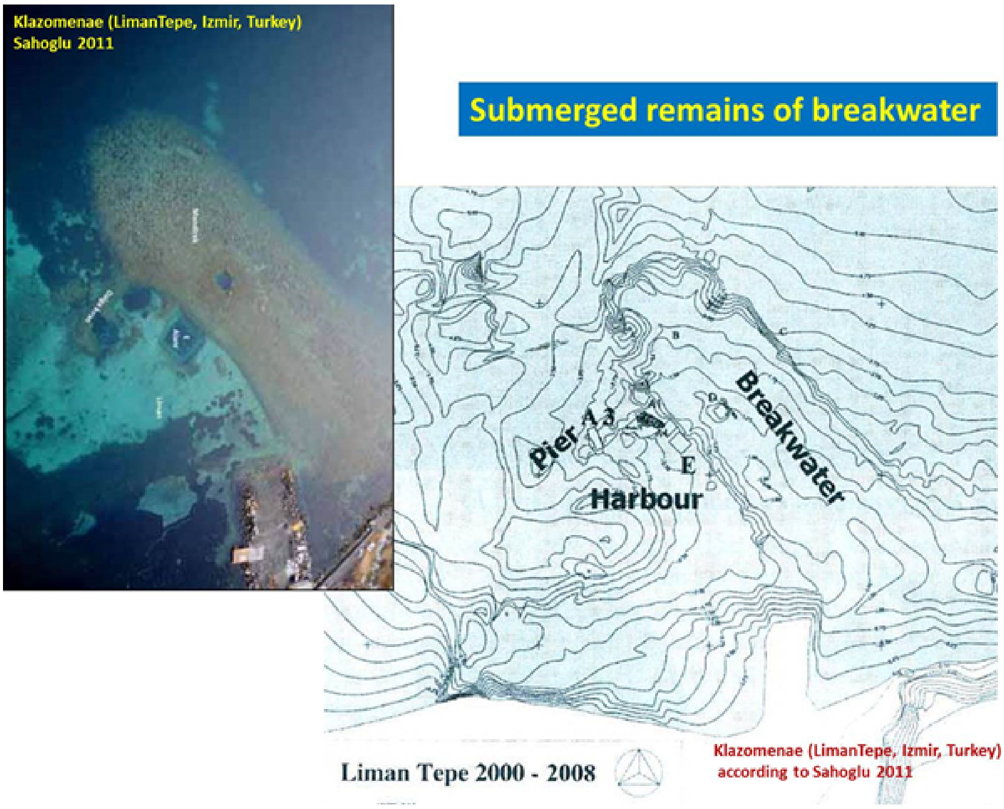
1 In addition to vertical breakwaters made of ashlar blocks or concrete poured into wooden caissons, many rubble mound breakwaters were built in Antiquity to provide better shelter for ships (Haggi, 2005). Rubble-mound breakwaters consist of piles of stones more or less sorted according to their unit weight : smaller stones for the core and larger stones for an armour layer protecting the core from wave action.

2 This kind of structure has probably existed for around 3000 years (e.g. the Phoenician breakwater at Athlit in Israel is dated to the 9^{th} or early 8^{th} century BC, Haggi, 2005) and modern coastal engineers still build them to create harbours sheltered from wave action. Ancient breakwaters may have been over- or undersized with the result that some are still well-preserved today while many others are now submerged as a consequence of thousands of years of storms and wave action. Without going into the details of breakwater design (e.g. Rock Manual, 2007), the stability of a structure made of stones depends primarily on their size in relation to wave strength : breakwaters in open waters exposed to storms acting on large areas and therefore producing high waves must be built with larger stones than breakwaters located in sheltered areas.

3 The present analysis can be seen as a follow-up to work done previously by Foster (1977), Ahrens (1987), Vidal (1995) and Burcharth (2003). Some of van der Meer's tests (1992) and Ota's test reported by Kobayashi (2013), and other scale model tests, are also taken into account in the present analysis.

4 The goal of this study was to find a simple relationship between the governing parameters (water depth, structure height, stone size) and the equilibrium position of the rubble crest of mound breakwaters subject to long-term wave attack in breaking wave conditions.

Figure 2



Klazomenae (Liman Tepe near Izmir, Turkey) is a major Bronze Age harbour settlement and an example of a submerged breakwater dated to the 6th century BC. The remains are 140 m long and 45 m wide in a water depth of around 4 m at its seaward roundhead. The crest of the structure is 1 to 1.5 m below present sea level (NB: the ancient water level was 0.30 to 0.50 m lower, see Morhange, 2014). It should be noted that the location of this structure inside the Bay of Izmir is relatively sheltered from offshore waves and this may explain why it has survived so well over time. This ancient harbour has been intensively studied by Vasif Sahoglu and his colleagues from the Ankara University Research Centre for Maritime Archaeology.

5 Careful examination of Google Earth images enables us to see quite a number of breakwaters in shallow waters. Some remarkable ancient rubble mound breakwaters can be listed as follows :

- Thapsus (Bekalta, Tunisia, Lat : 35.624299°N, Long : 11.051314°E) : about 870 m long, submerged in open water (Younès, 2013) ;
- Leukas/Ligia (Lefkada island, Greece, Lat : 38.845037 °N, Long : 20.718422 °E) : about 540 m long, submerged in sheltered water,
- Tieion (Filyos, Turkey, Lat : 41.571794 °N, Long : 32.0247°E) : over 350 m long, submerged in open water ;
- Mytilini (Lesbos island, Greece, Lat : 39.113145 °N, Long : 26.55641 °E) : about 350 m long, submerged in sheltered water ;
- Sabratha (Libya, Lat : 32.810859 °N, Long : 12.477982 °E) : about 320 m long, submerged in open water ;
- Leptis Magna (Lebda, Libya, Lat : 32.637865 °N, Long : 14.300074 °E) : about 300 m long, berm breakwater in open water ;
- Methone (Modon, Greece, Lat : 36.813244 °N, Long : 21.709883 °E) : about 250 m long, submerged in fairly open water ;
- Neftina (Lemnos island, Greece, Lat : 39.98768 °N, Long : 25.351852 °E) : about 200 m long, submerged in open water ;

6 Others such breakwaters are referenced in a more comprehensive publication (de Graauw, 2014).

7 Obviously, questions remain regarding many of these structures, e.g. was the Thapsus structure a rubble mound breakwater or a vertical breakwater ? Is the feature in Kainopolis (60 km West of Apollonia, Libya) a breakwater or just beach rock ?

2 - Process of breakwater destruction by long-term wave action

8 Different types of rubble mound breakwater can be distinguished (see Rock Manual, 2007). **Emerging breakwaters**, which are stable if :

- a) they are not overtopped, i.e. they are high enough, for instance twice the water depth, if waves are breaking at their toe,
- b) they have a stable front armour layer, i.e. the stone size is large enough, at least around 20 % of the water depth, if waves are breaking at their toe (see definition of parameters below).

As an example of these (conservative) rules of thumb, consider a breakwater in water 5 m deep : the front armour layer stones should have a diameter of 1 m in order to be stable under wave action, and the crest should be 5 m above Still Water Level (SWL) so as not to be overtopped by waves … this was probably not a common feature of ancient breakwaters, and they therefore suffered damage over time, were eroded and eventually became submerged.
Submerged breakwaters have their crest at or below SWL and have a narrow crest (say 3 to 5 Dn) ; they are stable if made of large stones (Burcharth's rule : Dn > 0.3 d) and are eroded by offshore movement of front slope stones combined with onshore movement of crest stones falling behind the structure, the result being a lowering of the crest.
If they have a wide crest (say 50 Dn and more) the eroded stones remain there, the result being a rise in the crest similar to the reconstruction of an S-shaped beach.

9 Hydraulic scale models are used intensively to study the stability of breakwaters.

3 - Hydraulic studies using scale models

10 Many researchers, hydraulics specialists and engineers have used scale models for over a century, in particular in towing tanks. Scale models allow a design to be tested prior to construction, and in many cases are a critical step in the development process. Dimensional analysis is used to express the system with as few independent variables and as many dimensionless parameters as possible. The values of the dimensionless parameters are held to be the same for both the scale model and reality. This can be done because they are *dimensionless* and will ensure dynamic similitude between the model and reality. The resulting equations are used to derive scaling laws which dictate model testing conditions. It is often impossible to achieve strict similitude during a model test. The greater the departure from the application's operating conditions, the more difficult it is to achieve similitude. In these cases some aspects of similitude may be neglected, focusing on only the most important parameters (Heller, 2011).

11 Coastal engineers have chosen to apply the similitude law of William Froude (1810-1879) for their hydraulic models of coastal structures. This means that gravity is considered to be preponderant over the other forces acting on the structure (viscosity, capillarity, cavitation, compressibility, etc.).

12 The speed (V) is in agreement with Froude's law and the velocity scale is therefore the square root of the length scale, e.g. for a model with a length scale of 49 :

$$S_{(V)} = S^{1/2}_{(L)} = \text{sqrt}(49) = 7 \text{ (times slower than in real life)}$$

13 As time (T) is a distance (L) over speed (V), the time scale is :

$$S_{(T)} = S_{(L)} / S_{(V)} = S^{1/2}_{(L)} = \text{sqrt}(49) = 7 \text{ (times faster than in real life)}$$

14 The present analysis of long-term stability of breakwaters concentrates on cases with waves breaking between the toe and the crest of the submerged structure. These are the worst possible wave conditions and they are used in this study on the assumption that they will eventually occur in the long term. Hence, the local wave climate must include waves large enough to

break in the water in front of the submerged structure ; breakwaters in very sheltered areas are therefore not considered in this analysis.

15 Further details on designs for coastal structures in the Mediterranean area can be found on : http://www.ancientportsantiques.com/ancient-port-structures/design-waves/.

Figure 3 – Process of reshaping of a low crested breakwater consisting of relatively small rubble on a scale model at Sogreah's Laboratory in 2006.

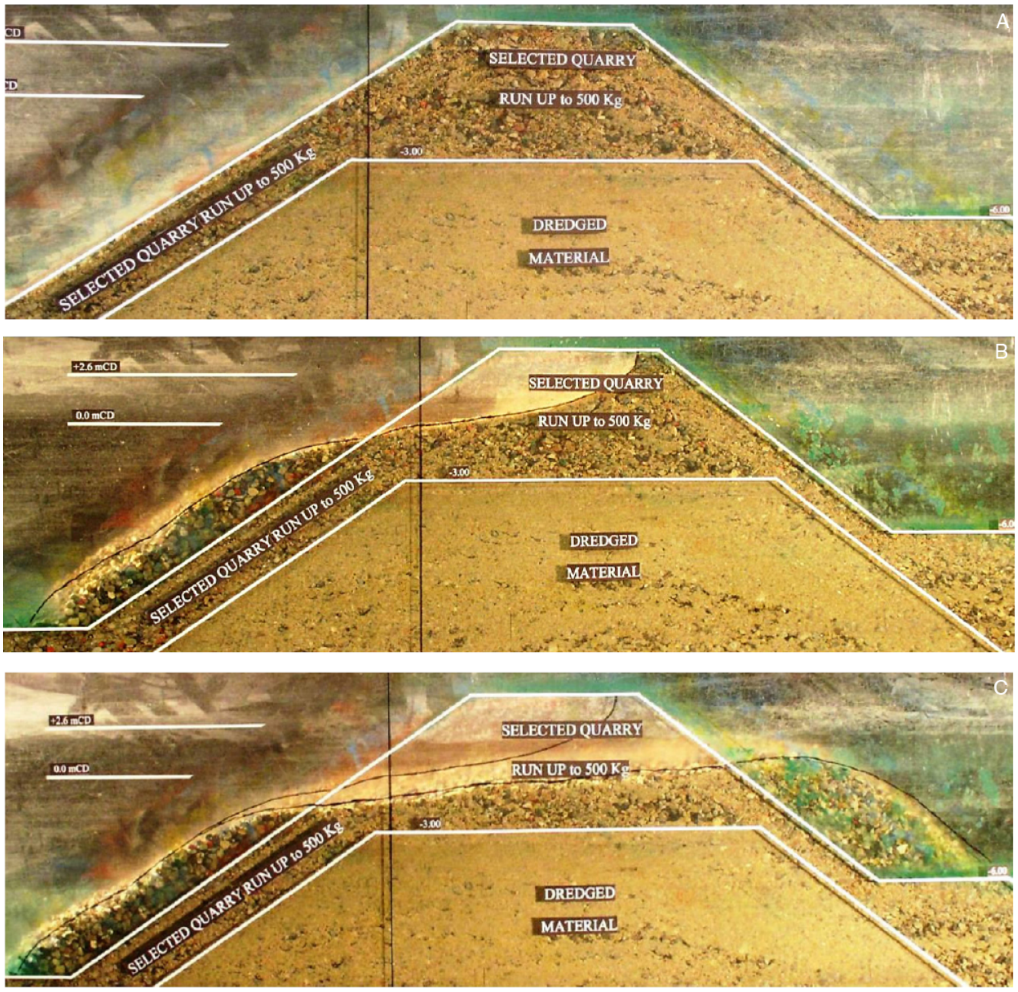


Fig. 3a shows the initial structure at the beginning of the test. Stone size on the model is Dn = 7 mm. The structure is 545 mm high and placed in a water depth h = 450 and 480 mm.
Fig. 3b shows the structure after a sequence of around 1700 waves with significant height Hs = 60 mm and peak period Tp = 1.15 s. Waves were obviously not breaking before the seaward toe of the mound as Hs/h = 0.13 only, but broke on the front slope of the structure. This led to erosion of the front slope, moving material from the crest down to the seaward toe, producing an “S-shaped” profile.
Fig. 3c shows the structure after a sequence of around 1500 waves with Hs = 80 mm and period Tp = 1.35 s. Waves were still breaking on the front slope. This resulted in further erosion of the crest, moving material from the crest to the rear side.The main limitation of the tests shown in Fig. 3 is that they were performed with non-breaking waves. Hence, wave attack on the structure was not the worst case scenario.

16 *This structure was nevertheless changed from an emerging breakwater into a submerged breakwater.*

17 Some unpublished scale model tests were performed in a wave flume at Sogreah's Laboratory in April 1993 by the author.

Figure 4 – Scale model tests on a submerged rubble mound structure.

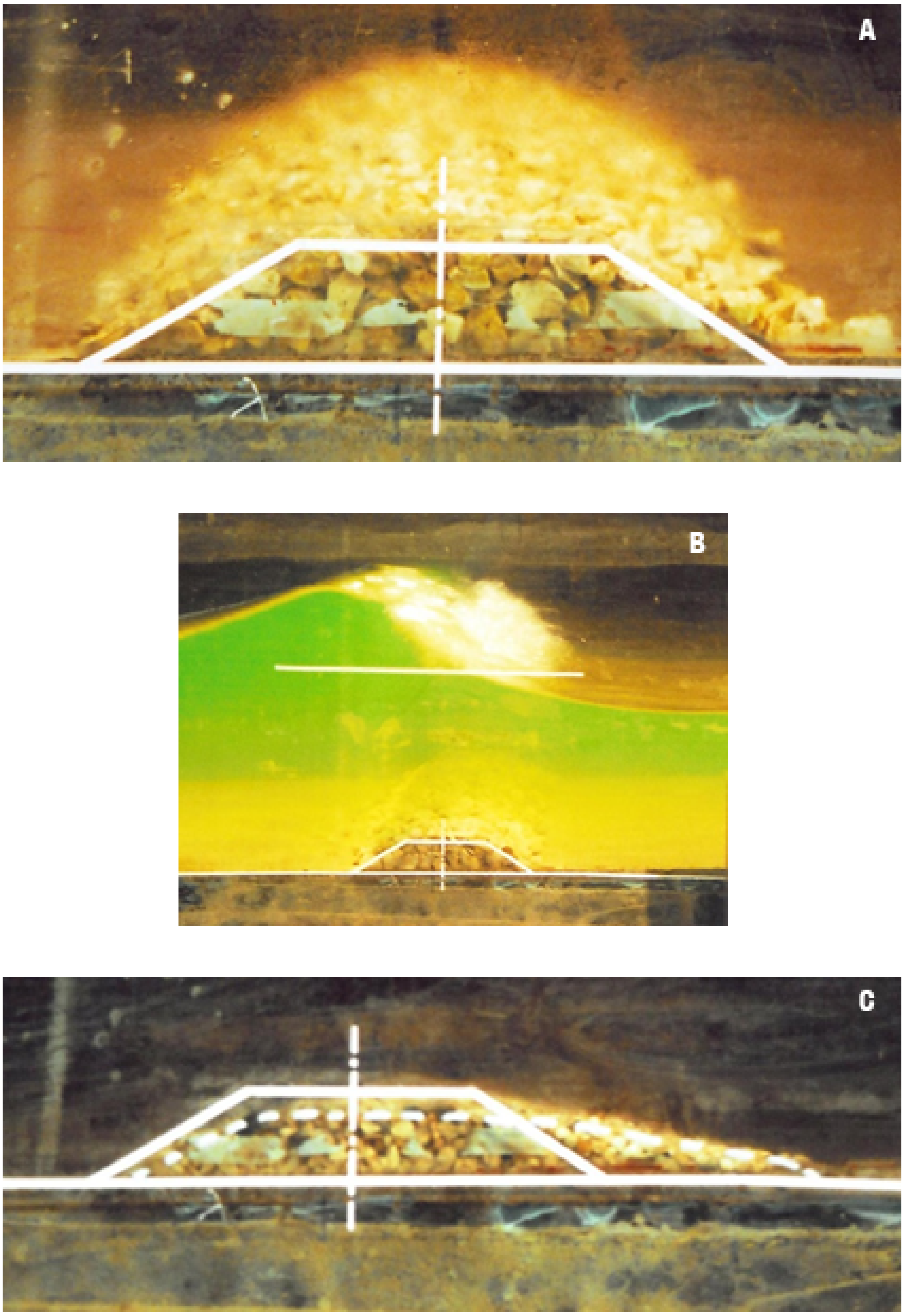


Fig. 4a - The initial structure at the beginning of the test was given a very simple trapezoidal shape with 1:1.5 slopes, a height of 40 mm and a crest 100 mm long. It was built with one single type of stone defined by its nominal Dn = 5 mm for the smallest size tested. The water depth h was 250 mm for most tests; hence, the 40 mm high structure was largely submerged.
Fig. 4b - The wave height was increased step by step during the test until full wave breaking occurred and no further increase in significant wave height could be obtained. The wave period was set at Tp = 1.75 s for most tests. Wave breaking was of the "spilling" type in all the tests.
Fig. 4c - The structure was reshaped by wave attack and finally stabilised in a rounded shape featuring a steeper front slope and a milder rear slope. The crest was lowered somewhat (2 to 3 Dn) and the rear toe moved backwards (about 18 Dn).

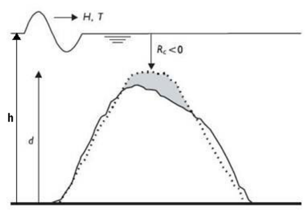
4 - Results

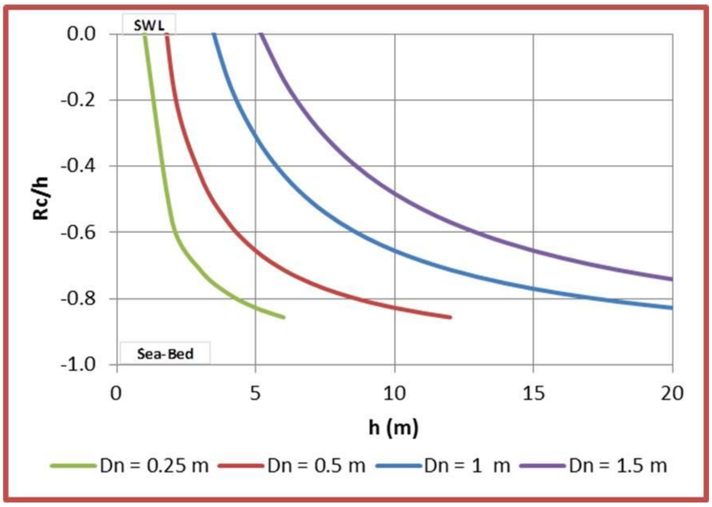
18 The tests shown in Fig. 4 are of course very limited and modest, but they confirm and extrapolate Kramer & Burcharth's results (2003), offering a much wider perspective on the

processes involved. It is concluded that undersized emerging rubble mound breakwaters which are eroded by wave action can erode and submerge breakwaters and that the crest below SWL can be located as follows after long-term wave action :

$$Rc/h = 3.45\ Dn/h - 1$$

Figure 5





For a given stone size, submerged breakwaters stabilize to the predicted crest level after long-term wave attack in breaking wave conditions; e.g. rock with diameter Dn = 1 m in water 5 m deep will yield a crest level at 30% of the water depth h below the water surface SWL.

19 This result is obviously very useful for defining breakwater construction phases, when the core of the structure may be exposed to breaking waves produced by storms, and for near-bed rubble mounds protecting pipelines.

It is also useful to determine the long-term equilibrium level of the crest of undersized breakwaters.

5 - Conclusion

20 It was concluded that initially undersized emerging rubble mound breakwaters reduce to submerged breakwaters and that, for a given stone size, submerged breakwaters stabilise to a predictable crest level after multi-secular long-term attack in breaking wave conditions.

21 For ancient rubble mound breakwaters, this means that :

- We may find ancient breakwaters still in good condition : they were emerging structures fulfilling modern design conditions (they may also have been uplifted by tectonic action, as at Kissamos, or have been somewhat oversized !) ;
- If they were slightly undersized, we may find ancient breakwaters that were reshaped into an S-shape by 2000 years of storms : the seaward side is lowered to below SWL and the landward side may reach SWL, as on Fig. 3b ;
- If they were much smaller, ancient breakwaters have been eroded by wave action and eventually been submerged, with their crest located below SWL, as on Fig. 5.

22 We must also remember that, in tectonically stable areas, the SWL has risen about 0.3 to 0.5 m since Antiquity (Morhange, 2014), so that breakwaters that were stable at that time in shallow water (a few metres water depth) may no longer be stable because larger waves can reach them nowadays. These impacts can be alleviated or accentuated by additional positive or negative tectonic movements.

23 In tidal areas, the worst conditions for stability occur when the largest waves occur together with the highest water level. The probability of this happening is lower than for a fixed water level, but that may not change the final result in terms of long-term stability.

6 - Parameters

- Hs : significant wave height in front of breakwater (m)
- Tp : peak wave period (s)
- h : water depth in front of breakwater (m)
- Rc : crest elevation of breakwater above water level (Rc < 0 if under water) (m)
- d : height of breakwater above sea-bed (m)
- Dn : nominal diameter of rock (m) = $(M_{50}/\rho)^{1/3}$
- ρ : specific mass of rock (kg/m^3)
- M_{50} : median mass of rock (kg)
- SWL : Still Water Level

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À propos de l'auteur

Arthur de Graauw
ARTELIA, Director Port Revel Shiphandling

Résumés

Destruction des brise-lames à talus sur le long terme

Les brise-lames en enrochements existent depuis sans doute 3000 ans et les ingénieurs maritimes modernes les construisent encore pour créer des espaces à l'abri de la houle. Certains brise-lames antiques sont encore en bon état aujourd'hui, alors que beaucoup d'autres sont maintenant érodés et submergés à la suite de plusieurs millénaires de tempêtes.
La présente étude vise à découvrir une relation simple entre les paramètres qui régissent la position d'équilibre de la crête des brise-lames à talus (profondeur d'eau, hauteur de structure, taille des enrochements) sous l'effet de l'attaque répétée de la houle déferlante pendant de nombreux siècles.
Il est conclu qu'un brise-lame initialement émergeant mais sous-dimensionné, sera érodé par la houle et finalement réduit à une digue submergée dont la hauteur au-dessus du fond marin dépendra de la taille des enrochements utilisés et de la profondeur d'eau.

Rubble mound breakwaters have probably existed for around 3000 years and modern coastal engineers still build them to create harbours sheltered from wave action. Some ancient breakwaters are still well preserved today, while many others are now eroded and submerged as a consequence of thousands of years of storms and wave activity.
The present study aims to find a simple relationship between the governing parameters (water depth, structure height, stone size) and the equilibrium position of the crest of rubble mound breakwaters subject to repeated wave attack in breaking wave conditions over many centuries.
It is concluded that an initially undersized emerging rubble mound breakwater will be eroded by the waves and finally reduced to a submerged breakwater whose height above the sea bed depends on its stone size and on the water depth.

Entrées d'index

Mots-clés : stabilité des brise-lames, modèle réduit hydraulique, action de la houle
Keywords : breakwater stability, hydraulic scale model, wave action
Géographique : Kissamos, Klazomenae, Thapsus, Leukas, Tieion, Mytilini, Sabratha, Leptis Magna, Methone, Neftina

Notes de l'auteur

I am deeply grateful to Nic Flemming for having challenged me on this subject and for his support and thoughtful comments. I am also very thankful to the reviewers for their help in improving this paper.

Scientific Appendix

Stability of overtopped and submerged rubble mound breakwaters

Arthur de Graauw (Director Port Revel, ARTELIA)

Abstract

The present analysis can be seen as a follow-up of work done previously by Foster (1977), Ahrens (1987), Vidal (1995) and Burcharth (2003). It aims at finding some simple relation between the governing parameters (water depth, structure height, stone size) and the equilibrium position of the crest of rubble mound breakwaters subject to long term wave attack in breaking wave conditions.

Some of van der Meer's tests (1992) and Ota's test reported by Kobayashi (2013) are also taken into account in the present analysis.

A few scale model tests were performed confirming the general trend.

It is concluded that undersized emerging rubble mound breakwaters reduce to submerged breakwaters and that the crest can be located as follows:

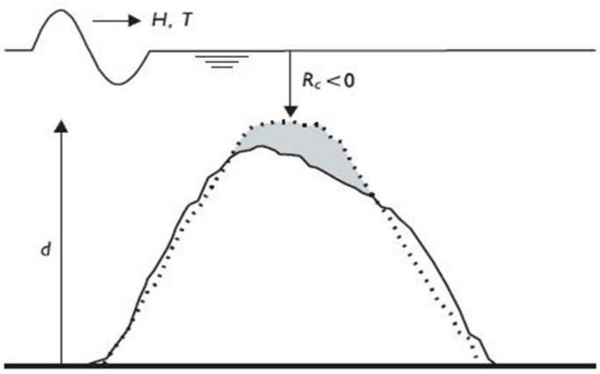
$R_c/h = 3.45\ D_n/h - 1$ valid for $1 < h/\Delta D_n < 30$ and for $\Delta = 1.6$.

For a given stone size, submerged breakwaters stabilize to the predicted crest level after long term wave attack in breaking wave conditions.

The present analysis of long term stability concentrates on the worst possible wave conditions, considering that they will *eventually* occur in the long term. This means that *we consider only cases with waves breaking near the submerged structure* . Hence, the local wave climate must include waves large enough to break on the water depth in front of the submerged structure and breakwaters in very sheltered areas are not considered in this analysis. Similarly, breakwaters located in water depths larger than say 20 m are not likely to be subjected to breaking waves in the Mediterranean area and are therefore not considered in this study.

Let's first consider the processes involved. When a wave is breaking on a submerged structure, some of its energy is reflected back, some of its energy is found in the surf zone between the breaker line and the shore line, but a large part of its energy is "lost". This "lost" energy is converted into turbulence (heat) and into reshaping of the breakwater (hereafter called "BW"). If the BW was made of sand like the neighbouring sea bed, the obstacle would be eradicated in order to come back to the initial situation without any obstacle, as "castles made of sand slip into the sea, eventually" (J. Hendrix). But the BW being made of blocks of stone, the crest of the submerged structure is lowered until waves do not erode the crest anymore. The crest of this equilibrium profile results from a limited reduction of the crest level which obviously depends on the stone size.

Definitions (from the Rock Manual, 2007):



with:
Hs: significant wave height in front of breakwater (BW) (m)
h: water depth in front of BW (m)
Rc: crest elevation of BW above water level (Rc < 0 if under water) (m)
d: height of BW above sea-bed (m)
Dn: nominal diameter of rock (m) = $(M50/\rho)^{1/3}$
ρ: specific mass of rock (kg/m^3)
M50: median mass of rock (kg)
Δ: relative buoyant density of rock = Sr - 1 = around 1.58 for granite in sea water (-)
Sr: specific mass of rock/specific mass of water = 2.65/1.025 for granite in sea water (-)

Different types of breakwater are usually distinguished (see Rock Manual, 2007):
>> **Emerging BW**, they are stable if:
a) they are not overtopped, i.e. they are high enough, say d > 2 h if waves are breaking at their toe,
b) they have a stable front armour layer, i.e. the stone size is large enough, say Dn > 0.2 h if waves are breaking at their toe.
If an emerging BW is not stable, it will be eroded and eventually become a submerged BW.
>> **Submerged BW**, have their crest at or below Still Water Level (SWL) and have a narrow crest (say 3 to 5 Dn); they are stable if made of large stones (Burcharth's rule: Dn > 0.3 d) and they are eroded by offshore movement of front slope stones combined with onshore movement of crest stones that fall behind the BW, the result being a lowering of the crest.
If they have a wide crest (say 50 Dn and more) the eroded crest stones remain on the crest, the result being a rise of the crest similarly to the reconstruction of an S-shaped beach.
>> **Reef BW**, are low crested BW that do not have the traditional multi-layer structure; acoording to Ahrens (1987) "this type of breakwater is little more than a homogeneous pile of stones with individual stone weights similar to those ordinarily used in the armor and first underlayer of conventional breakwaters."
>> **Berm BW**, they are voluntarily unstable and reshaping into an S-shaped profile; the front slope is locally getting milder, rotating around a pivot point located under water at a distance of: 0.2 h + 0.5 Dn below SWL. The stone size is smaller than for the stable types of BW, typically Dn = 0.04 h to 0.08 h. Hence, the pivot point will be located at 0.22 to 0.24 h below SWL.
>> **Near-bed structures** are used for sea bed protection works and their heigth d is small compared to the water depth h; they are stable if made of medium size stones (say Dn = 0.05 h, if waves are breaking over them).

The parameters Rc/Dn and Hs/ΔDn (the latter also called stability number Ns) are widely accepted as representative parameters on which breakwater stability under wave attack depends. This includes submerged breakwaters (Rc < 0).
It is widely accepted that random waves are breaking when their height Hs is around 0.6 h (NB: this is valid for mild offshore bed slopes, up to say 1:20, but this breaker index Hs/h may increase to say 0.8 for steeper bed slopes and/or longer waves). See Goda (2010) for a detailed overview on this complex subject.
Anyway, this means that the stability number above can be written as h/ΔDn.
Hence, we will try to find some relationships between Rc/Dn (or Rc/h) and h/ΔDn.

Let's first consider **narrow crested BW**.
Although several hundreds of scale model tests were carried out on submerged and slightly emerging breakwaters, only (very) few were pushed until waves were breaking at the toe of the structure:
Vidal's data (1995) is for non breaking waves (Hs/h = around 0.3) and therefore of limited interest for this analysis; the same holds for van der Meer's tests (1988);
From Ahrens tests (1987), only the 4 tests with highest waves are taken over here (Hs/h = 0.63);
Burcharth's rule (2003) is for breaking waves and therefore very useful for this analysis;
An interesting study on model and prototype of the Rosslyn Bay BW is given by Foster (1977).
The range of validity of model tests is usually quite limited: Rc/Dn > -4.3 (Ahrens); Rc/Dn > -3 (Burcharth). The real case reaches Rc/Dn = -5.2 (Foster).
Available experimental data is shown in fig. 1 below.

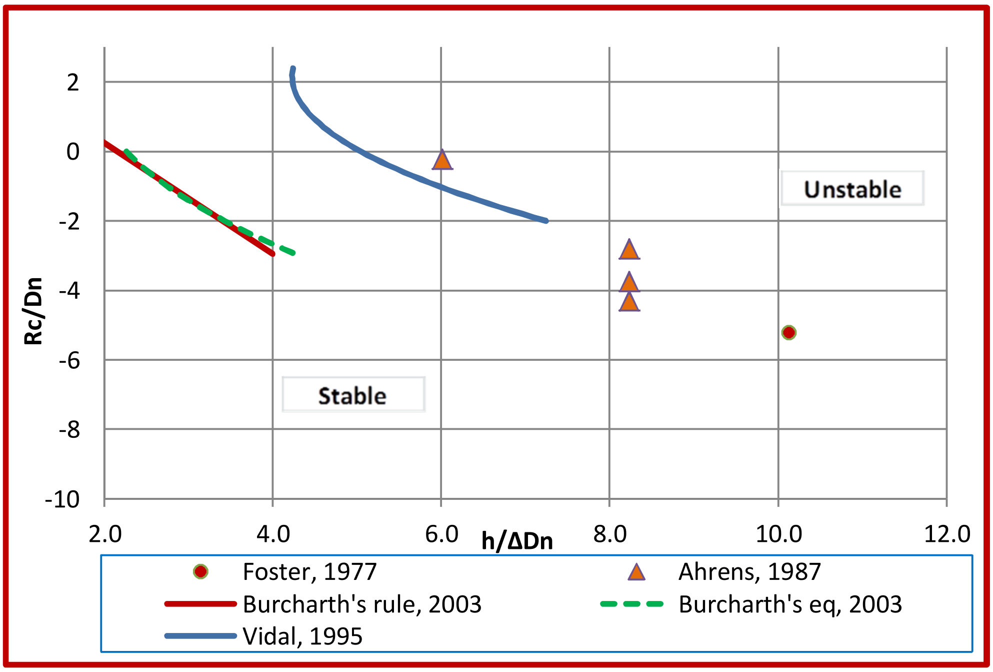


Figure 1. Stability of submerged breakwaters with breaking waves.

Burcharth's rule for stable submerged BW is (Burcharth, 2003):

Dn = 0.29 d valid for -3 < Rc/Dn < 2 (1)

with d = h + Rc, it can be written as:

Rc/h = +3.45 Dn/h - 1 (2)

This rule assumes Hs/h = 0.6 and Δ = 1.6.

It can be noted that Rc/h = -1 for very large h or very small Dn, Burcharth's rule is shown on fig. 1 as a straight line in upper left side of the figure.

Burcharth deduced his rule above from an analysis of his equation defining the worst conditions for stability:

$Hs/\Delta Dn = 0.06(Rc/Dn)^2 - 0.23\,(Rc/Dn) + 1.36$ (3)

This "Burcharth's equation" is shown in fig. 1 as a curved dotted line. It is obviously very close to his "Burcharth's rule" for Rc/Dn > -3.

Let's now turn to **wide crested BW.**

An interesting comparison is provided by van der Meer (1992) in his fig. 12. A low crested BW (d = 850 mm high in h = 800 mm water depth, with a crest width of around 1200 mm consisting of stones with Dn = 11 mm, hence a crest width of over 100 Dn) was submitted to waves with Hs/h = 0.24 (pretty far from breaking wave conditions). The initial crest level was Rc = +4.5 Dn (that is Rc/h = +0.06) and the final crest level rose to nearly +10 Dn during the test, generating an S-shaped profile with a slope around 1:3 to 1:5 near SWL.

He superimposed the final profiles of a non overtopped berm profile and this low crested BW, and it appeared that "a large part of the profile is the same". This shows that, at least for non breaking waves, *a rubble mound can behave in a similar way to a berm or a gravel beach* .

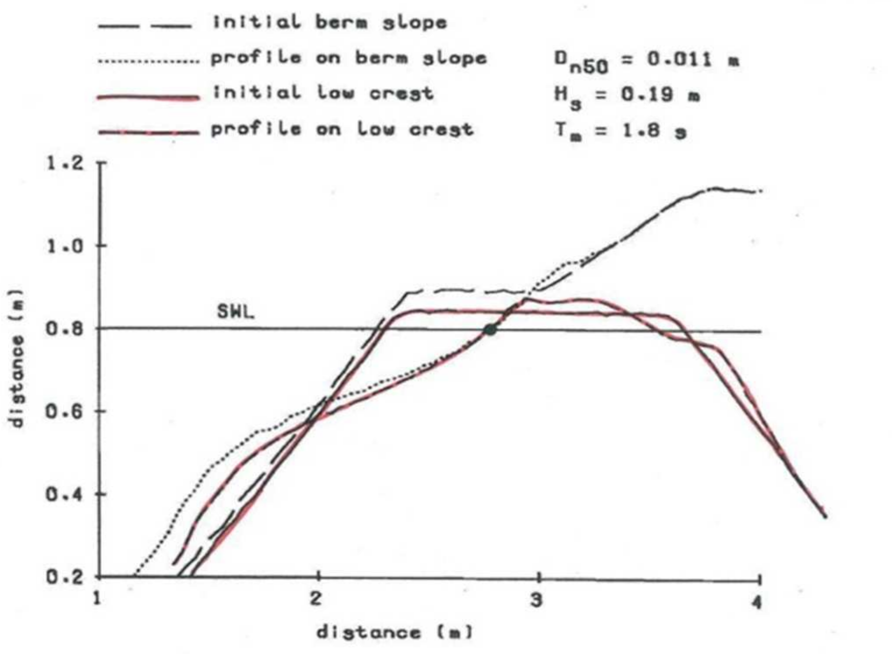


Figure 2. van der Meer's Figure 12 (1992)

A similar model test performed by Ota is reported by Kobayashi (2013). A reef BW (d = 167 mm high on h = 222 mm water depth, with a crest width of 1100 mm consisting of stones with Dn = 25.2 mm, hence a crest width of 44 Dn) was submitted to around 36 000 waves with Hs/h = 0.52 (which may be considered as breaking wave conditions). The initial crest level was Rc/Dn = -2.18 (that is Rc/h = -0.25) and the final crest level was around SWL: like in the van der Meer test above, the crest rose during the test. Stones were taken from the seaward side of the crest towards the landward side of the crest and heaped up there without falling down on the back slope of the BW. An S-shaped beach profile was building up similar to that of gravel or sand beaches.
It is also worth noting that the rising of the crest was linear in time and still ongoing after the very long testing time, unlike narrow crested BW that are known for their logarithmic damage progression, i.e. most damage occurs in the early stages of the storm.

The large width of the crest might give an explanation as waves seem not to have been able to move the stones as far as the rear slope where they would have fallen down without rising the crest level.
Waves cannot transport stones very far landwards on the crest of the submerged BW, hence a narrow BW will initially be lowered and flattened, until the crest reaches a certain width that does not allow stones to proceed further landwards under wave action. Hence, stones start to heap up and may reach SWL again like in van der Meer's and Ota's tests.

The example below illustrates this. All figures 3a, 3b and 3c are undistorded and at the same scale. The initial BW height of 2.5 m above SWL is reduced to 0.5 m above SWL. As no material is supposed to be lost (i.e. the cross-section of the BW remains around 120 m^2), the length of the submerged reshaped BW on the sea bed increased from 27.5 m up to nearly 33 m during the reshaping process (Fig. 3b: in this example, the choice of a front slope of 1:5 is arbitrary).
The question that remains to be answered at this stage is: will the BW further lower until it becomes submerged and further flatten out? If so, to which level under water (Fig. 3c with an arbitrary 1:10 front slope)?

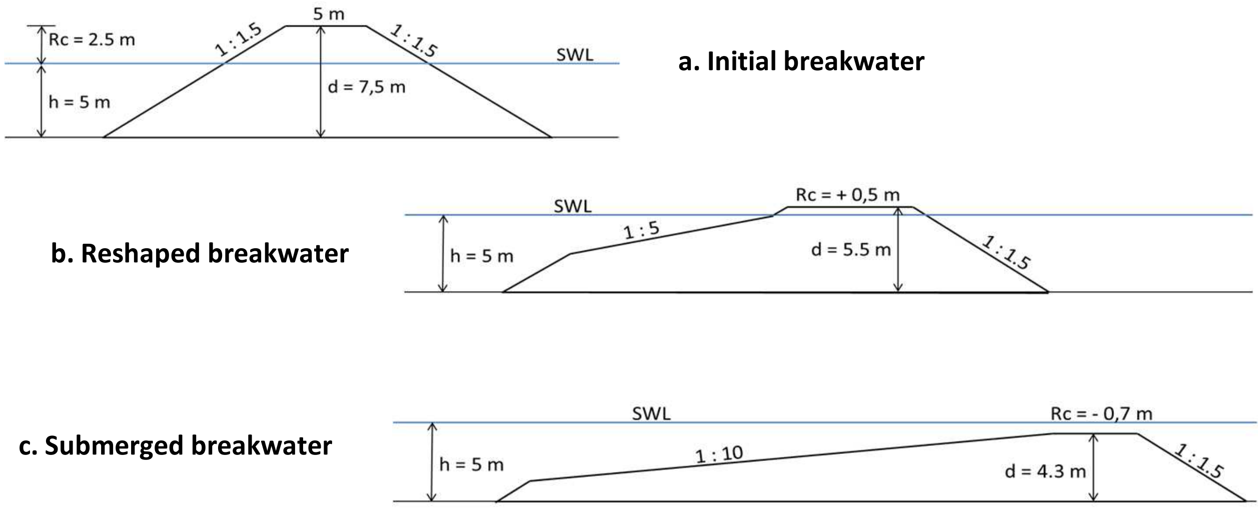


Figure 3. Destruction and reshaping of a breakwater.

It may be expected that the highest waves will break near the toe of the BW. Probably plunging heavily in that area. With the milder front slopes of Fig. 3b and 3c, the broken wave may further propagate as a translation wave at a speed around √gh, in the order of say 3 to 6 m/s (for resp. h = 1 m and 3.5 m).
If we consider a flow speed of 3 m/s on a water depth h = 1 m , a stone size of Dn = 0.20 m would be stable; for a flow speed of 6 m/s on a water depth h = 3.5 m, the stable stone size would increase to Dn = 0.60 m.

Some unpublished **scale model tests** were performed in a wave flume at SOGREAH's Laboratory in April 1993. The flume was 40 m long, 1 m wide and included 5 glass wall sections for observation. The flume was equipped with a wave generator capable of producing either regular or random waves. The wave maker was controlled by an integrated system for wave generation, data acquisition and analysis. An active wave absorption technology was used for a real-time absorption of the reflected waves at the paddle, allowing control of the incident wave field over the course of an experiment.
The seabed was represented as a non-erodible, concrete surface and was built with a 1.5% slope (1:66). A parabolic section with a mean slope of approximately 6% connected the flume bottom at the wave maker to the sea bed. The parabolic section was built with a mean slope lower than 10% in order to prevent spurious wave reflections.

The submerged rubble mound was given a very simple trapezoidal shape with 1:1.5 slopes, 40 mm high, and 100 mm long on the crest. The water depth h was 250 mm for all tests, except the last one when h was reduced to 200 mm. The wave height was increased step by step during the test until full wave breaking occurred and no further increase of significant wave height could be obtained. The wave period was set at Tp = 1.75 s for all tests, except the last one when Tp was increased to 2.5 s. Wave breaking was of the "spilling" type for all tests. The rubble mound was built with one single type of stone defined by its nominal Dn. Three different stone sizes were tested:
>> D = 12 - 18 mm with average mass = 4.77 g and Dn = 12.2 mm (Test 1)
>> D = 8 - 12 mm with average mass = 1.46 g and Dn = 8.2 mm (Test 2)
>> D = 4 - 8 mm with average mass = 0.34 g and Dn = 5.0 mm (Tests 3, 3a, 3b)
For all stones Δ was 1.65.
The trapezoidal mound structure was rebuilt after Test 1 and Test 2, but no repair was done during Test 3.

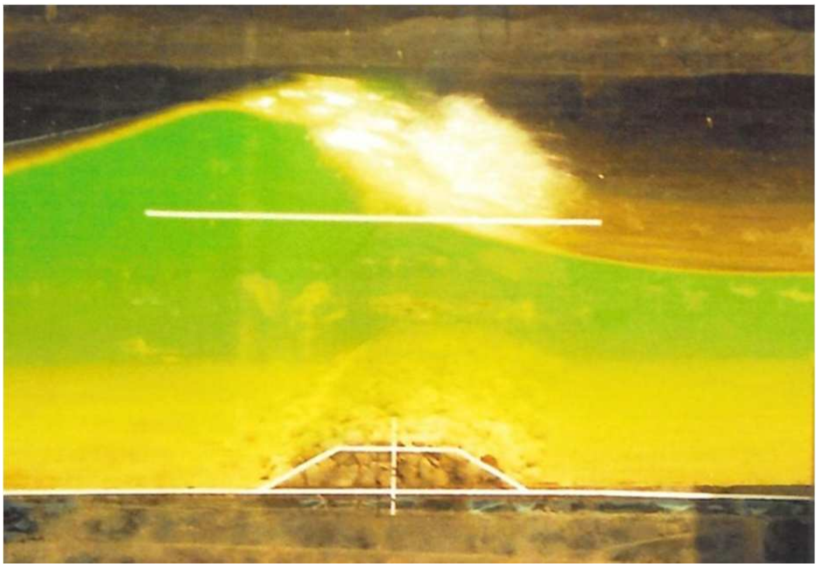


Figure 4. Model test on submerged rubble mound with breaking wave attack

Waves were increased in steps, starting from 45 mm. For Tp = 1.75 s, the highest waves that could be obtained on this water depth were measured as follows: Hs = 133 mm, with H1/10 = 157 mm and Hmax = 178 mm (note Hs/h = 0.53 and Hmax/Hs = 1.33). For Tp = 2.5 s, the measured maximum was Hs = 150 mm, and for h = 200 mm, the measured maximum was Hs = 138 mm (Hs/h = 0.69).
Each step of wave height was maintained for about 4 minutes (around 150 waves) until reshaping of the structure (if any) would stalibise. The last step of each test was maintained for about 45 minutes (around 1500 waves).
Test 1 with Dn = 12.2 mm: the structure was reshaped into a rounded mound that was globally stable with waves Hs = 133 mm.
Test 2 with Dn = 8.2 mm: the structure was reshaped into a rounded mound that was dynamically stable with waves Hs = 133 mm, i.e. some stones were continuously moving back and forth but the overall mound shape was maintained.
Test 3 with Dn = 5.0 mm: the structure was reshaped into an asymetric rounded mound that was dynamically stable with waves Hs = 133 mm, i.e. the front slope was steeper than the rear slope so that the whole mound was moving slightly backwards.
Test 3a with Dn = 5.0 mm and Tp = 2.5 s: the same processes were going on with Hs = 150 mm as the structure had now lost 5 to 8 mm of its initial crest height and the rear toe had moved 50 mm backwards before stabilising.
Test 3b with Dn = 5.0 mm and Tp = 2.5 s and h = 200 mm: the same processes were going on with Hs = 138 mm as the structure had now lost 10 to 15 mm of its initial crest height and the rear toe had moved 90 mm backwards before stabilising.

The test results are summarised in the table below.

N°	h (mm)	Dn (mm)	Hs (mm)	Tp (s)	Rc (mm)	Rc/Dn	h/ΔDn
1	250	12.2	133	1.75	-210	-17	12.4
2	250	8.2	133	1.75	-210	-26	18.5
3	250	5.0	133	1.75	-210	-42	30.3
3a	250	5.0	150	2.50	-215	-43	30.3
3b	200	5.0	138	2.50	-170	-34	24.2

Results of Tests 3a and 3b provide two new experimental points which are shown in the figure below.
These tests are of course very limited and modest, but they yield most important results enabling a much wider perspective on the processes involved.

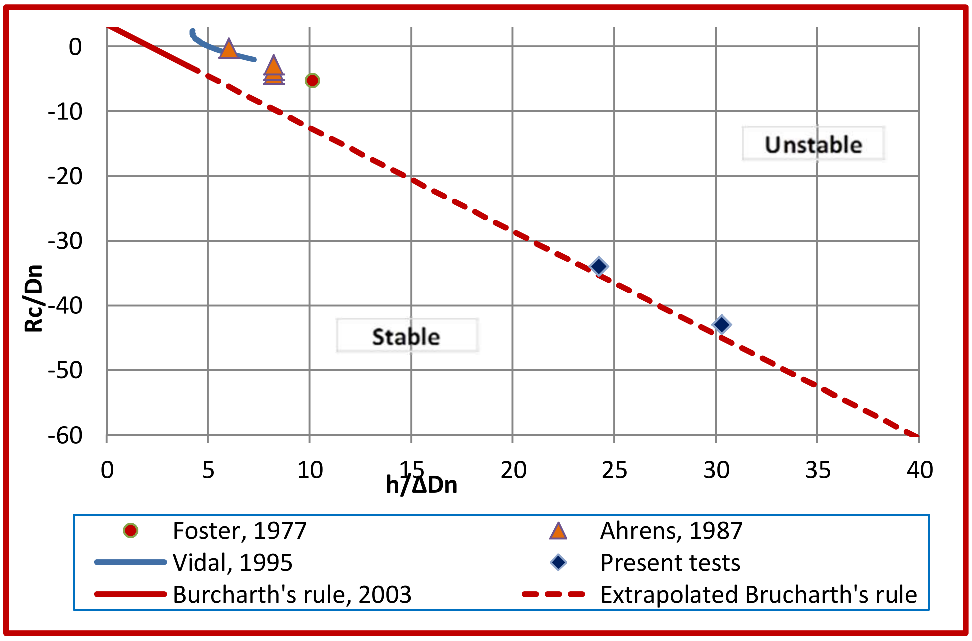


Figure 5. Stability of submerged breakwaters with breaking waves.

Figure 5 is no more than an out-zooming of fig. 1. Existing data shown in fig. 1 is now gathered into the upper left corner of the graph.
The new data from the model tests very well fits Burcharth's rule (2).

This is the simple relation which was sought at the start of this study. It is shown in fig. 6 below for a few values of Dn.

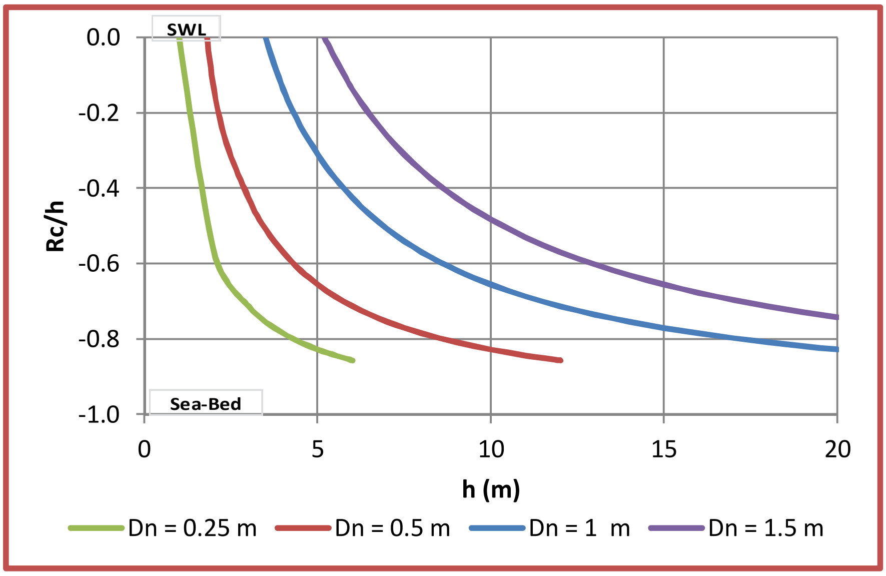


Figure 6. Stable submerged breakwater with breaking waves.

Note that this graph shows a typical "1/h effect" as we have set out a function of 1/h against h. It can nevertheless be seen that for e.g. a water depth of h = 10 m, stones with Dn = 1.5 m will be stable up to 50% of the water depth, Dn = 1 m will be stable up to 35% of the water depth, and Dn = 0.50 m up to nearly 20% of the water depth.

Conclusion:
It is concluded that undersized emerging rubble mound breakwaters reduce to submerged breakwaters and that the crest can be located as follows:
$Rc/h = 3.45\ Dn/h - 1$ valid for $\Delta = 1.6$ and for $1 < h/\Delta Dn < 30$ (that is $-0.86 < Rc/h < 0$)
For a given stone size, submerged breakwaters stabilize to the predicted crest level after long term wave attack in breaking wave conditions. In other words, and considering eq (1) again:

in breaking wave conditions,
a stable submerged breakwater cannot consist of more than 3 layers of stone .

This result is obviously very useful for the design of the construction phases of breakwaters, when the core of the structure may be exposed to storms inducing waves breaking on the structure.
It is also useful to determine the long term equilibrium level of the crest of undersized breakwaters and near-bed rubble mounds protecting pipes.

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