CHAPTER 151

Design aspects of block revetments

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1. Introduction

The increasing shortage and costs of natural materials in certain geographical areas has resulted in recent years, inter alia, in the rapid development of artificial (concrete) block revetments.
In general, two main types of revetments can be distinguished: permeable (stone pitching, placed relatively open block-mats) and (relatively-) impermeable (closed blocks, concrete slabs). Regarding the shape and/or placing technique a distinction can be made between: a) free (mostly rectangular-) blocks and b) interlocking blocks of different design (tongue-and-groove connection, ship- lap, cabling, blocks connected to geotextile by pins etc.).
In all these cases the type of sublayer (permeable/impermeable) and the grade of permeability of the toplayer are very important factors in the stability of these revetments. The design also needs to be made (execu- ted) and maintained. Both aspects must therefore already be taken along within the stadium of designing.

At the moment there is a large variety of types of revetment-blocks and other defence systems (i.e. block-mats), see Fig. 1. Until recently no objective design-criteria were available for most types/systems of blocks. The choice (type and size) of the revetments built sofar is only based on experience and on personal points of view, sometimes supported by small-scale model investigations.
In the light of new (stricter) rules regarding the safety of the Dutch dikes, as they have been drawn up by the Delta-Commission, the need for proper design-criteria for the revetments of dikes has evidently grown.

Because of the complexity of the problem no simply, generally valid mathematical model for the stability of the revetment are available yet. For restricted areas of application however, fairly reliable criteria (often supported by large-scale tests) have been developed in the Netherlands not only for the kind of revetment, but also for conditions of loads. This new approach is discussed in (Klein Breteler, 1988). This paper presents a short state-of-the-art review of existing know- ledge on the designing of different types of revetments and, where ever possible, the available stability criteria are mentioned. There is also given some comparison of the different types of revetments with their advantages and disadvantages and suggestions regarding their practical application.

2. Design requirements

In the design process of revetments, besides the specific functional requirements, the following technical aspects have to be taken under consideration:

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PLACED STONES

(VILVOORDSE STONE)

PLACED BLOCKS

TYPE 'HARINGMAN'

STONE PITCHING (BASALT)

GOBI BLOCK

BUILDING BLOCKS

TONGUE- AND GROOVE TYPE

SHIP LAP TYPE

MODIFIED TONGUE AND GROOVE TYPE

WAFFLE TYPE

STEPPED TYPE

interlocking blocks

'A BLOCK'

BASALTON

BASALTON REVETMENT

ARMORFLEX BLOCK AND MAT
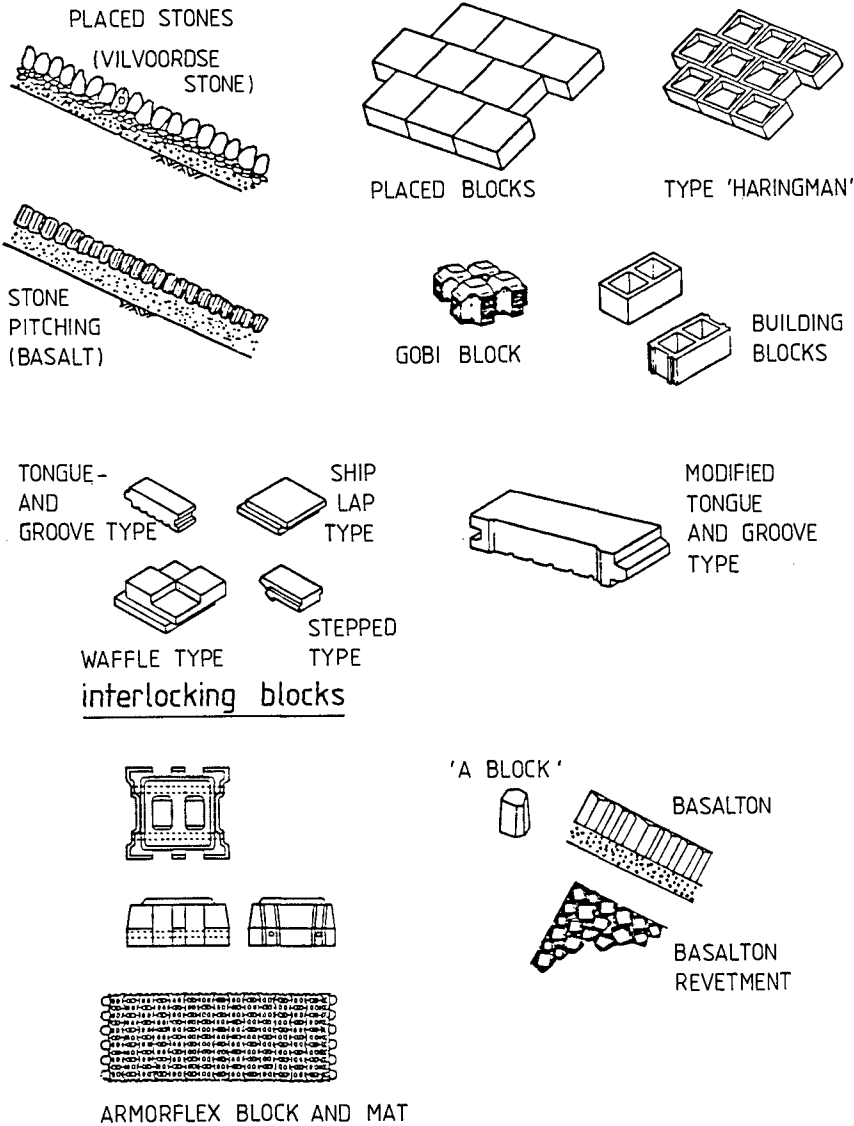
Figure 1. Examples of blocks tested on large scale

- stability (toplayer, sublayers, suboil)
- flexibility
- durability (toplayer/concrete, geotextile, cables etc.)
- possibility of inspection of failure (monitoring of damage)
- low cost (construction/maintenance)

The best revetment is one which combines all these functions.
Some of the aspects mentioned above will be discussed successively.

3. Stability criteria ("black-box" approach)

The total strength of a stable toplayer can be regarded as the sum of the contributions of different strength factors i.e. the static weight of the toplayer, the friction forces on the interface of adjoining elements, the jamming forces induced by sand or other granular materials in the voids/interspaceses between adjoining elements. The toplayer is instable when the hydraulic loads exceed the stabilizing forces. Hydraulic loads are created by waves inducing time dependent pressures on the toplayer, that are transmitted to the sublayers causing pressure differences across the toplayer, that tend to lift blocks from the revetment. These pressure gradients cause also watermotions in the sublayers that endanger the internal stability of these granular layers or the stability of the interface between successive sublayers, causing a gradular deformation which may affect the stability of the toplayer.
When the hydraulic loads (uplift pressures) exceed the stabilizing forces than the additional strength factors are mobilized to prevent damage to the toplayer i.e. inertia forces of the block and the water underneath, and pressure fall under the block to enable the inflow of water in the growing space between the moving element and the sublayers. For relatively smooth block revetments and for openings-percentage smaller than 10%, the drag forces are neglectable, and the (in-)stability of the block revetments is mainly influenced by the uplift forces. These uplift forces are directly dependent on the composition (hydraulic permeability) of the sublayers. That means also that the stability of the block revetments can not be treated separately from the sublayers and/or subsoils.
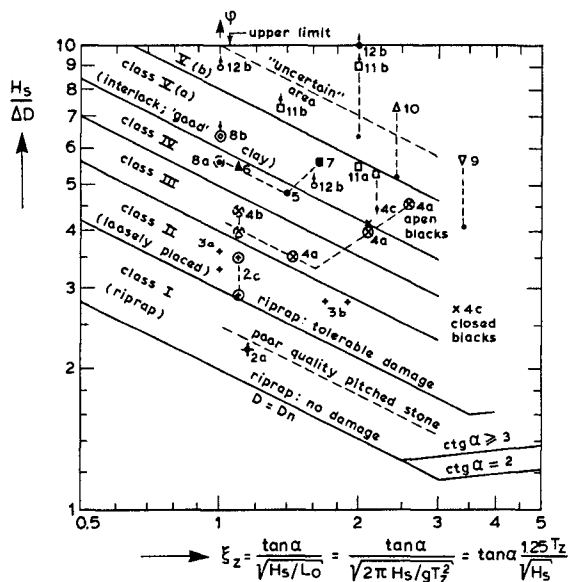
This last remark (conclusion) has very important practical consequences, namely:
- results from the small-scale model have limited value for practical application because these models are not able to reproduce the prototype sublayers and subsoils (the scaling rules are still not properly known); this explains also a large scatter in the results from the small-scale models,
- "black-box" approach (even based on a large-scale data) has limited value and should be applied with caution; in the black-box approach all the forces discussed above are integrated to one strength number – the changing of the composition of revetment (i.e. permeability of toplayer or sublayer) may strongly affect the total stability which is difficult to deduce from the black-box stability numbers,
- the problems mentioned above can be overbridged by applying the mathematical models as being recently developed in the Netherlands (Klein Breteler, 1988).

For the rough (first) approximation of the necessary dimensions of block revetments the following "black-box" model is being developed by Pilarczyk (1987) (PIANC, 1987) (see Fig. 2):

$$\frac{H_s}{\Delta D} = \psi \cdot \frac{\cos\alpha}{\sqrt{\xi_z}} \approx \psi \cdot \xi_z^{-0.5}$$

$\dfrac{H_s}{\Delta D}$

φ — upper limit

class V (b)

class V (a)

(interlock; good; clay)

class IV

class III

class II (loosely placed)

class I (riprap)

"uncertain" area

riprap: tolerable damage

poor quality pitched stone

riprap: no damage $D = D_n$

$ctg\,\alpha \geqslant 3$

$ctg\,\alpha = 2$

open blocks

x 4c closed blocks

$$\xi_z = \frac{\tan\alpha}{\sqrt{H_s/L_0}} = \frac{\tan\alpha}{\sqrt{2\pi\,H_s/gT_z^2}} = \tan\alpha\frac{1.25\,T_z}{\sqrt{H_s}}$$

Note :

$\updownarrow$ — no damage appeared

Δ^{10} — numbers refer to table

— possible replacement due to translation to irregular waves

D — block thickness
　D = D_n for riprap

$$D_n = \left(\frac{M_{50\%}}{\rho_s}\right)^{1/3}$$

　$M_{50\%}$ = average mass of stone
　ρ_s = density of stone

H_s — significant wave height

T_z — average wave period

$\tan\alpha$ — slope gradient; $ctg\,\alpha \geqslant 2$

φ — strength coef. defined at $\xi_z = 1$

ξ_z — breaker similarity parameter

$$\boxed{\frac{H_s}{\Delta D} = \varphi\,\frac{\cos\alpha}{\sqrt{\xi_z}} \approx \frac{\varphi}{\sqrt{\xi_z}}}\quad \left(\begin{array}{c}\text{assumed}\\\text{function}\end{array}\right)$$

$\underline{\xi_z < 3}$　(breaking waves)

Figure 2. Classification of strength of block revetments

for $\xi_z < 3$ (breaking waves) and $\text{ctg}\alpha \geqslant 2$

and $\xi_z = \dfrac{\tan\alpha}{\sqrt{H_s/L_o}} = \tan\alpha \; \dfrac{1.25 \; T_z}{\sqrt{H_s}}$ (breaker index)

where: $H_s/\Delta D$ = strenght parameter, H_s = significant wave height, α = slope angle, T_z = average wave period, D = thickness of block, $\Delta = (\rho_s - \rho_w)/\rho_w$, relative density of block and ψ = stability factor. For riprap $D = D_{n50} = (W_{50}/\rho_s)^{1/3}$, ($W_{50}$ = 50% by mass). For $\xi_z > 3$ the constant $H_s/\Delta D$- value in $\xi_z = 3$ can be kept safely (N.B. for some types of block revetment the $H_s/\Delta D$- values can increase a lot when ξ_z is large).

Note: The results of the recent large-scale tests (1987) indicated that the stability of the loosely placed blocks (cat. II), placed on the granular sublayer, can be approximated better by (Fig. 3):

$$\frac{H}{\Delta D} = \frac{\psi}{\xi_z} \quad (1 \leqslant \xi_z < 5 \text{ and } \text{ctg}\alpha > 2)$$

where: $\psi = 3.5$ - for less permeable (closed) blocks, and
$\psi = 4.0$ - for relatively permeable blocks
(open area 5 - 20%)

The open blocks have more reserve-stability than closed blocks; the $\psi = 5$ value can be applied as an upper-limit (tolerable movement of blocks).

In the case of frequent double-top storms it has to be advised to reduce the $H_s/\Delta D$- values with 25% because of the long-term effect of loading.
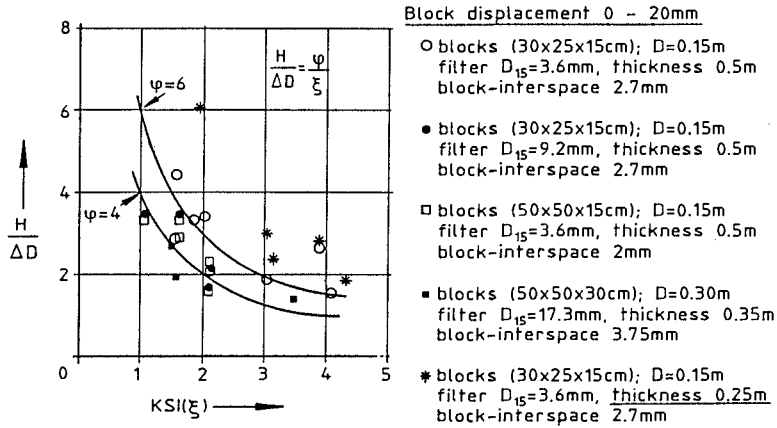
This model works rather well for riprap on relatively impermeable core (i.e. sand) and it also gives a good approximation for some block revetments. By using this model the strength of various types of block revetments can be directly compared to the strength of riprap revetments.

Stability factor (ψ) has been determined empirically. In view of the problems on the translation of the results of small-scale models into prototype, only the large-scale tests have been taken into account (Fig. 1). The results of this have been summarized below (ψ is defined at $\xi_z = 1$):
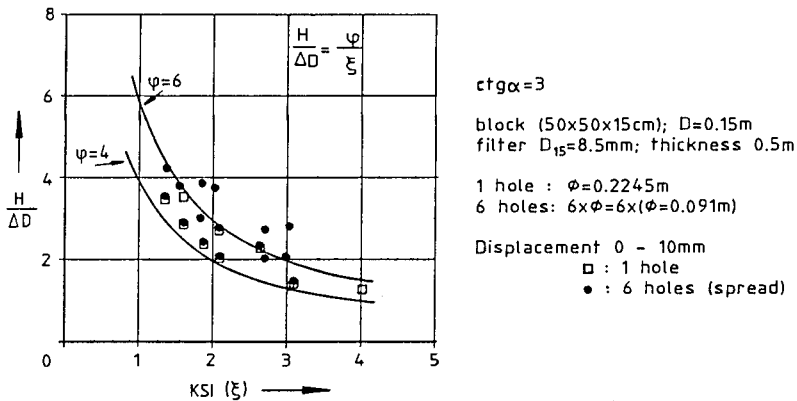
I   : $2 \leqslant \psi \leqslant 3$ riprap (2 layers) $N \leqslant 3000$ waves; $\psi = 2$ denotes "no-damage" and $\psi = 3$ denotes max." tolerable damage
II : $3 \leqslant \psi < 4$ pitched stone, loose placed blocks, blocks connected by geotextile
III : $4 \leqslant \psi < 5$ blocks interlocked by friction, grouted blocks connected by geotextile, cabled blocks
IV : $5 \leqslant \psi < 6$ loose blocks directly on "good clay"
V   : $6 \leqslant \psi$ grouted (cabled-) blocks, mechanically interlocked blocks.

Remarks:
1 The upper and lower limits within a category are generally dependent on the quality of design and construction,
2 Filter requirements of the soil have to be met by the geotextile and/or granular sublayer,
3 Blocks placed directly on geotextile and well-compacted sand: max H_s = 1.2 m,
4 "Good-clay" = according to requirements given in the Guidelines (CUR/TAW, 1984) and smooth surface (no cavities),

Block displacement 0 – 20mm

O blocks (30x25x15cm); D=0.15m
   filter D_{15}=3.6mm, thickness 0.5m
   block–interspace 2.7mm

● blocks (30x25x15cm); D=0.15m
   filter D_{15}=9.2mm, thickness 0.5m
   block–interspace 2.7mm

□ blocks (50x50x15cm); D=0.15m
   filter D_{15}=3.6mm, thickness 0.5m
   block–interspace 2mm

■ blocks (50x50x30cm); D=0.30m
   filter D_{15}=17.3mm, thickness 0.35m
   block–interspace 3.75mm

✳ blocks (30x25x15cm); D=0.15m
   filter D_{15}=3.6mm, thickness 0.25m
   block–interspace 2.7mm

$$\frac{H}{\Delta D} = \frac{\varphi}{\xi}$$

a) Stability-function for closed-block revetments

$$\frac{H}{\Delta D} = \frac{\varphi}{\xi}$$

ctgα=3

block (50x50x15cm); D=0.15m
filter D_{15}=8.5mm; thickness 0.5m

1 hole : Φ=0.2245m
6 holes: 6xΦ=6x(Φ=0.091m)

Displacement 0 – 10mm
   □ : 1 hole
   ● : 6 holes (spread)

b) Stability-function for open-block revetments

Figure 3. Stability-criteria for loosely placed blocks (1987).

5 Cat. V ($\psi \geqslant 6$) must be carefully designed and examined especially regarding the stability of sublayers (large scale check of design is recommended),

6 Because of practical reasons the block thickness less than 10 cm is not recommended (for cabled blockmats 8 cm).

4. Composition of construction

There is a large number of different types of toplayer, sublayer and subsoil and, it is obvious, that there are many possible combinations that can lead to a large number of possible constructions. This does not simplify the choice of a revetment. Some possible aspects and solutions that can play a part in the choice of the construction of the revetment are mentioned below.

● Stability of top-layers strongly depend on the sort/composition of sublayers and they must therefore be regarded as a whole. As an example, from the large-test results it appears that a block revetment on a sublayer of "good clay" provides more stability than one on a permeable sublayer.

● Instability (erosion) of sublayers and/or subsoil can lead to failure of a toplayer. The stability of top-layers and sublayers must therefore be designed steadily (with an equal opportunity of failure).

● A good tuning of the permeability of the toplayer and sublayers (including geotextiles) is an essential condition for an equal design. The permeability (k) of the different parts of the construction must increase from underneath to top: k, ground $<$ k, sublayer $<$ k, top-layer.

The strength of revetment increases with increasing the permeability of the toplayer and decreasing the permeability of the sublayer. Moreover, a thin permeable sublayer, reduces the uplift forces, but increases the internal gradients (the internal stability of the sublayers decreases).

● The granular filters are mostly expensive and difficult to realize (especially under water) within the filter-requirement limits. A substitutional solution is a geotextile (filter function) with a certain thickness of graded stone layer (with function to dump the internal hydraulic loads). A good and cheaper solution can also be realized by applying a thick layer of broadly graded waste products as minestone, slags, silex, etc. (well compacted).

● The use of blocks directly on sand-body (with geotextile in between) is restricted, at the present state of knowledge, to wave height of $H_s = 1.2$ m. The good compaction of sand is essential to avoid sliding or even liquefaction. For loads higher than $H_s = 1.2$ m a well graded layer of stone on a geotextile is recommendable (e.g. layer 0.2-0.3 m for 1.2 m $<$ H_s $<$ 2.5 m).

● For placement of blocks directly on clay subsoil/sublayer, besides the requirement of right composition and homogenity, the proper compaction and smooth surface (blocks placed as close as possible to the clay surface) are of primarily importance (CUR/TAW, 1984). In the case of "poor clay" (concerning composition and/or surface preparation) it should be recommended to protect the clay-surface by a multilayer (non-woven) geotextile and to use a lower value of ψ (i.e. 4 $<$ ψ $<$ 5).

● The stability of (real) loose blocks is rather low ($\psi \approx 3$). The strenght of these blocks can be increase by introducing of the clenching forces between blocks, caused by friction and wash-in-material, or interlocking.

● The main advantage of applying block-mats and/or interlocked systems are:

- in general, higher stability of toplayer
- mechanical placement (also from water side)
and the main disadvantages (or uncertainties):
- durability/damage of binders (cables, pins, etc.)
- less flexibility and inspection problems in respect to failure sub-
  layer
- repair problems (especially under water)
- connection of adjoining mats (especially under water)
Many of these problems will be omitted if the sublayer is designed
properly.
Although the grouting of these systems (i.e. grouting/ washing in by
fine broken stones) decreases the flexibility, it can be helpful for
some reasons.
● Disadvantages of non-grouted systems:
- individual blocks can move (less stability of toplayer)
- cables/pins loaded more frequently
- abrasion of geotextile
- erosion sublayer/subsoil can take place more easily
● Advantages of grouted (blinded) systems:
- higher stability of toplayer (no movement of individual blocks)
- if (at heavy attack) the mat will be lifted out, then there is less
  loading of cables/pins and interlocked-elements, and less abrasion
  of geotextile, because such mat will move as integral unit.
● Not every system can be grouted; if the interspaces between the blocks
are too large, the grouting material will be easily washed out. In
this respect the basalton-system (grouted but not cabled - see Fig. 1)
has more advantages than other systems, because of the tapered verti-
cal form and lack of cabling, the blocks can still follow a limited
settlement, the settlement is immediately evident, and a washing out
of grouting material is limited.
● Erosion or damage often starts at joints and transitions. Therefore,
an important aspect of revetment construction, which requires special
attention, are the joints and the transitions; joints onto other
revetments materials, and transitions onto other revetment parts or
other structures. If they are inevitable the discontinuities introdu-
ced should be minimized. This holds for differences in elastic and
plastic behaviour and in the permeability of the sand tightness.
Proper execution is essential in order to obtain satisfactory joints
and transitions.

5. Conclusions

● Stability of block revetments strongly depend on the sort and composi-
tion of toplayers and sublayers and they must be regarded and treated
as a whole.
● Because of scaling problems of sublayers the small-scale models are
not suitable for investigation of stability problems of revetments.
● The value of "Black-Box" approach based on large scale tests is mainly
limited only to the construction tested; the extrapolation to other
compositions of construction involves many uncertainties.
● The "Black-Box" model as presented in this paper can be applied only
for the rough (first) approximation of necessary dimensions of revet-
ments.
● For detail design and/or more complicated cases the mathematical model
as developed in the Netherlands (Klein Breteler, 1988) or large scale
tests are recommended.
● Whatever calculation method and protective system is adapted, (local)
experience and sound engineering judgement play on an important part
in a proper design of protective structures.

The research on dike protection and other coastal defence systems is still going on in the Netherlands. Research is now being directed towards a better probabilistic description of the design, better understanding of the failure mechanisms, application of new or alternative materials, monitoring of damage, economical aspects of design and optimal choice of constructions applied incorporating future maintenance aspects.

6. References

(1) CUR/TAW (1984). Guide to concrete dike revetments. Netherlands Centre for Research, Codes and Specification for Concrete (CUR) and Technical Advisory Committee on Water Defences (TAW), Report 119 (English version available).
(2) BURGER, A.M., et al. (1988). Design method for block revetmen, 21st Internat. Conf. on Coastal Engineering, Torremolinos, Spain.
(3) PIANC, PTC I, W.G.4 (1987). Guidelines for the design and construction of flexible revetments incorporated geotextiles for inland waterways.
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No. Reference	Toplayer		Sublayer	Slope ctgα	$\dfrac{H_s}{\Delta D}$	ξ_z	$\psi = \dfrac{\dfrac{H_s}{\Delta D}}{\xi_z = 1}$	Class
1a M1983 1b WL Pub No. 332, 1984	Riprap – no damage "Tolerable" Riprap–damage	L L	Granular filter thick 2D50	2:6	full range D = Dn		2:2.25 3.0	I ref.
2a M2036 2b Sollitt 2c M2036 3a M1795 3b M1881-IX	Vilvoordse (pitched) Pitched stone, D=Dn Pitched basalt Placed blocks Placed blocks	L L L L L	brick rubble crushed stone brick rubble gravel gravel	3.5 2 3.5 4+berm 3	2.20 2.80R 2.9÷3.5 3.3÷3.6 2.8	1.15 1.3÷2.6 1.10 1.0 1.7÷1.9	2.5 3.0 3.5 3.5 4	II
4a C.E.R.C. (US) 4b C.E.R.C. 4c M1881-XII	Gobi blocks + geo- tex.(open blocks) Open/building blocks Placed blocks (closed)	L L L	fine gravel, 40% 2mm coarse sand sand 0,4 mm/ geotextile sand 0,2 mm/ geotextile	3.5 5 3	3.5R 4.0R 4.55R 4÷4.4R 4.16R 2.70R	1.45 2.10 2.60 2.10 3.30	4.0 4.5* 5.0*	III
5 M1900 6 M2036 7 M1910 8a M1795	Basalton (basalt) Placed blocks (haringman) Armorflex-blocks Placed blocks	L O L L	crushed stone (silex) minestone + thin l. gravel crushed stone/ good clay with rough surface	3 3.5 3 4	4.80 5.50 5.60 5.60	1.40 1.10 1.65 0.95	5.0 5.5 5.5 5.5	IV
8b M1795 9 C.E.R.C. 10 C.E.R.C. 11a Oregon (US) 11b M1910 12a 12b	Placed blocks Ship-lap blocks Tongue-and grove "modified" (6 mm relief slot) Armorflex-mats (grouted) Armorflex blocks (grouted) Placed blocks with interspaces (grouted) Basalton (grouted)	L I I C+G G C C	good clay crushed stone crushed stone sand 0,5 mm/ geotextile crushed stone/ gravel gravel crushed/stone/ silex	4 2 2 3 3 3 3 3	6.40 5.71R 7.3R 5.30R 5.50 7.3 9.0R 7.0R 5.0R 10.0R 15.0R	1.00 3.40 2.43 2.20 2.00 1.35 2.00 1÷2.5 1.60 1.30 2.00	6.0** 6 a 7 7 a 8 7 a 8 8.0 8.0 10.0	V

Note: L = loose placed blocks, O-old; natural reinforcement/interlocking (i.e. sand, grass)
        G = grouted (blinded/chocked by gravel, silex, slags, crushed stone)
        C = cabled, I–interlocked blocks (artificial); R = tests with regular waves
       *) Blocks/mats directly on compacted sand + geotextile only for H_s < 1.5 m
    **) 'Good' clay: proper composition, compaction and smooth surface acc. to criteria