



STABILITY OF PATTERN PLACED REVETMENT ELEMENTS

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Abstract: A revetment of pattern placed elements, or a so called pitching, is used worldwide to protect shorelines and embankments. Also in The Netherlands more than 500 km of river, lake and sea dikes is protected by pitchings. Until the 60's the design and construction of pitchings was based on experience. After the first damages on pitchings and the negative assessment results, an intensive investigation program on pitchings was carried out. The results are commonly used nowadays in the Dutch dike reinforcement works. When comparing pattern placed block revetments with other revetments, the remarkable difference is that the amount of material to be used is significantly less than when using loose riprap. However placing blocks is more labour intensive. This is a specific advantage for countries with a large inexpensive labour force. In China, Vietnam and Bangladesh these are very common constructions. The leakage length Δ , describing the relationship between top layer elements and sublayer properties, is the most important design parameter; a small leakage length is favourable for the stability of the pitching. The maritime commission of PIANC has in 2007 decided to start a working group to make a small document on the design of pattern placed revetment elements. This PIANC MARCOM working group 57 report is now available (PIANC report 114, 2011). This paper presents an outline of this new knowledge of pattern placed block revetments, required for assessment and design purposes usable all over the world. It follows more or less the contents of the new PIANC report.

Keywords: *pitching; pattern; placed; concrete; blocks; revetment; design*

INTRODUCTION

Pattern placed elements, or a so called pitching, is used worldwide to protect shorelines and embankments. Also in The Netherlands more than 500 km of river, lake and sea dikes is protected by pitchings. Until the 60's the design and construction of pitchings was based on experience. Even after the storm surge and flooding in 1953, less attention was paid to these constructions because the dikes mainly failed due to overtopping. The first damaged pitchings were registered in the seventies. Slowly an investigation on the stability of pitchings was started up. Large scale model tests were carried out and the development of a new analytic method enabled the engineers to predict the stability and safety level of pitchings. As a result of the first 5 yearly safety assessment of the high water defence system in The Netherlands in 1995, hundreds kilometres of the pitchings were found to be insufficient to withstand the storm surge conditions. Action was needed. A huge national investigation program was developed and has been carried out. Not only with the goal to give a more appropriate method for the safety assessment of all kind of pitchings, but also for the design of new ones. Based on this new knowledge still a lot of dike reinforcement works are carried out along the Dutch lakes and shore.

The maritime commission of PIANC in 2007 decided to start a working group to make a small document on the design of pattern placed revetment elements. A working group with

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representatives from several countries started this work, but because lack of available time of the group members, this did not lead to an internationally supported draft report. Therefore MARCOM has invited the chair of this working group to form a small Expert group to finalise the report. This PIANC MARCOM working group 57 report is now available (PIANC report 114, 2011).

DEFINITION OF A PATTERN PLACED BLOCK REVETMENT

A block revetment is a protection of a shoreline with stony material, usually natural stone or concrete, with a thickness of only one layer of elements, and of which the elements are placed in a pattern (Fig. 1). The blocks might have some connections. These types of revetments were developed in areas with a limited supply of natural stone. The stones were placed by hand to ensure a maximum friction between the block. In general the experiences with these pattern placed natural block are good; however, they have two practical problems:

1. It is difficult to find nicely shaped natural rock (e.g. basaltic columns), or it has to be cut to the correct shape at high costs.
2. It is a labour intensive type of work, because it is difficult to mechanise (Fig. 2).



Fig. 1 Pattern placed revetment with shaped natural rock (Vietnam)



Fig. 2 Pattern placed revetment with natural basaltic columns (Netherlands)

Because of the irregularities with natural stone, artificially shaped blocks have been developed (Fig. 3 and 5). The advantages of artificially shaped blocks (usually made from concrete), is that they all have the same height, and therefore placement is much easier. The basic type of artificial block is a rectangular block. Because these blocks are rather impermeable, the stability is limited (see further), and therefore newer loose blocks have a column shape and more open space between the elements (Fig. 4 and 5).



Fig. 3 Concrete blocks



Fig. 4 Placing of Hydroblocks®

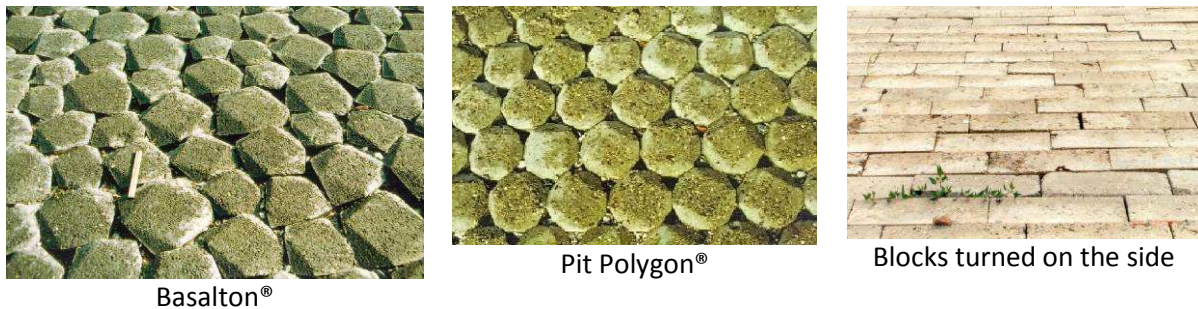


Fig. 5 Top view of some pattern placed concrete blocks and columns (The Netherlands)

Blocks may get an increased stability by introducing interlock. Individual interlocking blocks cannot be removed simply; a whole section has to be lifted away. This makes interlocking structures more stable, but also less flexible and more difficult to repair. Also it is quite difficult to make curves in a section with some interlocking blocks.

In the early days of pitching construction in The Netherlands concrete blocks were placed directly on clay (Fig. 6). But after several years damage occurred as a result of gullies (due to erosion or animals) just under the blocks (Fig. 7).

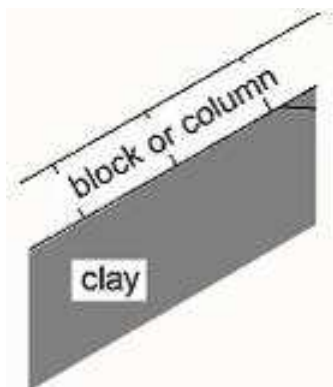


Fig. 6 Construction detail blocks on clay



Fig. 7 Gullies under the blocks in the clay subsoil

Therefore a pitching should be placed on a granular layer which functions as a filter or as a fill layer (intermediate layer) when a geofabric is used as a filter (Fig. 8).

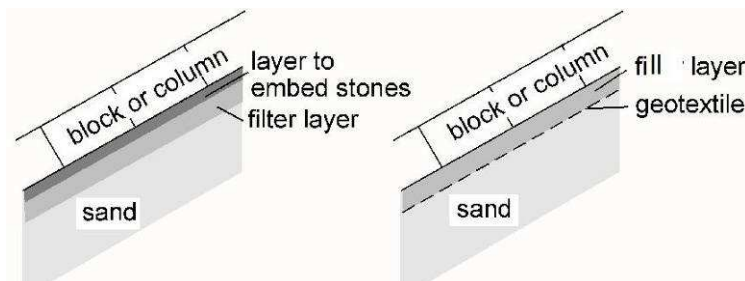


Fig. 8 Construction detail of sub layers



Fig. 9 Basaltic columns on a fill layer

When comparing pattern placed block revetments with other revetments, the remarkable difference is that the amount of material to be used is significantly less than when using loose riprap. However placing blocks is more labour intensive. This is a specific advantage for countries with a large

inexpensive labour force. In China, Vietnam and Bangladesh these are very common constructions. On the other hand, when comparing these revetments with continuous linings, like asphalt and concrete plates, the advantage is the higher permeability and consequently the lesser overpressure formation inside. Also pattern placed block revetments can be very flexible, if well designed.

In general the layer thickness of a block revetment is less than a layer of riprap. This means that the transport costs are less and the structure weight is less. This makes block revetments an appropriate revetment structure in areas where there are no quarries in the neighbourhood and with relatively soft soil conditions. In Deltaic areas, this is often the case.

Usually block revetments are applied on a slope of 1:2 to 1:6 (ver:hor), but in some cases blocks are also placed on steeper slopes. However, for steep slopes, the design formulas as presented in this paper are not valid.

Because placing blocks under water is difficult, the range of application is usually limited to the area above the low water mark. This makes block revetments especially attractive in areas with medium to large tidal ranges. At low water the load is usually small, and the slope above low water can be placed in dry conditions.

In general revetment blocks will be applied for slopes struck by design waves (wind and/or ships) with an H_s in the range from 0.5 to 3 m.

BLOCK STABILITY PRINCIPLES

The loads on block revetments can be wave action (by wind waves or ship waves), current action or a combination. Special cases as overtopping, ice loads and rapid water level changes are not discussed. The main failure mode of a placed block revetment is the instability of the block because the pressure force from the inner side of the revetment (upwards forces) is higher than the sum of deadweight and friction forces (downward forces). Basically a block revetment is designed to be stable against this main failure mechanism. However, there are also some additional failure mechanisms. These additional failure mechanisms should also be considered, because in special cases these additional mechanisms may lead to failure of the structure. The relevant additional mechanisms are: liquefaction of the subsoil under the block, erosion of the material under the blocks, failure of the toe structure and damage to the blocks themselves.

Pressure differences

The stability for wave loads is based on the pressure difference over the block revetment. This pressure difference depends on the permeability of the top layer. The parameter to describe the relative permeability of the top layer is the leakage length Λ . A small leakage length is favourable for the stability of the blocks. In case of a relatively thin block revetment with a very short leakage length the wave impact may also increase the load on the subsoil considerably.

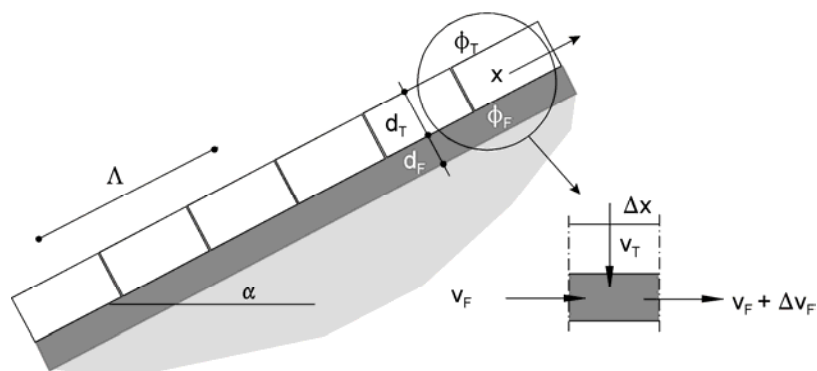


Fig. 10 Flow through block revetment and leakage length

The flow in the granular filter or fill layer can be expressed as:

$$v_F = -k_F \frac{d\phi_F}{dx} \quad (1)$$

and through the top layer:

$$v_T = k_T \frac{(\phi_F - \phi_T)}{d_T} \quad (2)$$

Based on continuity, $\Delta v_F \cdot d_F = v_T \cdot \Delta x$, see Fig. 10, hence $v_T \approx d_F \cdot dv_F / dx$, from which follows:

$$\frac{d^2\phi_F}{dx^2} = \frac{-k_T (\phi_F - \phi_T)}{k_F d_T d_F} = -\frac{(\phi_F - \phi_T)}{\Lambda^2}$$

$$\rightarrow \phi_F - \phi_T = -\Lambda^2 \frac{d^2\phi_F}{dx^2} \quad (3)$$

From this equation it can be seen that the head difference over the top layer depends directly on Λ , defined in equation 3. A relatively thick and permeable filter layer and/or a relatively impermeable top layer give a large Λ and hence, a large head difference over the top layer. This equation can be solved analytically if boundary conditions are highly schematized and if flow in the filter layer is assumed to be laminar (or more precisely: the relation between velocity and pressure is presumed to be linear).

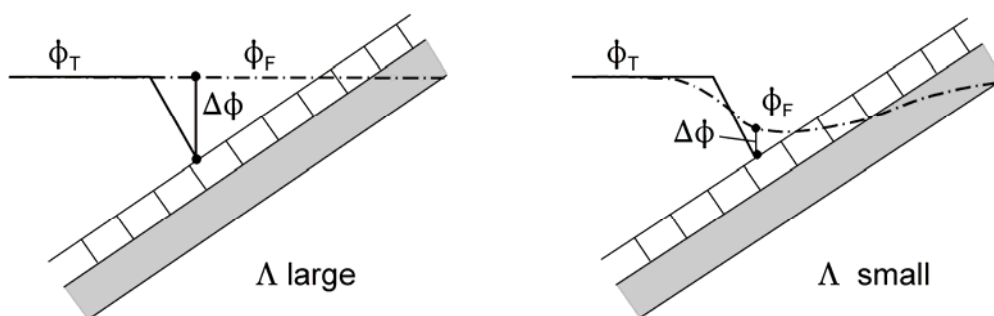


Fig. 11 Head difference over a block for large and small leakage length

Figure 11 shows the situation with a very high value of Λ and with a very small value. **So, a small leakage length Λ , is favourable for the stability of the blocks.** It is clear that a permeable top layer and an underlayer with lower permeability will lead to the most stable structure. This means also that filter layers should be kept as thin as possible!

With this knowledge it is easy to understand that blocks directly placed on an impermeable layer of clay seemed to be a good idea. But this theory also makes clear that the forming of gullies just under the blocks decreases the stability of the pitching because the permeability of the sublayer considerably increases and therefore the leakage length increases significantly.

Liquefaction

At the location of the wave impact there is the possibility that liquefaction of the sublayer will occur with the consequence the top layer might slide down. Especially with very open, but interlocking structures one may fear for this mechanism. Also omitting the intermediate layer (fill layer) and placing the blocks directly on a geotextile on sand will increase the risk of liquefaction. Normally a well compacted sand layer under an intermediate layer will prevent liquefaction.

Erosion of material under the blocks

Erosion under blocks may occur when the size of the gaps or joints between the blocks allows migration of subsoil or grains from the granular filter or fill layer. This is the case with blocks directly placed on clay but also in cases where an improper filter has been applied between the blocks and the core layer. Therefore blocks directly placed on cohesive, but fine material is not recommended. The grain size of the granular filter or fill layer must be adjusted to the gaps or joint widths between the blocks or the other way round to prevent washing out of the material and to provide a sufficient low value of the leakage length.

Failure of the toe construction

Every placed block revetment needs support at the toe, so a failing toe will cause the revetment to fail. Usually, some vertical structure is used as a toe. One has to take care that the soil adjoining seaward of this vertical structure is not eroded. To prevent this in most cases a riprap toe protection is used.



Fig. 12 Detail of a toe construction



Fig. 13 Toe construction with riprap toe protection

Damage to the blocks themselves

The block themselves should be strong enough to withstand mechanical damage. For normal, prefabricated concrete this is no problem, but with locally made blocks, sometimes problems occur.

DESIGN METHODS

The general stability formula for a block can be expressed in terms of $H/\Delta d$. Tests in both small scale and large scale facilities have indicated that for blocks the ratio $H/\Delta d$ is a function of the Iribarren number ξ . For well-placed blocks on a well-designed (and constructed) granular filter or fill layer (layer thickness about 10 cm, grain size as small as possible but such that washing out through the top layer is not possible, see further) the design formula is (TAW, 2003):

$$\frac{H_s}{\Delta_m d} = 6\xi^{-2/3} \quad \text{for } 2 \leq \cot \alpha < 8 \quad (4)$$

in which:

H_s - significant wave height [m]

d - height of pitching elements [m]

Δ_m - relative density of elements [-]

ξ - breaker parameter or Iribarren number [-]

For oblique wave attack the usual reduction with $\sqrt{\cos \beta}$ can be applied.

In case current (wind driven currents, tidal currents, return current from ships) is relevant to the design, the block size must be selected in such a way that the blocks are also stable. Current forms a low pressure on top of the block, and this may cause lifting. A practical value for the stability can be found using:

$$\frac{u}{\sqrt{\Delta_m g d}} < 1.5 \quad (5)$$

According to the leakage length theory a very permeable top layer seems to be a good idea. But in that case not only the friction or clamping between the blocks will decrease, but also the pitching becomes vulnerable for direct wave impact, resulting in high uplift forces. For more detail see (TAW, 2003).

In the case of relatively steep slopes and long waves there is a risk of the complete revetment sliding, or liquefaction under the filter/clay layer can occur. This should be checked. The resistance against sliding is sufficient when (TAW, 2003):

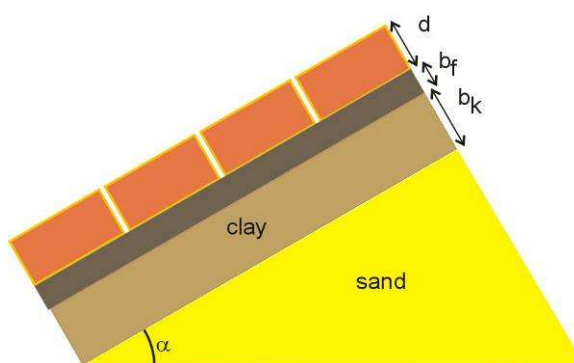


Fig. 14 Sliding, layers under a revetment

$$\Delta d + b_f + b_k > \min \left\{ 0.16 H_s^{0.2} T_p^{1.6} (\tan \alpha)^{0.8}; 1.5 H_s \right\} - 1334 \cdot (1 - 1.19 \tan \alpha) d_{15} \sqrt{T_p} \quad (6)$$

in which:

d - thickness of the revetment blocks [m]

- b_f - thickness of (granular) intermediate (fill) layer [m]
- b_k - thickness of clay layer [m]
- α - slope of structure [°]
- d_{15} - representative grain size of the sand layer under the intermediate layer or clay layer [m]

In normal slopes (1:4 – 1:2,5) a clay layer thickness of about 1 m will be sufficient.

DESIGN IMPLEMENTATION

Sub layers

The sub layers consist of an intermediate (fill) layer and a geotextile. The geotextile has to have good filter properties and a reasonable strength. For details on geotextiles see PIANC report 113 (MARCOM Working Group 56). Because the material of the intermediate layer does not consist of large rocks and this material is not dumped from a large height, the strength of the geotextile is not the determining feature.

The intermediate layer should have good filter properties, but should not be too permeable (this would increase the leakage length, which is undesirable). A layer of 10 cm is usually sufficient (thicker layers will also increase the leakage length). A layer thickness of less than 5 cm is not advisable. Sometimes (especially in the inter-tidal zone) the layer has to be increased sometimes for reasons of executions. A practical grading for the intermediate layer under concrete blocks is crushed stone 16-32 mm or 20-40mm. In case rectangular concrete blocks are placed tight next to each other, the permeability of the top layer might be small due to the small joint width between the blocks; the grain size of the granular filter or fill layer can be smaller and also should be smaller to provide a sufficient small value for the leakage length.

In the case of series of blocks with relatively large gaps or porosity one should prevent that stones from the intermediate layer are washed out via these holes. Normally, the holes are initially filled with filling material to increase the friction or clamping; it is acceptable that during storm conditions 50% of the material is washed out of these holes (e.g. the erosion depth (Y) in the holes should be no more than 0.5 times the block size d). Tests have resulted in the following relations for the erosion depth:

$$Y > 0.23G \cdot (H_s / d_{50})^{0.33} \quad \text{for } G \geq 0.1m$$

$$Y > 0.04G \cdot (H_s / d_{50})^{0.50} \cdot \Omega^{-0.75} \quad \text{for } G < 0.1m \quad (7)$$

in which G is the diameter of the hole, d_{50} the size of the filling material and Ω the ratio of open space in the top layer. Dutch experience teaches us that the minimum block height is about 0.25 m to prevent washing out of the filling material over the full block height.

Transitions

Revetments are not endless thus transitions have to be made. Such transitions are weak spots in the construction, and therefore special attention is needed. Many alternative designs for a transition are possible. But in all cases one should keep in mind that the construction should be permeable for water and closed for sand migration. Local water overpressure should be avoided.

A transition can decrease the strength and/or be subjected to an increased load. Figure 15 shows the transition between a concrete block revetment and a loose rock protection. The board (toe construction) is meant to keep the blocks in place. Due to subsidence of the soil, a split can occur resulting in a decreased strength (unprotected soil under the blocks). The board may also lead to an increased load: the wave pressures against the blocks are higher due to locally insufficient drainage.

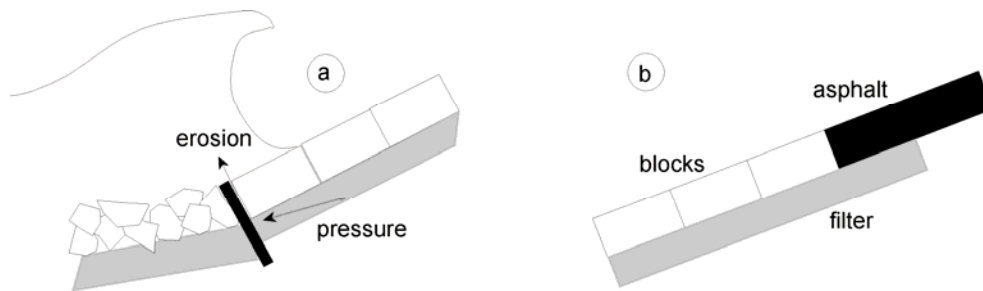


Fig. 15 General aspects of transitions

The ideal transition should be just as strong and flexible as the adjoining layers. This is very hard to realize, therefore the following aspects should be considered:

- **Care:** possibly the most important aspect. With extra attention during construction, inspection and maintenance, many problems can be avoided
- **Permeability:** when there is a difference in permeability of the revetment on both sides of the transition, the transition should be dimensioned with the difference in mind, see Fig. 16.
- **Overlap:** a split down to the sand should be avoided, there should always be some overlap between layers, see Fig. 16.

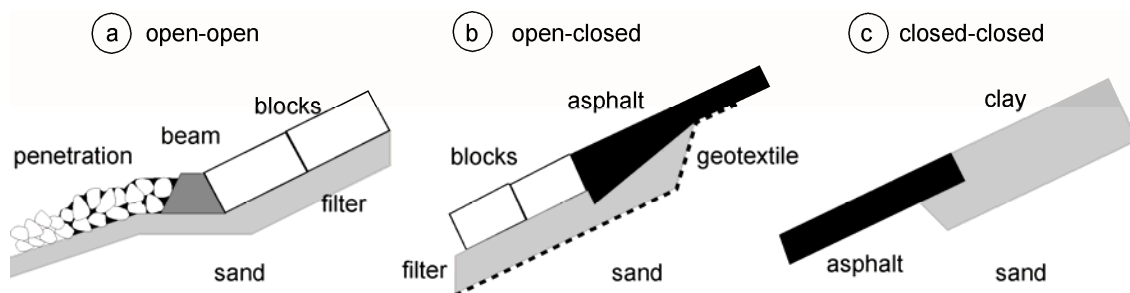


Fig. 16 Transitions between open and closed revetments

Open-open

Figure 16a shows a transition between two open revetments with different permeabilities: concrete blocks and loose rock. The very permeable rock can cause extra pressure under the blocks. By penetrating the first meter or so of the rock with asphalt, the wave pressures will penetrate less easily. The support of the blocks above the transition is guaranteed by the concrete beam, which has a special shape.

Open-closed

Between the blocks and asphalt in Figure 16b there is an overlap in the filter layer in order to avoid a clear cut seam. Via the blocks, an extra pressure under the asphalt can build up. The asphalt layer should be thicker at the transition to withstand this pressure.

Closed-closed

A filter is not necessary in this case, but a seam down to the sand layer must be avoided in order to prevent a pressure leak from inside which will cause erosion, see Figure 16c.

Many other transitions can be required (Fig. 16 and 17), e.g. between blocks and grass. If cattle grazes on the slope, the animals can damage the transition. Partially open blocks, which allow grass to grow through, can serve as a gradual transition.



Fig. 17 Transitions between different pitching types



Fig. 18 Transition construction of penetrated rock

Furthermore the PIANC Report also describes the aspects execution, costs, monitoring, maintenance and repair.

REFERENCES

- TAW [2003] Technical Report Stone Pitching; in Dutch: Technisch rapport steenzettingen, TAW REPORT TR25 ([PART 1](#), [PART 2](#), [PART 3](#))
- PIANC-MARCOM21 [1992] [Guidelines for the construction of flexible revetments incorporating geotextiles in marine environment](#), 197 pp, ISBN 2.87223.044.0
- PIANC report 113 [2011] [The application of geosynthetics in waterfront areas](#), 113pp, ISBN 978-2-87223-188-1
- PIANC report 114 [2011] [The stability of pattern placed revetment blocks](#), 23 pp ISBN 978-2-87223-189-8