PU Solutions
Elastogran

BASF Polyurethanes GmbH

Elastocoast

Compilation of the Technical Design Guidelines for Elastocoast

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Authorities Responsible for Coastal Protection at the German North and Baltic Sea Coast

LKN	Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz (State Corporation for Coastal Protection, National Park and Sea Protection), Schleswig-Holstein
NLWKN	Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küstenschutz und Naturschutz, Niedersachsen (Lower Saxonian State Corporation for Water Management, Coastal Protection and Nature Conservation, Lower Saxony)
StAUN	Staatliches Amt für Umwelt und Natur (State Office for the Environment and Nature), Mecklenburg-Vorpommern

Abbreviations

BAW	Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute)
WSV	Wasser- and Schifffahrtsverwaltung (Federal Waterways and Shipping Administration)
LWI	Leichtweiß-Institut für Wasserbau (Leichtweiss-Institute for Hydraulic Engineering and Water Resources), Technische Universität Braunschweig (Technical University Braunschweig)

Authors

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Codes and Standards for Revetments

[1] EAU (2004) Empfehlungen des Arbeitsausschusses „Ufereinfassungen“ Häfen und Wasserstraßen, Verlag Ernst & Sohn

[2] EAK (2002) Empfehlungen für die Ausführung von Küstenschutzwerken, Die Küste, Heft 65, Publisher: Kuratorium für Forschung im Küsteningenieurwesen, Westholsteinische Verlagsanstalt Boyens & Co.

[3] EAK (1993) Empfehlungen für die Ausführung von Küstenschutzwerken, Die Küste, Heft 55, Publisher: Kuratorium für Forschung im Küsteningenieurwesen, Westholsteinische Verlagsanstalt Boyens & Co.

[4] Bundesanstalt für Wasserbau (2004) Grundlagen zur Bemessung von Böschungs- und Sohlsicherungen an Binnenwasserstraßen (GBB)

[5] Bundesanstalt für Wasserbau (1993) Merkblatt Anwendung von geotextilen Filtern an Wasserstraßen (MAG)

[6] Bundesanstalt für Wasserbau (1989) Merkblatt Anwendung von Kornfiltern an Wasserstraßen (MAK)

[7] Bundesanstalt für Wasserbau (2008) Merkblatt Anwendung von Regelbauweisen für Böschungs- und Sohlensicherungen an Binnenwasserstraßen (MAR)

[8] Bundesanstalt für Wasserbau (2008) Merkblatt Anwendung von hydraulisch and bitumengebundenen Stoffen zum Verguss von Wasserbausteinen an Wasserstraßen (MAV)

Further Documents

[9] Herbich, J.B. (2000) Handbook of Coastal Engineering, McGraw-Hill, New York

[10] Bijlsma, E. (2010) Private communication from the 26 April 2010 (Arcadis)

[11] StAUN (2009) Regelwerk Küstenschutz Mecklenburg-Vorpommern, Übersichtsheft, Staatliches Amt für Umwelt und Natur, 1st edition, March 2009

Sources on Elastocoast

All documents and sources on Elastocoast are listed and compiled in Appendix 1.

1 Introduction

1.1 Background and Motive

The material “Elastocoast” distributed by BASF Polyurethanes GmbH (BASF PU) renders it possible to construct revetments in a new way [13]. In this novel procedure, the revetment stones are completely coated with the material and bonded together resulting in a porous, stable and also relatively thin plate-type revetment.

With regard to the use of Elastocoast in constructional hydraulic engineering (e.g. in revetment construction), BASF PU has commissioned several studies and model tests in recent years in order to develop design guidelines for the practical application for such revetments. Numerous documents and technical data (see Appendix 1) have been compiled. This report will elaborate on this further. As a consequence of these findings, Elastocoast has been used successfully for the construction of revetments in Germany and all over the world (cf. Appendix 2).

1.2 Task and Objective

The task with which IMS Ingenieurgesellschaft mbH (IMS) was commissioned included the systematic compilation of the available technical design rules for Elastocoast with regard to its application and technical equivalency in revetment construction in coastal and estuary areas in Germany.

The objective of the present report is to compile all essential structural engineering information on Elastocoast in a summary report intended for the authorities responsible for coastal protection, the executing construction companies and consulting engineers. This report is to include all information required for the planning, design, approval and construction of a revetment with Elastocoast (see following Figure 1-1).

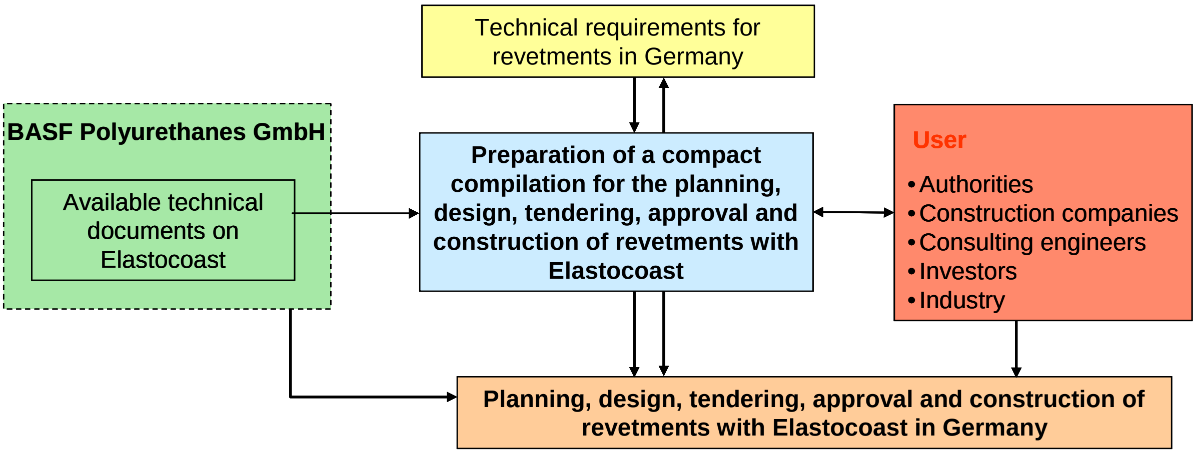


Figure 1-1: Procedure

In detail,

- the requirements for the design of revetments on the basis of relevant German codes and standards are compiled,
- first coordination talks with the authorities responsible for coastal protection (amongst others the BAW, LKN, StAUN, NLWKN) are held,
- the available studies and documents on Elastocoast are examined and design relevant information is extracted,
- all existing information is collected in the present report.

1.3 Notes Regarding the Application of the Guidelines

This report is to be understood as a documentation summarizing the currently available technical design guidelines for Elastocoast revetments. In this context, the available basic principles are depicted in a condensed form. More comprehensive information on the individual topics is detailed in cross references. This documentation is constructed in a modular way and may be continued and complemented with further information.

In Section 2, Elastocoast and its possible fields of application are described.

In Section 3, the requirements for the planning, design and construction of a revetment in Germany are given. On the basis of this, the course of action when establishing the technical equivalence of the Elastocoast revetment is presented.

On the basis of the technical design criteria compiled in Section 4, this report may also be applied for the planning, design, approval and installation of an Elastocoast revetment. That is to say, it is possible to dimension the design of an Elastocoast revetment according to the location specific design parameters. Thus, Section 4 is to be understood as instructions for the dimensioning of Elastocoast revetments.

Further information on the planning, design, approval and installation of an Elastocoast revetment are given in Section 5.

The reference projects with Elastocoast revetments completed to date are compiled in Section 6.

2 Brief Presentation of the Product “Elastocoast”

2.1 Material and Properties

Elastocoast is an innovative bonding system with which, on the basis of a two-component plastic (polyurethane), armour stones are completely coated and fixed together permanently at their contact points. The environmentally friendly polyurethane bonds the armour stones to a monolithic, three-dimensional and stable structure (cf. Figure 2-1). The low ratio of binding material causes the structure to remain completely porous [12] which, in turn, has a positive effect on the hydraulic properties of the system.

Figure 2-1: Basic idea for Elastocoast [12]

To date mainly stones with sizes ranging between 20 mm and 80 mm were used for revetments with Elastocoast (cf. Figure 2-2). According to present findings by BASF PU, these stone sizes result in an optimum number of contact points, applied amount of Elastocoast and overall stability. Further developments and applications are possible.

Figure 2-2: Exemplary photo of an Elastocoast revetment on the Hallig Langeness (Photo BASF PU)

The following properties and modes of action are attributed to Elastocoast:

- high porosity (open porosity)
- energy dissipation of waves running up
- reduction of the wave run-up
- resistant to cold / heat
- economic advantages
- ecologically compatible
- easy application and installation
- large range of applications.

2.2 Existing Documents on Elastocoast

In recent years, a number of studies were carried out on Elastocoast as well as on its application in revetment construction. These studies may be divided into the following fields:

- technology
- ecology
- ecotoxicology
- water quality
- dismantling and removal.

The respective documents are documented in Appendix 1.

2.3 Preparation and Construction Process

Elastocoast can be quickly prepared on site. The clean and surface-dry stones are mixed with a binding material (approx. 3 vol. %) by a mixer (duration: a few minutes) and installed at the location.

The stones coated with binding material are installed at the respective location, mechanically distributed and positioned as stipulated. The Elastocoast/stone mix remains ready-to-use for about thirty minutes. The Elastocoast revetment can be accessed after a cure time of one day and will achieve its full load bearing capacity after two or three days.

In the following Figure 2-3, the manufacturing process is documented by means of photos by the LKN.

The polyurethane is filled into containers

The crushed rocks are filled in the compulsory mixer

The polyurethane is added to the mixer

The rocks are tumbled with the polyurethane and transported to the construction site

Installation at the construction site

Final works

Figure 2-3: Exemplary installation of an Elastocoast revetment (Photos LKN)

Further detailed information on the installation of an Elastocoast revetment may be found in Section 5.5.

2.4 Application Areas and Reference Projects

Thus far, Elastocoast was mainly used in numerous revetment construction projects. Reference is made to Figure 2-4 as an example of this. However, other application areas in the hydraulic engineering sector are possible as well.

A detailed compilation of to date existing reference projects is provided in Section 6.

Figure 2-4: Elastocoast revetment on the Hallig Langeness (Photo LKN)

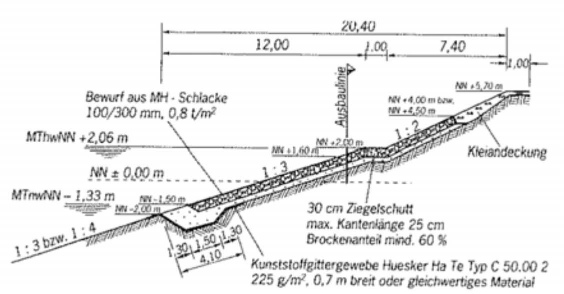
3 Summary of the Requirements for the Construction of a Revetment in Germany

3.1 General Overview on Revetments

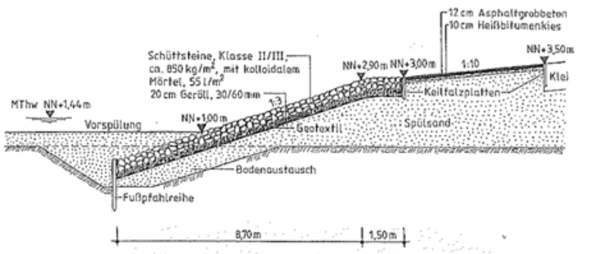
The basic task of revetments in coastal protection and within the area of flood control structures is to protect slopes, transitions between different types of terrain as well as areas against acting forces (sea state, current and ice), to counter possible damages or destructions and, thus, to prevent morphological changes. Due to their construction, weight and the composite effect of the stones, revetments are able to resist these acting forces.

Revetment Designs in Coastal and Estuary Areas

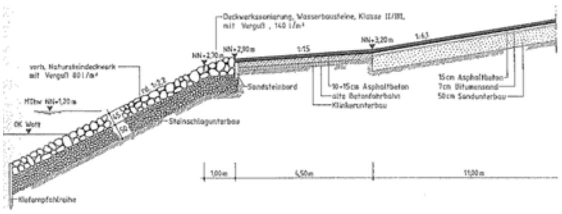
Along the German coast of the North Sea and Baltic Sea, revetments can be found as structures running parallel to the coast protecting and safeguarding dunes, beaches, forelands, dikes and other structures. These revetments with various designs are dimensioned for the acting and location specific loads and strains (cf. Figure 3-1).



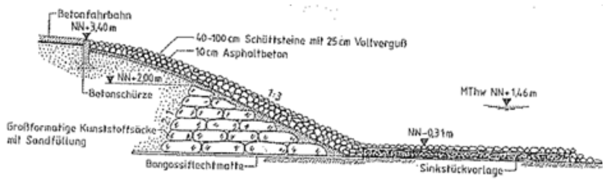
Hamburg, EAU (2004)



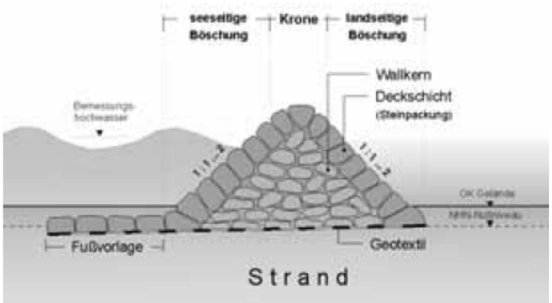
Sea dike Hattstedt Marsch, EVU (1990)



Outer Ems, EVU (1990)



Outer Jade, EVU (1990)



Standard cross-section of a breakwater, StAUN (2009)

Standard design of a revetment, StAUN (2009)

Figure 3-1: Examples of revetments on the coast of the North and Baltic Seas

As a basic principle, revetments consist of an outer cover layer which may be designed as an open or closed protective layer according to the respective requirements and an underlying filter layer which may be designed minerally as a granular filter or geotextile. The different design alternatives of a cover layer are shown schematically in Figure 3-2 and exemplarily in Figure 3-3.

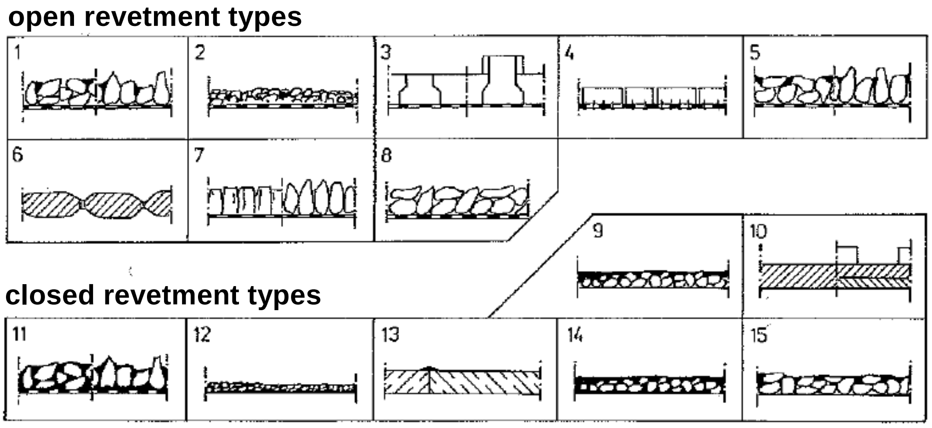


Figure 3-2: Revetment types with open and closed surface on the coastline, EAK (1993)

Figure 3-3: Design alternatives for revetments on the coastline

Revetment Designs in Inland Areas

For the area of inland waterways, in particular within the area of Federal Waterways under the responsibility of the Federal Waterways and Shipping Administration (German abbreviation: WSV), standardised revetment construction methods consisting of a cover and filter layer have become accepted against the background of the occurring loads and strains. The different cover layer types are shown in the following Figure 3-4. The filter layer is only hinted at in Figure 3-4 and may be designed as a granular filter according to MAK [6] or as a geotextile according to MAG [5].

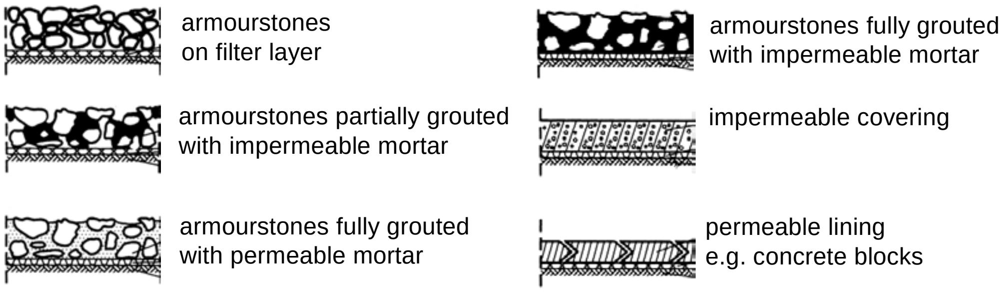


Figure 3-4: Standard revetment types at Federal Waterways according to MAR (1993)

Loads and Relevant Processes of Revetments

The different revetment types also reflect the different loads acting on the revetments. The possible load types and the failure mechanisms which can be derived from these are shown schematically in the following Figure 3-5.

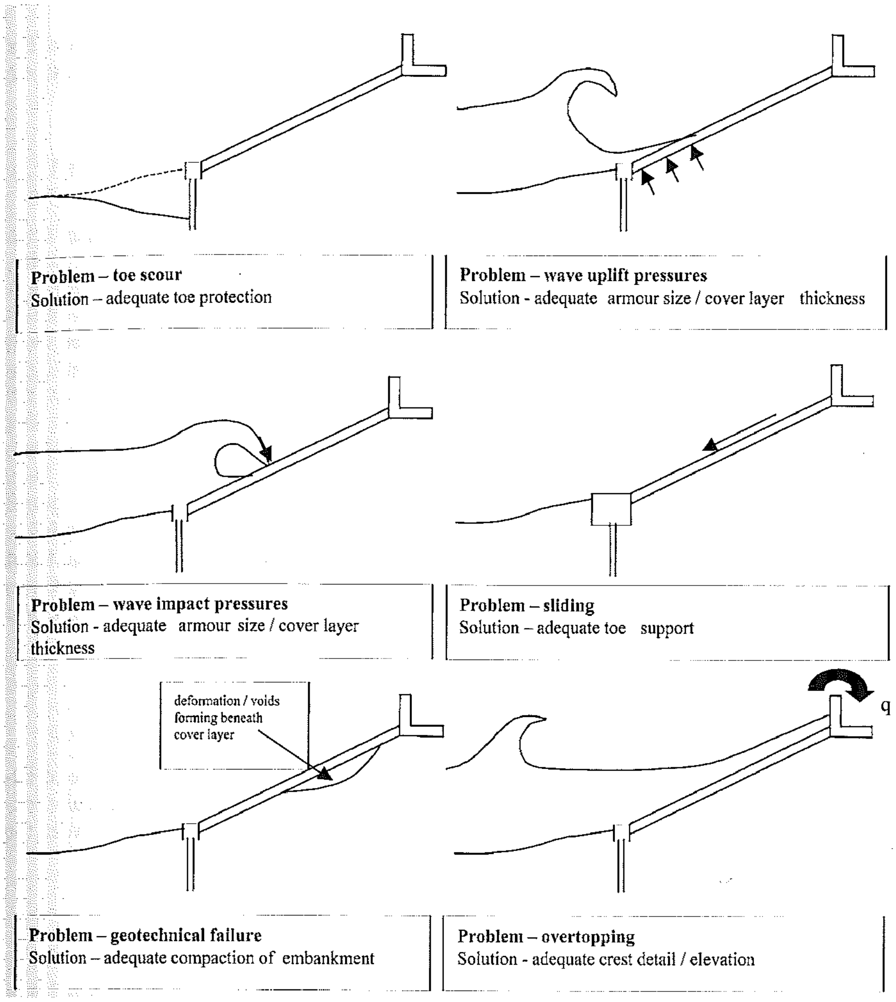


Figure 3-5: Load types and failure mechanisms of revetments [9]

Since revetments are normally located in splashing area in the range between low and high water levels, significant loads caused by

- breaking waves
- currents occurring parallel to the slope during wave run-up and run-down
- pore pressures occurring beneath the revetment and possible resulting soil displacements

may occur for the revetment itself. In Section 4, these significant loads and their effect on the dimensioning of the Elastocoast revetment are explained in detail.

3.2 Relevant Codes and Standards for the Design of Revetments in Germany

In Germany, a number of codes and standards on the design of revetments are in existence. These codes and standards differentiate between coastal and estuary areas and inland areas. The following Table 3-1 provides an overview of the relevant codes and standards including the respective differentiation.

Table 3-1: Overview of the codes and standards for the design of revetments relevant in Germany

Coastal, estuary and inland area	
EAU Recommendation of the Committee for Waterfront Structures Harboursand Waterways (2004)	– Design of revetments (Ch. 12.1) – Revetments in sea ports with tidal conditions and in inland ports (Ch. 12.2) – Application of geotextile filter layers in revetments and bed protection (Ch. 12.5) – Design of armour layer (Ch. 7.10.4)
EAK Empfehlungen für die Ausführung von Küstenschutzwerken (1993, 2002)	– Recommendations E, EAK 1993 – Examples to Recommendations E, EAK 2002 – Revetments with armour layers of quarrystone and common shaped blocks (Ch. 4.2.6)
inland waterways	
Bundesanstalt für Wasserbau **GBB**	Rules for Design of Bank and Bottom Protection on Inland Waterways, Mitteilungsblatt Nr. 87, 2004
Bundesanstalt für Wasserbau **MAR**	Code of Practice Use of Standard Construction Methods for Bank and Bottom Protection on Waterways, 2008
Bundesanstalt für Wasserbau **MAK**	Code of Practice Use of Mineral Filters on Waterways, 1989
Bundesanstalt für Wasserbau **MAG**	Code of Practice Use of Geotextile Filters on Waterways, 1993
Bundesanstalt für Wasserbau **MAV**	Code of Practice Use of Cement Bonded and Bituminous Materials for Grouting of Armourstones on Waterways, 2008

As a result of the list in Table 3-1, it has to be noted that

- *in coastal and estuary areas*
  the revetments may be designed individually by using EAK and EAU, i.e., no mandatory standard construction methods exist. The codes and standards for revetments in inland areas are, in parts, also used for Federal Waterways in estuary areas.

- *in inland areas*
  the construction and functionality of revetments are clearly specified by standard construction methods and codes as well as standards by the BAW, i.e., mandatory/binding standard construction methods exist.

The individual design of revetments in coastal or estuary areas is generally due to the different location specific design parameters and experiences.

In inland areas on the other hand, standardised design parameters and revetment construction methods are applied.

3.3 Procedure for Establishing the Technical Equivalence of an Elastocoast Revetment

From the remarks on revetments in Germany and the relevant codes and standards for revetments in coastal and estuary areas, it can be inferred that no revetment type which could be compared with an Elastocoast revetment exists.

Consequently an analysis of its fitness for purpose and the technical equivalence of an Elastocoast revetment has to be carried out for the external hydraulic loads and geotechnical boundary conditions existing on each particular site. That is to say, the occurring loads and boundary conditions are immediately included in the design of the Elastocoast revetment.

For the design of the Elastocoast revetments, the design parameters (revetment thickness and design, etc.) specified in Section 3.4 are to be dimensioned subject to the occurring external loads (design parameter) as well as the subsoil (cf. Section 4).

This procedure when designing and performing a technical equivalence analysis of an Elastocoast revetment is also supported by the authorities responsible for coastal protection.

3.4 Relevant Design Parameters

The relevant design parameters of a revetment – i.e. depending on the soil, the geotechnical and hydraulic boundary conditions as well as if applicable other specifications characteristic of geometric and material specific parameters for the revetment – are to be determined in accordance with Figure 3-6:

– the cover layer and the filter layer, each with design, material and thickness
– the slope angle
– the revetment transitions (at the upper and lower extent of the revetments) and
– the toe support.

In how far a toe support is required has to be examined within the scope of geotechnical considerations.

The design parameters “slope angle” and “revetment transitions” are constructional details based on existing geometrical boundary conditions or structural elements.

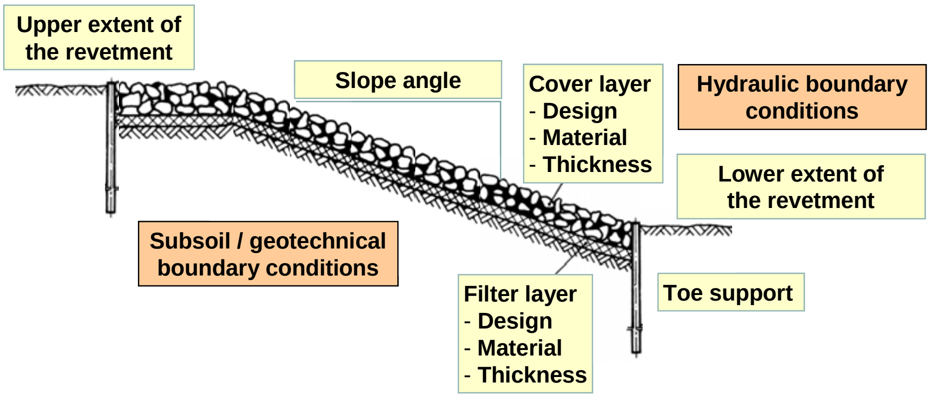


Figure 3-6: Design parameters of a revetment

In contrast to this, the design, material and thickness of the cover layer and the filter layer are to be dimensioned subject to the design parameters. The following Section 4 systematically refers to the interdependencies between the design parameters “cover layer” and “filter layer”.

4 Compilation of the Technical Design Documents for an Elastocoast Revetment

4.1 General

The documents, studies and experts' reports on Elastocoast revetments (cf. Section 2.2 as well as the list of all existing documents in Appendix 1) available at BASF PU which are concerned with the technique and design of Elastocoast revetments were systematically examined against the background of the requirements developed for Elastocoast revetments. The present report does not focus on available documents on other topics such as, for example, environmental compatibility. Therefore, these documents are only listed as existing without referring to their contents.

Essential principles for the preparation of the technical design guidelines for Elastocoast revetments may be taken from [20] and [28], these are

– ARCADIS (2009) Polyurethane bounded aggregate revetment, Design Manual, Version: 14 September 2009 and

– LWI (2010) Hydraulic Performance, Wave Loading and Response of Elastocoast Revetments and their Foundation – A Large Scale Model Study –, Leichtweiß-Institut für Wasserbau, LWI Report No. 988, Final Report, 8 January 2010.

In the following, the design guidelines for the dimensioning and design of an Elastocoast revetment are presented on the basis of the above mentioned reports and subject to the load parameters which are to be taken into account.

4.2 Information on the Design of an Elastocoast Revetment

According to definition (cf. Section 3.1), a revetment consists of a cover layer and an underlying filter layer (cf. Figure 4-1). This means, only the cover layer stones are coated with polyurethane and bonded together.

The filter layer beneath the cover layer is loosely placed on top of a geotextile base and not bonded. This filter layer fulfils an important function during the hydraulic processes and for the stability of the entire revetment (cf. [28]).

In some reference projects, no filter layer was used and the cover layer was directly placed on top of a geotextile base. In case of adequate subsoil, the geotextile could be omitted as well, for example, if an Elastocoast revetment is laid on top of an existing revetment.

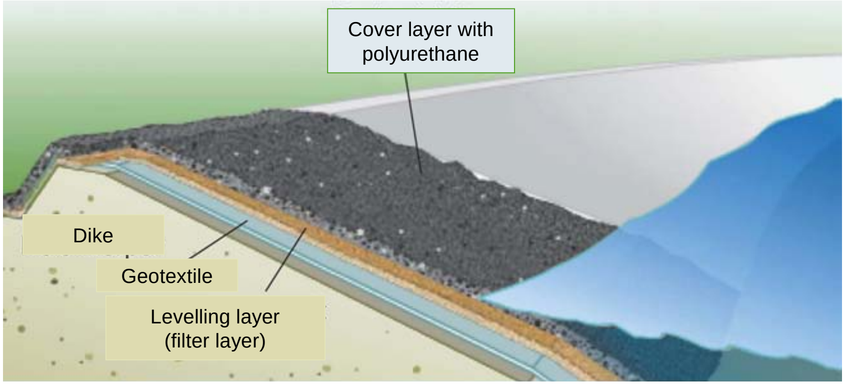


Figure 4-1: Elastocoast revetment according to [14]

The following Figure 4-2 shows the two possible design alternatives for an Elastocoast revetment.

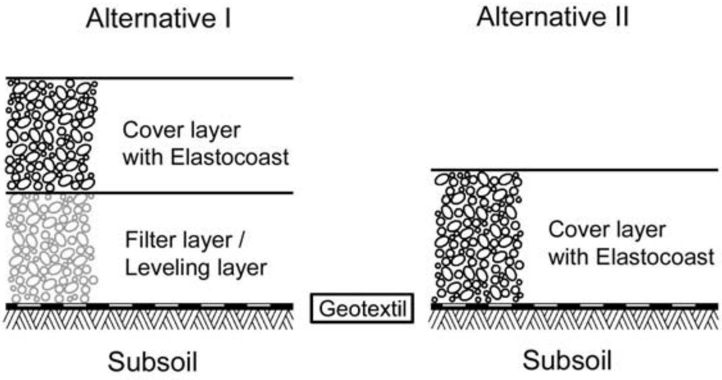


Figure 4-2: Possible design alternatives for Elastocoast revetments

The geotextile on the subsoil serves as a filter as well as a separating layer. Alternative I shows a filter or levelling layer beneath the cover layer. Normally, the type of stones used for the filter and cover layer are identical. However, no standards exist for this.

The cover layer consists of crushed stones which are bonded together by the polyurethane material “Elastocoast” (in the following referred to as: Elastocoast cover layer).

The question whether an Elastocoast revetment will be made with or without a filter layer has to be decided in the course of the individual planning and design stage and is also subject to the respective geometrical, geotechnical and hydraulic boundary conditions.

To date, mainly stone sizes ranging between 20 mm and 80 mm of different stone types (cf. [13] and [20]) were used for Elastocoast cover layers (cf. Sections 2.3 and 6).

4.3 Design Parameters for Determining the Cover Layer Thickness of an Elastocoast Revetment

The required thickness of an Elastocoast cover layer depends on certain design parameters as, for example, the wave height etc.

The location specific design parameters (water levels, wave height etc.) have to be determined and defined separately in the run-up to the installation works. With regard to this, reference is made to EAK (2002), Recommendations A.

In the following, the design parameters for the determination of the required cover layer thickness for an Elastocoast revetment are considered. Effectively, this results in one specific required thickness of the Elastocoast cover layer for each relevant design parameter. Ultimately, the largest determined cover layer thickness is decisive for the revetment design.

4.3.1 Wave Height

The waves breaking on an Elastocoast revetment are one important design parameter. Especially, collapsing breakers can heavily strain the revetment. In such a case, the Elastocoast cover layer acts as a stiff plate (with defined bending stiffness) which is supported in different ways according to the respective subsoil and revetment design.

The following Figure 4-3 shows the chosen alternative model which is applied by [20] as a design basis to determine the cover layer thickness of the Elastocoast revetment with an E-module of E = 4.000 MPa and a flexural strength of 1.0 MPa.

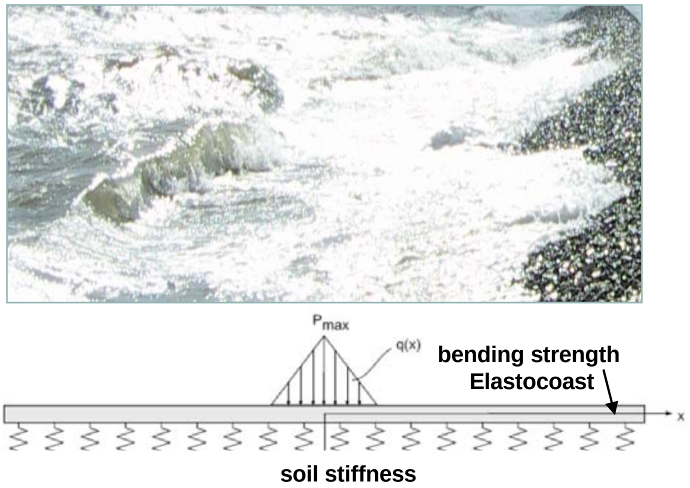
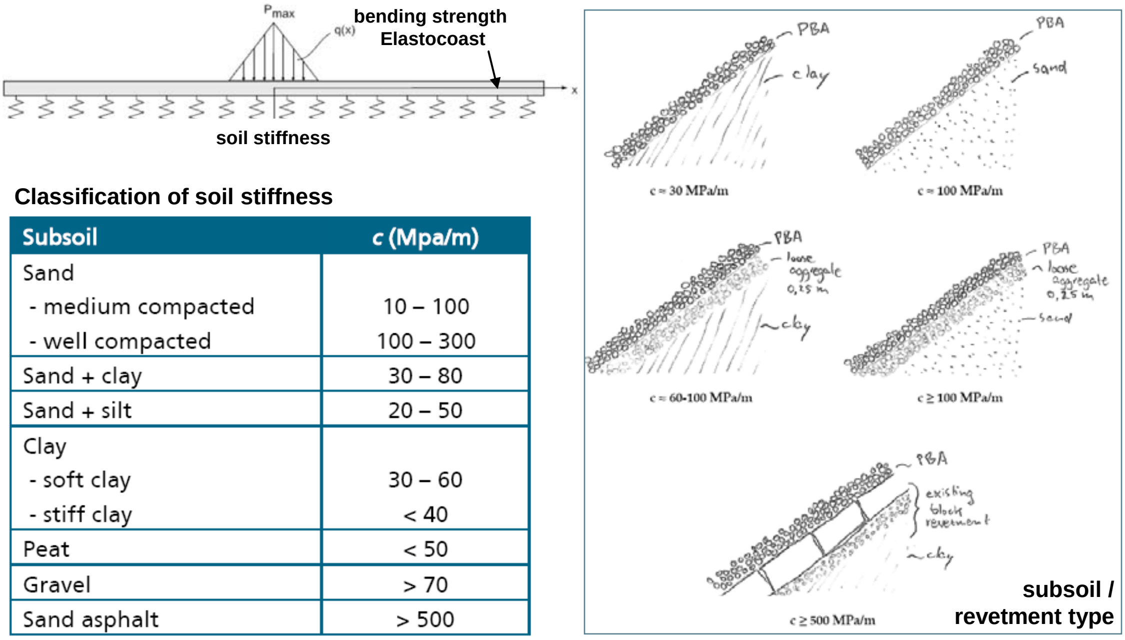


Figure 4-3: Alternative model of the Elastocoast revetment for wave loads [20]

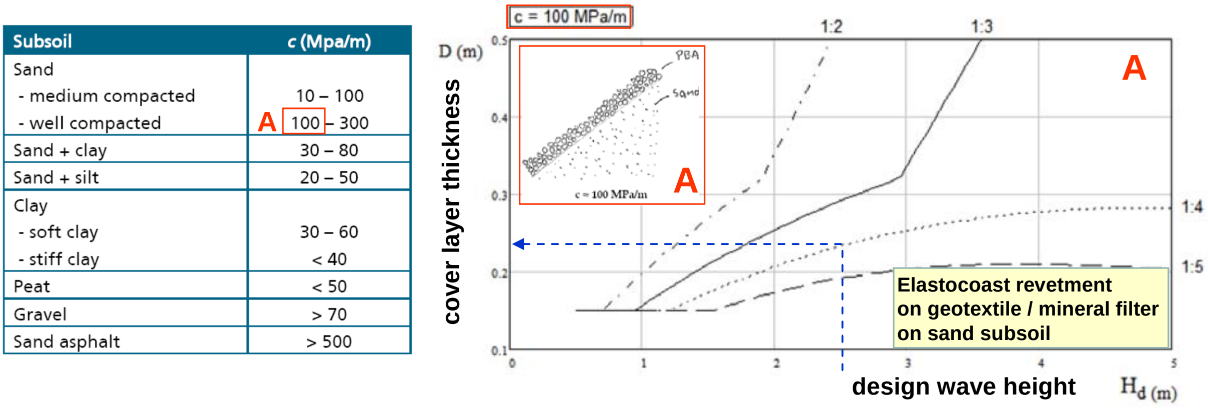
Subject to the foundation of the Elastocoast revetment or the respective subsoil (to be found in Figure 4-4), the required revetment thickness may be taken from the available design diagrams, as exemplarily shown in Figure 4-5, as a function of the slope angle and the design wave height H_d.

In Appendix 2, the design diagrams [20] are specified for different foundations with c = 30 MPa/m, c = 60 MPa/m, c = 100 MPa/m and c = 500 MPa/m (cf. classification of the subsoil in Figure 4-4)



Subsoil	c (Mpa/m)
Sand	
- medium compacted	10 – 100
- well compacted	100 – 300
Sand + clay	30 – 80
Sand + silt	20 – 50
Clay	
- soft clay	30 – 60
- stiff clay	< 40
Peat	< 50
Gravel	> 70
Sand asphalt	> 500

Figure 4-4: Classification of the soil stiffnesses and attribution to the different revetment types [20]



Subsoil	c (Mpa/m)
Sand	
- medium compacted	10 – 100
- well compacted	100 – 300
Sand + clay	30 – 80
Sand + silt	20 – 50
Clay	
- soft clay	30 – 60
- stiff clay	< 40
Peat	< 50
Gravel	> 70
Sand asphalt	> 500

Figure 4-5: Exemplary determination of the cover layer thickness for an Elastocoast revetment (according to [20])

For more details on the design of Elastocoast revetments with the parameter “wave height”, see [20] and Appendix 3 in which the revetment thickness may be calculated deterministically according to directions and subject to the occurring wave loads.

4.3.2 Wave Pressures

Within the scope of the model tests in the Large Wave Flume [28], comprehensive analyses of the wave loads on and beneath the Elastocoast revetment were performed. In this context, only the most important results are to be referred to.

It is necessary to differentiate wave loads (see Figure 4-6) with regard to the different waves, breaker types and loads on and beneath the Elastocoast revetment. Collapsing breakers result in impact loads. Surging breakers, on the other hand, tend to non-impact loads.

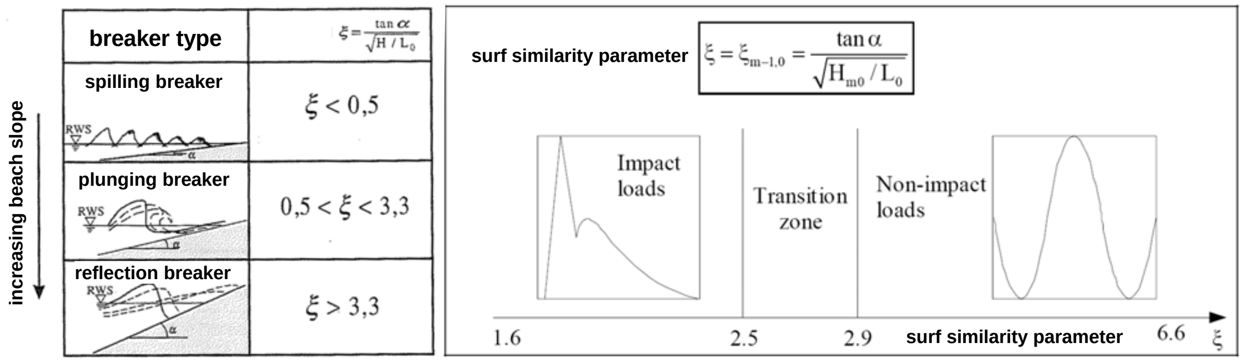


Figure 4-6: Classification of wave loads subject to the surf similarity parameter (breaker type)

The measured data was analysed on the basis of the rendered parameterisations. The results of the pressure loads on and beneath the Elastocoast revetment for the two load types *impact load* (Figure 4-7) and *non-impact load* (Figure 4-8) are presented in the following.

In case of the wave impact loads, a differentiation between the load levels on and beneath the revetment is discernable (cf. Figure 4-7). The difference between the two curves in Figure 4-7 shows the damping of the wave pressure by the revetment.

In case of the non-impact loads, virtually the same pressure rates appear on and beneath the revetment (cf. Figure 4-8).

Further and more detailed studies, analyses and explanations may be found in [28] to which we would like to refer to at this point.

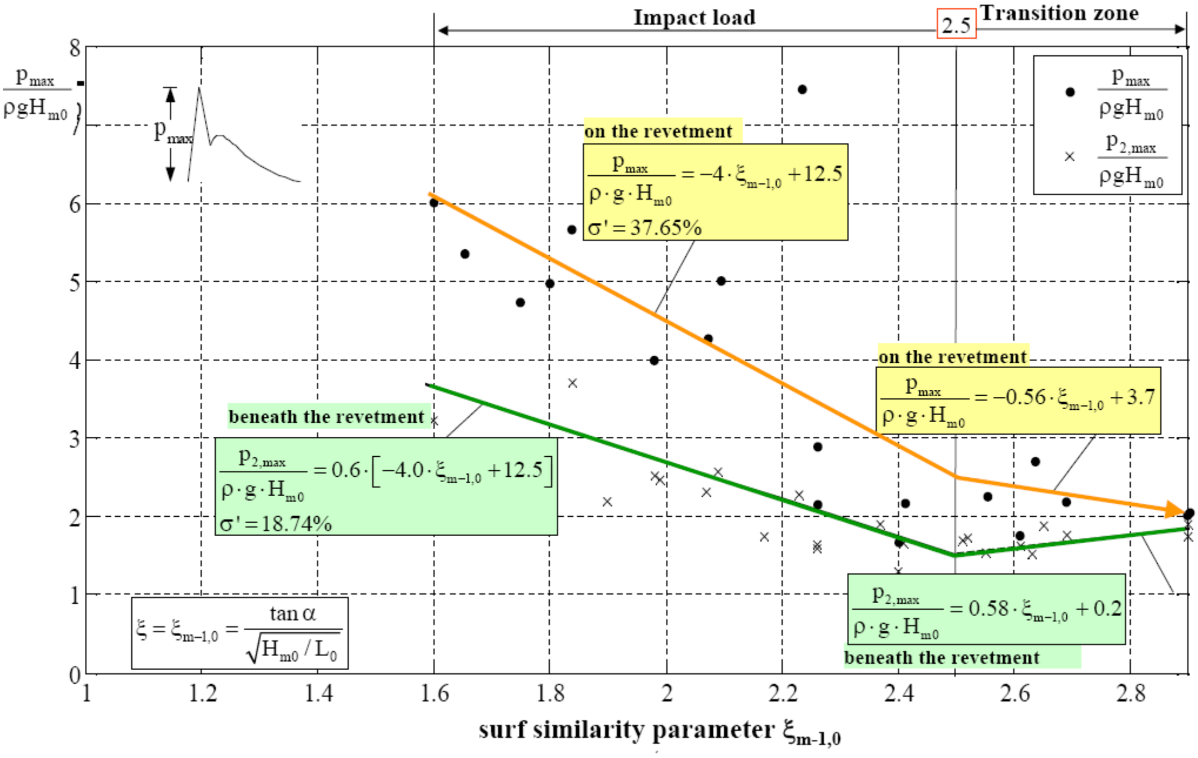


Figure 4-7: Maximum compressive load on and beneath the revetment due to dynamic impact loads [28], [16]

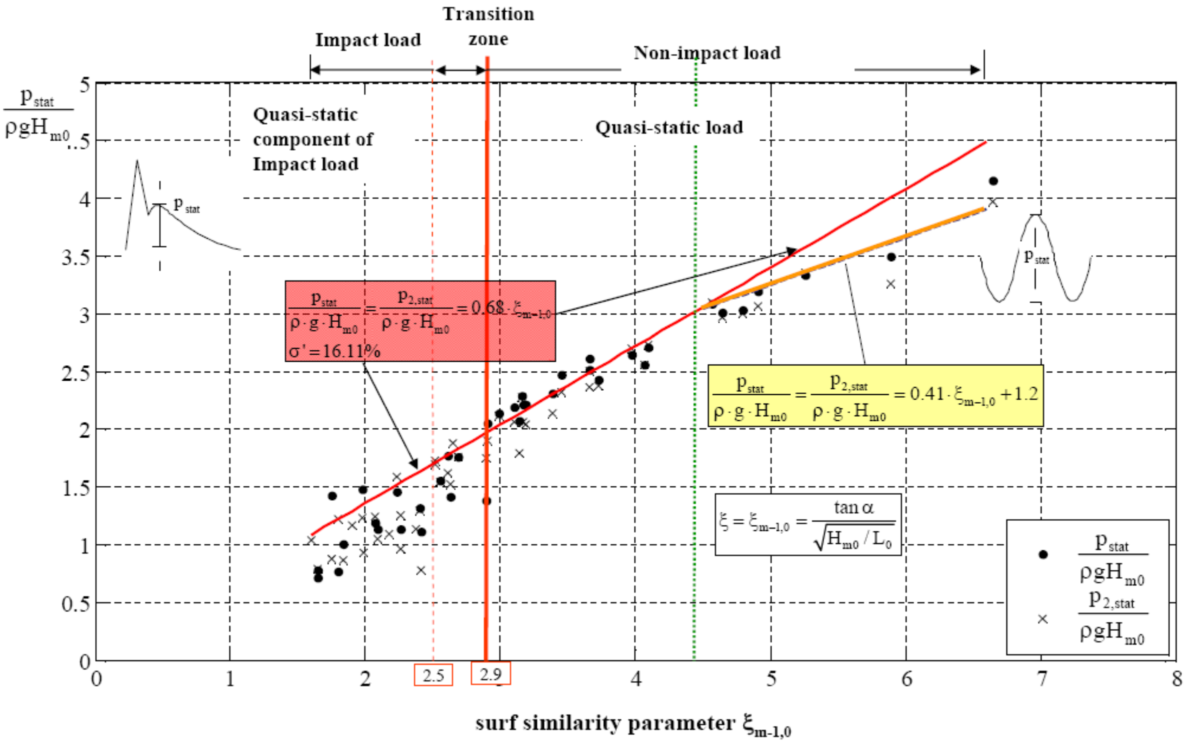


Figure 4-8: Maximum compressive loads on and beneath the revetment due to non-impact loads [28], [16]

4.3.3 Wave Run-Up

The porosity of the Elastocoast revetment results in an altered hydraulic mode of action, that is to say, the wave run-up also behaves differently than with other revetments. The wave run-up was examined at a slope of 1:3 within the scope of large-scale model tests carried out in the Large Wave Flume in Hanover [28].

The following Figure 4-9 shows the relative wave run-up as function of the surf similarity parameter for the tests performed at model B and C in the Large Wave Flume [28] in comparison to an impermeable slope.

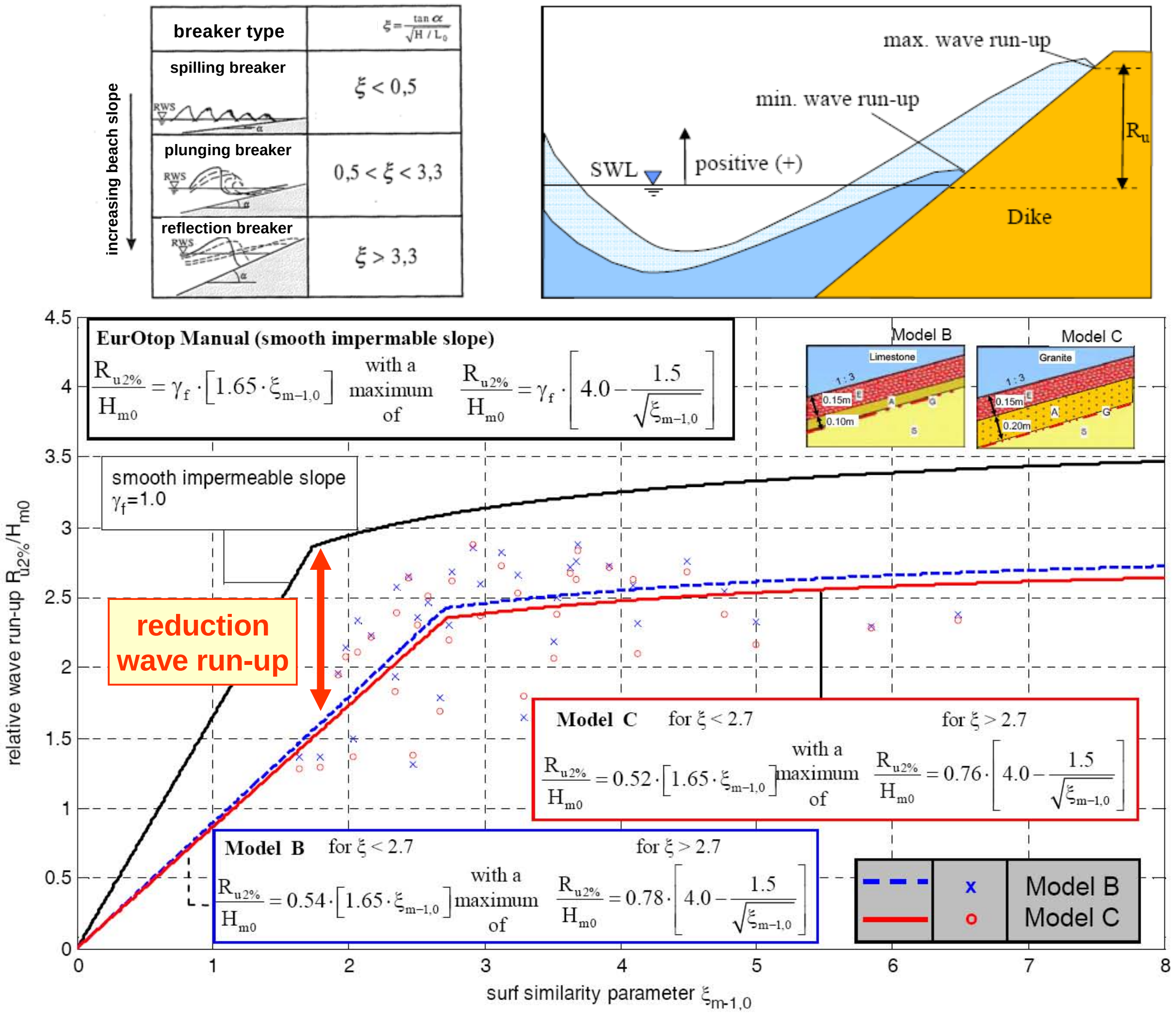


Figure 4-9: Relative wave run-up as function of the surf similarity parameter for the tests performed at model B and C in the Large Wave Flume in comparison to an impermeable slope [28]

The surf similarity parameter ξ as a non-dimensional parameter provides information on the breaking behaviour of the waves (cf. Figure 4-9). It is defined as follows

$$\xi = \frac{\tan\alpha}{\sqrt{H / L_0}}$$

and includes the slope angle tan α as well as the wave steepness H/L_0, consisting of the wave height H and the wave length L_0 in deep water. Small surf similarity parameters stand for milder slope angles and spilling breakers, large surf similarity parameters stand for steeper slopes and the corresponding breaker types such as collapsing or surging breaker (cf. overview of breaker types in Figure 4-9).

Figure 4-9 indicates that, according to the respective surf similarity parameter, the wave run-up can be reduced by 25% and up to 50% with an Elastocoast revetment (blue/red line in Figure 4-9) in comparison to an impermeable slope (black line in Figure 4-9). The potential reduction of the wave run-up can be taken into account when designing and planning an Elastocoast revetment.

Comparative values of the reduction coefficient for revetments with other surfaces are specified in EAK (2002) in Table A 4.2.2. With regard to comparative considerations, reference is made to the respective sections in EAK (2002).

4.3.4 Wave Run-Down

With regard to the wave run-down in case of an Elastocoast revetment, the tests in the Large Wave Flume [28] can also be revert to.

In the following Figure 4-10, the test results for the wave run-down are shown analogous to Section 4.3.3.

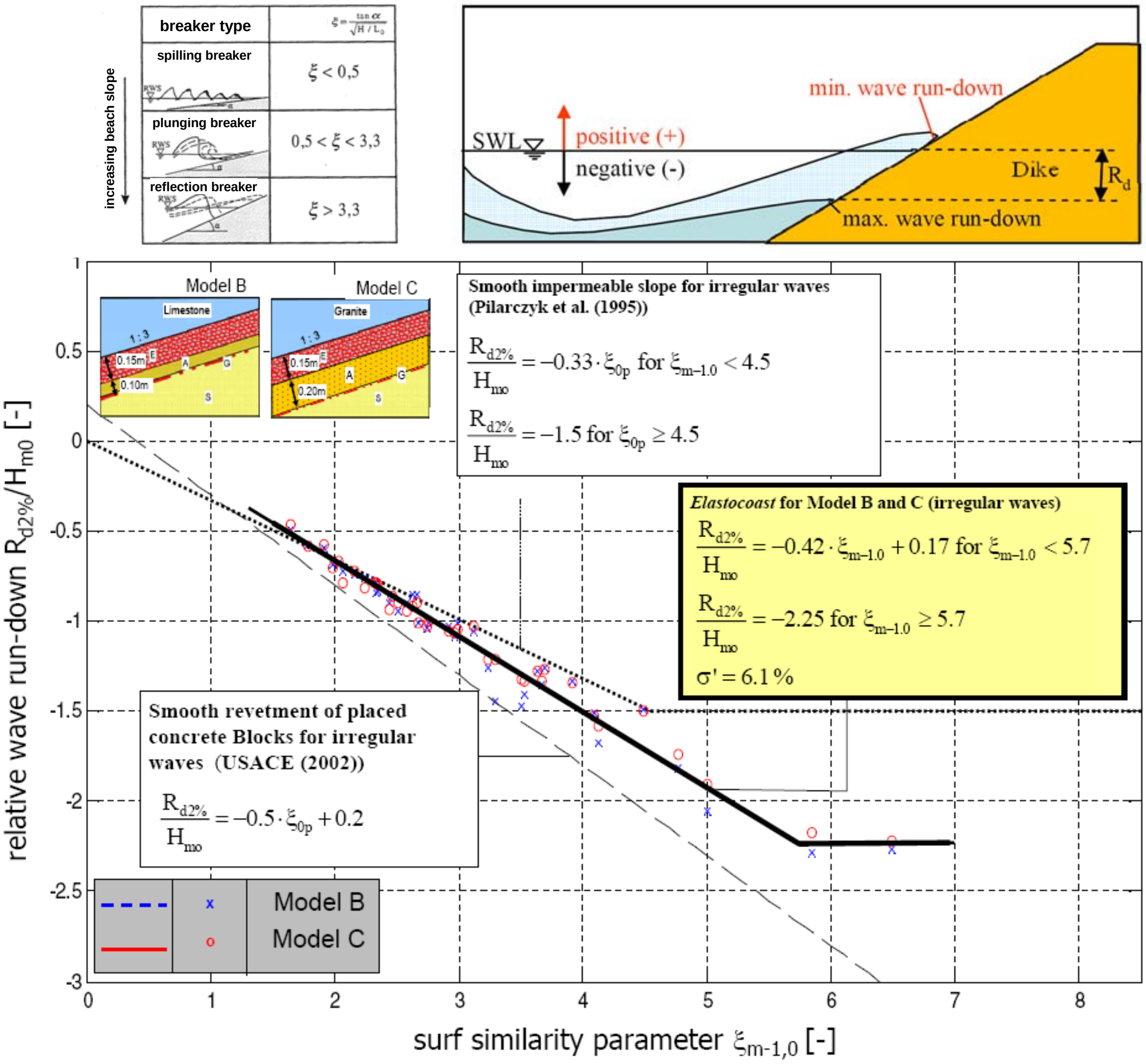


Figure 4-10: Relative wave run-down as function of the surf similarity parameter for the tests at model B and C in the Large Wave Flume in comparison to an impermeable slope [28]

4.3.5 Wave Overtopping and Overflow

In The Netherlands, tests with Elastocoast revetments were carried out on the inner slope of a dike. In these tests, large quantities of water were discharged over the inner slope from a water tank placed on the crest of the dike (cf. Figure 4-11) in order to analyse the revetments' structural integrity.

During these tests, the Elastocoast suffered no damages from overtopping volumes of up to 125 l/s/m. For comparison, it should be noted that overtopping volumes ranging between 2 up to 10 l/s/m are taken into account when planning and designing flood control structures. From this it can be inferred that the structural integrity of the revetment can be taken for granted even in case of large overtopping volumes.

Figure 4-11: Tests on the inner slope of a dike [13]

Subject to further tests, the overtopping volume of 125 l/s/m is applied as the design threshold for Elastocoast revetments in [20].

4.3.6 Current Velocities

Information on current velocities may also be linked to the tests presented in Section 4.3.4. [20] is based on the assumption that the structural integrity of an Elastocoast revetment is given even in case of very high current velocities[1]. However, concrete specifications regarding the critical current velocities for Elastocoast revetments do not exist. Velocities occurring during wave run-up and run-down are considered as noncritical for the stability of the Elastocoast revetment.

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[1] Normally, velocities of more than 5 m/s are recognised as very high current velocities.

4.3.7 Wave Reflection

With regard to the wave reflection of an Elastocoast revetment, tests in the Large Wave Flume [28] can be revert to.

The following Figure 4-12 shows the reflection behaviour of an Elastocoast revetment in comparison to a smooth slope and a two-layer rock armour. [28] also states that the reflection coefficient depends on the wave period. For further explanations, reference is made to [28]

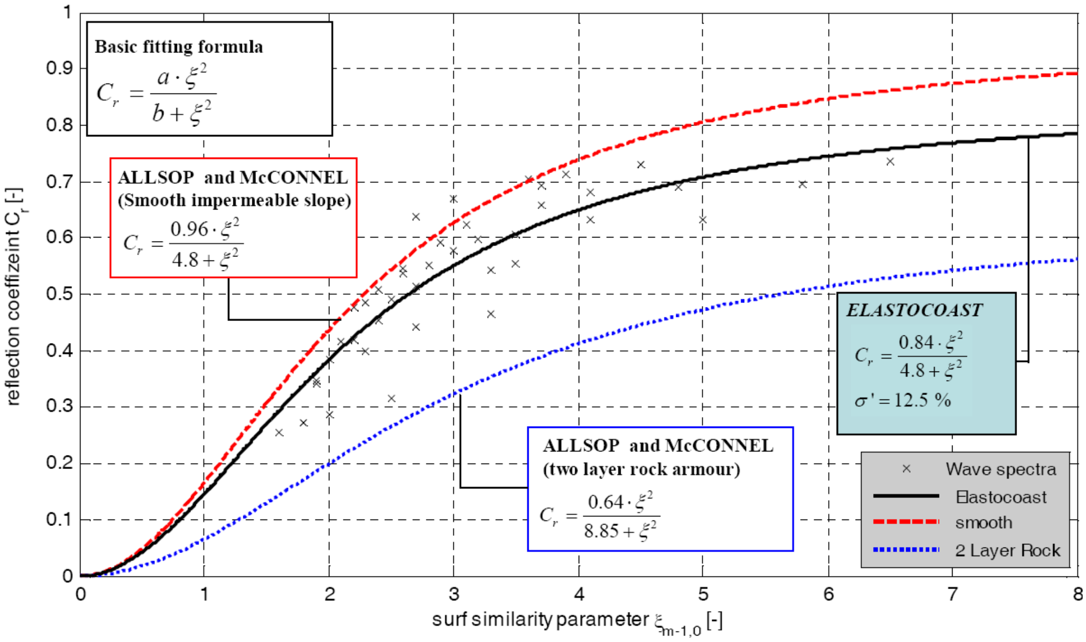


Figure 4-12: Wave reflection of the Elastocoast revetment [28]

4.3.8 Deformations / Flexural Displacements

Within the scope of the model tests performed in the Large Wave Flume, the measured displacements/flexural displacements of the Elastocoast revetment were examined as well.

The analyses in [28] show the displacements which an Elastocoast revetment exhibits subject to the sea state load. In the following Figure 4-13, the results for the Elastocoast revetments tested in the Large Wave Flume are shown.

For further details and information, reference is made to [28].

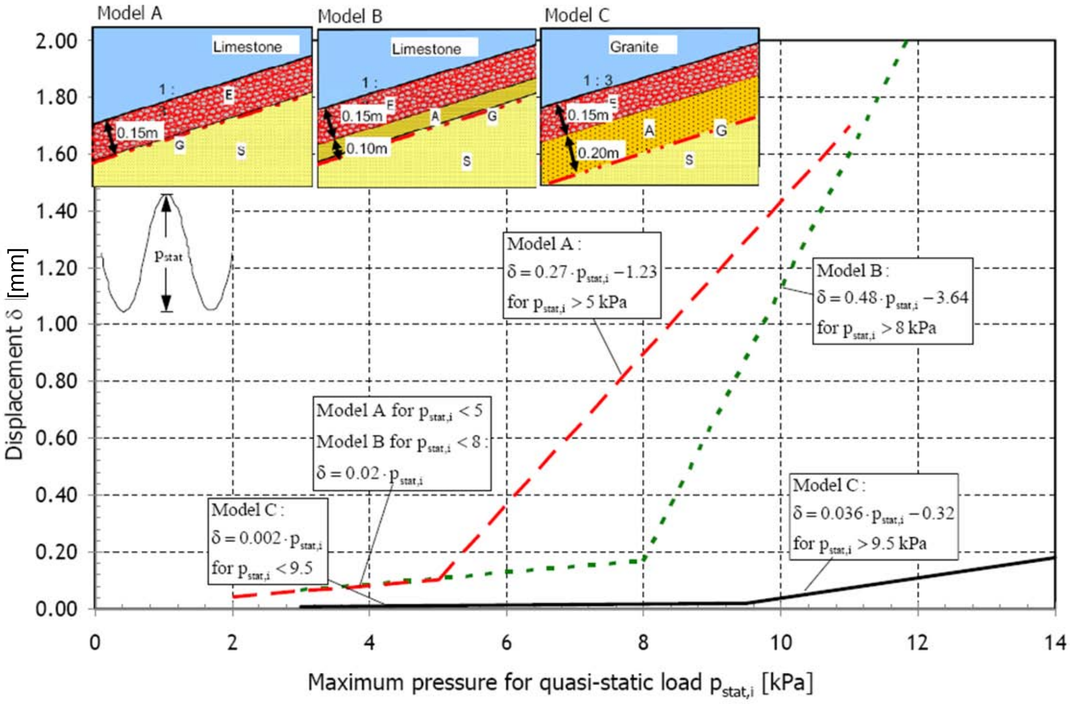
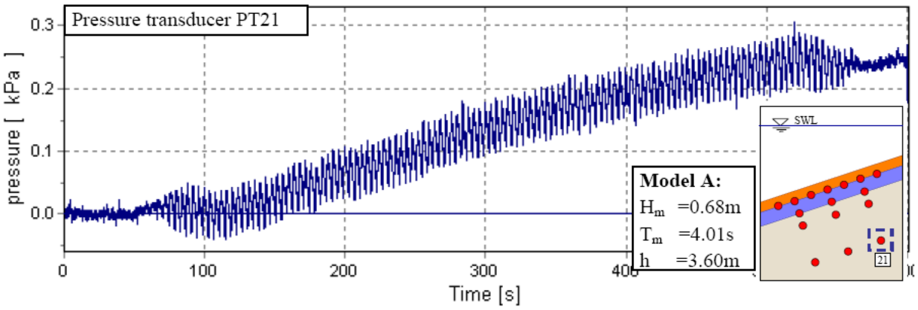


Figure 4-13: Maximum displacements of the constructed Elastocoast revetments as function of the maximum compressive load [28]

4.3.9 Pore Pressures

Pore pressures are particularly important for the global structural integrity of the Elastocoast revetment. Pore pressures beneath the revetment are caused by tide fluctuations (nearly static processes) and sea state conditions (dynamic processes).

With regard to the resulting pore pressures, it is differentiated between transient and residual pore pressures (Figure 4-14).



a) Time series of non filtered pore pressure (pressure transducer PT21)

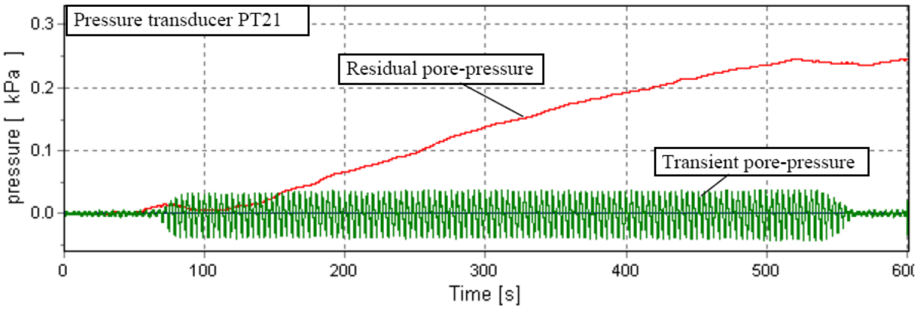


Figure 4-14: Definition and differentiation of transient and residual pore pressures [28]

Damping in the Soil Body

Pore pressures are damped in the soil body, i.e., as the depth in the soil body increases, the pore pressure fluctuations decrease strongly.

The damping of the maximum wave-induced pore pressures is shown in the following Figure 4-15.

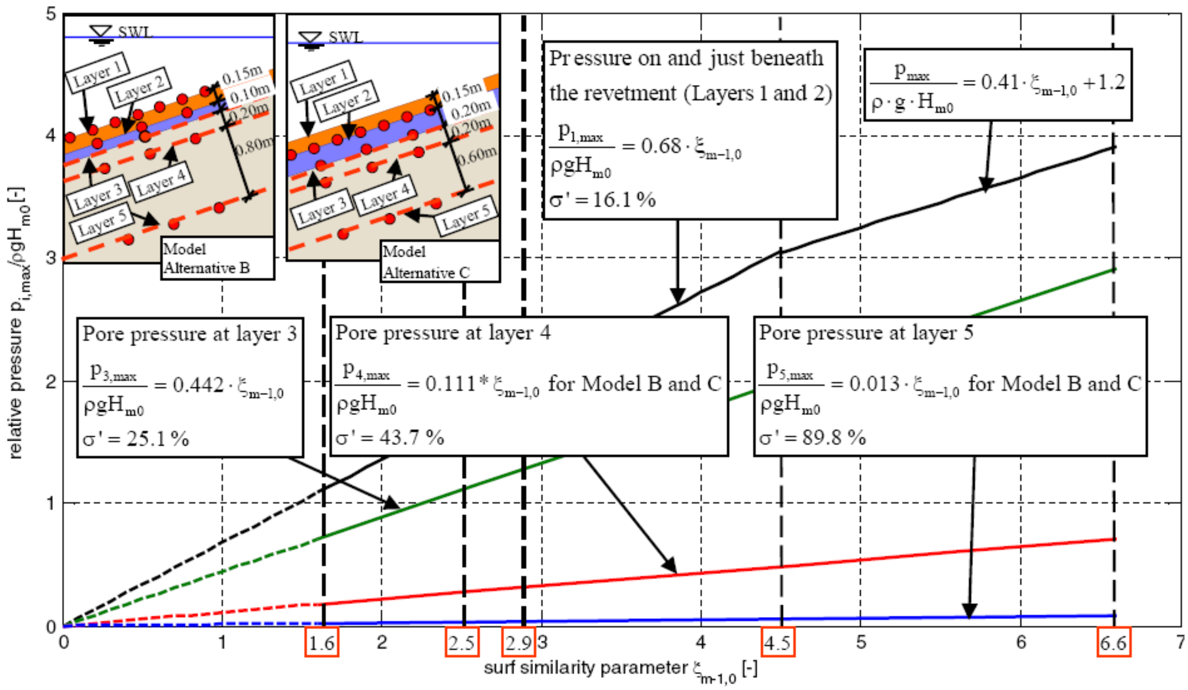


Figure 4-15: Relative pore pressure for different layers in the sand core beneath the Elastocoast revetment as function of the surf similarity parameter [16], [28]

Stability Analysis for Loads to be Expected Due to Pore Pressures

When designing and dimensioning the Elastocoast revetment, it has to be ensured that the occurring pore pressures (transient and residual) do not result in liquefaction, shiftings and subsequent damages (cf. Case of Damage A during the model tests in the Large Wave Flume [28]). This can be guaranteed by sufficiently dimensioning the filter layer in consideration of the subsoil.

This proof can be furnished and/or examined by means of a stability analysis. The basic principle of the vertical equilibrium of forces is shown in the following Figure 4-16.

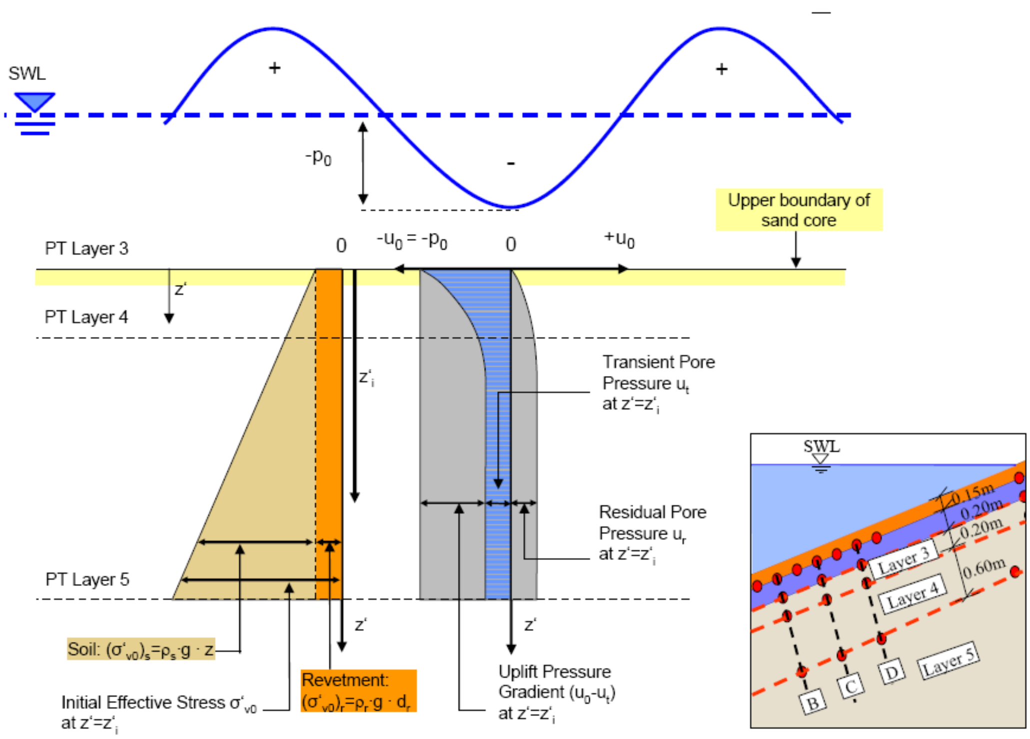


Figure 4-16: Schematic representation of the vertical forces occurring during the stability analysis

In the end, the lift forces directed upwards due to the pore pressure must not become larger than the forces directed downwards due to the dead weight of the Elastocoast revetment and the soil. An exemplary result is provided in Figure 4-17. As soon as soil liquefaction appears in a soil layer beneath the revetment, damages to the revetment have to be taken into account.

That is to say, the lift forces to be expected have to be bridged by sufficiently dimensioning the cover layer and filter layer. If pore pressures have to be taken into account as design parameters, the respective analysis has to be performed.

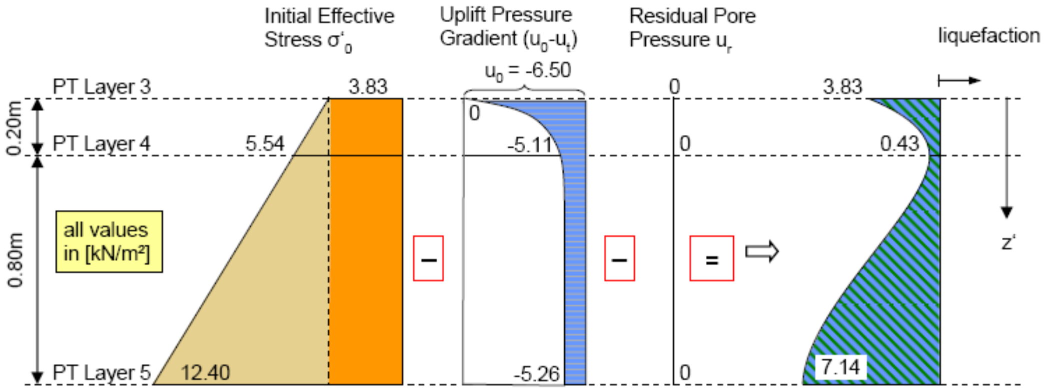


Figure 4-17: Exemplary result of the stability analysis

Approximate Stability Analysis

ARCADIS (2009) assumes that, due to its porosity, the Elastocoast revetment is well suited to discharge water level differences and pore water. Under the assumption that the geotextile is becoming completely impermeable in the soil due to redistributions of fines, [20] offers the possibility to estimate the required revetment thickness by means of the design diagram in Figure 4-18. In addition to this, a corresponding deterministic approach for determining the revetment thickness is presented in [20] as well.

Figure 4.29

Design for overpressures with flexural moment capacity of 1.0 MPa.

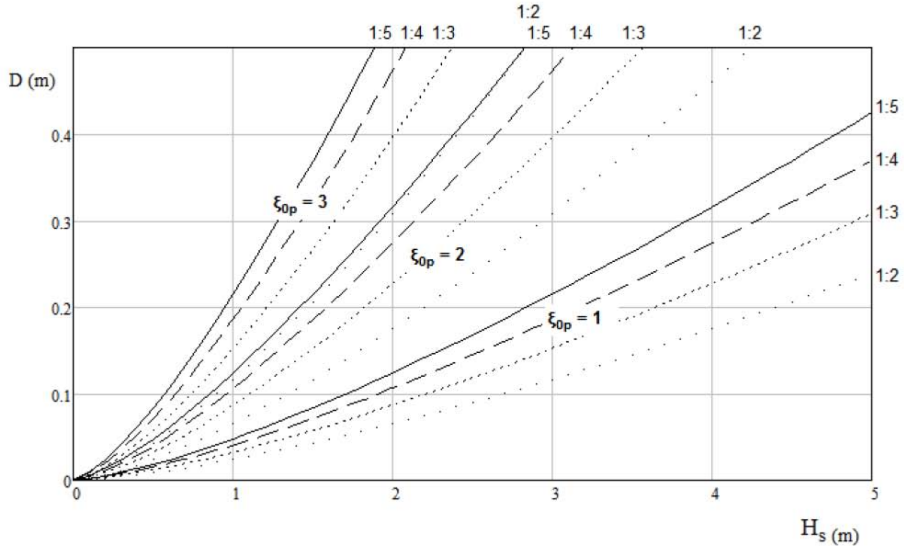


Figure 4-18: Design diagram of the cover layer thickness D in the event of overpressures as function of the significant wave height H_s [20]

4.3.10 Ice Loads

It is generally noted by [20] that ice and ice loads do not pose any problem for Elastocoast revetments. Due to the relatively smooth surface of Elastocoast revetments, ice loads cannot become concentrated at individual points and thus cannot cause any damages.

The following details are provided by [20] with regard to the design of the revetment:

- rough an uneven surfaces in the revetment design at which ice loads may become concentrated are to be avoided.

- when planning revetments within areas in which ice loads may occur, slope angles steeper than 1 : 3 should be avoided.

For further information on ice loads, reference is made to EAK (2002), Recommendation A, Section 7.

4.3.11 Traffic Loads

Basically, the Elastocoast revetments are designed for occasional traffic loads which might, for example, occur within the scope of maintenance works. These vehicles can exert heavy loads on the revetment.

Actual tests at an Elastocoast revetment were carried out with a chain dredger in The Netherlands. Despite the rotating dredging movements, no significant damages occurred on the surface of the revetment. For further information, reference is made to [13].

In case of known traffic loads, ARCADIS (2009) recommends the following approach for determining the required revetment thickness D for the Elastocoast revetment.

$$D = \sqrt[5]{\frac{P^4}{\sigma_{\max}^4} A}$$

$$A = \frac{27E}{16c(1-\nu^2)}$$

Parameter

σ_{max} = flexural moment capacity [MPa]
P_{max} = maximum axle load per tire [kN/m]
c = coefficient of compression of subsoil [MPa/m]
E = Young's modulus of the cover layer [MPa]
D = thickness of the cover layer [m]
ν = constant of Poisson (assumed to be ν =0.35) [-]

For a traffic load of 1,000 rides per year, a minimum revetment thickness of

- D = 0.20 m in case of a sand foundation and
- D = 0.25 m in case of a clay foundation

is recommended.

4.4 Design of the Revetment Structure

The design parameters specified in Section 4.3 and the design parameters resulting and derived thereof in particular with regard to the revetment design and thickness (cf. 3.4) are to be specified in the course of the dimensioning which has to be carried out. Thus, a stability analysis for the revetments under the occurring loads and the existing boundary conditions is available.

According to ARCADIS (2009), the cover layer thickness ranges between 0.1 m and 0.5 m.

With reference to the model tests in the Large Wave Flume with the documented case of damage [28] as well as the loads occurring at the revetment, in particular wave and pore pressures (cf. Sections 4.3.2 and 4.3.9), it is recommended to closely examine the necessity of a filter or levelling layer beneath the cover layer.

Recommendations on the Design of the Cover Layer

The design parameter for the cover layer thickness determined in Section 4.3 should be rounded to 5 cm.

With regard to the reference projects in Section 6, a minimum thickness of 0.15 m is recommended for the cover layer of the Elastocoast revetment.

According to Section 4.3 , the analysis of the required cover layer thickness has to be performed also in consideration of the applied type of stones, i.e. in particular the stone size (cf. Section 4.6.1).

Recommendations on the Design of the Filter or Levelling Layer

In case of Elastocoast revetments with a slope angle of 1:3 or steeper, a minimum thickness of 0.15 m is recommended for the filter or levelling layer.

In case of milder slope angles, the question whether a filter or levelling layer is necessary has to be examined in consideration of the existing hydraulic and geotechnical boundary conditions, the applied stone sizes, the occurring loads and the influencing processes. A respective analysis of the revetment stability (cf. Section 4.3.9) has to be performed.

4.5 Notes on Construction Details for Transition Zones

The transitions to other structures and the borders of revetments are very important areas with regard to the structural integrity of a revetment. They have to be designed according to the existing boundary conditions as well. In an extreme case, the transition details of a revetment may be decisive for the structural integrity of the entire revetment.

ARCADIS (2009) states some particulars regarding the transition details of an Elastocoast revetment which are shown in the following in Figure 4-19.

Further information on transition details may be gathered from the reference projects or requested from the responsible authorities (see [13]). Figure 4-20 shows some transition details which were realised in the reference project on Amrum.

Basic information on the design of revetments in transition zones to existing structural components are also to be found in the codes and standards by the BAW (cf. e.g. [7]).

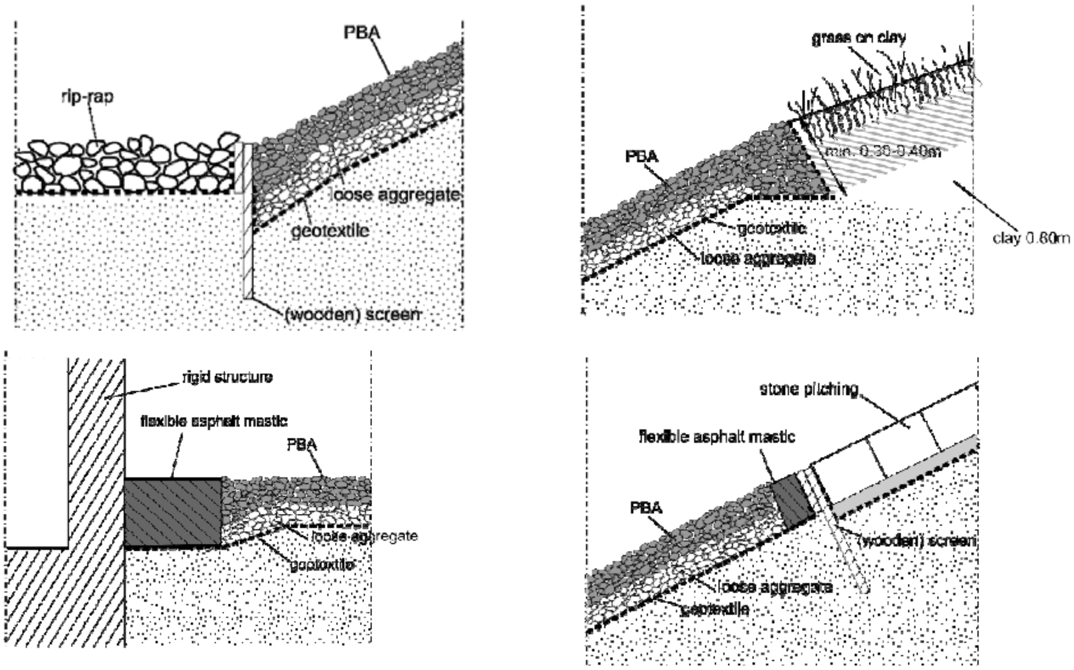


Figure 4-19: Exemplary transition details according to [20]

Figure 4-20: Transition details from the reference project on Amrum (Photos: IMS)

4.6 Additional Information, Requirements and Properties

In the following, some further details on Elastocoast revetments are provided. In general, reference is made to the statements provided by ARCADIS (2009) as well as all other available documents and data to be found in Appendix 1.

4.6.1 Stone Types and Stone Sizes Used for Elastocoast Cover Layers

The chosen stone types and the respective grain sizes influence the cover layer thickness. According to ARCADIS (2009), it is possible to use different stone types for Elastocoast cover layers.

With regard to already applied stone types, it is referred to the reference projects in Section 6, BASF PU as well as to [13] .

Basically, the cover layer should have a minimum thickness of

- 2 x D_{50} from a functional point of view
- 2.5 x D_{max} from a practical point of view

These minimum thicknesses are to be considered against the background of the dimensioning of the cover layer thickness in Section 4.3.

The material properties of different revetment stones are specified more precisely by ARCADIS (2009).

4.6.2 Upgrading of Existing Revetments

Basically, it is possible to upgrade existing revetments with an Elastocoast revetment. In such cases, the planning and design of the Elastocoast revetment are defined by the respective boundary conditions.

In Chapter 4.3.7, ARCADIS (2009) provides information on Elastocoast revetments used to upgrade existing revetments. For this purpose, Elastocoast has to be designed for the prevailing loads. ARCADIS (2009) assumes that no permanent bonding between the Elastocoast revetment and the other revetment may be applied. In this regard, reference is made to the associated deterministic design approach in [20] and other reports and studies.

The LKN has made positive experiences regarding the combination of Elastocoast revetments with existing rubble revetments in the reference project on Amrum (cf. Figure 4-19).

It is also very easy to upgrade Elastocoast revetments.

4.6.3 Resistance to Freeze and Thaw

The *Prüfinstitut für Baustoffe and Umwelt GmbH* has tested the resistance of Elastocoast to freeze and thaw. According to the test results, Elastocoast is to be judged as sufficiently resistant against freeze/thaw cycles (see [20]).

4.6.4 Removability

In the event of a removal of the Elastocoast revetment, the data, documents, etc. on the topic “removal” listed in Appendix 1 are to be applied for the disposal and subsequent use of Elastocoast [29].

With regard to this, it is stated in [12]:

> *“The composite composed of the fully cured polyurethane and stones can be treated like conventional waste at the end of its life cycle. According to the European Waste Catalogue EAK (German abbreviation) 070213, fully cured polyurethane and stones do not have to be treated as hazardous waste. If treated as demolition waste with a ratio of less than 5 vol. % polyurethane, EAK 170117 or 170504 (mixture of cement, bricks, tiles or ceramic) applies. In case of more than 5 vol. %, EAK 170904 (mixture of construction site and demolition waste) is applied. It is possible to re-use the composite material for road construction.”*

4.6.5 Environmental Aspects

Environmental aspects wil not be addressed here in detail. With regard to this, a number of studies and tests have been carried out on behalf of BASF PU. A survey of the existing data and documents on ecology, ecotoxicology and water quality is provided in Appendix 1.

In [12], reference is made to scientific studies on the return of vegetation and other organisms to Elastocoast revetments in The Netherlands. As a result, it is said that *“the colonisation by microalgae and animals may take place quickly and permanently under favourable conditions”*.

4.6.6 Planting of Vegetation on Elastocoast Revetments

It is basically possible to plant vegetation on an Elastocoast revetment. With regard to the revetment design, however, it is recommended to act on the assumption of a reduced porosity and permeability of the Elastocoast revetment. In this regard, reference is made to the sections on the design of Elastocoast revetments subject to the existing geotechnical and hydraulic boundary conditions. If vegetation is planted on Elastocoast revetments, the relevant analyses have to be performed. An example for natural plantation on the Hallig Nordstrandischmoor is provided in [12] (cf. Fig. 2.6.2.10).

4.6.7 Additional Anchoring

If an Elastocoast revetment is strained by pore pressures accompanied by possible subsoil displacements and a lifting of the revetment, it is generally possible to use additional anchoring systems, e.g. ground anchors. The respective details on the intended anchoring system and the associated analyses have to be provided.

4.6.8 Porosity

The porosity of the Elastocoast revetment corresponds to the porosity of the applied type of stones. The film of polyurethane coating the individual stones does not reduce the porosity.

4.6.9 Resistance to UV Radiation

The resistance of Elastocoast to UV radiation was tested.
According to ARCADIS (2009), tests by BASF PU have shown that – after 3,000 h of exposure to UV light – no negative influence on the compressive strength of the tested material was identifiable. This volume of exposure to UV light corresponds to a three years period of real sun light exposure in Central Europe.

Figure 4-21 shows the positive effect of sand applied on the surface of the “fresh” Elastocoast revetment. The additional sand grains not only increase the revetment’s accessibility but also protect it against UV radiation.

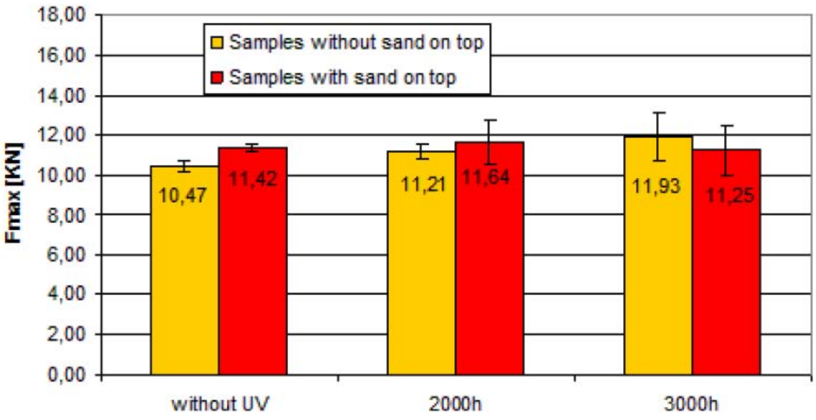


Figure 4-21: Resistance of Elastocoast to UV radiation

For further details, reference is made to [13] and [20].

4.6.10 Resistance to Salt Water

The resistance of Elastocoast to salt water was analysed and confirmed by means of an accelerated test procedure (EN ISO 2578). In the findings, it was observed that Elastocoast is fully stable and resistant to sea water. Its life span ranges between 80 and up to 100 years. For further details, reference is made to [13] and [20].

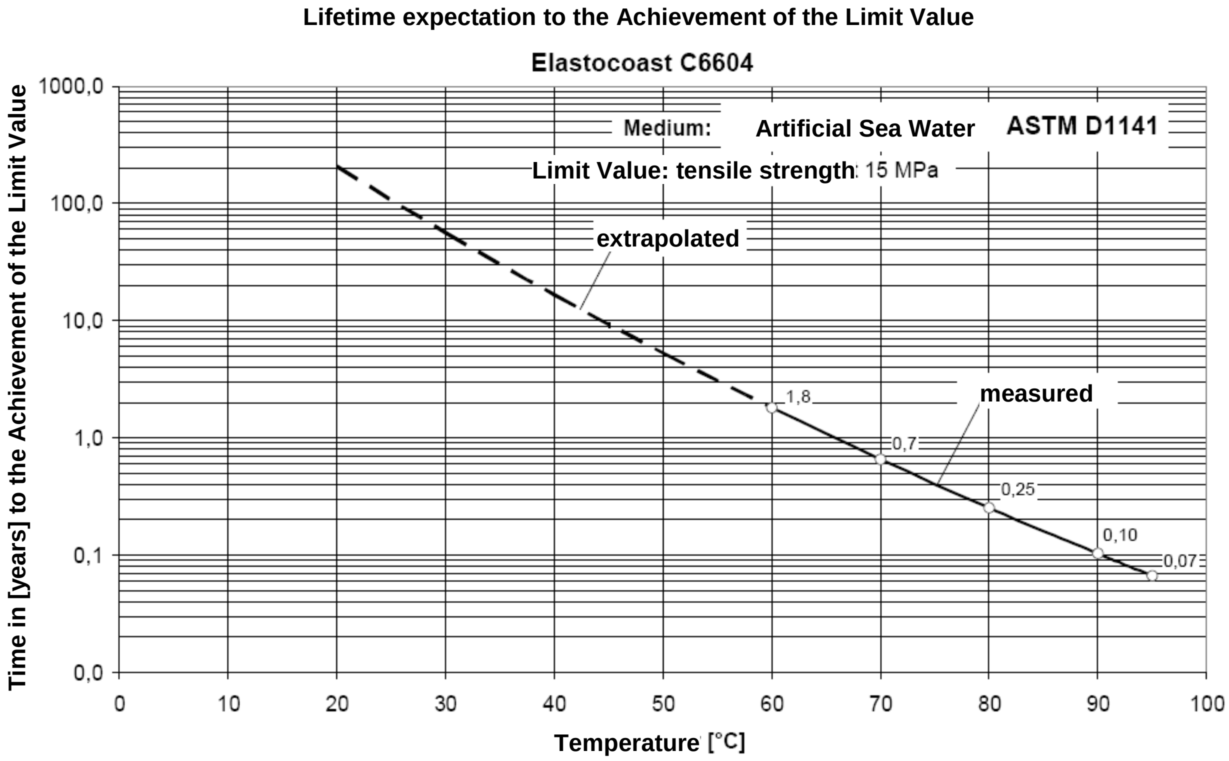


Figure 4-22: Resistance of Elastocoast to salt water (in [20])

5 Notes on the Planning, Design, Approval, Tendering and Construction of an Elastocoast Revetment

5.1 General

In consideration of the design rules compiled in Section 4, it is possible to design an Elastocoast revetment for given hydraulic, geotechnical and constructional boundary conditions. In the following, some additional notes on the planning, design, approval and construction of an Elastocoast revetment are provided.

5.2 Planning and Design

The Elastocoast revetment can and must be designed in consideration of the basic principles specified in Section 4.

In case the technical equivalence between a conventional revetment and an Elastocoast revetment has to be established, the same course of action is to be taken, i.e., the technical equivalence has to be established for the different design parameters in consideration of the individual, known design parameters.

5.3 Approval

The approval of construction projects and measures in coastal protection has to be obtained from the responsible Federal State authorities of the coastal states.

Details concerning questions relevant for approval may be inferred from the document on hand. Further information is not known at present.

5.4 Tendering

The tendering stage for an Elastocoast revetment requires the design and approval of said structure.

The invitation to tender has to refer precisely to the requested construction method and the construction materials required in this regard. In addition to this, it has to name the construction method as is the rule with the invitation to tender for conventional revetments.

For the precise description of the material “Elastocoast”, BASF PU should be contacted in order to clarify the exact specification.

In addition to this, it should be inquired in the invitation to tender whether the executing construction company has already gained any experiences in building of Elastocoast revetments. In any case, it should be considered and explicitly tendered that consulting services are to be rendered by BASF PU during the tender stage as well as the subsequent construction phase.

5.5 Construction

The following information and requirements have to be provided for the construction of Elastocoast revetments:

– *Clean and surface-dry revetment stones*
  The applied revetment stones have to be clean and surface-dry when mixed with Elastocoast. Moisture remaining on the stones would otherwise lead to a reaction between the bonding material and water resulting in the fact that no permanently stable granular structure could be achieved (cf. Figure 5-1).

Figure 5-1: Example for a quality defect caused by residual moisture on the granular material during the mixing process (Photos: IMS)

– *dust on the stones*
  Dust on the applied revetment stones has to be avoided. Too many fine rock particles and fragments results in an increased amount of required binding material.

– *installation under water*
  If the clean and surface-dry revetment stones have been mixed correctly and coated with Elastocoast, it is also possible to subsequently install them under water. At present, experiences has been gained in a limited water depth [13].

– *application of sand on the surface*
  It is possible to improve the visual appearance and accessibility of the revetment by applying sand on the surface before the material is fully cured. Thus, the revetment is also better protected against UV radiation (cf. Section 4.6.9).

– *temperature*
  According to ARCADIS (2009), it is possible to build Elastocoast revetments at temperatures ranging between 5 °C and 30 °C.

- *humidity*
  Basically, humidity does not pose any problems provided it does not have any influence on the existing moisture remaining on the applied stones.

- *working direction*
  When building an Elastocoast revetment, it is recommended to construct it in load bearing direction (cf. Figure 5-2).

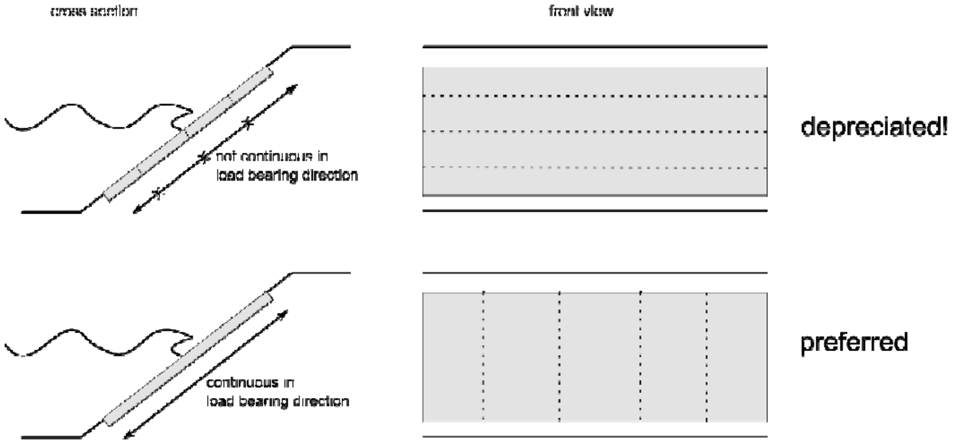


Figure 5-2: Recommendations for the design of transition zones and internal transitions when constructing Elastocoast revetments according to [20]

Processing Notes

The manufacturer BASF PU gives the following notes on how to process Elastocoast:

1. Dry weather conditions
   - no precipitation
   - ambient temperature at least 10 °C
2. The stones have to be delivered dry and preferably washed
   - no dirt on the stones
3. The mixer has to be dry
4. The subsoil has to be prepared according to the planning specification
5. The specified stone quantity has to be determined and filled in the mixer. Example: 33 kg of PU / 1 m³ of stones (approx. 3 vol. %)
6. B components have to be poured into A components and mixed together
   - safety data sheets have to be observed
   - protective clothing has to be worn!
7. The ready mixed adhesive has to be added to the stones and tumbled
8. The stone/adhesive mixture has to be applied and distributed on the designated area
9. Sand has to be applied to the revetment.
10. If the construction process is interrupted, the mixer has to be mechanically cleaned with new, dry stones.

Recommendation

In order to ensure quality control, it is recommended that the manufacturer BASF PU renders consulting services and/or technically monitors the construction works.

Construction companies with, to date, no experience regarding the application of Elastocoast may gain experience in advance through BASF PU. This represents another quality management component.

5.6 Monitoring

Monitoring programmes for individual Elastocoast revetments were already performed. The respective particulars on how to proceed when carrying out monitoring measures are provided by ARCADIS (2009), Chapter 6.

6 Reference Projects

6.1 Reference Projects with Elastocoast Revetments

Elastocoast revetments have been applied mainly in Germany but also in The Netherlands, France and Great Britain as well as in Canada. Table 6-2 provides a complete list of these reference projects also stating the construction dates. With regard to further information on the individual reference projects, reference is made to BASF PU [13].

Table 6-1: Reference projects for Elastocoast revetments [13] (06/2010)

Deutschland	Niederlande
» Obermaubach (09/2009)	» Bathpolder (07/2009)
» Kühlungsborn (08/2009)	» Harlingen (11/2008)
» Cuxhafen (07/2009)	» Petten (10/2007)
» Norddeich (06/2009)	» Zuidbout (09/2007)
» Emden (05/2009)	Frankreich
» Kranenburg (04/2009)	» La Bouille (05/2009)
» Amrum (11/2008)	» St Pierre de Manneville (04/2009)
» Langeness (08/2008)	» Bollène (03/2009)
» Nordstrandischmoor (06/2008)	» Le Havre (05/2008)
» Niebuell (12/2007)	Großbritannien
» Lemförde (09/2007)	» Holland on sea (10/2008)
» Sylt Munkmarsch (09/2007)	» Walton (04/2008)
» Hallig Gröde II (06/2007)	Kanada
» Hallig Gröde (07/2006)	» Fighting Island (09/2007)
» Sylt Ellenbogen (11/2005)	Sonstige
» Hamburger Hallig (10/2004)	» Trinkwasser Zulassung in Großbritannien

6.2 Reference Projects on the German Coast of the North Sea and Baltic Sea

The reference projects with Elastocoast revetments on the German coast of the North Sea and Baltic Sea are documented in more detail in Table 6-2. In addition to the construction year, it also lists geometrical parameters such as the size, length (parallel to the slope), revetment thickness as well as the slope angle on the sea and inland face for the individual reference projects. Moreover, Table 6-2 specifies the applied type of stones and provides information on the revetment foundation.

The Elastocoast revetments covering the largest area were built on the Halligen Gröde, Nordstrandischmoor and Langeness as well as on the island of Amrum.

The largest seaward slope angle with 1 : 1.5 which nevertheless covers a smaller area was realised on the Hamburg Hallig.

Granite gravel and iron silicate gravel with sizes ranging between 20/40 mm and 50/60 mm were used.

A geotextile base was normally used as foundation.

Table 6-2: Overview of the most important reference projects of Elastocoast revetments on the North Sea and Baltic Sea stating essential revetment parameters

Project Name	**Year of Construction**	**Area** [m²]	**Length** [m]	**Thickness** [cm]	**Seaward slope** [1 : m]	**Inland slope** [1 : m]	**Material**	**Foundation**
North Sea								
Sylt Ellenbogen	2005	270		25 - 30	1 : 10	--	iron silicate stones	sand with geotextile
Hallig Gröde I	2006	500	--	25	1 : 3	1 : 3	granite gravel 50/60	rubble with geotextile
Hallig Gröde II	2007	3,000	500	25	1 : 3	1 : 3	granite gravel 50/60	rubble with geotextile
Hamburg Hallig	2008	120	--	30	1 : 1.5	1 : 1	no specifications	existing rubble core
Amrum	2008	1,875	254	15	1 : 3	--	granite gravel 20/40	geotextile base
Hallig Nordstrandischmoor	2008	1,800	--	--	--	--	granite gravel 40/60	rubble core/ geotextile
Hallig Langeness	2008	1,500	--	--	--	--	granite gravel 40/60	rubble core/ geotextile
Baltic Sea								
Kühlungsborn	2009	100	--	--	--	--	granite gravel 32/64	geotextile base

In case of the reference project on the Hallig Langeness, the existing seaward revetment was raised with an Elastocoast revetment in form of a mound to a triangular-shaped elevation (cf. Figure 6-1). The existing revetment as well as a newly laid geotextile base were used as foundation.

With regard to the hydraulic mode of action, reference is made to Figure 2-4. Due to its porosity, the Elastocoast revetment is able to “swallow” part of the water quantities arising during wave run-up.

In this case, it is possible – due to the porosity of the Elastocoast revetment (cf. Section 4.6.8) – that water resulting from wave run-up can be transported to the inland face of the revetment and to the Hallig foreland. Amongst other things, this also has the positive effect that waves breaking over the mound in the event of a continuously increasing water level, break into an existing water cushion which has a highly damping i.e. positive effect from a hydraulic point of view.

Figure 6-1: Existing situation and Elastocoast revetment on the Hallig Langeness (Photos: LKN)

6.3 Large-Scale Model Tests in the Large Wave Flume

Large-scale model tests with Elastocoast revetments were performed on a slope with a 1 : 3 increase in the Large Wave Flume in Hanover (cf. Figure 6-2).

The systematic tests include, amongst others, the hydraulic effectiveness of the revetment (wave run-up, reflection behaviour, impact loads beneath the revetment, damping), mechanical effects due to hydraulic loads and strains (movements/ displacements of the revetment) as well as the analyses of the geotechnical boundary conditions (pore overpressures, soil liquefaction).

In the tests with model A (Elastocoast cover layer with a thickness of 0.15 m on geotextile), the cover layer failed. The subsequent analysis showed that pore overpressures in the subsoil beneath the revetment led to liquefaction and a resulting displacements of the subsoil which, in the end, caused a revetment failure for model A. With regard to further explanations and analyses of the failure, reference is made to [28].

In comparison to the two models B and C, it is pointed out that a sufficient self weight of the revetments (equal to the revetment thickness) is necessary, in particular, in case of steeper slope angles.

Here, reference is made to the documentation of the results in [28].

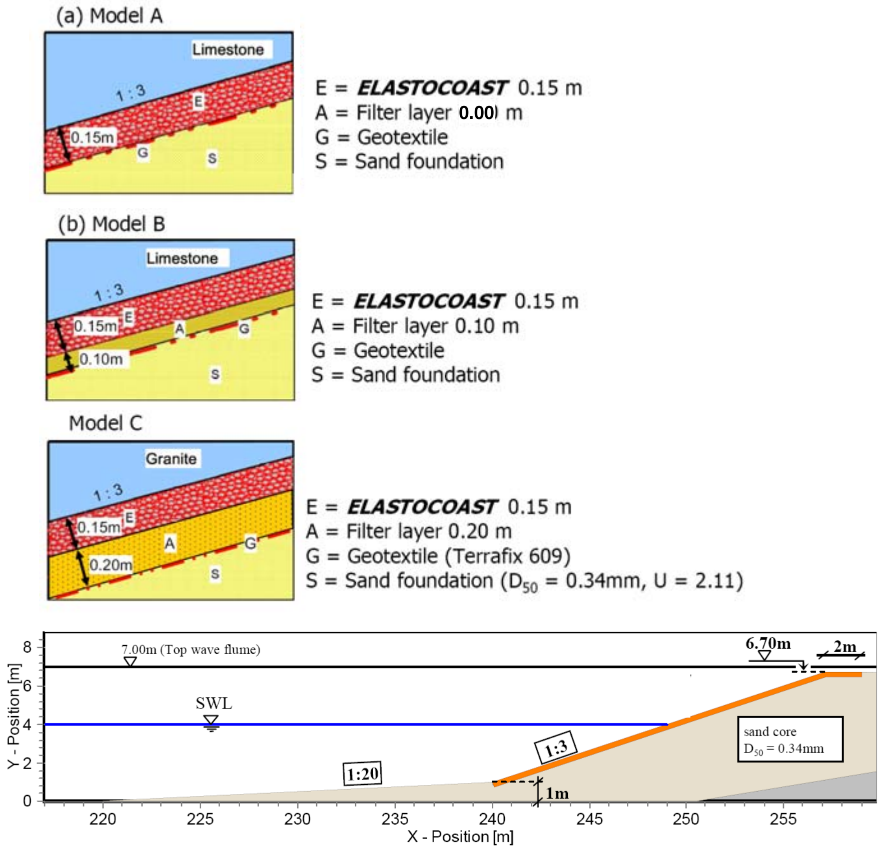


Figure 6-2: Analyses of Elastocoast revetments in the Large Wave Flume in Hanover [28]

7 Concluding Remarks

The report on hand presents the technical design guidelines for an Elastocoast revetment on the basis of available information, data and documents. In this connection, the reports by ARCADIS (2009) and LWI (2010) have to be named as a matter of priority. The documented design guidelines mainly focus on revetments in coastal and estuary areas.

Within the scope of the preparation of this report, IMS held talks with the relevant authorities responsible for coastal protection. As a result, these authorities are quite open to new methods in coastal protection. This can also be inferred from the existing reference projects.

During the talks with the authorities, it became clear that two basic issues repeatedly came to the foreground with regard to an application of Elastocoast revetments in coastal areas: The possibility to install Elastocoast under water and to the required total volume for the Elastocoast revetment. In addition to this, the Elastocoast revetment is also regarded in connection with the existing subsoil. LWI (2010) basically reports on the hydraulic and geotechnical parameters as well as processes acting on and beneath an Elastocoast revetment and the design parameters which can be derived from this. Therefore, the results of LWI are included in the present design guidelines.

Another point discussed concerned the flexibility of the Elastocoast revetment. Due to the composite effect, the material on the whole is not as flexible as loose revetments and, thus, cannot react so elastically to movements of the area and washouts. This characteristic of the Elastocoast revetment has to be taken into account accordingly within the scope of the planning and design.

Elastocoast has already been used very successfully at some coastal sections e.g. in Schleswig-Holstein. This applies in particular to the protection of the Halligen (e.g. triangular-shaped, raised structure on the Hallig Langeness). Here, Elastocoast is already recommended by the LKN as a construction method in the field of coastal protection. So far, the experiences are very positive.

Hamburg, 30th June 2010

IMS Ingenieurgesellschaft mbH

signed Peters signed Teschke

Appendices

Appendix 1 Compilation of the Existing Documents on Elastocoast and its Application in Revetment Construction

Appendix 2 Design Diagrams on the Wave Height, Excerpts from [20]

Appendix 3 Further Information on the Design of the Elastocoast Revetment on the Wave Height, Annex 1 from [20]

Appendix 1

Compilation of the Existing Documents on Elastocoast and its Application in Revetment Construction

Available Documents on Elastocoast

General Documents

[12] Elastocoast – Innovative Technologie im Küstenschutz ... heute und morgen, Informationen, Referenzen und Dokumente, BASF, Issue 2008

[13] BASF Polyurethanes GmbH, information on the web, http://www.polyurethanes.basf.de/pu/Coastal-Defense

[14] BASF Polyurethanes GmbH, Informationsbroschüre Elastocoast - Alles, was Sie über modernen Küstenschutz wissen müssen, 2010

[15] Polyurethane-Schotter-Verbund für Küstenschutzdeckwerke, Bautechnik 87 (2010), Issue 6

[16] BASF Polyurethanes GmbH, Veranstaltung Zukunftsichere Küsten mit innovativen Materialien, Information day in the Town of Husum and the Island of Amrum, 10/11 May 2010, Presentation of lectures

Technology

[17] BASF PU, Technische Merkblatt, Elastocoast 6551/100, 6 June 2006

[18] Gu (2007) Hydraulic Properties PUR-Revetments compared to those of open Stone Asphalt Revetment, TU Delft, Msc. Thesis Report, 08/2007

[19] Bijlsma (2008) The Elastocoast System – A study of possible failure mechanisms, TU Delft, Msc. Thesis report, 09/2008

[20] ARCADIS (2009) Polyurethane bounded aggregate revetment, Design Manual, 14 September 2009

[21] FZK (2009) Large-scale model test on Elastocoast revetment in GWK, Presentation to the Demonstration test on the 16th June 2009

[22] Elastomeric Revetments with ElastoCoast – Its Perspectives in River and Coastal Protection-Presentation by Pasche / Evertz

[23] TUHH (2008) Fortführung wissenschaftliche Untersuchungen an ElastoCoast-Pilotanlagen in Schleswig-Holstein, Final Report, 31 July 2008

[24] TUHH (2005) Elastomerische Deckwerke, Eigenschaften – Bemessung – Anwendung, Draft by Evertz, July 2005

[25] Hübsch (2004) Ableitung der maßgebenden Angriffskräfte auf die Tragkonstruktion eines Polyurethan-verklammerten Deckwerks auf der Basis von Naturmessungen, TUHH, Dissertation, March 2004

[26] Klauder (2004) Ermittlung der Grenzwiderstandskräfte der Tragkonstruktion einer Polyurethan-verklammerten Steinschüttung auf der Basis experimenteller Untersuchungen, TUHH, Dissertation, March 2004

[27] Evertz (2009) Verfestigung von Deckwerken mit Polyurethan, Dissertation, Hamburg University of Technology (TUHH), Institute of Hydraulic Engineering

[28] LWI (2010) Hydraulic Performance, Wave Loading and Response of Elastocoast Revetments and their Foundation – A Large Scale Model Study -, Leichtweiß-Institut für Wasserbau, LWI Report No. 988, Final Report, 8 January 2010

Removal – Waste Classification and Disposal

[29] Elastogran GmbH (2005) Die Entsorgung von Abfällen aus der Polyurethan-Herstellung und –Verarbeitung in der Bundesrepublik Deutschland, 06/2005

[30] Länderarbeitsgemeinschaft Abfall (2003) LAGA-Merkblatt: Anforderungen an die Stoffliche Verwertung von mineralischen Reststoffen/Abfällen – Technische Regeln, 5th Edition, 6 November 2003

Ecology

[31] Pilots Elastocoast, results for the storm season 2007/2008, Egon Bijlsma, Marcelle Lock, ARCADIS

[32] Early colonization of littoral communities on polyurethane substrates, A field and laboratory study, Marcelle Lock, ARCADIS

[33] Ecological Research Elastocoast, Dutch Pilot Locations Petten and the Zuitbout, Report, Marcelle Lock

Ecotoxicology

[34] Elastogran GmbH (2008) Bewertung des Einflusses von ausgehärtetem Elastocoast 6551/100 auf aquatische Ökosysteme, Letter by Dr T. Schupp from the 13th November 2008

[35] Institut Fresenius (2007) Anwendungstest: Elastocoast 6551/100, Test Report No 331466 from the 18th May 2007

[36] Fraunhofer Institut Molekularbiologie und Angewandte Ökologie (2009) Study Plan: Alga, Growth Inhibition Test, 23 April 2009

[37] Fraunhofer Institut Molekularbiologie und Angewandte Ökologie (2009) Study Plan: Zebrafish, Fish EmbryoToxicity Test, 23 Aril 2009

[38] Fraunhofer Institut Molekularbiologie und Angewandte Ökologie (2009) Study Plan: Daphnia magna, Reproduction test (OECD 211), 17 April 2009

[39] Fraunhofer Institut Molekularbiologie und Angewandte Ökologie (2009) Study Plan: Sediment – water chironomid toxicity test using spiked water (OECD 219), 17 April 2009

[40] Fraunhofer Institut Molekularbiologie und Angewandte Ökologie (2009) Study Plan: Pseudomonas putida Growth Inhibition Test, 22 April 2009

Water Quality

[41] Drinking Water Inspectorate (2009) Approval given under regulation 31(4)(a) of the water supply (water quality) regulations 2000 No. 3184 and of the water supply (water quality) regulations 2001 (Wales) No. 3911, Letter from the 27th April 2009

[42] Elastogran GmbH (2009) Instruction for use (IFU), Application of Elastocoast 6551/100 for water reservoirs before treatment, Issue No. 1.3, 5 May 2009

[43] Elastogran GmbH (2008) Water regulations advisory scheme, BS6920 Test on effect of water quality, product: Elastocoast 6551/100, 11 November 2009

[44] Elastogran GmbH (2008) Water regulations advisory scheme, BS6920 Test on effect of water quality, product: Elastocoast 6551/102, 9 December 2009

[45] Elastogran GmbH (2008) Water regulations advisory scheme, BS6920 Test on effect of water quality, product: Elastocoast 6551/103, 9 December 2009

Appendix 2

Design Diagrams on the Wave Height, Excerpts from [20]

Figure 4.25

Design for wave impacts. Required layer thickness for PBA placed directly on clay. E = 4.000 MPa, σ_{max} = 1,0 MPa.

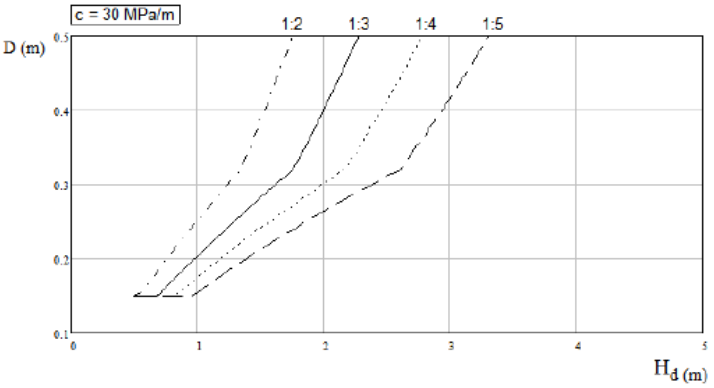


Figure 4.26

Design for wave impacts. Required layer thickness for PBA placed on granular filter layer on clay. E = 4.000 MPa, σ_{max} = 1,0 MPa.

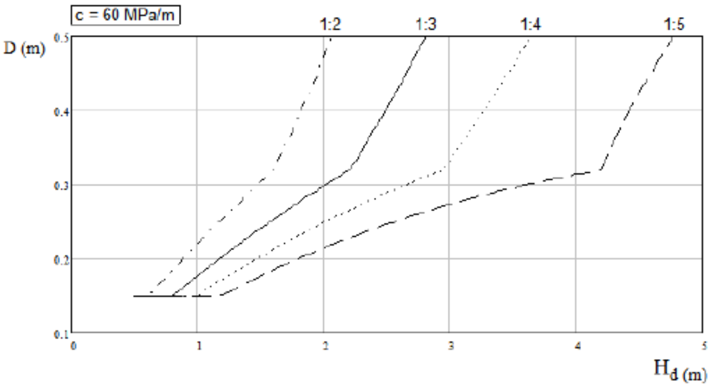


Figure 4.27

Design for wave impacts. Required layer thickness for PBA placed directly on geotextile on sand or with granular filter layer on sand. E = 4.000 MPa, σ_{max} = 1,0 MPa.

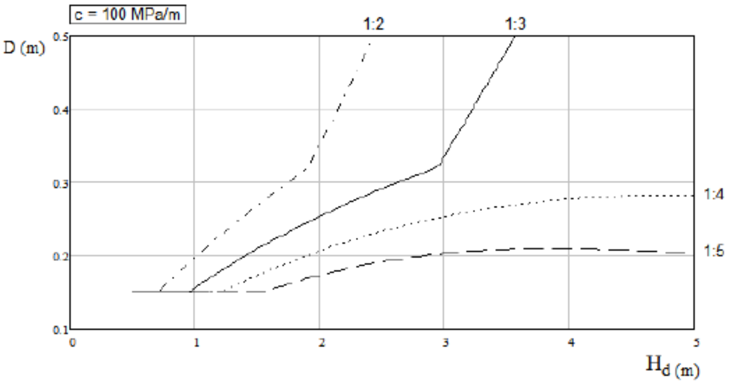
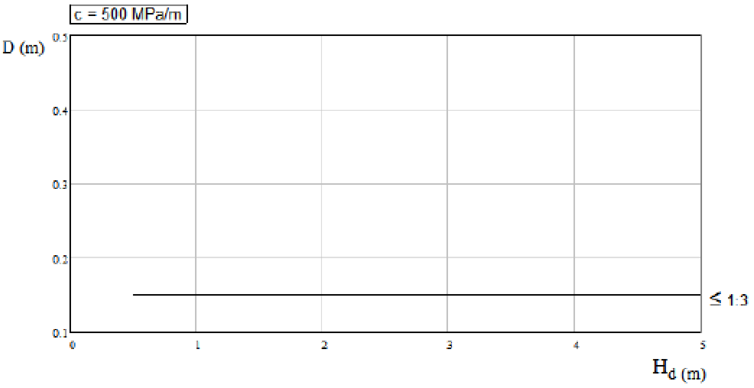


Figure 4.28

Design for wave impacts. Required layer thickness for PBA placed directly on a stiff foundation. E = 4.000 MPa, σ_{max} = 1,0 MPa.



Appendix 3

Further Information on the Design of the Elastocoast Revetment on the Wave Height, Annex 1 from [20]

ANNEX 1 Backgrounds for the design for wave impacts

Schematization method

Analogous to asphaltic revetments the PBA structure will be schematized as a plate on linear-elastic foundation (TAW, 2002) [lit. 14]. The plate is loaded by a wave impact, schematized as a triangular distributed load q(x) with a maximum of P_{max} and a base width equal to H.

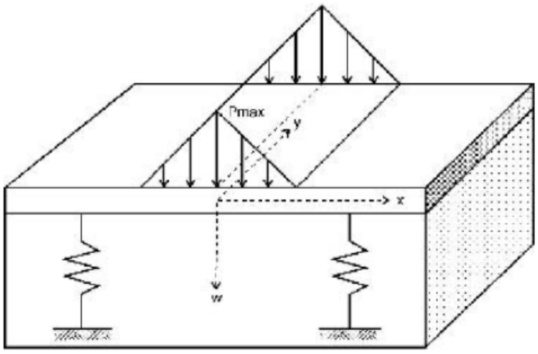


Figure A1.1

Schematization of the wave impact by a triangular load (TAW, 2002).

The determination of design plate thickness is done in three steps:

- Step 1: Determination of design wave impact load
- Step 2: Choice of representative material parameters
- Step 3: Determination of required plate thickness

Below a short description is given on choices and actions taken with each step. This section ends with some pre-calculated graphs that can be used for design.

Step 1: Determination of design wave impact load

Schematized wave impact pressure

For wave impacts the design wave height H_d should be chosen sufficiently high such that the chance of exceedence of this wave height is acceptable. The wave impact load is schematized as a triangular load with a base width equal to H_d. The maximum impact pressure occurs in the middle of the wave load and is estimated with the following equation.

$$P_{\max} = \rho_w \cdot g \cdot q \cdot H_d$$

Where:

ρ_w = mass density of water [kg/m^3]
g = gravitational acceleration [m/s^2]
q = wave impact parameter [-]
H_d = design wave height [m]

Wave impact parameter q

In the wave impact parameter q both the probability of an incoming wave resulting in a wave impact and the severity of that impact are incorporated. The probability density function for the impact parameter, valid for a slope of 1:4, is given in figure A1.2.

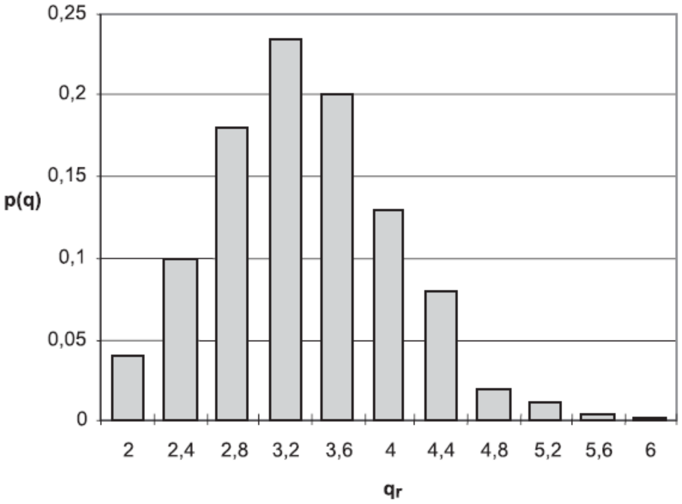


Figure A1.2

Probability density function of the wave impact parameter q for slopes of 1:4 (TAW, 2002).

Values for the wave impact parameter have been found empirically for slopes of 1:4. For design calculations a conservative value of q_r = 5.0 is chosen. This value corresponds with a probability of exceeding of approximately 2%.

Figure A1.3 shows the impact pressure P_{max} as a function of design wave height H_d, dependent on the choice for q.

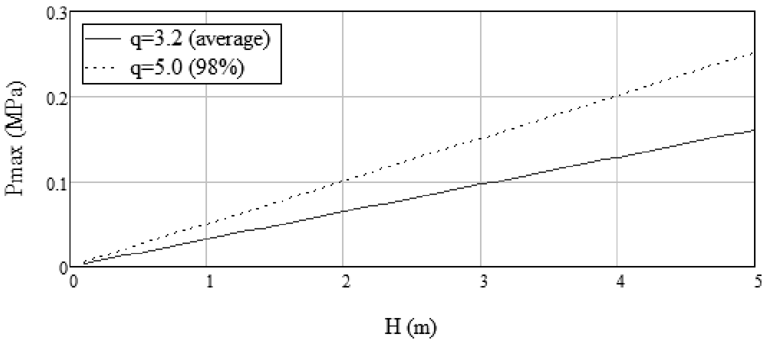


Figure A1.3

Relation between wave height and maximum impact pressure, for a 1:4 slope.

The value for the parameter q depends on the slope angle. Values for other slopes can be derived as follows (TAW, 2002):

$$q_\alpha = \frac{\tan\alpha}{0.25} q_r$$

In which:

q_α = wave impact parameter for a slope angle α [-]
tan α = tangent slope angle [-]
0.25 = tangent of the slope 1:4 [-]
q_r = wave impact parameter for a slope 1:4 [-]

Step 2: Choice of representative material parameters

Foundation stiffness

The stiffness of the foundation has a large influence on the stresses in the PBA cover layer when loaded. A higher soil stiffness results in a larger part of the load being directly transferred to the subsoil, which is a favourable condition for the loading of the PBA cover layer. The stiffness of the foundation can be expressed in the soil compression parameter *c* [MPa/m]. This parameter is related to the dynamic stiffness E_{dyn} of the soil. Table A1.1 shows values for the soil compression parameter for several foundation types (see also section 4.2.4 of this manual).

Table A1.1

Soil compression constant (TAW, 1984).

Subsoil	*c* (Mpa/m)
Sand - medium compacted - well compacted	 10 – 100 100 – 300
Sand + clay	30 – 80
Sand + silt	20 – 50
Clay - soft clay - stiff clay	 30 – 60 < 40
Peat	< 50
Gravel	> 70
Sand asphalt	> 500

The soil stiffness depends on many factors, including soil grading and compaction. Because it is difficult to make a reliable estimate of the soil stiffness it is advised to use a conservative value (= low value) for the compression parameter *c* in design calculations.

PBA stiffness

PBA has a relatively high stiffness when compared to open stone asphalt. The stiffness of PBA depends on the type and grading of the aggregate and on temperature (see also section 2.4.2 of this manual). For design calculations a conservative value of E = 4,000 MPa can be used.

PBA flexural strength

PBA has a relatively high flexural strength when compared to open stone asphalt. Flexural strength can be in the order of 2.5 MPa (see also section 2.4.4 of this manual). The strength is mainly dependent on type and grading of the used aggregate. For design calculations a conservative value of σ_{max} = 1.0 MPa is used. The choice of this conservative value accounts for some uncertainties in the mechanical properties of the material.

Step 3. Determination of required plate thickness

When the wave impact load and the material parameters have been determined, the maximum tensile stress in the bottom of the PBA revetment, directly under the wave load (x=0) can be determined as follows:

$$\sigma_{\max} = \frac{P_{\max}}{4\beta^3 z}\left[1 - e^{(-\beta z)}(\cos(\beta z) + \sin(\beta z))\right]\frac{6}{D^2}$$

with:

$$\beta = \sqrt[4]{\frac{3c(1-\nu^2)}{ED^3}}$$

In which:

σ_{max}	= flexural moment capacity	[MPa]
P_{max}	= maximum pressure of schematized wave load	[MPa]
c	= coefficient of compression of subsoil	[MPa/m]
E	= Young's modulus of the cover layer	[MPa]
D	= thickness of the cover layer	[m]
v	= constant of Poisson (assumed to be ν =0.35)	[-]
z	= half the triangular load width, z=0.5H	[m]
H	= wave height	[m]

In figure A1.3 an example is given of the resulting relation between plate thickness and actual tensile stress. The curve in figure A1.4 shows a local maximum (in this case at a plate thickness of approximately 0.10 m and a tensile stress of 1.2 MPa). Only points at the right hand side from this local maximum (i.e. thicknesses larger than 0.10 m), may be used for design calculations.

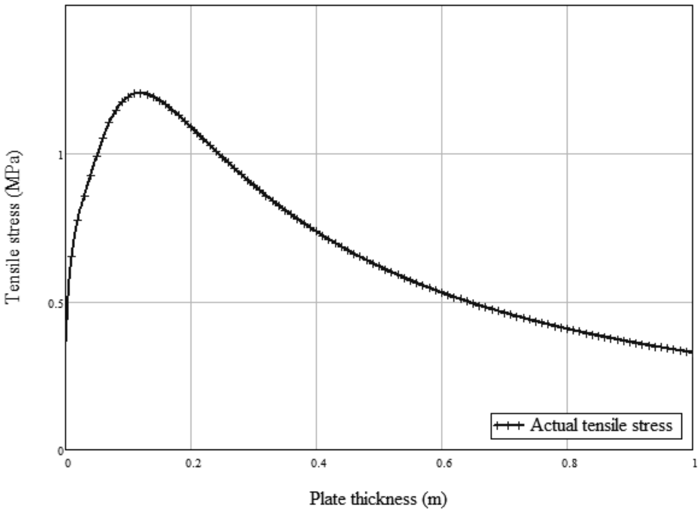


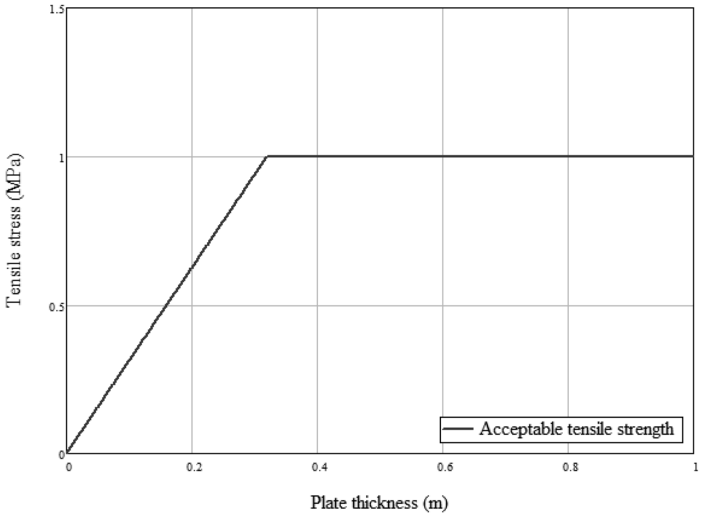
Figure A1.4

Actual tensile stress as a function of plate thickness for:
H_d = 2.5 m
q = 5.0
c = 30 MPa/m
E = 4,000 MPa

The basic assumption is made that the macroscopic properties of the plate apply if the thickness of the plate is not smaller than a predefined number of stone sizes D_{n50}. It is assumed that a thickness of at least 8 times D_{n50} is required for the plate to reach full design flexural strength. For smaller plate thicknesses the maximum tensile stress is found by linear interpolation. Figure A1.5 shows the resulting design strength in relation to plate thickness, for aggregate with a grading of 30/60 mm, D_{n50} = 40 mm.

Figure A1.5

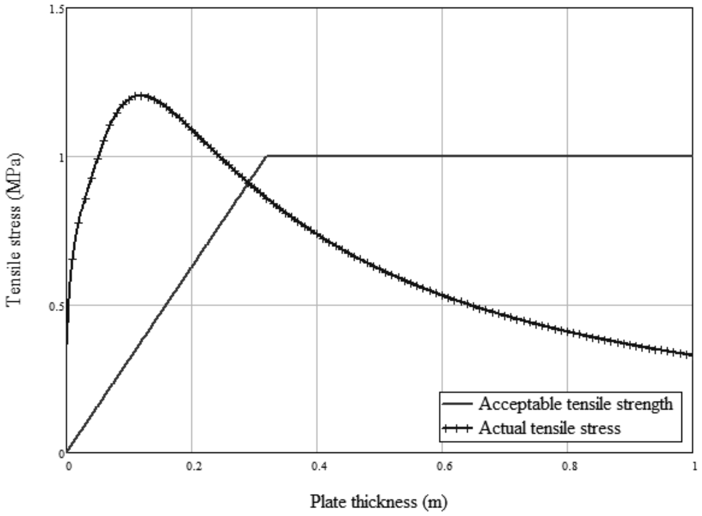
Assumed development of flexural strength as a function of plate thickness.



Finally, in order to determine the minimum required plate thickness given the input wave load and material parameters, the calculated maximum tensile stress is equalled to the design flexural strength. This can best be done visually, as shown in figure A1.5. It is important that the intersection of the two lines is at the right of the local maximum of the local maximum in the actual tensile strength curve.

Figure A1.5

Graphical determination of required layer thickness.



Pre-calculated design graphs

The calculation and graphical presentation of the actual tensile stress as a function of plate thickness cannot easily be performed by hand calculation. Below, several typical scenario's are pre-calculated for use in preliminary design of PBA structures. Together with the definition of acceptable tensile strength given above, these graphs can be used to quickly determine the minimum required plate thickness. Also, in section 4.3.3 of this manual design graphs are given relating design wave height to layer thickness.

Figure A1.6

Pre-calculated stress curves for c = 30 MPa/m, E = 4,000 MPa,

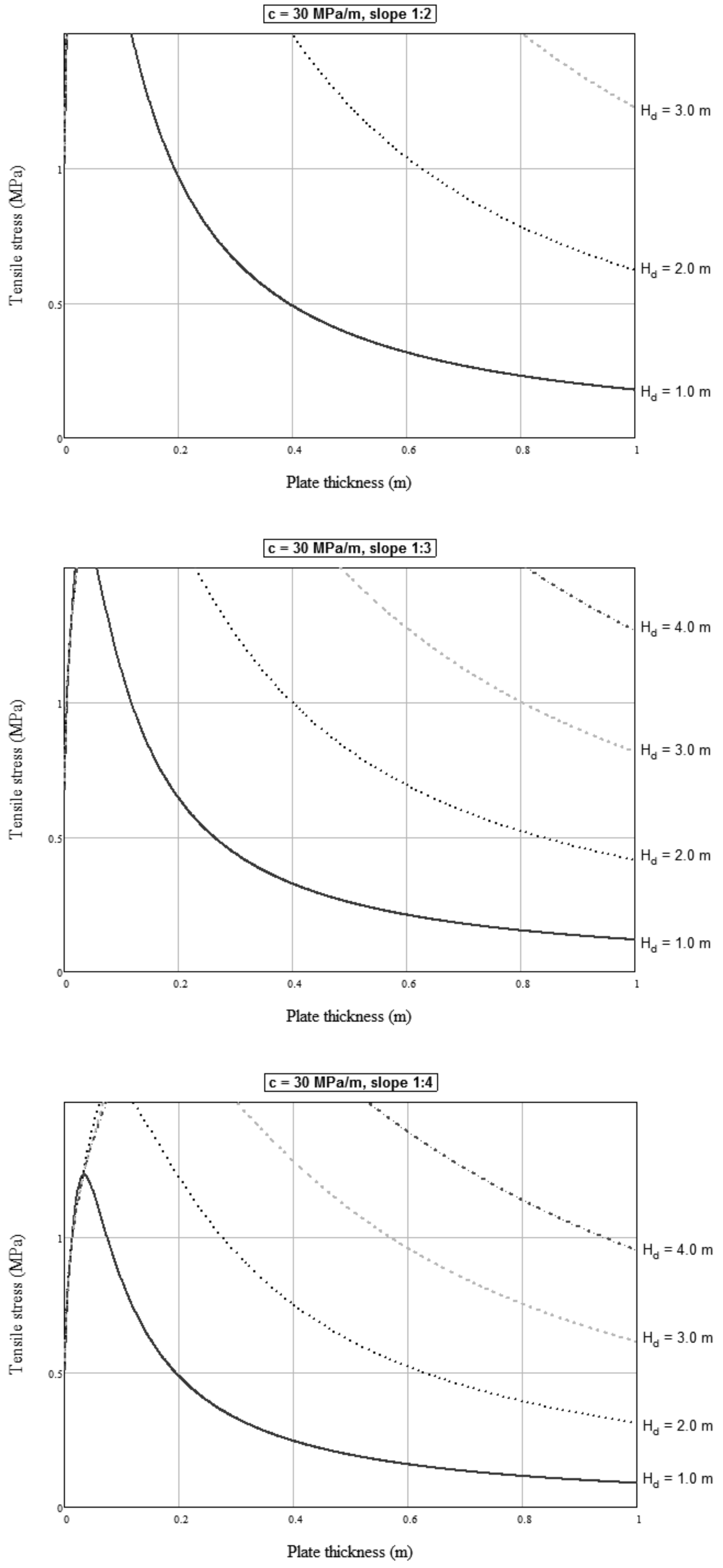


Figure A1.7

Pre-calculated stress curves for *c* = 60 MPa/m. E = 4,000 MPa.

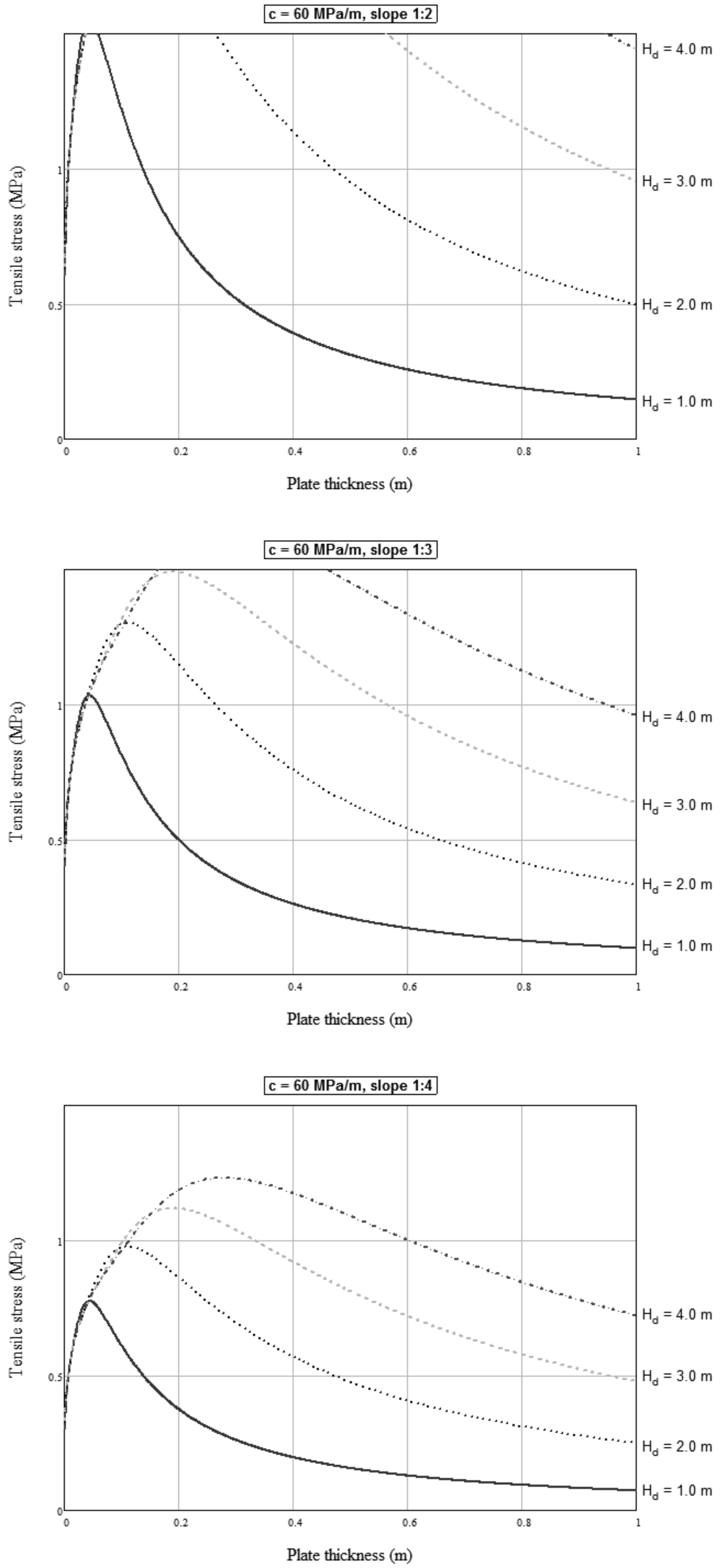


Figure A1.8

Pre-calculated stress curves for *c* = 100 MPa/m. E = 4,000 MPa.

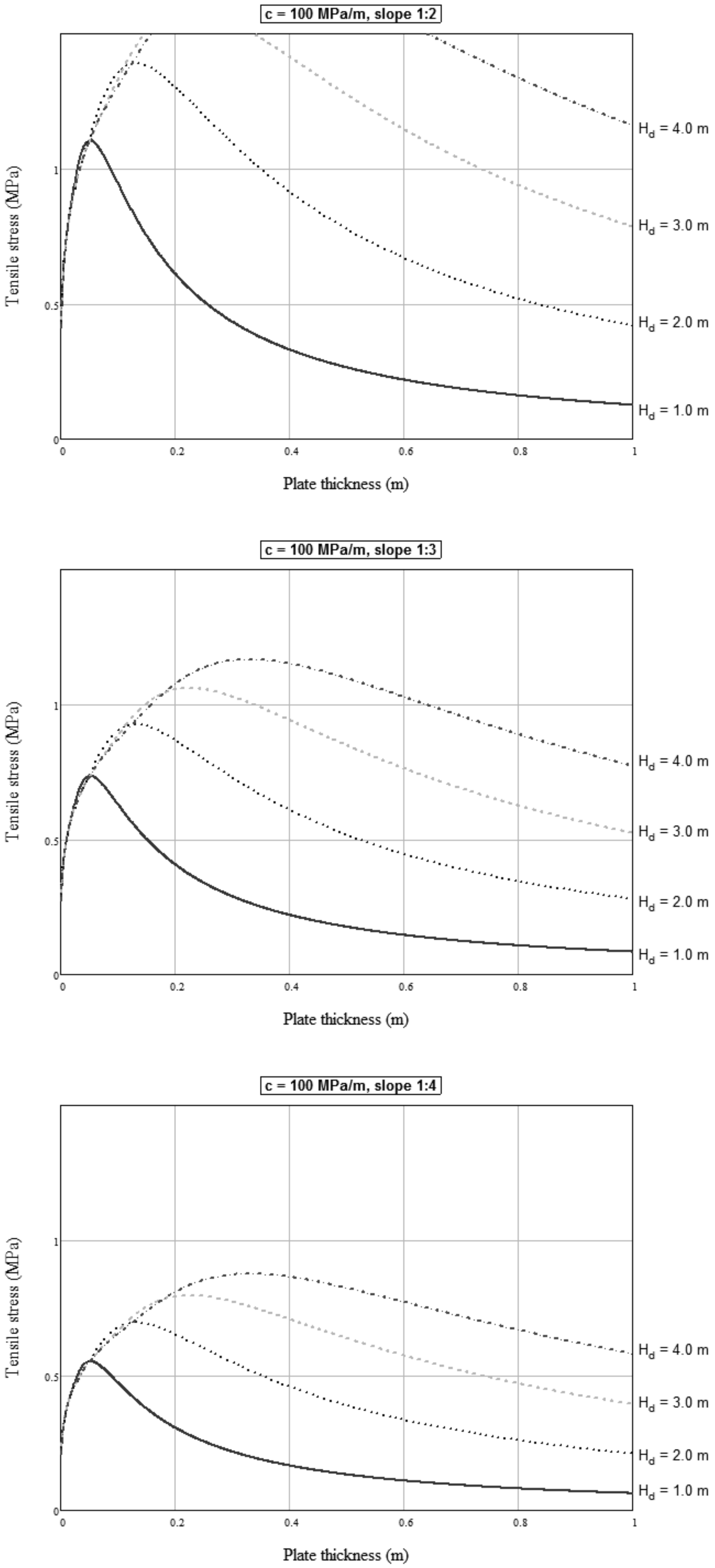
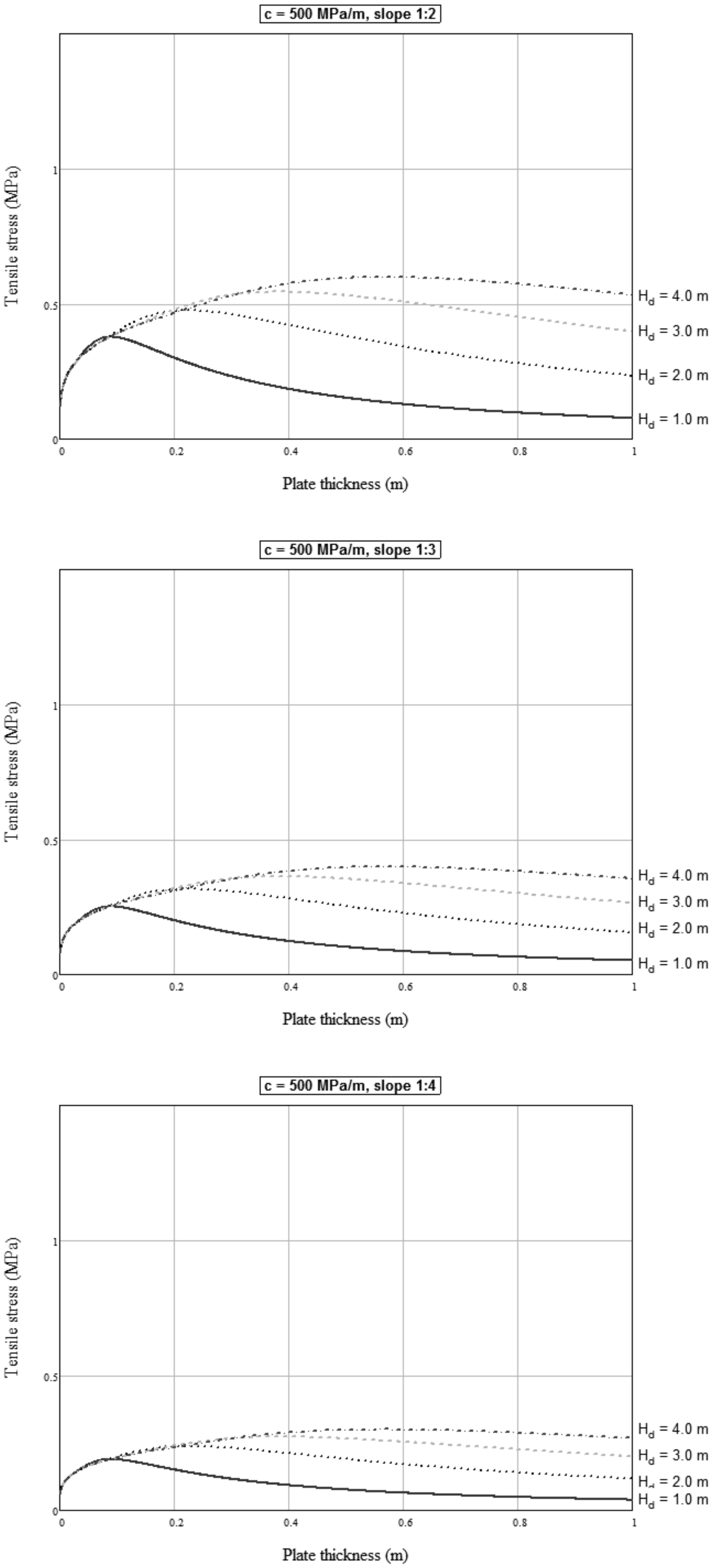


Figure A1.9

Pre-calculated stress curves for *c* = 500 MPa/m. E = 4,000 MPa.



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