**Destruction des brise-lames à talus   
sur le long terme**

**Failure of rubble mound breakwaters in the long term**

**Arthur DE GRAAUW**ARTELIA, Director Port Revel Shiphandling

**Résumé –** 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. Les brise-lames antiques peuvent avoir été surdimensionnés ou sous dimensionnés avec pour résultat que certains sont encore en bon état aujourd’hui et 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.

**Abstract –** Rubble mound breakwaters have been around for probably 3000 years and modern coastal engineers still build them to create harbours sheltered from wave penetration. Ancient breakwaters may have been over- or undersized. The result is that some breakwaters are still in good shape today and many others are now eroded and submerged as a consequence of thousands of years of storms.   
The present study 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 repeated wave attack in breaking wave conditions during many centuries.  
It is concluded that an initially undersized emerging rubble mound breakwater will be eroded by the waves and finally reduces to a submerged breakwater whose height above the sea bed depends on its stone size and on the water depth.

1. **RUBBLE MOUND BREAKWATERS**

Figure 1

Besides vertical breakwaters made of ashlar blocks or concrete poured into wooden caissons, many rubble mound breakwaters have been built in Antiquity to improve sheltering for ships. 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 as an armour layer protecting the core from wave attack.

This kind of structure has been around for probably 3000 years (e.g. the Phoenician breakwater of Athlit in Israel is dated to the 9th or early 8th century BC) and modern coastal engineers still build them to create harbours sheltered from wave penetration. Ancient breakwaters may have been over- or undersized with the result that some breakwaters are still in good shape today and many others are now submerged as a consequence of thousands of years of storms. Without going into the details of breakwater design, it can be understood easily that stability of a structure made of stones depends primarily on the stone size in relation to the strength of wave action: breakwaters in open waters exposed to storms acting on large areas and therefore inducing high waves, must consist of larger stones than breakwaters located in sheltered areas.

The present analysis can be seen as a follow-up of 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 a few more scale model tests, are also taken into account in the present analysis.   
The goal of this study was to find some 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 long term wave attack in breaking wave conditions.

Figure 2

Careful examination of historical 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): about 870 m long, submerged in open water (Younès, 2013);
* Leukas/Ligia (Lefkada island, Greece): about 540 m long, submerged in sheltered water,
* Tieion (Filyos, Turkey): over 350 m long, submerged in open water;
* Mytlilini (Lesbos island, Greece): about 350 m long, submerged in sheltered water;
* Sabratha (Libya): about 320 m long, submerged in open water;
* Leptis Magna (Lebda, Libya): about 300 m long, berm breakwater in open water;
* Methone (Modon, Greece): about 250 m long, submerged in fairly open water;
* Neftina (Lemnos island, Greece): about 200 m long, submerged in open water;

and many others, to be found in a more comprehensive pdf publication on “Ancient breakwater remains” (<http://www.ancientportsantiques.com/wp-content/uploads/pdf/AncientBWremains.pdf> ).

Obviously, questions remain on 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 some beach rock? etc.

1. **PROCESS OF BREAKWATER DESTRUCTION BY LONG TERM WAVE ACTION**

Different types of rubble mound breakwaters are usually distinguished (see Rock Manual, 2007):   
**Emerging breakwaters,** they are stable if:   
a) they are not overtopped, i.e. they are high enough, say 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, say 20% of the water depth, if waves are breaking at their toe (see definition of parameters below).  
As an example of these (conservative) thumb rules, consider a breakwater on a water depth h = 5 m: 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 at 5 m above Still Water Level (SWL) in order not to be overtopped by waves … this was probably not a common feature for ancient breakwaters, and they therefore suffered damage over time, being eroded, and eventually becoming submerged breakwaters.  
**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 they are eroded by offshore movement of front slope stones combined with onshore movement of crest stones that fall behind the breakwater, 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.

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 between the toe and the crest of 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.

Figure 3

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

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

Figure 4

The tests shown in Fig. 4 are of course very limited and modest, but they confirm and extrapolate Kramer & Burcharth’s results (2003) enabling a much wider perspective on the processes involved. It is concluded that undersized emerging rubble mound breakwaters which are eroded by wave action reduce to submerged 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

This result is obviously very useful for the design of breakwater construction phases, when the core of the structure may be exposed to storms inducing waves breaking on the structure, 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.*

1. **CONCLUSION**

It was concluded that 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 long term wave attack in breaking wave conditions.

For ancient rubble mound breakwaters, this means that:

* We may find ancient breakwaters still in perfect condition: they were emerging and fulfilling modern design conditions (they may also have been lifted by tectonic action like at Kissamos, or been somewhat oversized!);
* If 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 like on Fig. 3b;
* If more undersized, ancient breakwaters are eroded by wave action and, after long term wave action, reduce to submerged breakwaters the crest of which can be located below SWL with Fig. 5.

We must also remember that, in tectonically stable areas, the SWL rose 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 meters water depth) may not be stable anymore because larger waves can reach them nowadays. This effect is obviously influenced by additional rising or sinking tectonic movements.

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

Further hydraulic details are to be found in a more comprehensive pdf publication on “Stability of submerged breakwaters” (<http://www.ancientportsantiques.com/wp-content/uploads/pdf/SubmergedBW.pdf> ).

1. **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) = (M50/ρ)1/3

ρ: specific mass of rock (kg/m3)

M50: median mass of rock (kg)

SWL: Still Water Level

1. **ACKNOWLEDGEMENTS**

I am deeply grateful to Nic Flemming for having challenged me on this subject and for providing me support and thoughtful comments. I am also very thankful to the reviewers for their contribution to improve this paper.

1. **REFERENCES**

AHRENS, J. (1987), *Characteristics of reef breakwaters*, Technical Report CERC 87-17, Vicksburg, MS, 66p.

AURIEMMA, R. & SOLINAS, E., (2009), Archaeological remains as sea level change markers: A review, *Elsevier Quaternary International* 206, p.134–146.

CIRIA, CUR, CETMEF, (2007), *Rock Manual* *- The use of rock in hydraulic engineering,* (2nd edition), Published by C683, CIRIA, London, 1304 p.

DE GRAAUW, A., (2014), *Ancient Ports and Harbours, The Catalogue*, 4th ed., Port Revel, 233 p.  
<http://www.ancientportsantiques.com/wp-content/uploads/pdf/SubmergedBW.pdf>  
<http://www.ancientportsantiques.com/wp-content/uploads/pdf/AncientBWremains.pdf>

FLEMMING, N. & PIRAZZOLI, P., (1981), Archéologie des côtes de la Crète, *Dossiers d'Archéologie* N° 50, p.66-81.

FOSTER, D., (1977), Model simulation of damage to Rosslyn Bay breakwater during cyclone "David", *6th Australian Hydraulics and Fluid Mechanics Conference*, Adelaide, p344-347.

GODA, Y., (2010), Reanalysis of regular and random breaking wave statistics, *Coastal Engineering Journal*, Vol. 52, N° 1, p.71-106.

HAMPSA, H., (2006), *Tesi Dottorato, i porti antichi di creta*, Università degli Studi di Salerno, 341 p.

KOBAYASHI, N., (2013), Deformation of reef breakwaters and wave transmission, *ASCE J. Waterway, Port, Coastal, Ocean Eng*., 139, p.336-340.

KRAMER, M. & BURCHARTH, H., (2003), Stability of low-crested breakwaters in shallow water short crested waves, *ASCE, 4th Int. Coastal Structures Conf*., Portland, OR, p.137-149.

LARONDE, A., (1983), Kainopolis de Cyrénaïque et la géographie historique, in: *Comptes rendus des séances de l'Académie des Inscriptions et Belles-Lettres*, 127e année, N° 1, p.67-85.

MORHANGE, C., (2014), Ports antiques et variations relatives du niveau marin, *Géochronique* N°130, p.21-24.

SAHOGLU, V., (2010), Ankara University Research Center for Maritime Archeology and its role in the protection of Turkey’s underwater cultural heritage, *Proceedings of the World Universities Congress*, Canakkale, October 2010, p.1572-1590.

VAN DER MEER, J., (1992), Stability of the seaward slope of berm breakwaters, *Coastal Engineering*, 16, p.205-234.

VIDAL, C., LOSADA, M., & MANSARD, E., (1995), Stability of Low-Crested Rubble-Mound Breakwater Heads, *ASCE J. Waterway, Port, Coastal, Ocean Eng*., 121(2), p.114-122.

YOUNES, A., (2013), Le paysage portuaire de Thapsus de l'antiquité à nos jours, *5e Rencontres Internationales du Patrimoine Architectural Méditerranéen*, Marseille, p.38-42.



Figure 1 – The Kissamos breakwater (Crete) is a typical example of a rubble mound breakwater (picture from Hariclia Hampsa’s PhD thesis, 2006). This particular structure has been luckily preserved as it survived 2000 years of wave attack because tectonic action raised it several meters above its initial level (Flemming, 1981). However, most of the ancient breakwaters were destroyed by wave action and remains are found under water as “submerged breakwaters”.

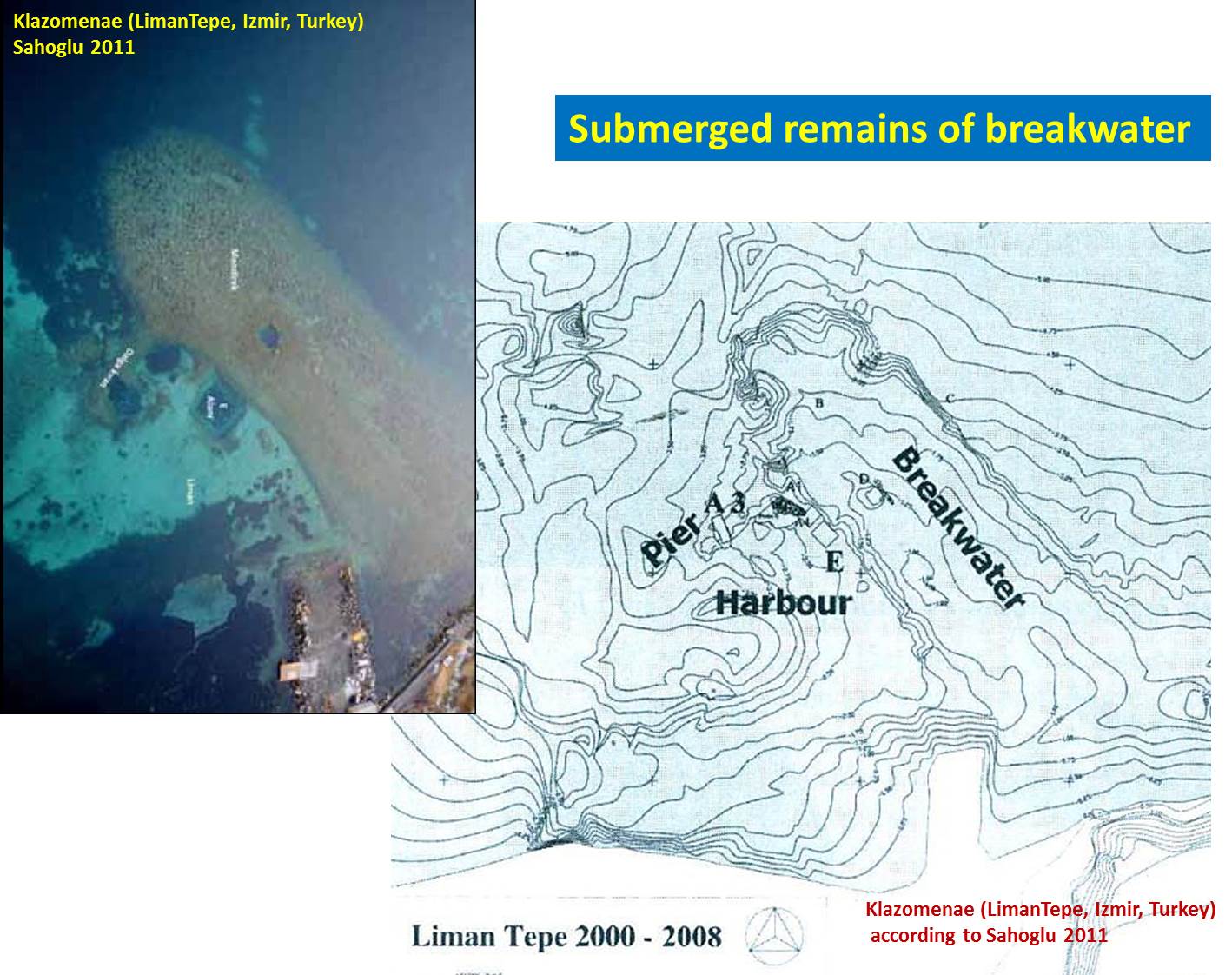


Figure 2 – Klazomenae (Liman Tepe near Izmir, Turkey) is a major bronze age harbour settlement and an example of a submerged breakwater dated to the 6th century BC. The remains are 140 m long and 45 m wide in a water depth of around 4 m at its seaward roundhead. The crest of the structure is at 1 to 1.5 m below present sea water level (NB: the ancient water level was 0.30 to 0.50 m lower, see Morhange, 2014). It must be noted that the location of this structure inside the Bay of Izmir is rather sheltered from offshore waves and this may explain why this structure has survived so well in time. This ancient harbour has been intensively studied by Vasif Sahoglu and his colleagues from the Ankara University Research Centre for Maritime Archaeology.





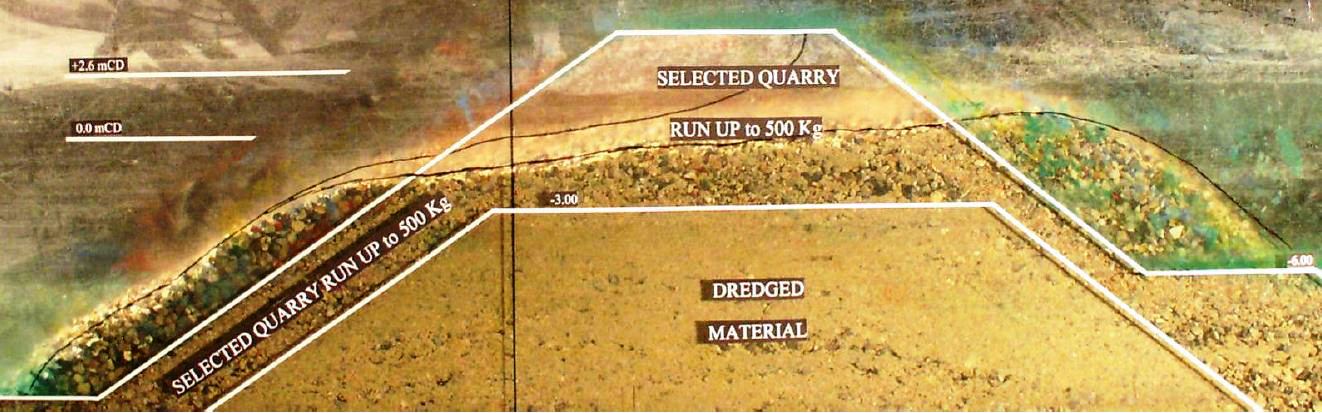
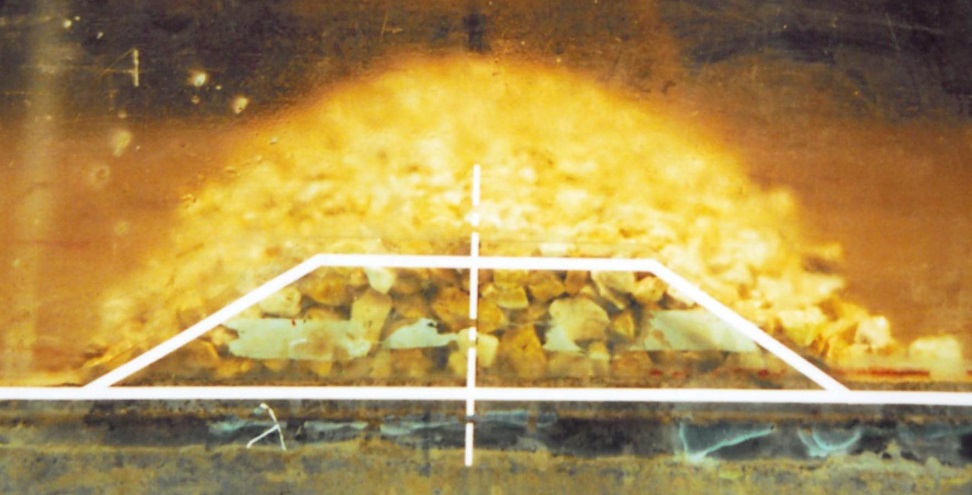


Figure 3 –Process of reshaping of a low crested breakwater consisting of relatively small rubble on a scale model at SOGREAH's Laboratory in 2006.   
Fig. 3a shows the initial structure at the beginning of the test. Stone size on the model is Dn = 7 mm. The structure is 545 mm high and placed in a water 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 structure front slope. This induced an erosion of the front slope, moving material from the crest down to the seaward toe leading to 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 structure front slope. This induced further erosion of the crest, moving material from the crest to the rear side.



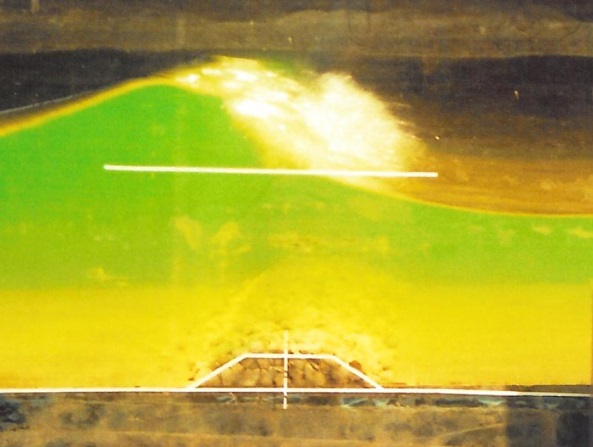




Figure 4 – Scale model tests on a submerged rubble mound structure.  
Fig. 4a - The initial structure at the beginning of the test was given a very simple trapezoidal shape with 1:1.5 slopes, 40 mm high, and 100 mm long on the crest. It was built with one single type of stone defined by its nominal Dn = 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 of 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 for all 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).

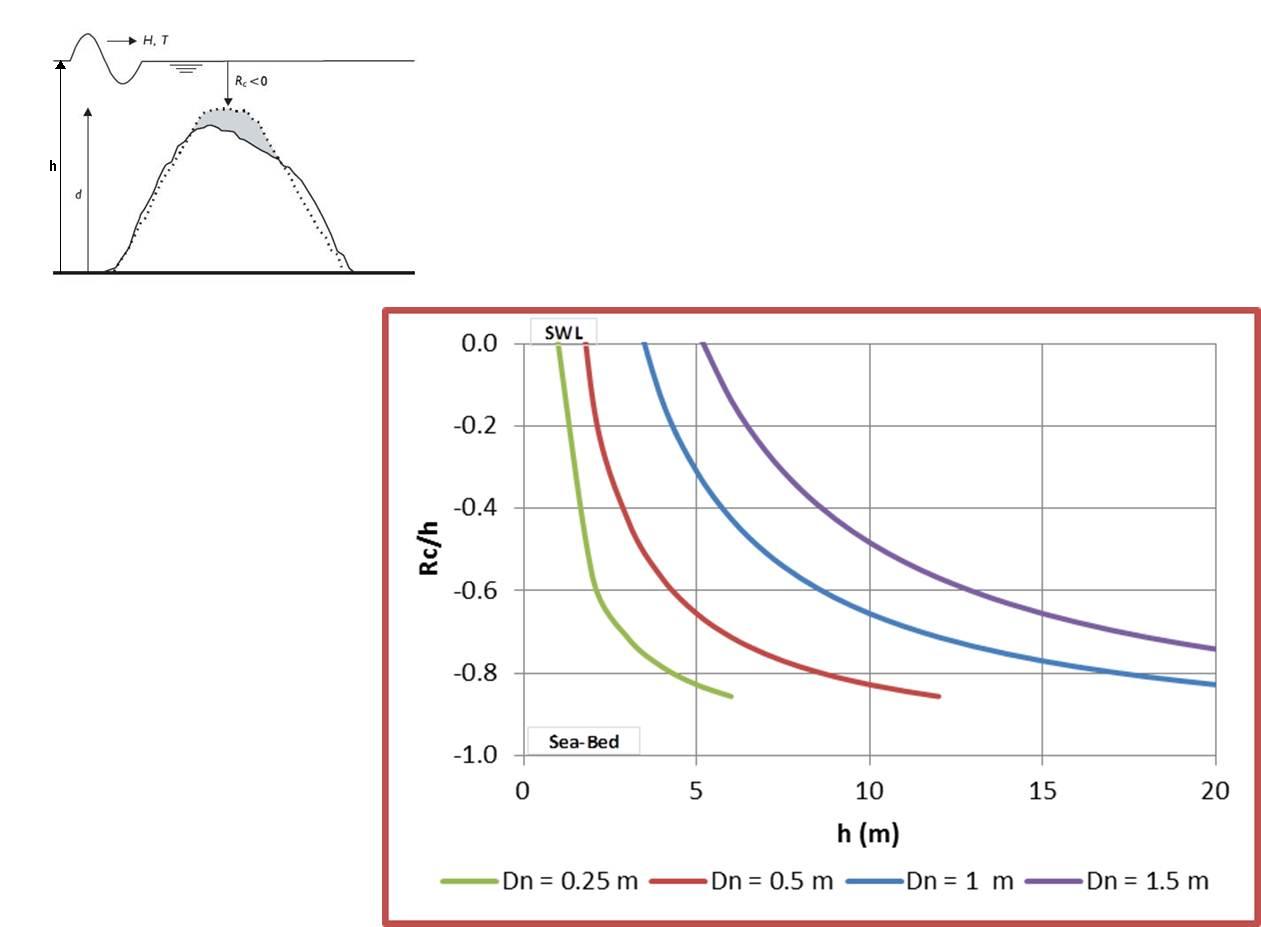


Figure 5 – For a given stone size, submerged breakwaters stabilize to the predicted crest level after long term wave attack in breaking wave conditions;   
e.g. rock with diameter Dn = 1 m in a water depth of h = 5 m will yield a crest level at 30% of the water depth h below the water surface SWL.