

## EFFECT OF CORE PERMEABILITY ON ARMOUR LAYER STABILITY

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The permeability of a breakwater core affects the stability of the breakwater armour. No design guidelines are available to account for the effect of a geotextile container core on armour stability. This paper discusses the present knowledge on the effect of core permeability on armour layer stability, both for rock and concrete armour units. Results are presented from project specific model tests on Xbloc armoured breakwaters with geotextile container cores. A prototype case is presented where damage has occurred, which may be attributed to low core permeability. Recommendations are given for the design of breakwaters and seawalls with low permeability cores.

### INTRODUCTION

Rubble mound breakwaters generally consist of a permeable core, under layer and armour layer. When a wave impacts on a rubble mound breakwater, the wave penetrates into the rubble mound and energy is dissipated by turbulent flow. If the core is less permeable, increased reflection occurs, leading to higher loads on the armour layer. Therefore a core with low permeability requires larger armour than a core with high permeability. This effect is often not addressed adequately during design and construction.

For a breakwater core, generally quarry run is applied as this is an economical construction material. During the design stage the core is normally assumed to be permeable. When the breakwater design is verified with physical model testing, the core is scaled in such a way that turbulent flow is also maintained in the scale model. This implies that the core in the physical model has a different length scale than the armour and under layer. When the design has been verified by model testing, breakwater construction can take place. Normally an existing quarry is used or a quarry is opened. The majority of the production will yield quarry run. A certain percentage will be under layer and armour layer stone. Depending on the rock quality and the production method, large quantities of fines may be present in the quarry run. These fines will affect the core permeability. Removing these fines means running the quarry run through a grizzly, as shown in Figure 1. As this is an extra effort, contractors want to avoid this. If the quarry run includes fines, the core permeability of the constructed breakwater may differ substantially from the value assumed by the designer.

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**Figure 1. Separating fines from core through a grizzly at Limbe, Cameroon.**

Recently rubble mound breakwaters have been constructed using a core of dredged material. This is being done in areas where the dredging of port basins and approach channels in hard seabed materials can be combined with breakwater construction. Use of dredged material as breakwater core can have a significant economic advantage. However, if the dredged material is relatively soft, for instance for coral or limestone, the core permeability can be substantially affected.

Another trend is the application of sand cores and geotextile container cores. Application of sand filled geotextile containers in a breakwater core may require larger armour due to the reduced core permeability.

In this paper the effect of core permeability on armour stability is discussed. The available knowledge is presented, prototype damage cases are analysed and new research findings are given. A typical example of prototype damage is given in Figure 2. This figure shows the southern breakwater at IJmuiden, The Netherlands, where a 45 tons cube has been displaced. This breakwater has an impermeable core.



**Figure 2.** 45 tons cube and toe rock displaced from breakwater front (IJmuiden, The Netherlands).

#### **EFFECT OF CORE PERMEABILITY ON ROCK ARMOUR STABILITY**

Both the rock stability equations of Van der Meer (1988) and van Gent et al. (2004) include the effect of core permeability on rock stability. Van der Meer, through the notional permeability factor  $P$  and Van Gent through the term  $(1 + D_{n50,core} / D_{n50})^{2/3}$ . However, the outcome of both formulae differs significantly.

#### **Van der Meer**

The core permeability effect is included in the rock stability formula by Van der Meer (1988), through the notional permeability factor  $P$ .

$$\text{Plunging waves:} \quad \frac{H_s}{\Delta D_{n50}} = c_{pl} P^{0.18} \left( \frac{S_d}{\sqrt{N}} \right)^{0.2} \xi_m^{-0.5} \quad (1)$$

$$\text{Surging waves:} \quad \frac{H_s}{\Delta D_{n50}} = c_s P^{-0.13} \left( \frac{S_d}{\sqrt{N}} \right)^{0.2} \sqrt{\cot \alpha} \xi_m^P \quad (2)$$

As can be seen from formulae 1 and 2, there is a significant difference of the influence of  $P$  between plunging and surging waves. Values of  $P$  are given by Van der Meer ranging between 0.1 for armour on filter on an impermeable core till 0.6 for a structure consisting of armour only. For plunging waves this

difference in notional permeability leads to the requirement of a 38% higher  $D_{n50}$  value for armour on an impermeable core, equivalent to an increase of mass by a factor 2.6. For surging waves this difference is even more pronounced, depending on the wave period. Figure 3 shows the effect of notional permeability and wave period on the  $D_{n50}$  value, for a case with  $H_s = 4$  m, slope = 1:1.5, rock density of  $2650 \text{ kg/m}^3$ , seawater density of  $1025 \text{ kg/m}^3$ , number of waves  $N = 1000$ , damage level parameter  $S_d = 0.5$  and a ratio between the peak period  $T_p$  and mean period  $T_m$  of 1.15.

Figure 3 for  $P = 0.6$  shows that increasing  $T_p$  from 6 up to 10 s gives an increase in the required  $D_{n50}$ . It is however surprising that further increasing  $T_p$  from 10 up to 16 s gives a decrease in the required  $D_{n50}$ .

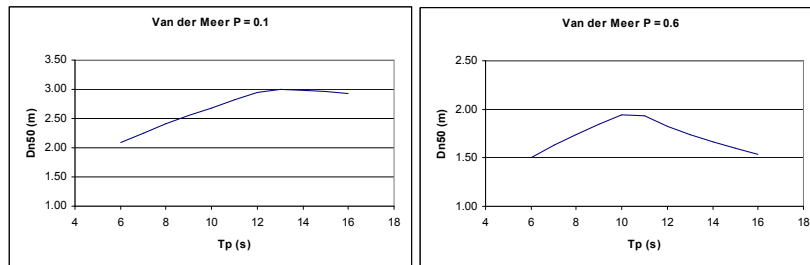


Figure 3. Example of influence of permeability and wave period on  $D_{n50}$ .

Figure 4 shows the ratio between the  $D_{n50}$  for  $P = 0.1$  and  $D_{n50}$  for  $P = 0.6$ . This Figure shows that the difference in required  $D_{n50}$  can range from 38% for plunging waves to 90% for surging waves. Increasing  $T_p$  from 6 up to 10 s gives a constant value for the required enlargement of  $D_{n50}$ . It is however surprising that increasing  $T_p$  from 10 up to 16 s gives a large increase of the required enlargement of  $D_{n50}$ . This leads to a factor 3.5 between the required mass of the armour stones for  $T_p = 6 - 10$  s and  $T_p = 16$  s. For  $T_p = 16$  s the difference in required mass between  $P = 0.6$  and  $P = 0.1$  is 6.9.

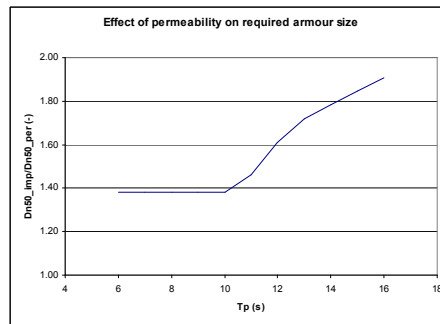


Figure 4. Effect of permeability and wave period on  $D_{n50}$ .

### Van Gent

The recent stability formula by Van Gent et al. (2004) uses the ratio between  $D_{n,armour}$  and  $D_{n,core}$  to account for the effect of core permeability:

$$\frac{H_s}{\Delta D_{n50}} = 1.75 \sqrt{\cot \alpha} (1 + D_{n50-core} / D_{n50})^{2/3} \left( \frac{S_d}{\sqrt{N}} \right)^{0.2} \quad (3)$$

Using the formula of van Gent et al. leads to the requirement of a 59% higher  $D_{n50}$  value in the case of an impermeable core, compared to a structure consisting of armour only. This is equivalent to an increase of armour mass by a factor 4.

### Comparison Formulae Van der Meer and Van Gent

Both formulae show that there is a substantial influence of core permeability on the armour layer stability. However, the outcome of both formulae differs considerably. The case of a breakwater core consisting partly of quarry run and partly of sand fill and the case of a rubble mound in front of an impermeable wall are not addressed in the Van der Meer and Van Gent formulae.

### Hudson Formula

The Rock manual (2007) gives guidance on the choice of  $K_D$  value for use in the Hudson equation for rock armour stability. This guidance is based on the data sets of van der Meer and van Gent. A  $K_D$  value of 1 is proposed for an impermeable core and a  $K_D$  value of 4 for a permeable core. This implies a mass difference of four between armour on a permeable and impermeable core.

### EFFECT OF CORE PERMEABILITY ON CONCRETE ARMOUR UNIT STABILITY

Both the formulae of Van der Meer and Van Gent et al are based on extensive tests on rock armour. For interlocking concrete armour units, no design guidance is available on the effect of core permeability on armour layer stability. The stability formulae given in the Rock Manual (2007) for concrete armour units do not include the effect of core permeability on armour stability.

Some guidance can be found in: Burcharth et al. (1998) on the effect of core permeability on Accropode® armour stability. Two types of core material have been applied in the model tests conducted by Burcharth et al.; fine core material with a notional permeability factor of approximately 0.2 and coarse core material with a notional permeability factor of approximately 0.4. Tests have been carried out with Iribarren numbers of 3.75 and 5.00. For both Iribarren numbers a considerable effect of the core permeability on the Accropode® stability was observed. For the short waves the stability number for zero damage was reduced from 3.5 to 2.4 when using fine core material instead of coarse core material. This is equivalent to a 46% increase in required  $D_{n50}$  for zero damage

conditions when having a core with notional permeability of 0.2 instead of 0.4. Burcharth et al. conclude that the sensitivity to core permeability is higher for Accropodes® than for rock armour.

#### HYDRAULIC MODEL TESTS

Hydraulic model tests have been carried out at Delft University of Technology (2006) and DHI (2007) with Xbloc armour on breakwaters with a core consisting of quarry run on geotextile container. The model tests showed that the armour stability was significantly reduced compared to Xbloc armoured breakwaters with a core of quarry run only. Therefore the armour size in the final design was significantly increased because of the reduced permeability of the core. One of the tested sections is shown in Figure 5. The design water level is indicated in the figure. The design significant wave height is 5 m. Based on a Xbloc design value of  $H_s/\Delta D_n = 2.8$ , a  $D_n$  value of 1.33 m would be required. Because of the reduction of core permeability by the presence of the geocontainer core and caisson a  $D_n$  value of 1.59 m was selected. Both rocking and displacements were monitored during model testing. This Xbloc size proved to be sufficiently stable. The increase in  $D_n$  value because of reduced core permeability is therefore 20%. This implies an armour unit size increase by a factor of 1.7.

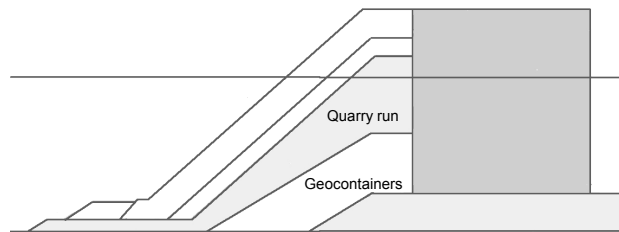


Figure 5. Composite breakwater cross section with geocontainer core.

#### PROTOTYPE DAMAGE ANALYSIS

An analysis has been made of damage to armour layers on structures with small cores and low core permeability's. A typical example is the breakwaters at IJmuiden in the Netherlands. These breakwaters were originally designed with a stone asphalt armour layer (Van Bussel 2003), see Figure 6. Already during construction this stone asphalt armour layer proved to be unstable and started to break up. Between 1968 and 2007 cube armour has been applied as a ballast layer on top of the stone asphalt (see Figure 7) to prevent breaking-up of the stone asphalt layer due to high wave pressures in the core. High pressures in the core do occur as the stone asphalt armour does not fully cover the core, and cracks are present. The outer armour at IJmuiden now consists of a single layer of heavy density cubes on an almost impermeable core, without a filter layer.

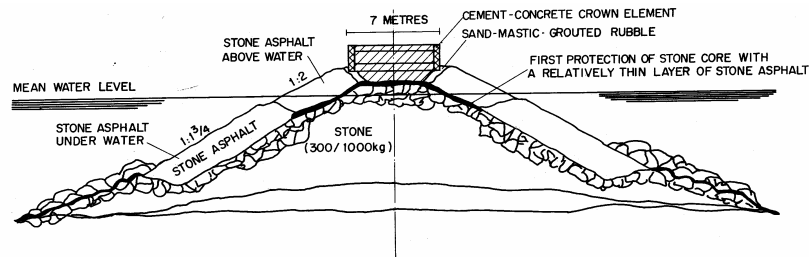


Figure 6. Original as built cross section IJmuiden breakwaters.

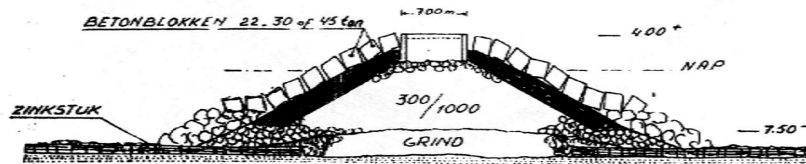


Figure 7. Cross section with added cube armour ballast.

For stability of single layer cubes reference can be made to the research by d'Angremond et al. (1999) and van Gent et al. (2000 and 2002), which led to the equations as given in the Rock Manual:

$$\text{Start of damage, } N_{od} = 0: \quad \frac{H_s}{\Delta D_n} = 2.9 - 3.0 \quad (4)$$

$$\text{Failure, } N_{od} = 0.2: \quad \frac{H_s}{\Delta D_n} = 3.5 - 3.75 \quad (5)$$

On the trunk of the southern breakwaters cubes are present with a nominal diameter of 2.5 m and a density of 2800 kg/m<sup>3</sup>. The 1:100 year design significant wave height at IJmuiden is approximately 7 m (Wagner 2005). This leads to an  $H_s/\Delta D_n$  value of 1.63. These 45 tons cubes are regularly displaced by winter storms at  $H_s/\Delta D_n$  values near 1.5 (see Figures 2 and 8). A single layer cube armour layer on a porous core would require cubes of a nominal diameter of 1.4 m (for a density of 2800 kg/m<sup>3</sup>,  $H_s = 7$  m at start of damage). The

required mass would thus be 8 tons for start of damage at  $H_s = 7$  m. The actual 45 tons cubes have a  $D_n$  value which is 78% larger. Because of the impermeable core they are still not stable.



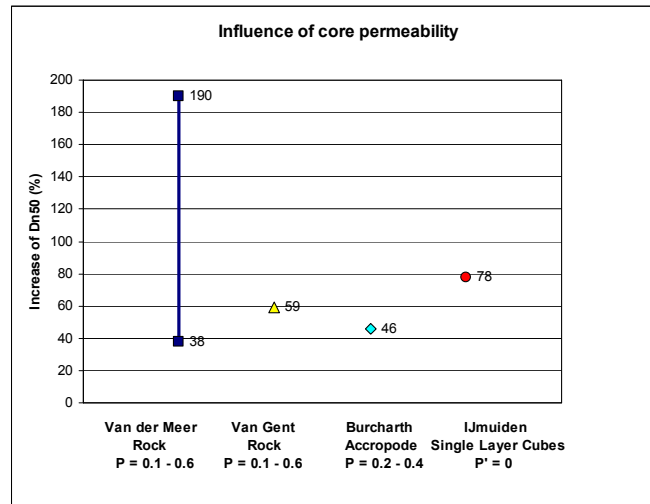
**Figure 8. Cubes displaced from impermeable core at IJmuiden breakwater.**

It is obvious that the impermeable core (and the absence of a filter layer) has a very large influence on the stability of the single layer cube armour at IJmuiden.

### **CONCLUSIONS**

It is concluded that the effect of core permeability needs to be addressed more carefully in design, during model testing and also during construction. Model tests are required to determine the effect of core permeability on armour stability. Proper scaling of core material in physical model tests is highly important. Core material used during construction should not contain too many fines, unless this has been taken into account during design.

Figure 9 contains an overview of the influence of core permeability on armour layer stability as discussed in this paper



**Figure 9. The influence of core permeability on the  $D_{n50}$  of armour units.**

The following holds for the different formulae and cases:

1. Van der Meer gives a range between 38% up to 190% in required increase of  $D_{n50}$  for rock, when going from a permeable core ( $P = 0.6$ ) to an impermeable core ( $P = 0.1$ ).
2. Van Gent gives 59% in required increase of  $D_{n50}$  for rock, when going from a permeable core ( $P = 0.6$ ,  $D_{n50c}/D_{n50a} = 1$ ) to an impermeable core ( $P = 0.1$ ,  $D_{n50c}/D_{n50a} \cong 0$ ).
3. Burcharth gives 46% in required increase of  $D_{n50}$  for Accropode® units when going from  $P = 0.4$  to  $P = 0.2$ .
4. The single layer concrete cubes have a 78% larger  $D_{n50}$  for the present situation with impermeable core ( $P' = 0$ ) to the required  $D_{n50}$  for a conventional rubble mound breakwater with permeable core and filter layer ( $P = 0.4$ ). The cross section of the breakwater of IJmuiden deviates from the cross sections giving by Van der Meer for determination of  $P$ . Therefore  $P'$  is used for this case, with  $P' = 0$  for the present situation of the breakwater as no filter layer is used.

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