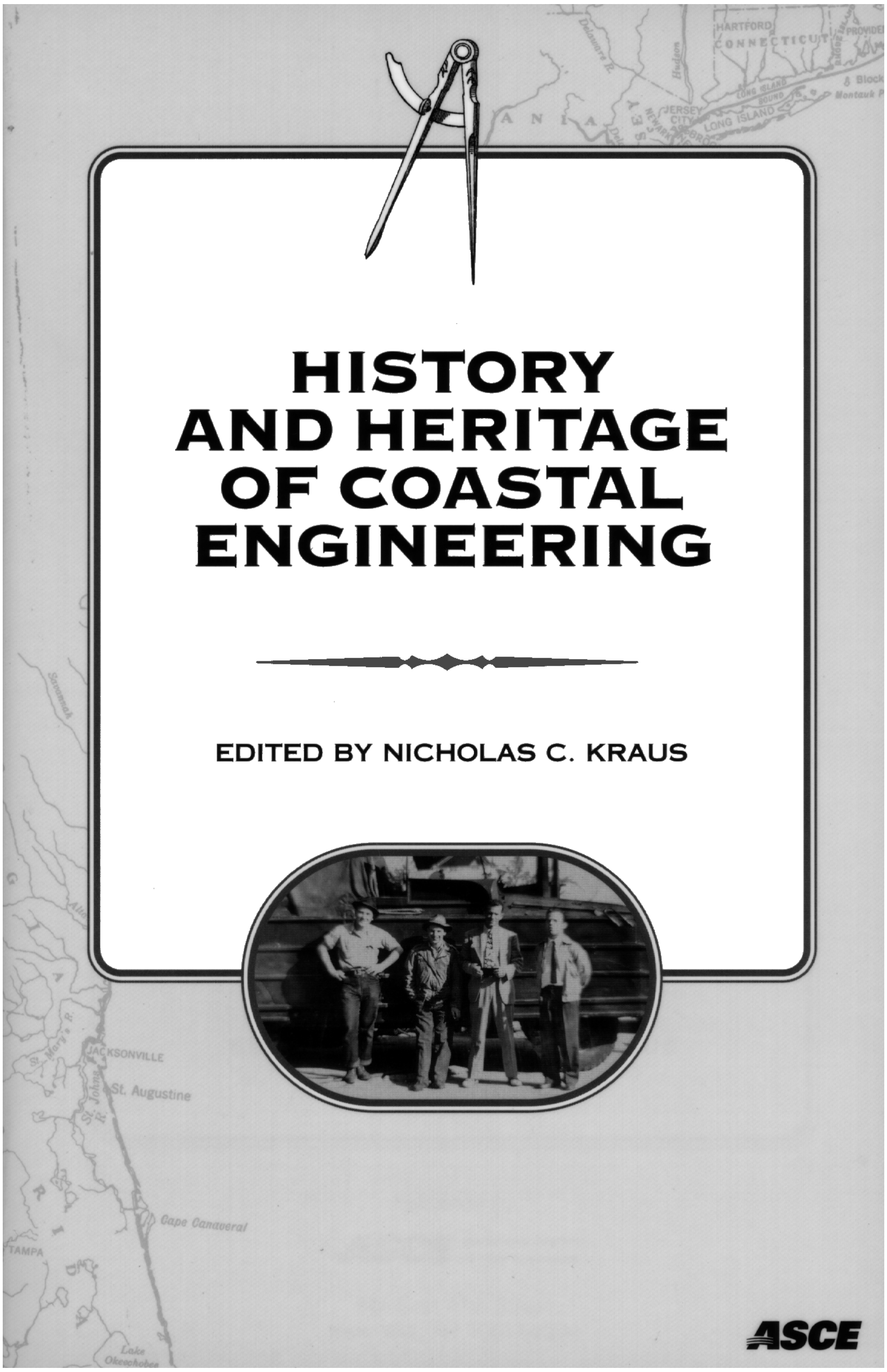
HISTORY AND HERITAGE
OF GERMAN COASTAL ENGINEERING

Hanz D. Niemeyer, Hartmut Eiben, Hans Rohde

Reprint from:



**HISTORY AND HERITAGE
OF GERMAN COASTAL ENGINEERING**

Hanz D. Niemeyer[1], Hartmut Eiben[2], Hans Rohde[3]

ABSTRACT: Coastal engineering in Germany has a long tradition basing on elementary requirements of coastal inhabitants for survival, safety of goods and earning of living. Initial purely empirical gained knowledge evolved into a system providing a technical and scientific basis for engineering measures. In respect of distinct geographical boundary conditions, coastal engineering at the North and the Baltic Sea coasts developed a fairly autonomous behavior as well in coastal protection and waterway and harbor engineering. Emphasis in this paper has been laid on highlighting those kinds of pioneering in German coastal engineering which delivered a basis that is still valuable for present work.

INTRODUCTION

The Roman historian Pliny visited the German North Sea coast in the middle of the first century A. D. He reported about a landscape being flooded twice within 24 hours which could be as well part of the sea as of the land. He was concerned about the inhabitants living on earth hills adjusted to the flood level by experience. Pliny must have visited this area after a severe storm surge during tides with a still remarkable set-up [WOEBCKEN 1924]. This is the first known document of human constructions called 'Warft' in Frisian (Fig. 1). If the coastal areas are flooded due to a storm surge, these hills remained

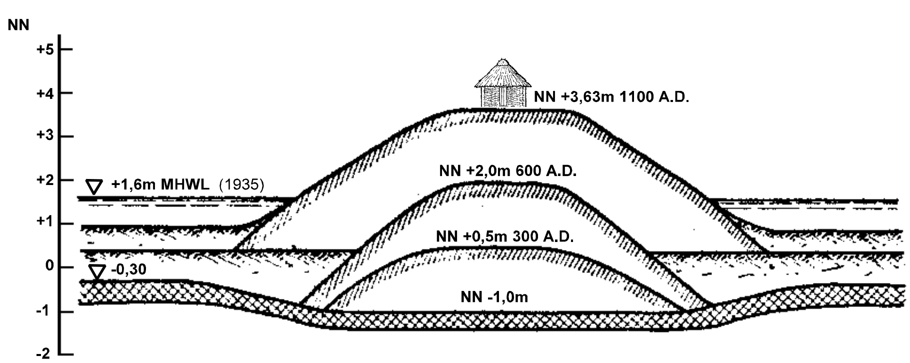


Figure 1. Scheme of a 'warft' with a single building and its adaptions to higher storm surge levels between 300 and 1100 A.D.; adapted from KRÜGER [1938]

1) Coastal Research Station of the Lower Saxonian Central State Board for Ecology, Fledderweg 25, 26506 Norddeich / East Frisia, Germany, email: niemeyer.crs@t-online.de
2) State Ministry for Food, Agriculture and Forests of Schleswig-Holstein.
3) formerly Coastal Branch, Federal Institute for Waterway Engineering.

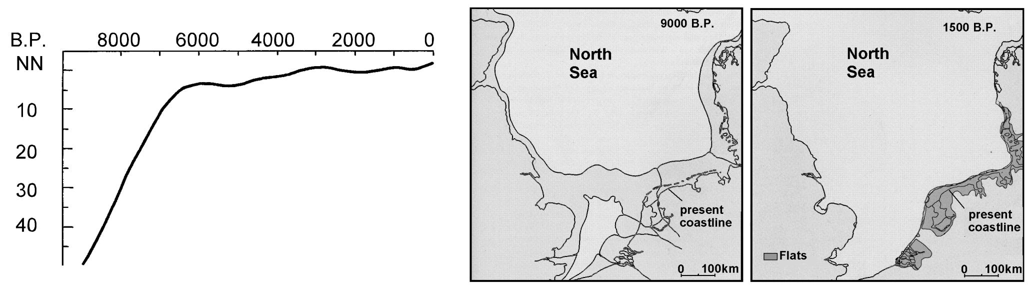


Figure 2. Sea level rise at the coast of Schleswig-Holstein [STREIF & KÖSTER 1978] between 9000 B.P. and present and coastal retreat at the southern North Sea between 9000 and 1500 B.P. [VEENSTRA 1976]

dry: safe havens for the coastal inhabitants, their housing, cattle, and goods. It makes the first engineering response against the sea after millenniums of human retreat enforced by regressive coastlines due to a rising sea level evident (Fig. 2). In modern terms the strategy had changed from retreat to accommodation. It was worthwhile for the inhabitants to take the burden to erect these earth hills and to bear this hostile environment because the accidentally flooded coastal marshes became very fertile due to accompanying sedimentation of silt. In some areas people joined their efforts and erected 'Warften' for whole villages. Partly they have been preserved as monuments of historical coastal zone management (Fig. 3). Though no longer a common standard of coastal protection, the report of Pliny documented the first stage of coastal engineering in Germany still in use today on small islets at the German North Sea coast without flood prevention such as dykes as an adequate and economic solution to protect life and property of the inhabitants.

These human settlements became possible since the coastlines no longer changed as rapidly as in the course of the preceding millenniums after the ice ages due to a deceleration of sea level rise (Fig. 2). In most of the coastal areas it was possible to remain by adjustment of the 'Warften' for the next thousand years (Fig. 1). After that period the construction of small dykes, a marked change in strategy started again: in spite of defending the settlements on the ‘Warften’ as singular points, whole areas enclosed by the dykes became to a certain extent protected against flooding allowing now more intensive agricultural use. Therefore, the Frisians called their dykes in the middle ages ‘Golden Ring’ [WOEBCKEN 1924]. In modern terms of coastal management strategy, the adaptive response has again changed: now from accommodation to protection. Moreover this was the first act of human intervention into the morphodynamics of the coastal areas at the southern North Sea. The coast had no longer an autonomous behavior, purely driven by natural forces. That kind of human intervention into the existing dynamical equilibrium caused responses by the sea of which

Figure 3. Aerial photograph of the village of Rysum in East Frisia. The ring road marks the border of the ‘Warft’; the church at the top functioned as a save haven as well during storm surges as against hostile invaders.

a remarkable number developed to disastrous lessons for the coastal inhabitants. The chosen strategy of protection required more than the empirical adjustment to the highest flood level for being sufficiently successful. Intervention into the coastal processes forced them to learn how to deal with them. Motivation for the efforts was the prospect of safety and economical welfare being endangered by the sea which was a threat for both the goods of the coastal inhabitants and even their life. The construction of dykes, their failures, and accompanying catastrophic events could be regarded as the fertilized soil for the roots of coastal engineering at the Wadden Sea coasts leading directly to first solutions of problems which are today still of importance.

For centuries the aims of coastal protection have been the driving forces for the efforts to gain further knowledge on coastal hydro- and morphodynamics. But step by step the requirements of sea trade and particularly the demands and efforts of existing ports to keep access to the sea stimulated additionally the processes of learning and the establishment of planning based on increasing knowledge. The aim of this contribution is therefore not to cover the whole field of problems in German coastal engineering but to focus on those subjects of coastal engineering for which a historical heritage exists being of potential interest to an international audience.

THE GERMAN COASTS

Germany borders the North Sea as the Baltic Sea which are mostly separated by the Cimbrian peninsula consisting nowadays of Denmark and the German Federal State of Schleswig-Holstein and intersected by Skagerrak and Kattegat (Fig. 4 + 6). In the North Sea, tidal motion is triggered by the Atlantic tides via the English channel and particularly via the northern approaches between Scotland and Iceland. Due to high damping in its intersection to the North Sea, particularly by the straits between Jutland and Sweden, there are only microtidal oscillations in the Baltic Sea. Both coasts have been shaped after the ice ages: The available material is predominantly clastic being moved and worked out by the huge glaciers covering these areas before. The present coastline were firstly touched by the sea about 9000 years ago in the North Sea area [STREIF & KÖSTER 1978] and about 6000 years ago in the Baltic Sea [NIEDERMEYER et al. 1987].

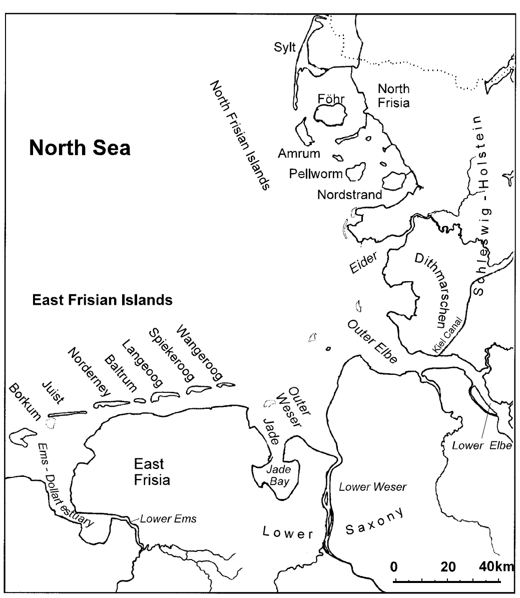


Figure 4. The German North Sea coast

The North Sea coast

The southeastern part of the North Sea is in the German Bight boardered by the German coast. It consists from west to east subsequently counterclockwise of the following parts: Ems-Dollart estuary, East Frisian Islands and Coast, Jade Bay and inlet, Weser estuary, Wursten coast and Elbe estuary. From south to north follow Dithmarschen coast, Eider estuary and North Frisian Islands and Coast (Fig. 4). The present state of the coast has been shaped by holocene transgression [STREIF & KÖSTER 1978] starting about 9000 years ago when the sea-level was about 45 m lower then today (Fig. 2). Its rise was rapid until 5000 years B. P. and decelerated afterwards remarkably with superimposed oscillations. Distinctions in the existing coastal shape and the amount of unconsolidated material caused interactions and specific regional variations. An example of sea-level rise for the coast of Schleswig-Holstein (Fig. 2) highlights the

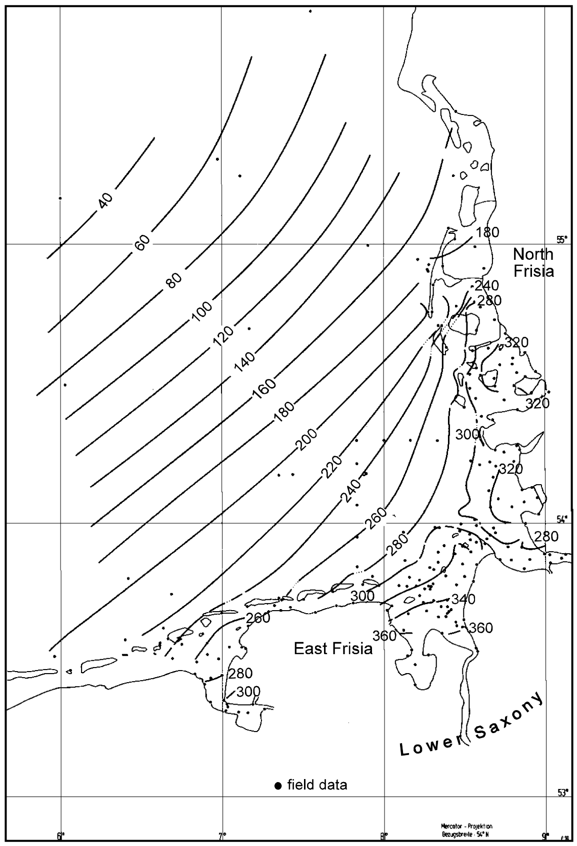


Figure 5. Mean tidal range [cm] at the German North Sea coast [LASSEN & SIEFERT 1991]

enormous changes in hydrodynamical boundary conditions for coastal development. The sediments are clastic and have been transferred into the present coastal areas by the glaciers during the ice ages. They have been reworked by currents, waves, and wind causing as well erosion as accretion of dunes, flats and marshlands. Only the island of Heligoland in the North Sea and the island of Rügen in the Baltic Sea have rockey coastlines. In the past storm surges created enormous land losses, particularly in areas with easily erodible soil such as peat for example. The coastal shape changed: Bays were enlarged or even newly created and in North Frisia remnants of former mainland became islands. Afterwards a reshaping of the coast took place driven both by sea and human intervention.

Nowadays mean tidal range increases from 2.2 m in the entrance of the Ems-Dollart estuary to nearly 3 m in the offshore area of Jade, Weser and Elbe estuaries and decreases to about 1.8 m in the offshore area of North Frisia (Fig. 5). The highest tidal range at the German North Sea coast occurs close to the landward border of the Lower Weser estuary in Bremen with about 4 m on the average. The yearly offshore mean significant wave height is about 1 m. Applying the classification of HAYES [1979] the German North Sea coast is high meso- to low macrotidal and in respect of wave climate tide dominated. The set up of storm surges has been measured with maximum values in the range between about 3 m at the islands and 3.7 m in the estuaries. In the offshore areas waves with maximum heights of about 10 m have been measured, on the shoreface of barrier islands of about 5 m and in front of mainland dykes of about 2 m.

At the Wadden Sea coast of the southern North Sea the prevailing longshore drift has an eastward direction bypassing the estuaries and tidal inlets with a remarkable offshore offset due to ebb-dominated tidal currents. They perform in dynamical balance with waves entering from offshore aggregations of sediments as shoals which are interrupted by channels. After the bypassing of the estuarine or inlet areas the ebb delta shoals have at their downdrift a landfall at large intertidal areas or barrier islands.

Most parts of the mainland coasts consist of low lying marshlands being performed by deposition of fine sediments during and after holocene transgression. Only in a few small areas remnants of the pleistocene perform the shore. The whole German North Sea coast is part of the Wadden Sea ranging from Den Helder in the Netherlands across the German Bight to Ribe in Denmark.

The Baltic coast

The northwestern part of the German Baltic coast is characterized by bays and firths, the eastern one by beach berms, spits and shallow lagoons, and islands. The shorelines are partly beach berm with shallow areas backward or sandy bluffs. The morphology has been partly shaped by glaciers during the ice ages

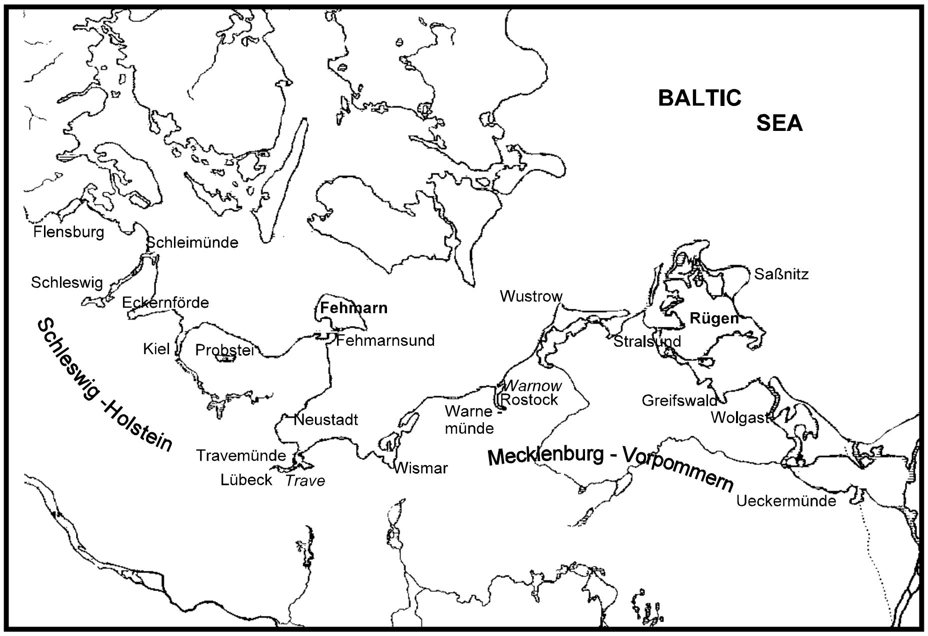


Figure 6. The German Baltic Coast

and later by holocene hydrodynamics. Evidently the present coast has been shaped in the last 6000 years. Basic materials were stones, shingle, sand, and till. The shores can be differentiated in bluffs, lowlands (Fig. 7) and lagoon coasts (Fig. 8). The lowland coasts have beach berms or spits at the shoreline. The beach berms are often created by storm surges. The bluffs have locally different sediment balances. Most changes occur due to storm surges which was already mentioned by HAGEN [1863].

The mean sea level of the Baltic Sea corresponds generally with that one of the North Sea via the intersections. Therefore variations of the North Sea mean level propagate into the Baltic Sea. Tidal oscillations decrease from west to east: An amplitude of about 0.2 m has been analyzed for Travemünde and of about 1 inch for Stolpmünde at the Pomeranian coast [HAGEN 1863]. Of higher importance are seiches and particularly basin oscillations which are triggered by wind action. The mean water level increases from west to east which is an effect of the predominant western wind directions. Eroding bluffs provide neighboring shallow coast with material via seaward bars which act both for transport and sorting. In interaction with local hydrodynamics the sediments create bars or beach berms or spits. In some cases areas with low or even no erodibility act stabilizing [HAGEN 1863].

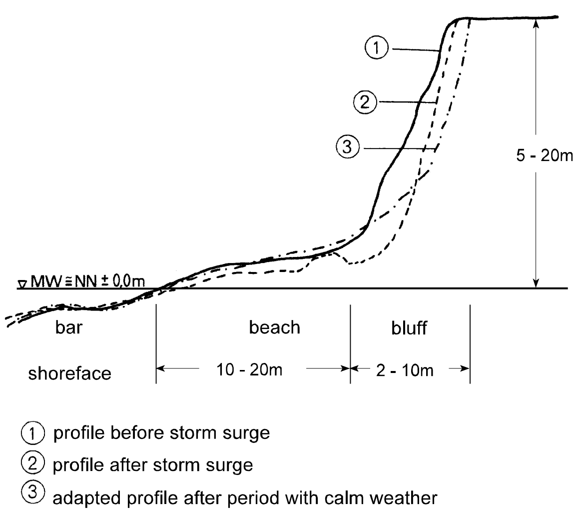


Figure 7. Cross-section of a bluff coast [EIBEN 1992b]
NN : German geodetic datum ≈ MSL

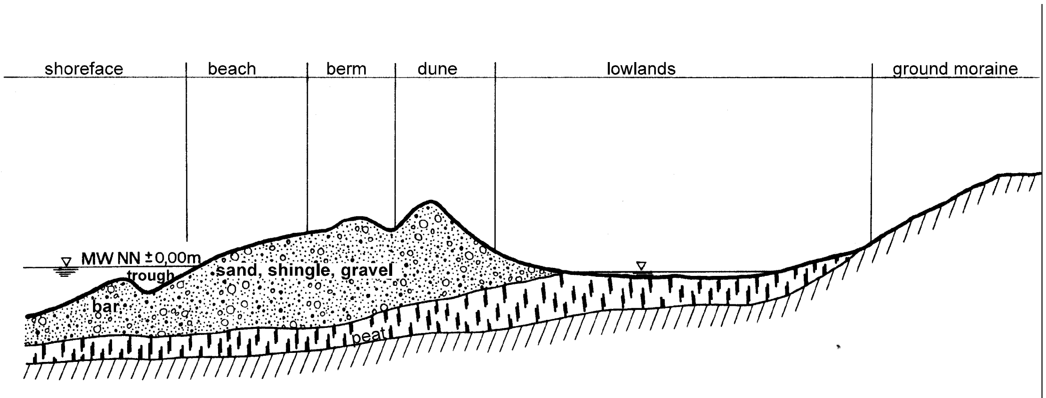


Figure 8. Scheme of a lowland coast [EIBEN 1992b]

Together these distinct shores perform 'physiographic or balanced units' [WYRTKI 1953] for which the longshore transport is balanced. This process has been made evident by tracing the eroded material which could be distinguished by higher variance from the well-sorted native one [KÖSTER 1979]. Coastal retreat at eroding bluffs varies between 0,25 m/year on the average [PETERSEN 1952] and 1m/year for exposed ones [KANNENBERG 1951] in Schleswig-Holstein. In Mecklenburg-Vorpommern the comparative figures are four times larger [GEINITZ 1903]. An extreme example is documented by KOLP [1955] for a coastal area at Darß where since 1827 a total retreat of 150 m occurred. The present state of knowledge allows to determine balanced units for the German Baltic coast (Fig. 9).

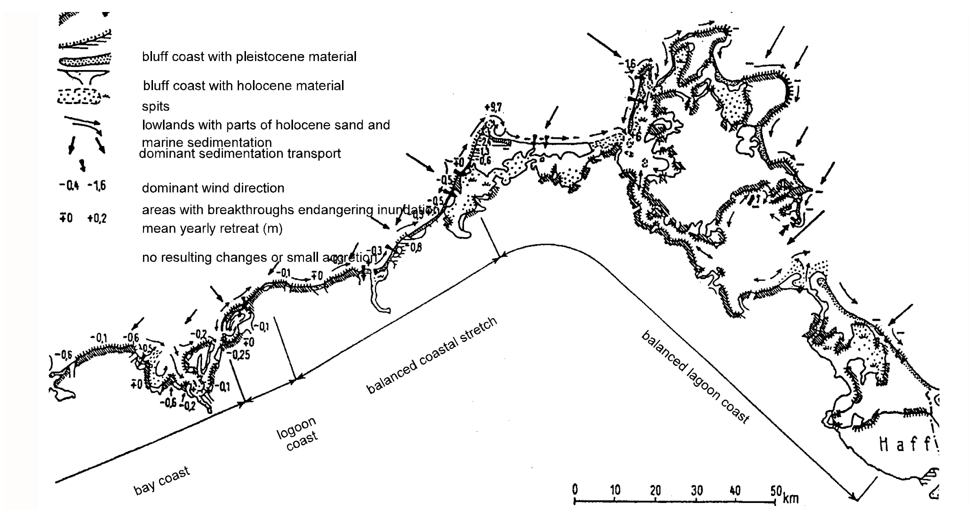


Figure 9. Example of balanced units at the Southern Baltic coast [WEISS 1992]

COASTAL PROTECTION AT THE NORTH SEA COAST

Basic hydro- and morphodynamics

Relative sea-level rise. BRAHMS [1754, 1757], who is nowadays regarded as the pioneer of modern coastal engineering in Germany was a Frisian ‘dyke judge’: elected head of one the numerous self-ruling communities at the Wadden Sea coast being responsible for coastal protection of its area. He recommended to check regularly the crest height of dykes in respect of mean high tide level which he recommended as a permanent basis for dimensioning dykes and relating them to their environment. Though not knowing or even considering a sea-level rise a thorough execution of that procedure would have highlighted at least the consequences of the sea-level rise for coastal protection. About 150 years later that effect was seriously mentioned by SCHÜTTE [1908], who evaluated a relative sea-level rise of about 33 cm per century being orientated at mean high water level and based on geological and archaeological investigations in coastal areas. KRÜGER [1922] evaluated a relative sea-level rise of about 20 cm per century by using the data of the gauges in Wilhelmshaven, Bremerhaven, and Cuxhaven taking the average of mean high and mean low tidal water level into consideration. Later he gave figures of centennial rises of 24 cm for high, 19 cm for low and 21.5 cm for half tide based on time series of 83 years at the gauge Wilhelmshaven [KRÜGER 1938]. Both still interpreted that effect as long-term subsidence of the coast being interrupted by periods of rising (Fig. 10). Their postulation stimulated an intensive discussion as well among coastal researchers as within the coastal community in their times and triggered the first of up to now three ‘coastal levellings’ in 1926: The repeated measurement of heights in coastal areas with reference to fixed points inside of the country regarded as vertically stable. Evidently there was then a lack of transatlantic communication among scientists: The explanation of that phenomenon by an eustatic sea-level rise was not taken into consideration though that idea was already introduced by MC LAREN [1842]. Since the 1950s of this century the effect of relative sea-level rise is taken into consideration for the design of coastal structures in Germany, particularly for the dykes at the coasts and tidal estuaries [HUNDT 1954]. Background for the introduction of that additional measure was that in the course of the last centuries the trend of the mean high water level had been nearly the same as that one of the envelope of the highest storm surges during that period (Fig. 11) [LÜDERS 1971; ROHDE 1977]. In respect of an anticipated change of global climate the question of relative sea-level rise is again a subject of the discussion concerning future coastal protection strategy, particularly for the lowlands. Basing on the data and established knowledge a comprehensive analysis on sea-level rise at the German North Sea coast has started [LOHRBERG 1989; LASSEN & SIEFERT 1991] partly also in cooperation with neighbor countries [JENSEN et al. 1993].

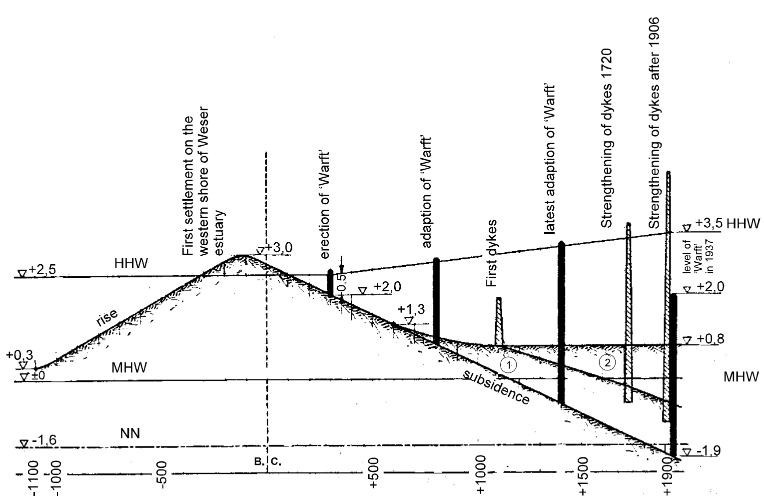


Figure 10. Interpretation of relative sea-level rise as coastal subsidence by KRÜGER [1938];
①: marshland growth and its stop after impoldering; : salt marsh growth;
MHW: Mean high tide; HHW: Highest storm surge level; NN: German Geodatic Datum

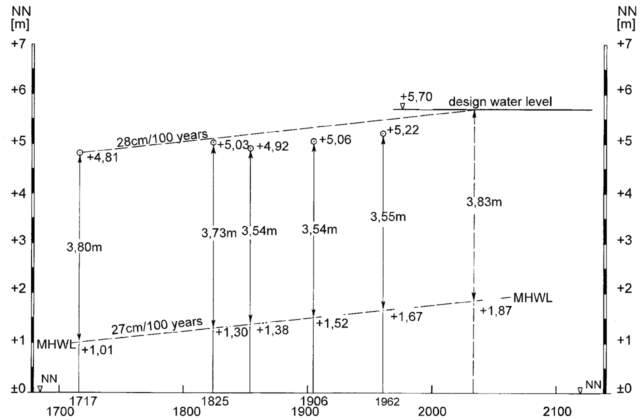


Figure 11. Reconstructed and measured levels of mean high tide and storm surge peaks at the Jade Bay since 1717 [LÜDERS 1971]

Tides and storm surges levels. The oldest known documentation of an ordinary tide at the German North Sea coast (Fig. 12) is inherited from BRAHMS [1754, 1757]. Later navigation purposes led to the installation of the first permanent gauges at the German North Sea coast [ROHDE 1975]. BRAHMS started furthermore the establishment of benchmarks of storm surges in the Jade area after the disastrous storm surge of Christmas 1717 with its high rate of death toll in the coastal areas. They were founded on a stable pleistocene basis in an area being sufficiently sheltered against waves. These benchmarks as well as those ones being measured later have been transferred to a new dyke after the enclosure of the original coastline acting as a monument of coastal engineering (Fig. 13). HUNDT [1954] used historical data at the western coast of Schleswig-Holstein under consideration of the long-term rise of the mean high tide in order to enlarge his data set for determination of return periods of extreme storm surge water levels. Since the coastal structures were rather vulnerable against frequent hydrodynamical impacts BRAHMS [1754, 1757] developed a specific tidal gauge recording the peak of storm surge still water levels (Fig. 14). He used these data to establish two kind of classifications for storm surges: one based on exceeding levels orientated at the distinct parts of the dykes and their seaward apron; the other at their return period. Both approaches are still used in German coastal engineering [LÜDERS 1956] though mostly in respect of the return periods at coastal areas [NIEMEYER 1987] delivering nowadays also basis for judgements on a possible change of storminess and increasing frequency of storm surges at the southern North Sea coast.

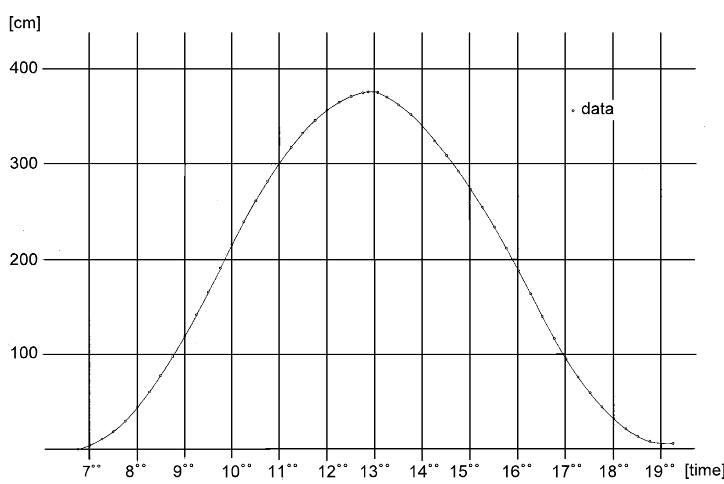


Figure 12. Cycle of an ordinary tide due to measurements of BRAHMS [1754, 1757]; reconstructed by LUCK & NIEMEYER [1980]

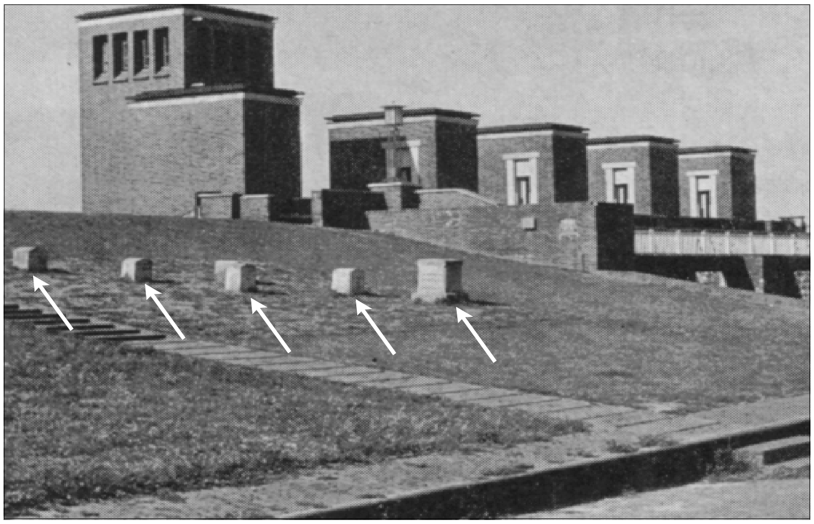


Figure 13. Benchmarks (↑) of historical storm surge peaks at Dangast, Jade Bay

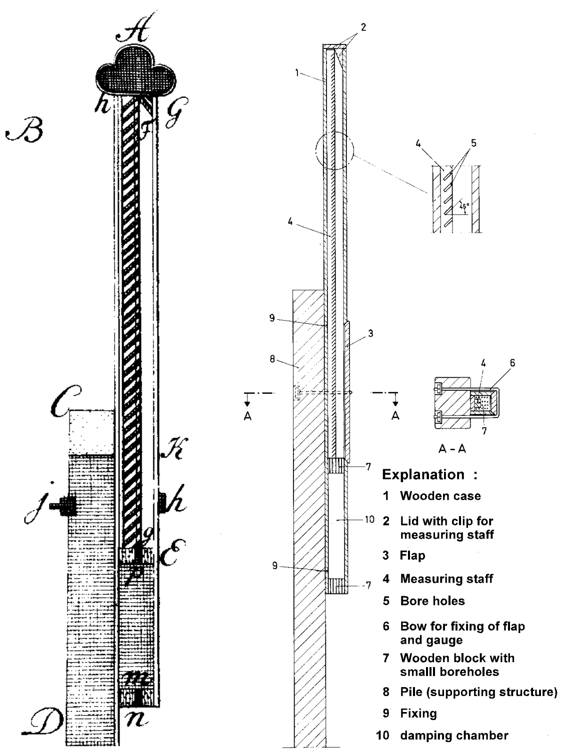


Figure 14. Gauge for the measurement of storm surge peak levels by BRAHMS [1754, 1757]; original drawing left, reconstruction by LUCK & NIEMEYER [1980] right

Waves. In order to consider wave attack for proper dyke design BRAHMS [1754, 1757] observed the nearshore wave climate on tidal flats and supratidal salt marshes close to the coastline. He related wave heights and water depths by

$$H = \sqrt{h}$$

in order to have a general basis for the derivation of local wave heights along all the coastal stretches where dykes had to be designed. It is nowadays well established knowledge that wave heights at Wadden Sea coasts correlate strongly with local water depths [FÜHRBÖTER 1974; SIEFERT 1974; NIEMEYER 1979, 1983]: the basic approach by BRAHMS [1754, 1757] has been modified, but is still not far beyond reality (Fig. 15).

The interactions of waves and coastal morphology in Wadden Sea areas has been quantitatively evaluated by KRÜGER [1911]: The width of intertidal areas is essentially depending on wave energy dissipation. Therefore those in the shelter of barrier islands are remarkably smaller than those positioned in estuarine areas unsheltered against offshore waves. At coasts with island sheltered flats, waves establish a gradient from the tidal inlets where the waves from offshore enter along

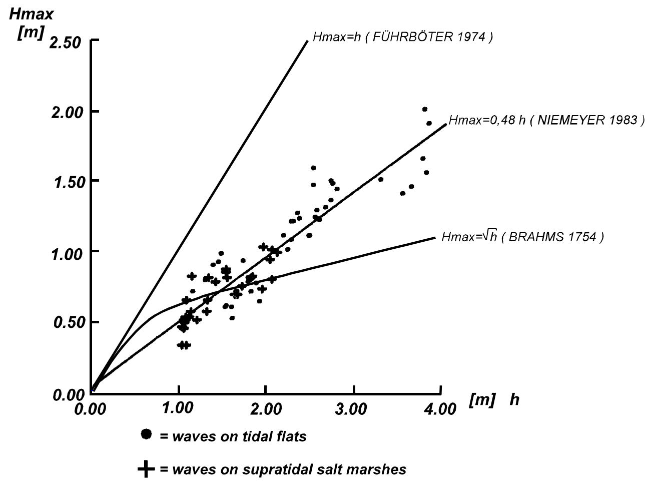


Figure 15. Field data of wave height/water depth relation on East Frisian tidal flats and salt marshes [NIEMEYER 1983] in comparison with the relation developed by BRAHMS [1754] from visual observation

their travel distance: increasing flat levels until the growth of supratidal salt marshes at marshes at sheltered coastal stretches and a tendency from coarser sand to fine silt with significant organic content. KRÜGER [1911] stressed the consequences for mainland protection: strongest wave attack in the vicinity of the inlets and the importance of islands for coastal protection on the sheltered coastal stretches of the mainland. He opposed with his arguments against a recommendation of FÜLSCHER [1905], a high ranking civil servant in the responsible ministry in Berlin, who argued islands were of no benefit for mainland protection and any efforts for their protection should be limited to those few ones which had already then sufficient economical values on their own. KRÜGER's sound description of these complex interactive processes were only based on observations with the human eye and the analysis of mid-term morphological changes. They all have meanwhile been verified by intensive field measurements [NIEMEYER 1979, 1983], evaluation of historical morphological situations [NIEMEYER 1995] and mathematical modeling [NIEMEYER et al. 1995a].

Wave-induced currents. The wave-induced current system on beaches is of high importance for local sediment balance. Intensive knowledge about this driving forces for transport processes on beaches has been gained since the end of World War II, particularly pioneered by the reports of MUNK [1949] on wave set-up, of PUTNAM et al. [1949] on longshore currents, being stimulated by observations of that phenomena made during exercises for allied landing operations of World War II, and of SHEPARD & INMAN [1951] on nearshore circulation. The transport processes due to wave-induced currents have considerable importance for the stability of beaches at the German North Sea coast and particularly on those of the East and North Frisian barrier islands which are partly seriously suffering from structural erosion. Therefore, the scientific findings of their American colleagues were eagerly adapted by German coastal engineers like e. g. LAMPRECHT [1955] who did intensive investigations on beach processes on the North Frisian island of Sylt. He as well as numerous contemporaries and successors were not aware that these phenomena had already been detected and published by predecessors in their own country: HAGEN [1863] described the set-up and undertow which he observed at the Baltic coast which will be discussed in the following chapter. KRÜGER [1911] was beside other obligations also in charge of the shoreline protection of the East Frisian island of Wangeroog and made enormous and successful efforts to understand the processes leading to beach erosion. One of the numerous substantial results is a report which highlights impressively longshore currents on the beaches of the island of Wangeroog: "Due to surfing, the waves drive the water alongshore and generate close to the shore a current which moves the sand being suspended by the breaking waves. During northwestern wind of Beaufort 6 during flood I observed between breaker line and beach a downward racing current in a water depth of 60 cm alongshore in eastern direction. It was impossible for me to keep kneeling on the spot, I was driven away. About 100 m offshore was another strong alongshore current. I did not go further offshore. It is reasonable that the current's strength will decrease further offshore. This assumption is verified by experience gained by landing on the beach across the surf zone. Offshore off the surf zone the current is the same as during calm weather. Between breaker line and beach the boat is driven into the same direction as that one of the incedenting waves. If there is more than one breaker zone a strong current appears at least landward of the central one.” Though this observation does not deliver a sound basis of transferrable knowledge according to present standards it does convey an enormous capability of intuitive feeling for natural processes and the target-oriented pragmatic approach to realized problems becomes evident. In recent years more knowledge has become available, particular by intensive prototype investigations. Pioneering efforts in this field have been carried out in recent years on the beaches of the island of Sylt [DETTE & FÜHRBÖTER 1975] stimulating a couple of successful site investigations on the subject of wave-induced nearshore circulation since then.

Ebb delta migration and sediment balance. The bypassing of the tidal inlets by longshore drift in the formations of ebb deltas is of high importance for the sediment balance of the beaches of the downdrift barrier island [GAYE & WALTHER 1935]. Updrift of the landfall of the ebb delta’s shoals occurs structural erosion requiring engineering countermeasures. Furthermore, the supply with sediment in the landfall area and downdrift depends on the successive welding of shoals. Therefore intermediate erosion may take place in the periods between and particularly immediately before the landfall [KRÜGER 1911, 1937]. This knowledge is very useful for the evaluation of the necessity of countermeasures or of their appropriateness. A thoroughful analysis and forecasting of these processes have been carried out by HOMEIER & LUCK [1971] and performed the basis for the abandonment of the implementation of costly solid structures (Fig. 16).

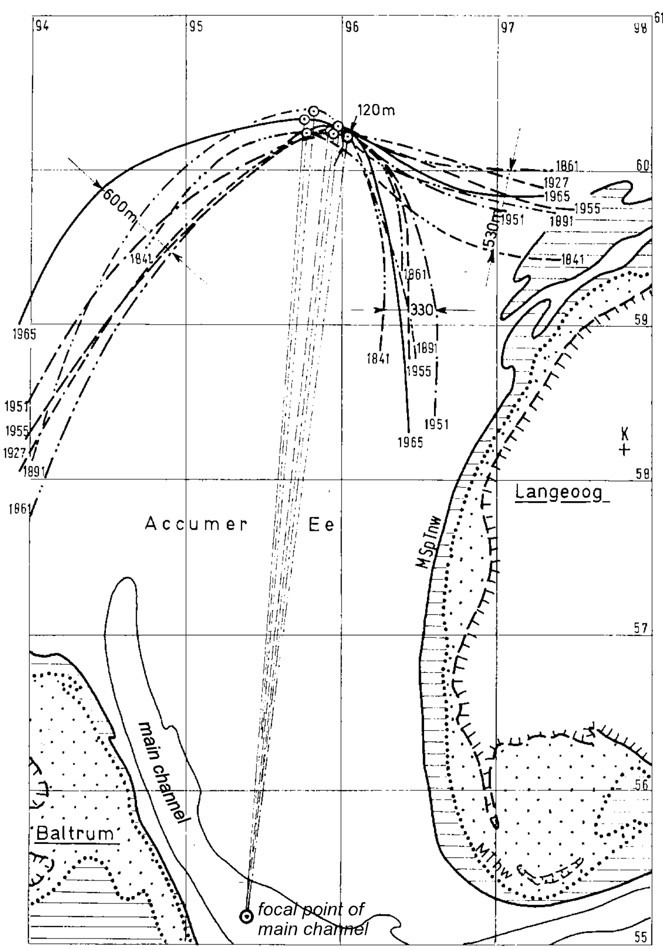


Figure 16. Mean pathways of migration of ebb delta shoals of the tidal inlet Accumer Ee and resulting sediment transport due to distinct landfall positions between 1841 and 1965 [HOMEIER & LUCK 1971]

Erosion and regeneration of beaches and dunes. Storm surges cause often severe erosion of dunes and also of beaches, particularly in front of revetments and seawalls due to scouring. The impression as well as beach profiles leveled immediately after such an event has provoked often countermeasures like beach fills in areas with structural erosion. The remaining buffer was regarded as insufficient with respect to safety. After a series of severe storm surges in 1973 and 1976 HOMEIER [1976] analyzed levelings of dunes and beaches suffering from structural erosion on East Frisian islands gained before, immediately after, and again weeks after the storm surges. He concluded that after a few weeks a regeneration of the beaches had taken places due to hydrodynamical transport. Dunes regenerated if the width of the dry beach is sufficient for wind transport capacity within months. In fact, the well-known phenomenon of winter and summer profiles of beaches and dunes is also valid for shorelines with structural erosion. It has been proven for a number of later storm surges and could also be explained for beaches by the erosional effects of undertows and the regenerating onshore transport due to nonlinear drift effects of steep waves [NIEMEYER 1991a].

Long-term morphological development. Historical maps - mostly for nautical purposes - give an impression of the changes the coast has experienced in the course of the last centuries. Additionally descriptions of the coastal ways called 'sailing handbooks' deliver information on earlier stages of coastal development. Though in nearly all cases not to the same extent reliable as present sources they could perform a basis for deeper insights into long-term processes still governing the present morphological development of the coasts, particularly if a composition of these sources can be justified by still available verification points like then used landmarks as e. g. churches. KRÜGER [1911, 1922] and PLATE [1927] based their impacts for the correction of the Jade and the Outer Weser: they took the anticipated morphological development of the regime into consideration in order to keep their impacts in tune with the tendency of continuing morphodynamical development. The reconstruction of former coastlines, their retreat and subsequent reclamation at the North Sea coast of Schleswig-Holstein has been reconstructed for the period between 1643 and 1648 and compared with the situation of 1888 by GEERZ [KREY 1918]. Particularly for the purposes of coastal protection all available sources for the Lower Saxonian North Sea coast have been evaluated by HOMEIER [1962, 1965, 1969] after World War II. He reconstructed the data from historical sea and land charts and many kinds of additional sources and related them to temporary geographical grids. Very valuable were particularly in the cases of medieval storm surge bays and their reclamation the geological investigations of SCHÜTTE [1908] and WILDVANG [1915]. As a still very useful spin-off HOMEIER [1962] elaborated 15 maps with documentary supplements describing his sources and their use covering the whole coast of Lower Saxony for the situation of 1650, 1750, 1860 and 1960. Each map incorporates the mean high and low water line, positions of the dune foot, border of supratidal salt marshes and dykes. The products of HOMEIER's work of about 30 years has, for example, formed a basis for numerous coastal engineering case studies at the coast of Lower Saxony and furthermore for specific morphodynamical investigations such as the model of tidal inlet migration by LUCK [1977] or the parametrization of long-term morphodynamical development by NIEMEYER [1995].

PROTECTION OF THE MAINLAND COASTS

The lowlands at the German North Sea coast are mainly marshlands developed as deposits of marine sediments settling during phases of flooding from the sea. Beside a few small stretches consisting of high-leveled pleistocene material the coastal areas are therefore below storm surge level and sometimes even below ordinary high tide. Since about 1000 A. D. dykes perform the protection of these areas against inundation. Their dimensions have increased since then (Fig. 17). Early adaptions have carried out due to disastrous experience by the coastal community but since BRAHMS [1754, 1757] an engineering approach has replaced more and more the simple response on catastrophic events in order to prevent another failure of the dykes by planning in advance. BRAHMS was elected as 'dyke judge' one year after the disastrous storm surge of 1717 with thousands of victims and remained in charge until 1752. The state of the art he documented in his 'basic art of dyke construction and hydraulic engineering' [1754, 1757] was unique and far ahead of his contemporaries. In comparison with the present state of knowledge it is evident that he already recognized nearly all key problems and delivered solutions which still must be regarded as breakpathing. To a certain extent this might be an explanation for the large gap between his findings and the continuation in modern German coastal engineering.

Design crest height for sea dykes. The handbook of BRAHMS [1754, 1757] is the oldest known document containing a guide line for the quantitative determination of the crest height of a dyke. His approach to summarize design water level and design wave run-up seems to be simple referring to present knowledge. But he gives further recommendations how to evaluate or estimate these parameters and how to increase the database for their determination.

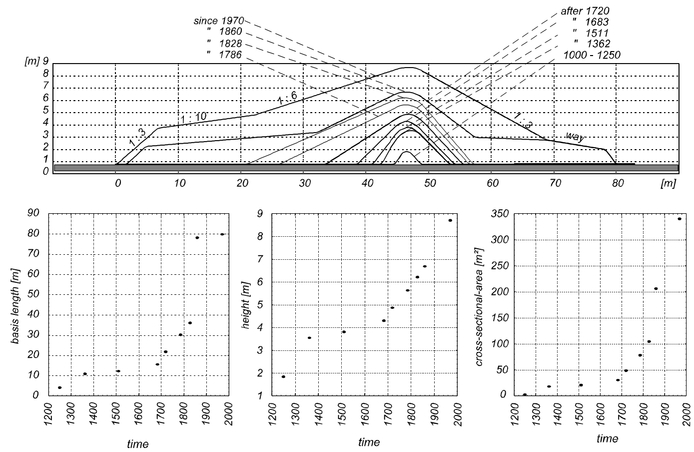


Figure 17. Development of sea dyke profiles at the west coast of the Butjadingen peninsula between the beginning about 1000 and 1972 A. D.; cross-sections adapted from NIEDERSÄCHSISCHE HAUPTDEICHVERBÄNDE [1988]

The determination of the design water level by BRAHMS [1754, 1757] was still based on already observed storm surge levels; a future increase was not anticipated. The major improvements were first his recommendation to gather the necessary basic data by measurements in all coastal areas by aid of his gauge (Fig. 14) and second his instruction to consider the subsidence of the construction in respect of the soft soil beneath the dyke. This approach remained state of the art until as well the discussion about coastal subsidence or respectively sea-level rise as the lessons taken from the disastrous storm surge of 1953 in the neighbored Netherlands led to procedures including a determined measure for future safety in respect of sea-level rise [HUNDT 1954; PETERSEN 1955; LÜDERS 1957] which was improved after the storm surge of February 1962 [LÜDERS et al. 1962; METZKES 1966] with a death toll of more than 300 people. At the North Sea coasts the design water level for sea dykes is still determined on the basis of these procedures. The specific demands in tidal estuaries have been met by the product of an interstate working group on behalf of the Elbe estuary: the design water level is evaluated by superposition of mean high tide, secular rise and the time series of surge set-up at the estuarine entrance [SIEFERT et al. 1988].

BRAHMS must have been aware that his database and theoretical basis were inadequate for derivating a generally applicable formula for the determination of wave run-up. Therefore he recommended first to level benchmarks of flotsam after storm surges marking the highest wave run-up above the still water level. About 200 years later a group of experts repeated his suggestion for getting a sound database [BOTHMANN et al. 1955]. Unfortunately these recommendations were only carried out rarely or the data are lost. Systematic measurements of benchmarks of flotsam are only available from recent storm surges since the 1970s and only a few ones from earlier times. Analysis of these data is carried out in the framework of a research project of the German Committee on Coastal Engineering Research (KFKI) in order to deliver information on the variation of wave run-up along the coastline and furthermore to provide a basis for the derivation of design wave run-up by extrapolation [NIEMEYER et al. 1995b]. Furthermore BRAHMS [1754] determined for specific boundary conditions the dimensions of a dyke. Implicitly these figures include also a relation between wave height and wave run-up [LUCK & NIEMEYER 1980]:

$$R = c \cdot H \cdot \tan \alpha$$

with a constant value of 10,33. The formula turns out to be rather similar to that one published by WASSING [1957] which is well known as the DELFT formula with a constant value of c = 8.

Functional design of sea dykes. The dykes at the Wadden Sea coasts consist of clay and nowadays of a sand core covered with a clay layer. The quality of the clay is of high importance for the capability of the structure to withstand hydrodynamical impacts without or with acceptable damages in respect of safety. But even for clay of good quality there are limitations of resistance. Therefore, the shaping of dykes should take into consideration both the quality of the clay and the hydrodynamical impacts. In order to keep the overtopping of waves he recommended to flatten the inner slopes up to 1:2 and more in respect of clay quality in order to remain stable if waves overtop. BRAHMS was convinced that wave overtopping had to be taken into consideration in order to avoid a failure of the dyke. This basic design philosophy was accepted by coastal engineers in the middle of the last century but rejected in the beginning of this century [PETERSEN 1954]. Basing on investigations in the Netherlands and particularly on the research results of HUNDT [1954] the overtopping of waves was again regarded as inevitable to be responded by a suitable functional design [PETERSEN 1954]. BRAHMS suggested as well a convex shape of the outer dyke profile in order to place the flattest slopes in the place of the design water level and accompanying wave attack (Fig. 18). HENSEN [1955] carried out hydraulic model tests leading him to a general recommendation to replace the then applied concave by a convex profile in order to reduce wave run-up for higher storm surge levels. FÜHRBÖTER [1991] supported that suggestion because a mild slope would decrease the wave impacts on the structure.

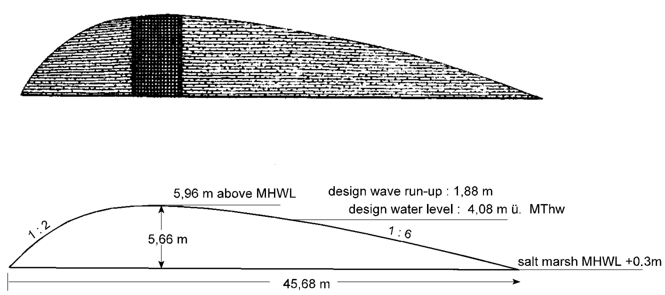


Figure 18. Sea dyke design by BRAHMS [1754]; original drawing above, reconstruction by LUCK & NIEMEYER [1980] down

Cost-benefit analysis. The members of the self-ruling communities being responsible for coastal protection had as well to raise money as to invest working capacity both for maintenance and construction of dykes. Therefore, they were reluctant to follow the ideas of BRAHMS [1754, 1757] which were revolutionary and required enormous higher efforts than the conventional state of the art. The argument of increased safety against disastrous flooding seemed to be insufficient to convince the members of his community though the lessons of the storm surge of 1717 with a death toll of more than 6800 people in the coastal areas between Ems and Weser [ARENDS 1833] were still very recent. BRAHMS [1754, 1757] evaluated first a comparison of different types for the dykes which had to be newly constructed after total damages of the storm surge of 1717 and the succeeding ones. His aim was to prove by detailed figures and costs that the set up of dykes with flatter slopes would not only increase safety but also decrease enormously efforts for maintenance. This kind of evaluation in respect of both economical and safety targets is nowadays called ‘optimization’. A very recent example for distinct types of modern sea dykes has been carried out by KRAMER [1977]. The members of the community suffered particularly from the economical losses due to the disastrous effects of the flooding after the storm surges and tried therefore to keep the burden of dyke maintenance as low as possible and were not enthusiastic about the strengthening of existing dykes. BRAHMS [1754, 1757] compared losses due to flooding with the earnings from a successfully protected landscape and the costs of dyke construction which is in terms of our time a typical cost-benefit analysis. Obviously BRAHMS was confronted with a problem being evident for all generation of coastal engineers, particularly in periods of social shortage of money. A later example is given by KREY [1918] who argued that the costs of coastal protection could not only be related to the taxes paid by the landowners of the coastal areas; the economical value of the coastal areas and furthermore the economical spin off for trade and employment should be taken into consideration. Both authors try to convince their audience by rational argumentation appealing to economical aims of human beings. Their approach implies the admission that coastal protection could not be regarded as a purpose on its own but does need social acceptance. Though the figures of BRAHMS are estimated the method is comparable to modern studies dealing with the economic efficiency of coastal protection in respect of the guarded values like that one of KLAUS & SCHMIDTKE [1990] carried out recently for a landscape at the German North Sea coast as a model case.

Land reclamation. The medieval storm surges caused enormous land losses at the Wadden Sea coasts. They enforced an enormous coastal retreat and created and enlarged numerous storm surge bays between Den Helder and the peninsula of Eiderstedt [WOEBCKEN 1924]. In North Frisia continued their impacts the creation of islands from remnants of the former mainland [KREY 1918; HEISER 1933]. In most cases their erosive forces had been very efficient, because the then existing soil of e. g. peat had only low resistance. Particularly the developing large bays got geometrical extensions which were unbalanced with the acting hydrodynamical boundary conditions leading particularly close to the shorelines to a subsequent silting up [NIEMEYER 1991b]. The coastal inhabitants supported this process by the land reclamation works in order to accelerate the growth of salt marshes which were afterwards impoldered. Step by step the coastlines were moved back seaward and the areas of most the storm surge bays were reduced dramatically and only remnants of a few have remained like Dollart, Ley and Jade Bay [HOMEIER 1969] and Dithmarschen Bay [HEISER 1933]. In Schleswig-Holstein the coastline was also moved back towards the sea and in North Frisia even the remaining islands have been enlarged by land reclamation (Fig. 19) [KREY 1918; HEISER 1933]. The reclaimed areas had improved enormously in comparison with the eroded soil from an agricultural point of view. The marine sediments performing the salt marshes delivered after impoldering farmland of very high quality. Numerous court documents of the last centuries report of conflicts between coastal inhabitants on behalf of the rights to reclaim land or the ownership. At the Frisian coast those conflicts initialized even civil wars between the then ruling chiefs. In respect of coastal zone management land reclamation had higher priority than e. g. inland drainage and navigation enforced the erection of numerous new drainage sluices and the cutting off from the access to the sea of historic ports at the Wadden Sea [NIEMEYER 1991b]. Since those days the Wadden Sea coast has experienced a dramatic change of its shape by both natural processes and human interference. There is an aphorism in Frisia referring to selfconfidence of the coastal community: ‘God created the sea, the Frisians the coast.’ The heritage of our ancestors’ efforts are not only the reclaimed landscapes but also unforeseen consequences: The partial enclosures of reclaimed salt marshes have partly created long-term morphodynamical processes being still of importance for present coastal engineering. E.g. the subcompartments of the intake area of the tidal inlet Osterems in East Frisia have changed both their areal extensions and tidal prisms due to the silting up and land reclamation in the Ley Bay. In consequence the

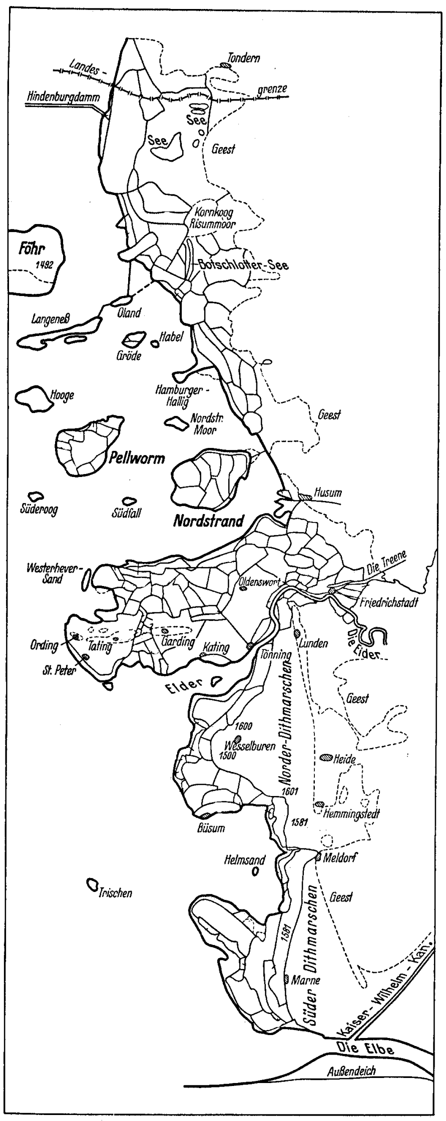


Figure 19. Land reclamation at the west coast of Schleswig-Holstein since 897 A.D. [HEISER 1933]

watersheds shifted and effected first a migration of the main channel of the tidal inlet counterdirectional to prevailing drift leading to erosion at the eastern beaches and dunes of the updrift island of Borkum. Second the tidal inlets migrated in response to the updrift reduction of their intake areas downdrift provoking structural erosion on the beaches of the downdrift islands [NIEMEYER 1995]. The traditional coastal management policy to enclose former storm surge bays has been totally changed in recent years: the preservation of this ecologically unique areas has nowadays priority: the planned enclosure of the Ley Bay in East Frisia as a coastal protection measure was abandoned and replaced by an alternative solving the problems of coastal protection, inland drainage, navigability and nature preservation [NIEMEYER 1991b].

The purposes of land reclamation at the Wadden Sea coasts have changed in the course of the last decades. Referring to national economy the gaining of additional farmland has become not only less attractive, it is counterproductive in respect of a total balance. But still land reclamation has been continued to a lesser extent. First the aim was to gain salt marshes serving coastal protection purposes as already explained by BRAHMS [1754, 1757]: dykes with a supratidal salt marsh in their apron do not need heavy solid revetments in their lower parts because the regular interaction with ordinary tides does not take place [HEISER 1933]. After a failure of the dyke repair will also be easier: there is no in- and outflow during ordinary tides. The salt marshes perform a reservoir of clay and saltwater-resistant grass sods being useful for repair purposes in the case of damages and emergency [ERCHINGER 1970]. The assumption wave attack on dykes landward of salt marshes would be reduced due to damping or even breaking [BRAHMS 1754, 1757; ERCHINGER 1970] has been discovered as a misunderstanding of interactions between waves and morphology in Wadden Sea areas [NIEMEYER 1979, 1983, 1995]. The dedication of salt marshes as part of the coastal protection system allowed still their agricultural use. Nowadays these areas are regarded as ecologically unique areas: they became parts of the recently performed National Parks Wadden Sea which implies changes in comparison to traditional use of these areas: prohibition or significant reduction of agricultural use and the limitation of reclamation structures for purposes of salt marsh preservation.

Storm surge barriers. Problems of inland drainage and coastal protection in the upper region of the Eider estuary led to the solution of a tidal barrier which was erected in 1936. The aims were first to avoid further strengthening of dykes on a weak soil which was regarded as difficult and costly. Second the inland drainage in the upper region was independent from tidal water level variations which particularly during storm surges provoked often inland flooding because no or only insufficient discharge due to hydraulic gradients could take place. But the barrier caused also a remarkable reduction of the tidal volume leading to an enormous downstream sedimentation which again hampered inland drainage [WEINHOLDT & BAHR 1952]. The unsolved problems required another solution [ROHDE & TIMON 1967] leading to the construction of storm surge barrier at the estuarine mouth after 1972. The experience with the Eider tidal barrier led to a new concept of a storm surge barrier. The catchment area of ordinary tides was not reduced, only tides with a set-up exceeding a threshold level were cut off by closing the gates. This concept was firstly realized on a small scale at the Lühe, a tributary of the Elbe estuary, in 1939 and second on a larger scale for the storm surge barrier of the Leda in East Frisia, a tributary of the Ems-Dollart estuary in 1952 [LIESE 1956]. Particularly after the storm surge of February 1962 the erection of storm surge barriers at the entrance of tidal rivers was regarded both economical and technical advantageous in comparison to strengthening all the dykes along the embankment of the rivers: the soil was often very weak requiring technically complicated and costly measures to create stable dykes. In total more than twenty have been built, the largest is that one at the mouth of the Eider estuary. An overview on the then existing storm surge barriers at the German North Sea coast was elaborated by GÄTJEN [1979].

Shore protection on islands

The islands at the German North Sea coast have experienced changes in their shape and partly also in their position: The sea borne East Frisian Islands have been reshaped by large-scale morphodynamical processes, particularly inlet and ebb delta migration [HOMEIER 1962; NIEMEYER 1995]. The North Frisian Islands, as remnants of former mainland, have kept their position but experienced enormous land losses which could only gained back partly by reclamation [KREY 1918; HEISER 1933]. In this chapter shoreline protection on islands or parts of islands consisting of lowland areas with cohesive holocene marine sediments is not discussed because the protection against flooding is carried out there by construction of dykes following the same rules as on the mainland. As well the specific situation on the small marshy islets, the 'Halligen', where the protection against flooding is gained by the adaption of artificial earth hills, the 'Warften', will not be part of this contribution. We focus on shoreline protection of the sandy coasts of the East Frisian Islands and those North Frisian Islands being positioned on a pleistocene core.

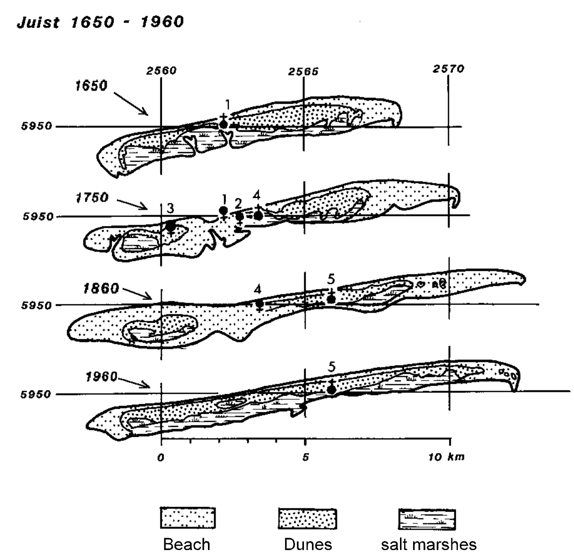
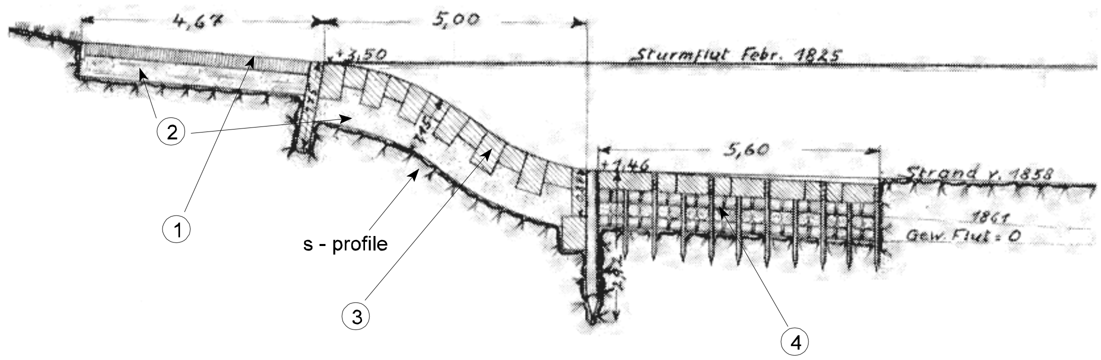


Figure 20. Adaption of settlements on islands to shoreline migration: Island of Juist/East Frisia; the numbers 1 - 4 mark churches built between 1300 and 1717 and abandoned between 1651 and 1779, no. 5 has been built 1779 in the center of the present main settlement on the island [HOMEIER 1962; STREIF 1990]

Looking back the abandoned position of, e. g., churches on the islands make evident that the inhabitants had no possibility beside retreat from areas endangered from the sea after severe structural erosion of beaches and subsequently dunes (Fig. 20). There were no tools available to fight structural erosion on sandy coasts and even if the substance of human goods would have been insufficient to justify the necessary costly impacts. Tourism which increased significantly step by step on all islands after the establishment of the island of Norderney as an official holiday resort in 1798 led to investments and properties of much higher values than before on the islands. Both the owners and the government(s) had as well a motivation as a justification for interfering into the processes endangering infrastructure and properties being worth to preserve even by significant costs. In the middle of the last century continuing downdrift inlet migration caused structural erosion of beaches and dunes at the western spit of the island of Norderney resulting in remarkable shoreline retreat [THILO & KURZAK 1949; HOMEIER 1962; LUCK 1977] which endangered the place, being then also the summer residence of the kingdom of Hannover. In 1858 the chief engineer for hydraulic engineering of the Province East Frisia TOLLE [1864] started the realization of his plans to keep the island's shoreline: the construction of dune revetments and beach groynes first as solid structures at sandy German North Sea coasts (Fig. 21). The introduction of these new construction material and method must have been initialized by the failure of the then traditional protection measures: Bush fences, wooden pile walls and groynes consisting of fascines fixed by wooden piles. After the 2nd World War the responsible administrations for the East Frisian Islands authorized experienced coastal engineers to perform critical state of the art reviews on the shoreline protection on the islands [LUCK 1975]: KATTENBUSCH (Borkum); THILO (Juist, Norderney, Baltrum, Langeoog, Spiekeroog); LÜDERS & WILLECKE (Wangerooge). Unfortunately these reports have remained unpublished though they served as a very valuable basis for both conserving gained knowledge and further improvement of engineering measures. The products of these reports have been used in the framework of published reports to which is here referred to.



1: clinker pavement; 2: concrete; 3: freestone quader; 4: fascine mattresses with wooden piles

Figure 21. Early dune revetment on the island of Norderney in 1858 with the levels of MHW and of the storm surge of February 1825; beach levels (Strand) of the year of implementation and of 1861 [TOLLE 1864]

Revetments and seawalls. After their introduction revetments came widely in use and were also built on other islands with eroding beaches. The design philosophy changed. The s-shaped profile introduced by TOLLE [1864] was replaced by structures with steeper slopes with the aim to 'push the waves back' [FÜLSCHER 1905]. Already KREY [1906] as well as later HEISER [1932], who favored the s-shaped profile, argued against that opinion. At least a flatter slope was introduced in order to reduce scouring at the toe. In 1936 the first revetment with a slope of 1:4 was built on the island of Sylt being still the prototype of revetments built since then. Design and dimensioning of revetments and seawalls is still widely empirical orientated at damage and survival of already existing structures. Though these structures are very costly the demand for a design procedure has not been very strict, because new constructions of revetments and seawalls have only taken place since the 50s of this century if existing structures must be replaced, in most cases immediately after damages did occur. Further extensions of existing structures for the adaption to eroding beaches are no longer carried out since the more economical tool of artificial beach nourishment is available [GAYE et al. 1952]. Nowadays the question of acceptable wave loads on existing revetments and seawalls is again actual at regularly nourished beaches. In order to determine the necessity of return periods of artificial shoreface or beach nourishments a correlation with the limitation of lowering of beach levels and resulting wave action in front of the structures is necessary if the major purpose of the beach fill is a limitation of wave attack on the structures and of resulting damages [NIEMEYER et al. 1995c]. The revetments fulfilled in nearly all cases their major aim but could not stop beach erosion. In cases of structural erosions extension became necessary in order to prevent damages or even the collapse of the structures. Toe protection and continuing adaption to the

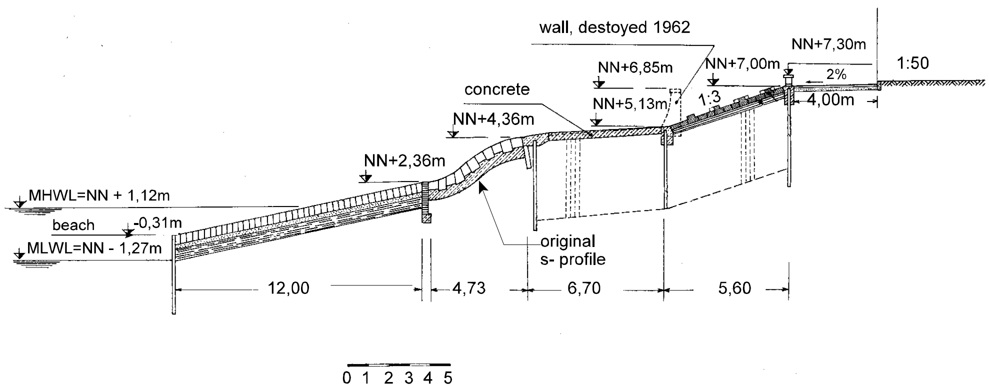


Figure 22. Present Seawall on the island of Norderney extended from the early dune revetment with its s-shaped free stone quader core

lowering levels of the eroding beaches must be carried out. The propagation of higher waves due to enlarged water depths in front of the revetment required also extensions in the upper part including a wide berm [HEISER 1932] in order to prevent to large overtopping volumes creating a return flow beneath the structure leading to damages or even to a total loss of stability [RAGUTZKI 1976]. The initial revetments migrated therefore in the course of the time to seawalls in which the initial structure was still as a small part existing if not destroyed by wave action (Fig. 22). The existing revetments and seawalls have fulfilled their major aim to keep the shoreline and to prevent a flooding of the hinterland. In cases of structural erosion further extensions are no longer economical in comparison with artificial nourishments [GAYE et al. 1952]. But up to now no revetment or seawall has been abandoned in favor of a nourishment: they are maintained and have even been reconstructed if necessary.

Groynes. The first groynes had the aim to prevent erosion of beaches. Already in the 19th century their use was discussed though nobody worked on that problem basically beside HAGEN [1863], who did hydraulic model tests in order to study their effectiveness before implementation. In cases of structural erosion groynes had limited success: At the most they decelerated beach erosion due to longshore currents but failed to stop coastal retreat. The lowering of the beaches made them more vulnerable against hydrodynamical impacts. There were more frequent damages and in some cases their stability was endangered. In order to prevent their collapse numerous groynes have been adapted to the changing morphological boundary conditions (Fig. 23). Most variations in groyne design were targeted at construction methods and the longevity of material but not at their functional purposes [LORENZEN 1954]. The demand of PETERSEN [1961] to carry out investigations delivering more detailed information is still valid. A remarkable approach has been carried out by KRAATZ [1966] who tried to shape groynes in respect of dominant wave climate, particular to reduce beach erosion at the central shore of the island of Sylt. His design was not carried out because the control of beach erosion by an artificial beach nourishment shaped like a groyne was regarded as the most effective tool for that area [FÜHRBÖTER et al. 1974]. As well as the existing revetments and seawalls most of the groynes are maintained and a few ones have been added to the existing scheme, e. g. on the island of Borkum [ASTER et al. 1990]. Particular in the vicinity of migrating tidal inlets the groynes on the beach had no effect to decelerate or even to stop that process. Particularly on the island of Norderney the existing protection structures and the infrastructure in the western part was endangered. Intensive hydrodynamical preinvestigations [GARSCHINA & PANSE 1898] made evident that the existing current

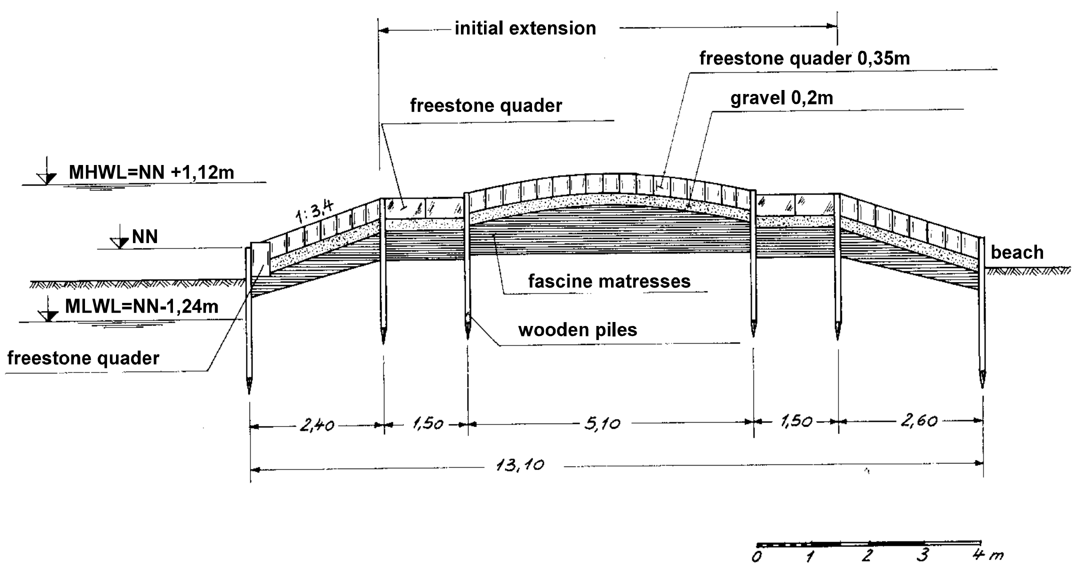


Figure 23. Cross-section of a beach groyne, island of Norderney; initial extension and adaption to lowering beach level

regime of the tidal basin generated a further downdrift migration of the tidal inlet. The chosen response to that development were extensions of the groynes on the beaches close to the inlet's main channel into its steep slope which was covered and successfully fixed. This solution was repeated at other places with comparable boundary conditions in order to stop there also tidal inlet migration and successing shore erosion on the downdrift island. Four of the six East Frisian tidal inlets have been fixed by structures of this type which are called 'stream groynes' in contrast to 'beach groynes' in German professional usage. LUCK [1975] complained that TOLLE had not obtained permission to erect stream groynes at the tidal inlet Norderneyer Seegat. A successful implementation of structures of that type would have provided the next generation of coastal engineers with the heritage of a wider beach than existing nowadays: a more convenient platform for effective beach nourishments. Already KREY [1906] had pointed out that, if necessary, stream groynes should be built as early as possible in order to avoid more costly construction works on steepening slopes.

Large scale groynes. A specific version of the groyne-type has been carried out in the East Frisian tidal inlet Harle: a large-scale structure with a length of about 1460 m. Its construction has not been finished in the course of the 2nd World War. Therefore, the crest height did not reach the design level fairly above mean high tide but remained at mean low tide and is nowadays partly even lower. Though never finished, its effectiveness was already proved a few years later [LÜDERS 1952]. This structure was not only aimed at prevention of further downdrift migration of the inlet's deep channel. It should and has also closed a newly generating secondary channel which was expected to take over the function of the inlet's main channel without any intervention. Furthermore the establishment of the structure should restore the morphodynamical boundary conditions of nearly 100 years ago which were more favorable in respect of sediment supply of the northwestern beaches of the island of Wangeroog (Fig. 24). A similar construction was also discussed after the war to solve the structural problems of the western and northwestern beaches of the island of Norderney but was abandoned because of the high costs and the high technical risks related to crossing the inlet's main channel [KURZAK et al. 1949; THILO & KURZAK 1952]. A beach nourishment was chosen in favor of such a large-scale solution [GAYE et al. 1952].

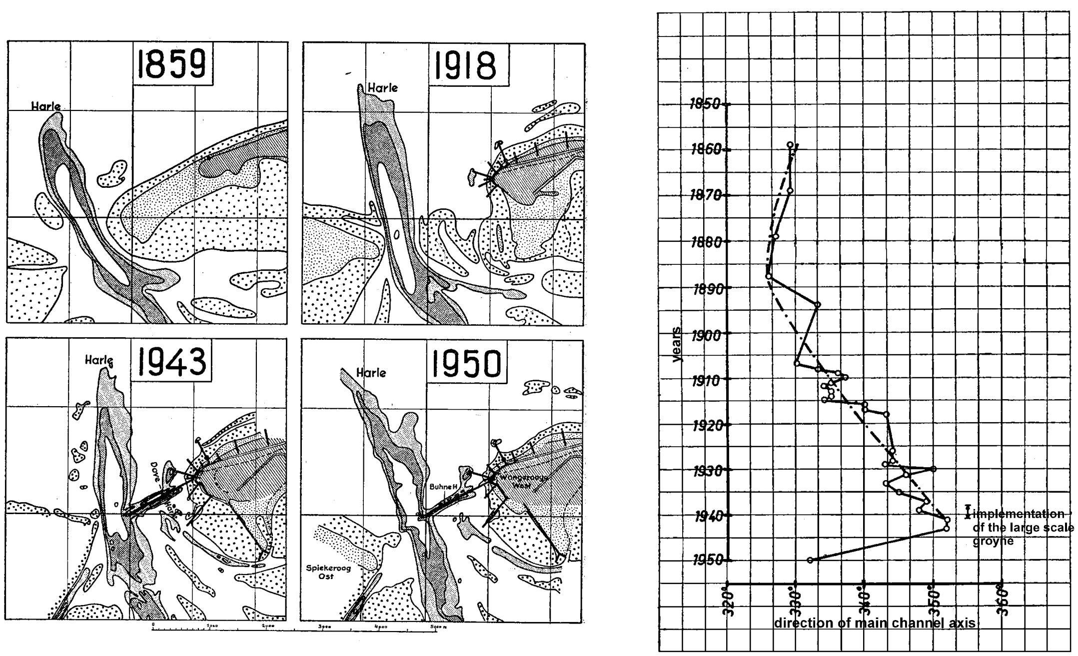


Figure 24. Clockwise migration of the deep channel of the tidal inlet Harle and its shifting backward after the implementation of the large scale groyne H [LÜDERS 1952]

Artificial beach and shoreface nourishments. The first beach nourishment at the German coasts was been carried out on the island of Norderney following recommendation of an expert group [GAYE et al. 1952] on the basis of intensive investigations carried out previously by the Coastal Research Station [KURZAK et al. 1949; THILO & KURZAK 1952]. Since then a remarkable number of nourishment projects have been carried out, particularly on the islands of Norderney [KUNZ 1991] and Sylt [ALW 1984], but also in other places. A very successful application has taken place on the island of Langeoog. Basing on thoroughful investigations on cyclic changes in the welding of shoals at distinct beach areas of the island (Fig. 16) [HOMEIER & LUCK 1971] the planned very costly implementation of revetments and groynes with probable necessary extensions due to their interference into the beach processes could be avoided by the combined application of a beach nourishment being armored by rubber pipes (Fig. 25) [LÜDERS et al. 1972]. Specific solutions of nourishments in respect of local boundary conditions have been discussed and sometimes also carried out: E. g. KRAMER [1960] recommended to counterbalance the structural erosion on the island of Norderney by continuous beach fill instead of repeated concentrated nourishments with return periods of a couple of years; on the island of Sylt a groyne shaped nourishment was carried out in order to feeder the adjacent beaches [FÜHRBÖTER et al. 1974]; later there the beach fills were carried out as deposits in front of the eroding dunes (Fig. 26) [ALW 1984]; on the island of Langeoog the welding process of shoals was accelerated by the closure of the gully in front of the beach by a fill [ERCHINGER 1985]. Already GAYE & WALTHER [1935] mentioned the positive effects on beach morphology on the island of Norderney achieved by dumping of suitable dredging material in their vicinity in the years between 1899 and 1909. This must have been the first nourishment of the shoreface at the German North Sea coast. Nearly one century later again the idea of a shoreface nourishment was renewed: A combined shoreface and beach nourishment was carried out on the island of Norderney. The major aim was to use the deposit on the shoreface as a feeder berm for the intertidal beach [NIEMEYER 1991a]. In order to gain a deeper insight into the governing morphodynamical processes a joint European project was established looking also after the effectiveness of shoreface nourishments in the neighbor countries Denmark and the Netherlands [NIEMEYER et al. 1995c].

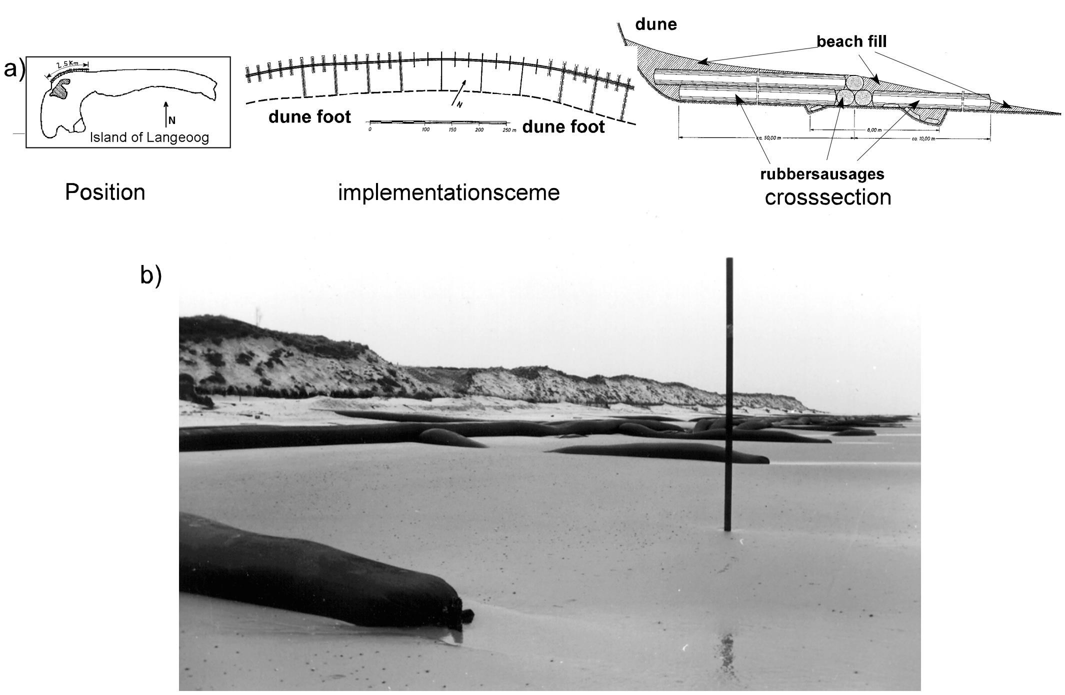


Figure 25. a) Combination of beach nourishment and rubber tubes for stabilization as temporary dune protection on the island of Langeoog
b)Beach nourishment and rubber tubes after implementation on the island of Langeoog

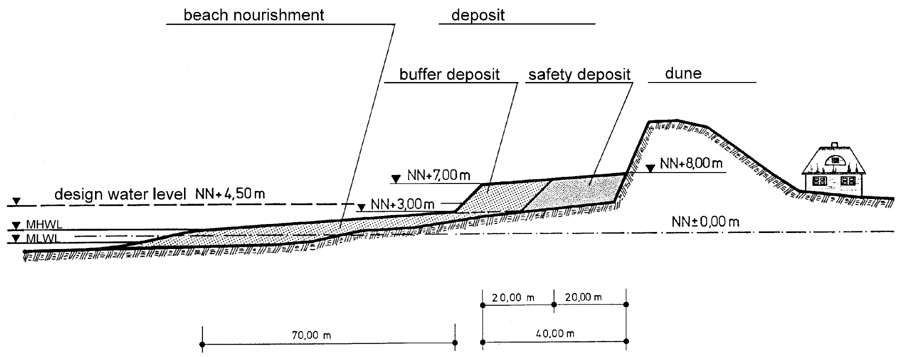


Figure 26. Dune reinforcement by combination of beach nourishment (wave dissipator) and a deposit consisting of a buffer and safety deposit an the island of Sylt. After erosion of the buffer deposit succeeding nourishment will start whereas the safety deposit guarantees that the dune can still withstand storm surges [ALW 1984].

COASTAL PROTECTION AT THE BALTIC SEA

Systematic investigations of water level providing a sound basis for the design of coastal structures has been available since the beginning of the 19th century. The Prussian Hydraulic Engineering Administration erected the first water level gauges in 1810 within the framework of preinvestigations for the construction of ports in Swinemünde, Kolberg, and Memel which belong nowadays to Poland and Lithuania. Therefore the heritage on long-term data sets is shared with coastal engineers in these neighbor countries. In the middle of the 19th century Gotthilf HAGEN [1863] published his encyclopedic manual on hydraulic engineering in which beside other subjects the state of the art for coastal protection at the Baltic coast and its hydro- and morphodynamical basics were described. The manual of HAGEN served for decades as the guideline for coastal engineering at the Baltic coast. The storm surge of 1872 with its disastrous damage stimulated further investigations, particularly on the meteorological boundary conditions and the hydrodynamical effects.

Basic hydrodynamics

Mean water level. In 1845 HAGEN introduced a procedure delivering comparable mean values of water levels for the whole Prussian Baltic coast: A daily value taken at noon. PETERSEN [1952] concluded that these daily water level data provide a sufficient basis for investigations in a medium time scale though a random value. In order to continue the existing time series these values are still documented and additionally the daily maximum and minimum. HAGEN [1863] used these data in order to evaluate the yearly variation of the mean water level by monthly means for distinct areas at the Baltic coast. This approach

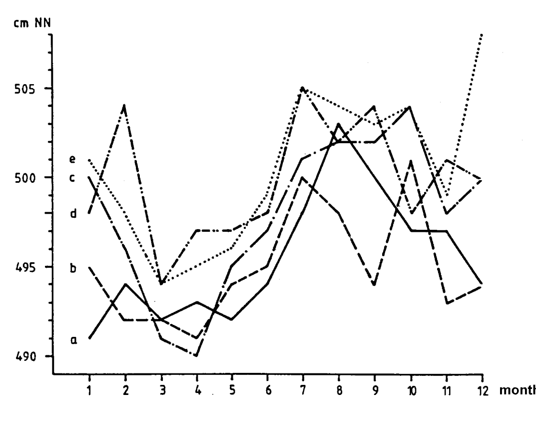


Figure 27. Seasonal changes of mean water level (10 year average) between 1931 and 1980

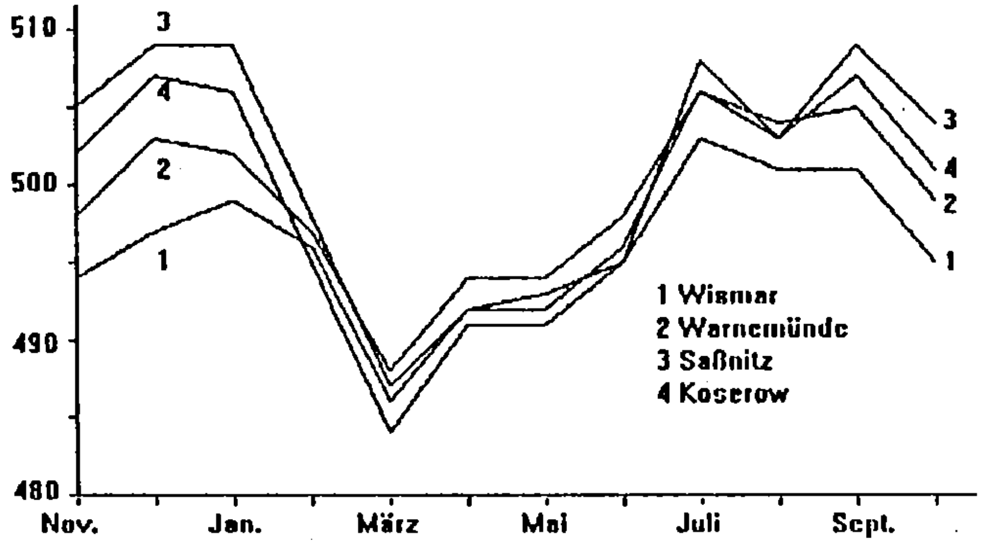


Figure 28. Monthly means (10 year average 1976-85) at four gauges at the southern Baltic Sea

was refined by WITTING for time series between 1898 and 1912 [EIBEN 1992a] which perform still an example for present analysis (Fig. 27 + 28). GAYE [1951] used the existing data sets and hints from HAGEN [1863] and MEYER [1913] for the determination of relative sea-level rise at the Baltic coast: a rate of 2,56 mm per year on the average for all considered gauges and 1,5 mm per year for the southern coast. WEISE [1962] analyzed the time series for the gauge Swinemünde and got for longer runs a rise of about 1 mm per year but got a similar result as GAYE [1951] if using the same data set.

Tidal oscillations. Already HAGEN [1863] delivered figures for the microtidal range of the Baltic Sea decreasing from west to east: At Travemünde 9-10 inches and at Stolpmünche 1 inch. MEYER [1913] evaluated tidal constants for the Baltic Sea and concluded the following results: small tidal range in the whole Baltic Sea, changing harmonic constants and decreasing tidal amplitude in eastward direction. MEYER [1913] succeeded furthermore to detect a tidal oscillation from the record of a gauge at the Imperial Dockyard in Kiel (Fig. 29). PETERSEN [1952] proved a mean tidal range of 19 cm for Travemünde.

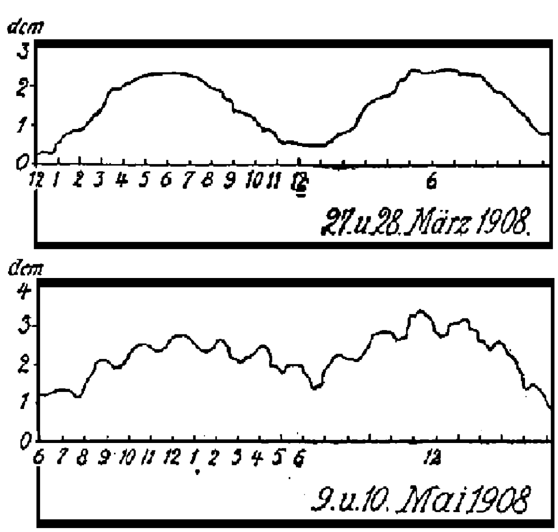


Figure 29. Tidal oscillations at Kiel [MEYER 1913]

Basin oscillations and Seiches. Wind fields induce in the Baltic Sea not only a set-up or set-down as they do, e.g., in the North Sea. They also trigger oscillations of water levels in the whole basin with duration of more than a day. A typical example for a basin oscillation has been recorded at the gauge Kiel in 1978 (Fig. 30): An initial set-down of about 0,6 m in the western part of the Baltic Sea and a set-up in its eastern parts occurred due to western wind. The decrease of the wind intensity rendered possible a basin oscillation with a maximum set-up of about 1.2 m and a succeeding maximum set-down of about 1.0 m in the western part after 36 hours. It is obvious that a superposition of such a basin oscillation with a change in storm direction could be

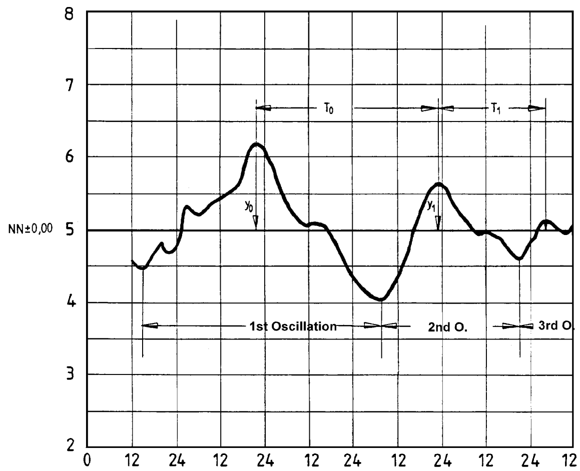


Figure 30. Example of damped basin oscillations, western Baltic Sea [EIBEN 1992a]

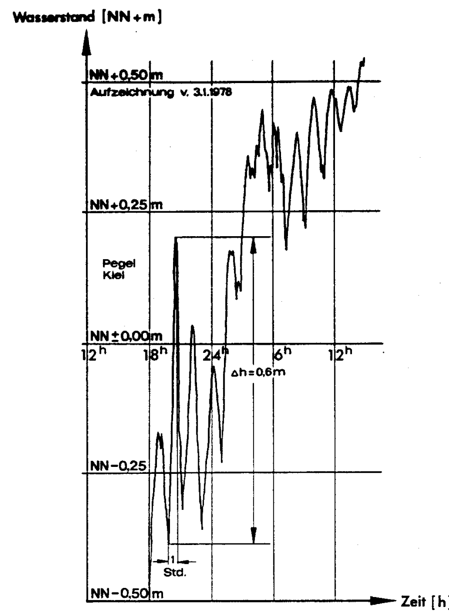


Figure 31. Registration of seiches at the gauge Kiel [EIBEN 1992a]

dangerous for the coast. Furthermore, seiches occur with periods in the range of hours; they appear often in coincidence with the rise of water level set-ups. Already MEYER [1913] had detected those seiches in the bay of Kiel both by measurements and by computation. Later theoretical analysis delivered that the typical seiches in the Baltic Sea are oscillations with one or two knots and duration of 19 or 28 hours [NEUMANN 1941; GEYER 1962]. Those with a duration of about 19 hours is more frequent. PETERSEN [1952] reported a seiches for Travemünde with an amplitude of 0,28 m and a period of 20 minutes. A seiche with an amplitude of 0,6 m and a period of 75 minutes (Fig. 31) has been reported by EIBEN [1992a] for the area of Kiel. The occurrence also of basin oscillations as seiches has often complicated the assessment of the actual development of storm surges, particularly if leading to temporary set-downs.

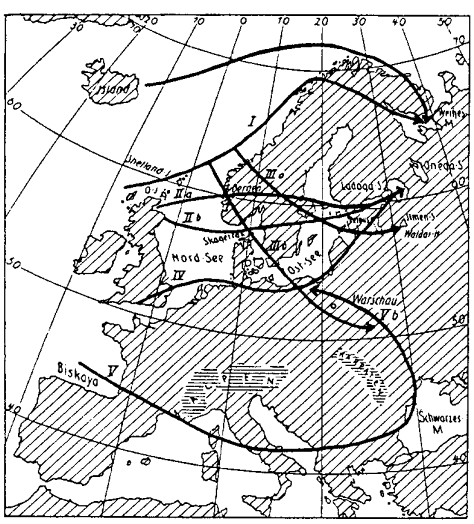


Figure 32. Main tracks of cyclones creating storm surges at the Baltic Coast [EIBEN 1992a]

Storm surge generation. The storm surge of 1872 with its disastrous effects on the German Baltic coast stimulated intensive research. Detailed data inventories on storm surge water levels and meteorological boundary conditions were carried out by BAENSCH [1875] and PRALLE [1875] covering the whole area of the Baltic Sea. Their efforts have been successfully supported by the Danish meteorologist COLDING who provided valuable information on the triggering of the set-up by wind action. The evaluation of main tracks of cyclones by BEBBER [KOLP 1955] and the analysis of resulting water level changes by KRÜGER [1910], REINHARD [1949], STARK [1952], and KANNENBERG [1955] allowed a generalized determination of three typical types of weather conditions resulting in storm surges. Type A: High pressure above North Scandinavia, cyclone tracing from the North Atlantic quickly across the western and southern Baltic Sea (track III or IV, Fig. 32) with initial

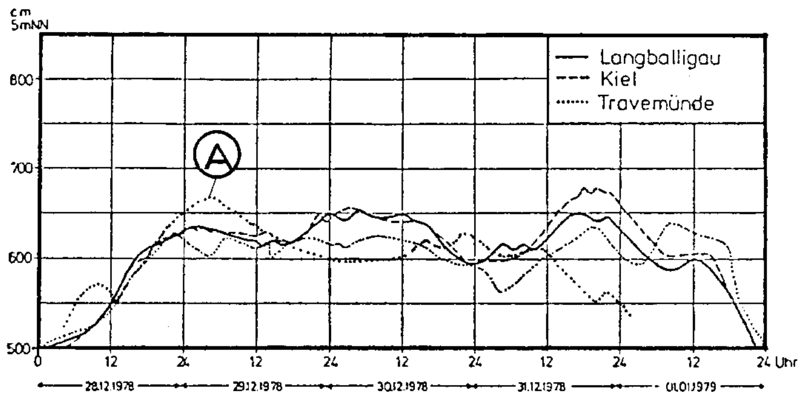


Figure 33. Comparison of storm surge water levels of 1898 (A) and 1978/79 [EIBEN 1992a]

storm directions west and southwest and after passing of the cyclone northeast. According to RODLOFF [1972] conditions of this type create about 50 % of storm surges at the German Baltic coast. Type B: High pressure above Scandinavia, low above the Mediterranean. Slow movement of both to East Germany (track Vb, Fig. 32). Storm from northeast to east with long duration, often turning to southeast and decreasing. According to KANNENBERG [1955] about 30 % of all storm surges are effected by weather conditions of this kind. Type C: Low pressure above North Scandinavia and high pressure in the southwest to west. Northeastern storm at the backside of the cyclone, a rare event. Type A represents both small surges as extreme events such as the one of 1872 due to combination with basin oscillations. The very unfavorable convergence of 1872 occurred due to a succession of three situations [BAENSCH 1875]:

1. Western storms with long duration generating a gradient of about 2 m between the intersection of North and Baltic Sea and a set-up in the eastern part of the Baltic Sea.

2. Gradual turning of the storm direction to northeast and increase of velocities and oscillating back of the set-up from the eastern part.

3. Further growth of the storm intensity up to Beaufort 11. Increase of the set-up from 2.0 to 3.2 m with rising velocities of the water level of up to 0.2 m per hour.

The storm surges occurring due to weather conditions of Type B are characterized by a wind-generated set-up due to onshore directed storms. They often have no significant peaks but set-ups remaining for longer periods on high levels as e. g. the storm surge of 1978 (Fig. 33). Investigations on the frequency of storm surges have been carried out due to German standard classification by STARK [1952] which have been recently updated by EIBEN [1989]. This procedure considers only water level peaks, but not duration and wave action. It is therefore an indicator but not a scale for the endangering of coasts and coastal structures.

Design water levels. The master plans of the Federal States at the Baltic Sea contain design water levels on the basis of the storm surge of 1872 with a set-up of about 3,5 m still following the recommendations of the Prussian Hydraulic Engineering Administration. Recently the probabilistic investigations by JENSEN & TÖPPE [1990] stimulated discussions about lower design levels for an event with a return period of 100 years and a set-up of 2,5m whereas the return period of the storm surge of 1872 with its set-up of about 3,0 m was estimated of about 1000 years. In spite of these suggestion the design water level will be taken in consideration of the set-up of the storm surge of 1872 and a relative sea level rise of 2.5 mm per year for a lifetime of 100 years. Considering uncertainties of the possible maximum of basin oscillation effects and an acceleration of sea-level rise a reduction of the design water level is not reasonable [WIEDECKE et. al 1979]. Furthermore there exist hints on two storm surges between 1320 and 1872 with a set-up of the same order of magnitude as that one of the storm surge of 1872 [KRÜGER 1910]. Considering that information the return period of a set-up of the storm surge of 1872 would be reduced to 180 to 200 years.

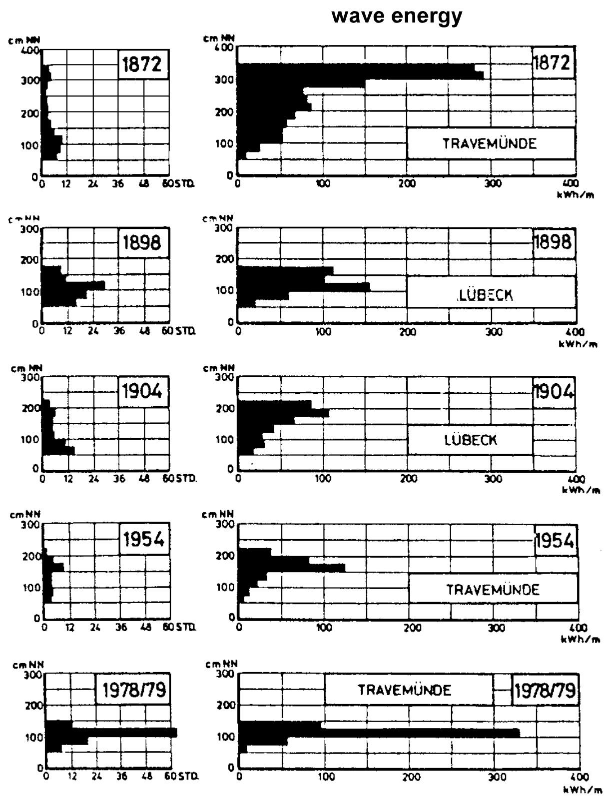


Figure 34. Examples of duration of exceedance of threshold water levels and wave energy for distinct storm surges [EIBEN 1992a]

Storm surge classification. The classification of storm surges has the major aim to get a measure for its severeness. The orientation at water level peaks at meso- or macro tidal coasts is quite reasonable because the variation of storm surge water levels due to tides is still significant and is in shallow coastal areas also a dominant boundary condition for wave action. But at a microtidal coast the duration of high storm surge levels is in some cases much longer than at meso- and macrotidal coasts. Therefore, a classification of storm surges limited to peak levels is insufficient for microtidal coasts. A number of water level thresholds and the duration of their exceedance has been introduced and furthermore an estimation of accompanying wave energy [FÜHRBÖTER 1979]. Though the execution of wave energy determination is rather questionable the basic approach is a very suitable tool for storm surge classification at microtidal coasts. A comparison of distinct storm surges at the Baltic coast makes the improvement evident which has been gained by this approach (Fig. 34).

Storm surge prediction. Severe storm surges occur at the Baltic coast rarer than e. g. at the North Sea coast but sometimes more surprisingly. In order to organize necessary countermeasures at vulnerable or endangered coastal sections a suitable storm surge prediction is urgently required. But it took quite a long time before first tools were introduced. In Mecklenburg-Vorpommern an empirical forecasting was introduced for the estimation of set-up and set-down due to direct wind action [MIEHLCKE 1956]. This prediction method did not consider the effect of basin oscillations and lacked by the very limited information on wind velocities and direction from the northern Baltic Sea. Both effects caused deficits in respect of reliability of prediction. In Schleswig-Holstein the method of KEULEGAN was applied by EIBEN [1983] in order to predict the set-up caused by direct wind action. The prediction delivered results with an accuracy of about 0,25 m if the application was limited on small coastal stretches. After the surprising storm surge of summer 1988 the German Hydrographic Service made great efforts to implement an operational storm surge prediction for the Baltic coast which was introduced in 1992: a numerical model for water levels and currents using predictions of wind action and air pressures and tidal computations. Up to now the accuracy of storm surge prediction has been proven as well sufficient as the phase shift to the occurrence of the event itself.

Wave set-up and undertow. In his manual on the arts of hydraulic engineering HAGEN [1863] mentioned observations of wave-induced set-up of water-levels at the coast during storms with heights of 0.9 to 1.2 m due to the water volume of breaking waves. Furthermore he explained the generation of a near-bottom current driven by the gradient which has been caused by the nearshore set-up. The observation of HAGEN [1863] became lost in the German coastal engineering profession and was brought back to the public more than hundred years later when field measurements had proven his observation [NIEMEYER 1991a].

Coastal protection by natural means

Dune stabilization: Relatively large parts of the German Baltic Sea coast, particularly before World War I and World War II, experienced a natural protection against the sea by foredunes. Therefore dune stabilization was a major concern. Initially its aim was primarily to prevent dune migration in order to avoid the filling of backside lagoons or waterways or the covering of agricultural or forestry areas. Human activities with the aim of dune stabilization at the Baltic coast are already known from the 13th century [WEISS 1992]: Fences have been erected and later pines and willow trees were planted. Knowing about the importance of dune stabilization the Society for Natural Sciences of the City of Danzig donated in 1768 an award for improvements in this field. The winner TITIUS recommended the erection of fences in combination with the planting of vegetation like bushes being replaced successively by trees. This scheme based on experience gained in Denmark by RÖEHL after 1738 by the combined implementation of fences and grass. Obviously a number of tools for dune stabilization have been known and were applied though still a lack of systematic knowledge is evident. A pragmatic approach to reduce these deficits was carried out by BJÖRN in the vicinity of Danzig after 1795: Based on existing knowledge he established test fields of schemes drawn up from sea landward and consisting of distinct kinds of fences in combination with a variety of vegetation (Fig. 35). Within a few years he gained remarkable

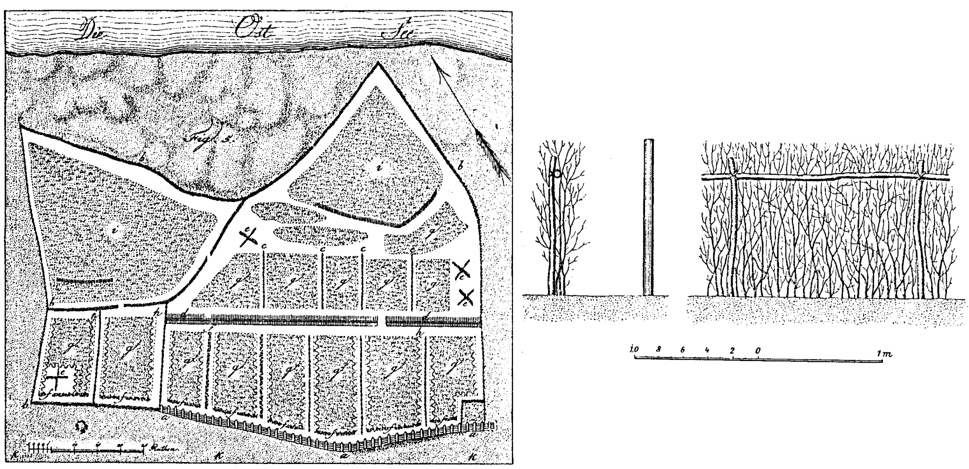


Figure 35. Test fields for dune stabilization by BJÖRN [GERHARDT 1900]

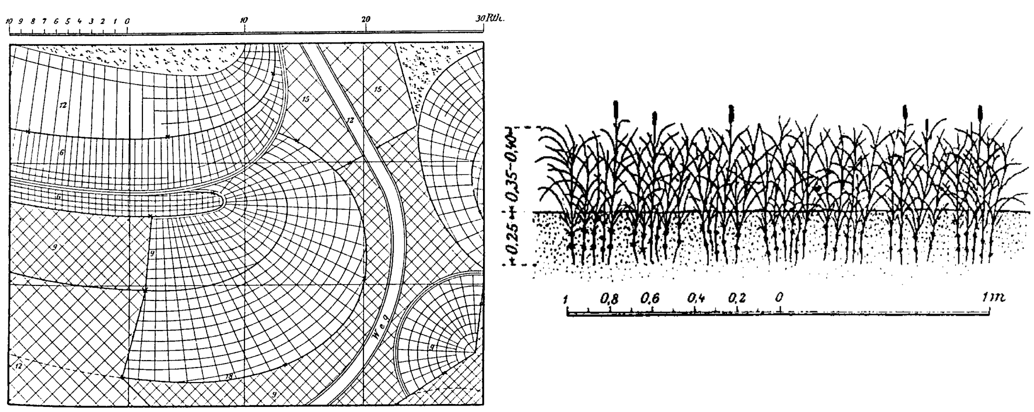
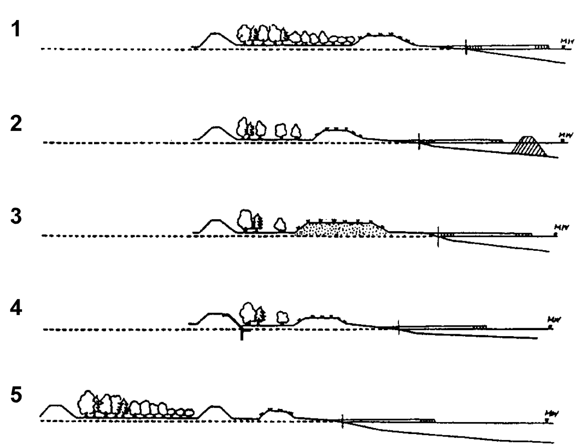


Figure 36. Implementation of sand reed in flexible grids by KRAUSE [GERHARDT 1900]

success allowing a further extension of his fields. After the Napoleon Wars which caused an interruption of these efforts KRAUSE [GERHARDT 1900] improved the scheme of BJÖRN [GERHARDT 1900] by implementation of rows of sand reed in flexible grids varying between 1,25 m and 5,65 m in dependence of dune steepness and wind action (Fig. 36). KRAUSE started furthermore the stabilization of foredunes as a direct coastal protection measure though still not realizing their function as part of the aeolian on- and offshore transport processes. Getting an insight into these processes HAGEN [1863] realized the necessity to equalize the cross-sections of the foredunes. His position as a high-ranking civil servant in the Prussian Ministry for Public Works allowed him to transfer his knowledge into practical application leading to dune reinforcements including in some cases even artificial nourishments and later the planting of sand reed. The motivation of HAGEN [1863] resulted from his insight in the crucial role of stable foredunes for the safety of the hinterland against inundation. But he did not recognize that this aim is only achievable at balanced coastal stretches. This fact was later realized by GERMELMANN [1904] describing the fate of foredunes in areas with structural erosion 'to become always a victim of the sea' which can only be avoided by an organized retreat. The state of the art then available on the basis of developments starting already in the 18th century serves still as the basis for present strategy and practice in dune stabilization at the Baltic coast into which additional materials and tools like synthetic materials and machinery equipment have been introduced.

Coastal protection forests. A unique application of natural vegetation for the purpose of coastal protection is the implementation of forest drawn up as coastal defense schemes (Fig. 37). Coastal protection forests have the function to dissipate wave energy in front of a dyke performing the most landward positioned part of the defense system for a lowland coast. It is expected though not yet proved that the coastal protection forests will absorb wave energy to such an extent that the dykes will experience neatly no wave attack and have only to keep the still water level during a storm surge. The implementation of the coastal protection forests is particularly an additional measure in areas where the capability of the foredunes is regarded as insufficient to guarantee its stability if a storm surge with long duration occurs. It is obvious that it is difficult to estimate or even to prove the effectiveness of coastal protection forest by conventional tools like hydraulic model tests or computations. Therefore, its capability can only tested in the case of a severe storm surge creating breakthroughs of the seaward parts of the system.



1 : Dyke with grass layer, wide coastal protection forest, dune at a balanced coast with or without groynes

2 : Dyke with grass layer, wide coastal protection forest, with minimum width, weak dune with offshore breakwaters and/or groynes at an eroding coast

3 : Dyke with grass layer, remnants of coastal protection forest, reinforced dune (repeated nourishments) at an eroding coast with groynes

4 : Exposed dyke with revetment; remnants of coastal protection forest, and dune at an eroding coast with groynes

5 : Retreat of the combined coastal defence system dyke - coastal protection forest - dune at an eroding coast with groynes. Dune and old dyke will merge by further coastal retreat

Figure 37. Distinct coastal defense systems with a coastal protection forest [WEISS 1992]

Coastal protection structures

Dykes. The lowlands at the Baltic Sea had in most cases a natural protection by foredunes or high beach berms. Therefore only a few dykes have been erected in the past. The first known construction at the German Baltic coast dates from 1581 at the Gelting Bay [KANNENBERG 1955]. Shape and position of this dyke are unknown, it was destroyed during storm surges in the 17th century. In this area

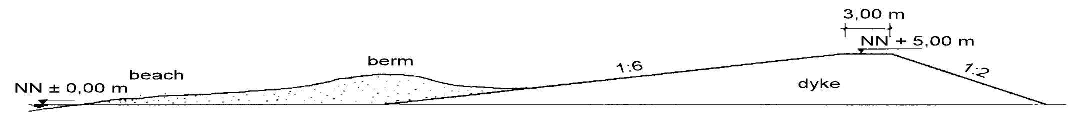


Figure 38. Cross-section of the Prussian Baltic Sea dyke of 1874 [EIBEN 1992b]

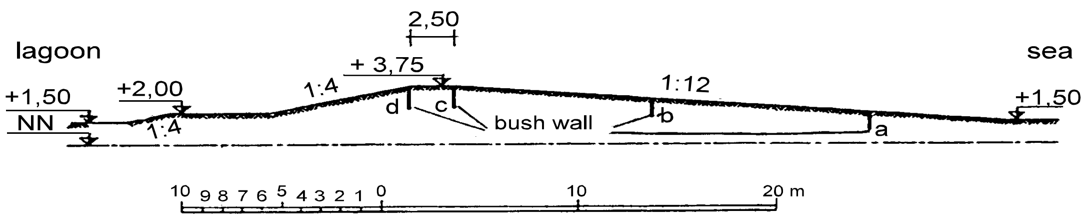


Figure 39. Cross-section of the sand dyke on the peninsula of Wustrow [WEISS 1992]

dykes have also been erected as protection of lowlands in the course of the 18th century. Further dyke construction started in other coastal areas of Schleswig-Holstein in the beginning of the 19th century. The disastrous storm surge of 1872 destroyed numerous foredunes and beach berms leading to the flooding of large areas and causing hundreds of victims. As well in the then Prussian provinces Schleswig-Holstein and Pomerania as in the Grand Duchy of Mecklenburg additional measures were regarded as necessary to keep the lowlands safe. Already 19 days after the event the Prussian government gave orders to erect dykes as additional protection of lowlands landward of foredunes or beach berms which should remained untouched but were regarded as too weak to withstand a very severe storm surge. The shape of the dykes was similar to present ones with a crest height of 5 m above mean sea level, a crest width of 3 to 4 m, an outer slope of 1:6 and an inner one of 1:2 (Fig. 38). If the position close to the shore was inevitable due to insufficient space landward of foredune or beach berm the dyke should be armoured by stone on a shingle layer and a toe protection of piles. The difference to the situations at the North Sea coast makes also the fact evident that at the Baltic coast no self-ruling communities for coastal protection existed. The Prussian government stimulated the coastal landowners to found such communities after the storm surge of 1872. In Mecklenburg dykes were unknown until the storm surge of 1872. But the lesson of this event lead also to the additional implementation of dykes in the coastal protection system. A remarkable construction was carried out in the framework of that programme on the peninsula of Wustrow in order to prevent a breakthrough: a sand dyke with an outer slope of 1:12 to withstand wave attack and an inner slope of 1:4 to reduce the sensitivity against erosion by overtopping (Fig. 39). It reflects a deep insight in the interactions of wave attack on structures

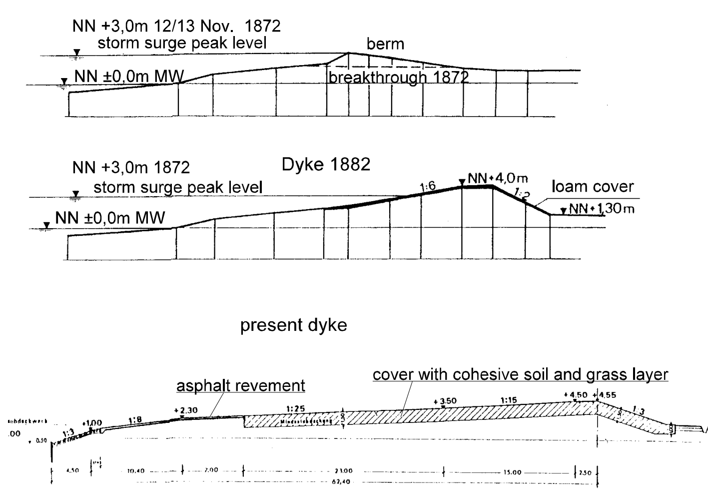


Figure 40. Initial beach berm, dyke cross-sections of 1882 and present at the Probstei coast, Schleswig-Holstein [EIBEN 1992b]

the capability of used material. Generally the design of dykes at the Baltic coast incorporated already all elements of present rules: design water level according to the highest known storm surge and empirical wave run-up in order to avoid overtopping and destruction of the steep inner slope. As well in the Prussian provinces of Schleswig-Holstein and Pomerania as in Mecklenburg in most cases the new dykes were positioned landward of the beach berm or foredune in distances between 100 and 200 m from the shoreline where wave energy was expected to be remarkably or even totally dissipated. This empirical approach proved itself as appropriate considering the fate of those dykes which had been erected close to the shoreline. The dyke in the Probstei was erected in the position of the beach berm after the storm surge of 1872 (Fig. 40). The dyke experienced a number of damages due to storm surges and needed additional armoring by revetments and toe protection before its replacement by a new construction in the beginning of the 80s of this century (Fig. 40) [EIBEN 1992b]. Already in 1898 the notes of a meeting of the local coastal protection community refers to that problem: ‘Obviously the danger for the dyke due to direct interaction with the shoreface has been underestimated.’ [KANNENBERG 1955]. In order to adress this problem recently the tool of beach nourishments has been introduced to reduce direct wave attack on the dyke. Nevertheless in general the programmes initialized after the storm surge of 1872 were successful, the Baltic coast experienced since then no comparable disaster. Honesty requires us to admit also that no comparable event had occurred in the meantime. Due to more recent assessments many of them would not have been able to withstand a storm surge like that one of 1872. After the World War II and particularly due to the experiences gained from the storm surges of 1954 and 1978 and 1979 reinforcements of existing or replacements by new constructions have increased the safety of lowland coasts at the Baltic Sea in the shelter of dykes.

Groynes. The first application of groynes at the German Baltic coast had the aim of reducing sedimentation at harbor entrances, e. g. at Pillau in 1811 and at Warnemünde in 1850 [GERHARDT 1900]. Later as well HAGEN [1863] as GERHARDT [1900] defined the purpose of groynes to preserve the shoreface and the beach. HAGEN [1863] regarded groynes as a part of coastal protection against storm surges: Keeping the beach as a wave energy dissipator by reducing or even minimizing erosion. He documented also the distinct construction methods of groynes in Mecklenburg and Pomerania being built in the first decades of the 19th century with lengths between about 18 and 37 m and a shore-parallel distance of about 23 m. At first groynes had only been implemented at bluff coasts but HAGEN [1863] recommended also their application at sandy lowland coasts. The design of the first groynes was purely empirical, the construction material was in the beginning fascines, later wooden piles and stones. The first known design criteria have been evaluated by GERHARDT [1900], unfortunately without explanation of their background: relation of length to distance between 1 and 1,5. In 1874 in Prussia the crest height was chosen to 0.2 m above mean water level [WEISS 1992]. In 1887 the first permeable groynes were implemented by spacing the wooden piles by 1/7 to 1/4 of their diameter. This completed the basic types of groynes still in use at the Baltic coast (Fig. 41)

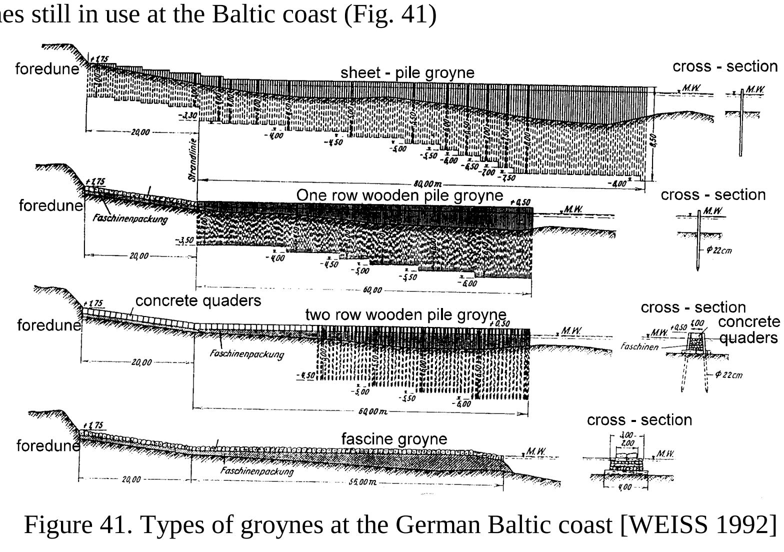


Figure 41. Types of groynes at the German Baltic coast [WEISS 1992]

COASTAL WATERWAY AND HARBOR ENGINEERING

The beginnings until the 19th century

Already in the first century A. D. Roman ships entered the estuaries of the Ems, Weser, and Elbe rivers for trading purposes. Sea trade at a larger scale started after the migration of peoples in Europe had finished in the middle of the first millennium A. D. Frisian sea traders built up settlements and trading places eastward of the Rhine along the North Sea coast but also entering the Baltic coast. In their times vessels were sufficiently small to find access to suitable coastal places by use of existing natural water depths. In the course of the 12th century A. D. by lead of the cities of Lübeck at the Baltic, of Hamburg and of Bremen close to the North Sea coast the Hanseatic League was established: a system of alliances between cities in the Northern hemisphere of Europe establishing an extended exchange of goods, particularly by seagoing vessels with a typical draft of 3,5 m. Those vessels could still get access to the large harbors by use of the existing natural waterways. In order to improve their safe traveling waterways were firstly marked by buoys, beacons and flares in the course of the 13th century.

Beside these efforts engineering activities were only necessary to install quays and similar facilities in the harbors enabling the ships to land and to take goods as easy and quick as possible. Before the 19th century engineering works in order to improve or to control waterways are only known for a few cases. The harbor of Emden had lost its access to the deep waterway in the Ems-Dollart estuary after a storm surge caused a break-through of a new channel in the 16th century and a silting up of the existing waterway. In order to give the seagoing vessels again access to the harbor the closure of this channel was at least tried in vain by erecting a wall of piles. First dredging (Weser estuary and Trave river) and implementation of groynes (Weser and Elbe estuary) is reported from the 18th century.

The operation of waterways and harbors demands for a certain standard of knowledge about available water depths and water level fluctuations. In order to meet these requirements as well survey and hydrographic mapping as water level measurements were established in the 16th and 17th century. A tidal gauge must have been available in the harbor of Hamburg in the 17th century, because since then the phase lag between high tide at London Bridge and this place is known for which a number of measurements is inevitably necessary [ROHDE 1975]. Unfortunately these data have been lost. Systematic tidal water level measurements in the harbor of Hamburg and their analysis had been initiated in 1786 by REINKE [1787] who considers them as needed for tidal compensation of soundings, information on extreme fluctuations and as design basis for engineering constructions. Other tidal gauges had been erected at the end of the 18th century at different places along the Elbe estuary, e.g., that one in Cuxhaven by WOLTMANN in 1784 who invented also an impeller for the measurement of current velocities in rivers [WOLTMANN 1790].

From the 19th century to present

In the course of the 19th century after the end of the Napoleon Wars sea trade with other continents gradually increased, particularly with Northern America which was also destination of an increasing number of emigrants from central Europe. Moreover Germany developed to an industrialized country importing raw material necessary for production and exporting goods. The use of steel instead of wood and the propulsion by steam instead of wind allowed the construction of larger vessels with larger draft demanding deeper waterways as access to the existing harbors [ROHDE 1970]. Thus in the middle of the 19th century modern waterway engineering got its driving force in Germany. The dimension of interference into the existing natural systems increased enormously and asked for a much sounder basis of process knowledge than ever before. As the theoretical knowledge was far beyond our present standard the common approach was empircal: a mixture of mostly regionally bounded observation or measurement in combination with basic process knowledge. According to that fact the history of German coastal waterway engineering will be discussed on the basis of the six most important coastal waterways: the Ems, Jade, Weser, and Elbe on the North Sea coast and Trave and Warnow on the Baltic coast.

EMS

After the already described break through of a new channel in the Ems river far away from the harbor, futile efforts for its closure and the subsequently silting up of its access channel the harbor of Emden lost its importance and position as one of the leading ports in Europe. But, during the last quarter of the 19th century, the import of ore for the industry of the Ruhr area and its coal export got shipped via a newly constructed canal to the port of Emden requiring a sufficient offshore access to the harbor which had to be established step by step. First off all a new harbor entrance was dredged and the harbor was closed off from tidal action and sedimentation by a lock acting moreover as a drainage sluice being used for concentrated outflows in order to maintain the entrance channel's cross-sections. The storm surge bay Dollart being enormously favorable with its large tidal prism for keeping cross-sections in the outer estuary stable was separated by a training wall from the waterway leading to the harbor entrance of Emden and further upstream in order to avoid import of sedimentation by the tidal ebb flow with high turbidity. Following the same purpose at least large tidal flats were enclosed and a new lock was established close to the waterway [SCHUBERT 1970]. In spite of further improvements by construction of new and enlargement of existing training walls the situation of the waterway to the harbor of Emden remained unsatisfactory in respect of the large quantities of maintenance dredging. In the 50s and 60s of this century another - at least again futile - approach to solve the problem was started: Interfering into the system by training walls and groynes in order to use the transport capacity of the flood tide for avoiding sedimentation in the Emden waterway and shifting it upstream where it would be less disadvantageous in respect of needed navigable water depth. In the 70s of this century a plan was introduced to close the Emden waterway by a new lock at both its seaward and upstream end, arranging new safe harbor areas on both shores being protected by a new dyke (Fig. 42). The river Ems should be passed through the storm surge bay Dollart [CARSJENS & CLASMEIER 1986]. Major aim of this plan was to avoid maintenance dredging in the Emden waterway and getting a smoother transition from the harbor entrance to the deeper parts of the estuary in which cross-sectional maintenance is supported by the tidal prism of the Dollart bay. Though never described this was an adaption on the basics of the concept which had been developed earlier and applied with remarkable success by KRÜGER in the Jade area. But the realization had to be postponed for years due to difficult negotiations with the neighbor country, the Netherlands. In the end, the project was abandoned for both ecological and economical reasons.

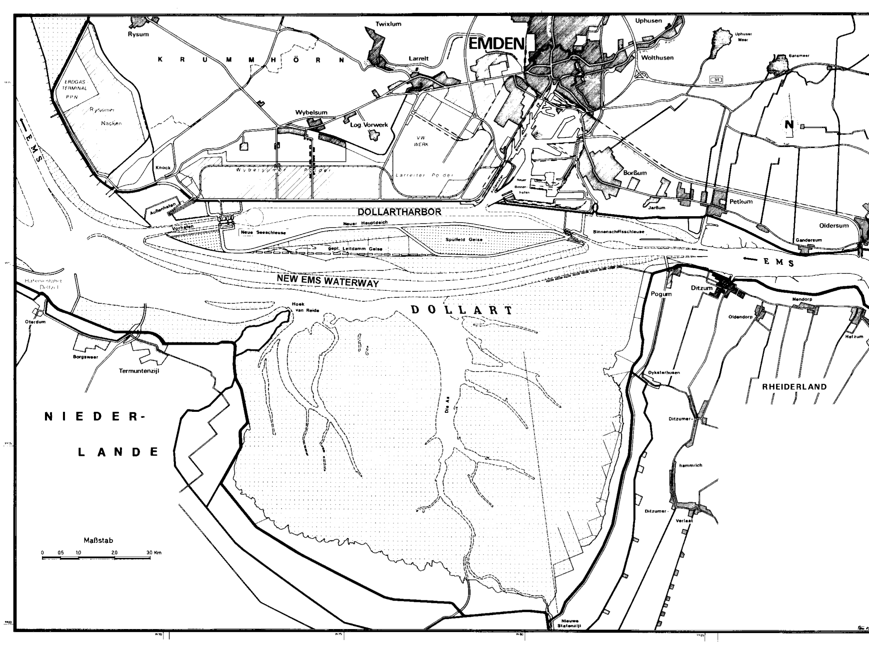


Figure 42. Dollart harbor (plan) [CARSJENS & CLASMEIER 1986]

JADE

The Jade inlet and bay were created by the erosive forces of storm surges after consecutive dyke breaks between the 13th and 16th centuries leading temporarily even to a link to the Lower Weser. The large tidal prism of the bay maintains large, stable cross-sections with remarkable water depths in the Jade inlet. Prussia though in possession of the harbor of Emden at the North Sea coast bought an area for the erection of a naval port called Wilhelmshaven at the Jade from the Grand Duchy of Oldenburg in order to use the natural advantages which became later more evident when the German Imperial Navy operated from that place large battleships of the ‘Dreadnought’ type.

The analysis of this area was carried out by HAGEN [1856], one of the best educated and most experienced German coastal engineers of his time. His heritage to our time beside others is the second historical record of an ordinary tide in the Jade area after that one inherited from BRAHMS about a century before [LUCK & NIEMEYER 1980]. Furthermore he combined his observations of tidal water levels with the fluctuation of silt content in the water column (Fig. 43). Later the migration of channels in the Jade and resulting occurrence of bars and shallows motivated the Imperial Navy to ask an experienced engineer of the harbor authority of Hamburg for an expertise. LENTZ [1899, 1903] recommended areal dredging in the Jade bay in order to increase the tidal prism and consequently its capacity of maintaining sufficiently large and deep cross-sections in the Jade inlet. The basics of that kind of indirect interference into the coastal processes is similar to the relation of tidal volume and channel cross-section which has become worldwide popular due to O’BRIEN [1931, 1967]. The knowledge about the important role of the bay’s tidal prism for the stabilty of the Jade waterway was credited by a legal act in 1883 which forbade any land reclamation or other impacts in the Jade area leading to a reduction of the local tidal prism.

After the invention of the ‘Dreadnought’ battleships with enormously increasing dimensions the concept of LENTZ was no longer regarded as suitable to deliver sufficiently stable cross-sections in the Jade waterway, particularly in its offshore area. There the updrift banks were fixed by training walls and large groynes creating a small artificial island: Minseneroog. Moreover regular dredging created a stable waterway requiring only limited maintenance [KRÜGER 1922]. Before interfering into the system KRÜGER [1911] had carried out intensive investigations on the acting hydrodynamical forces and the long-term morphological development in this area in order to get a sound basis for engineering measures. He improved his concept in the course of the following decades and even after retirement until

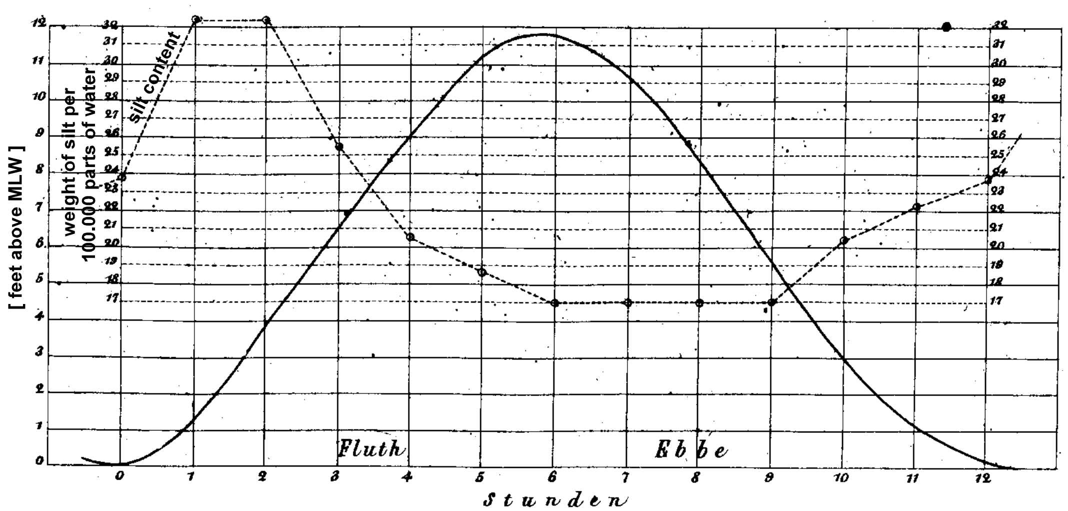


Figure 43. Tidal water level and silt content; Jade area (Fluth: flood; Ebbe: ebb; Wasserstand: waterlevel; Schlickgehalt: silt content) [HAGEN 1856]

his death incorporating an enormous number of scientists from coastal engineering and related disciplines. KRÜGER must be regarded as the initatior of interdisciplinary coastal research in Germany. Though the allied powers did not allow any maintenance of the Jade waterway after the World War II the correction of the Jade mainly inspired by KRÜGER was sufficiently successful to deliver a suitable basis for establishing at the Jade a deep water harbor for large tankers and bulk carriers step by step between 1958 and 1974. Vessels up to 250000 tdw and a maximal draft of 20 m are enabled to enter the piers at Wilhelmshaven [BRAUN & WITTE 1979].

WESER

The Weser estuary with the Outer and Lower Weser is the access for seagoing vessels to the port of Bremen. Since the 16th century the nautical conditions worsened more and more, particularly close downstream of the harbor of Bremen. In order to continue the profitable sea trade first harbor facilities were erected downstream of the existing harbor and at least in 1827 the port of Bremerhaven was founded in the transition area of Outer and Lower Weser by VAN RONZELEN [1857]. From there goods were transferred to Bremen by smaller vessels and land vehicles. For improving the safe access from the North Sea on a flat area bordering the Outer Weser a lighthouse was erected [VAN RONZELEN 1857] which is still in use as a basis for a radar based pilot system.

But still regaining an access by a sufficiently designed waterway in the Lower Weser guaranteeing sea trade as a major economical basis of the city of Bremen had political priority. The appointment of L. FRANZIUS, a very successful member of a well-known dynasty of East Frisian coastal engineers, as chief engineer of the harbor and waterway authority provided that aim with a feasible technical background: First of all the concept of FRANZIUS was contradictory to earlier local impacts the whole Lower Weser by creating a system of continuously increasing cross-sections in downstream direction with the major aim to minimize sedimentation and to achieve cross-sectional stability in the waterway requiring low maintenance efforts. As far as achievable, tidal flow was concentrated in the main channel by closing secondary ones and erecting groynes. The prospected effect was evaluated by estimated tidal curves which were expected to occur after the correction of the Lower Weser and used for computations of the tidal volumes. Applying the law of continuity an adaption of suitable cross-sections was carried out for getting nearly the same tidal current velocities along the estuary. Due to the impact of upstream freshwater a small dominance of ebb current was anticipated provoking a net seaward sediment transport [FRANZIUS 1888]. The approach of FRANZIUS was successfully carried out between 1883 and 1895 allowing ships with a draft of up to 5 m to get access to the harbor of Bremen (Fig. 44) by ‘riding on the tidal wave’ from Bremerhaven to Bremen. Remarkable also was that the expected effect of natural transport capacity was achieved: Only 50% of the necessary 50 million m^3 of sediment had been taken by dredging, the rest was evacuated by tidal flow. In order to stop the lowering of tidal water levels occurring after the correction of the Lower Weser further upstream in 1905 a tidal barrier was erected upstream of the harbor of Bremen [FLÜGEL 1988] reflecting the tidal wave there totally. The basic concept of FRANZIUS has been applied for a number of consecutive adaption of the Lower Weser waterway until the last one performed from 1974 to 1977 which enables ships with a draft of 12.5 m and

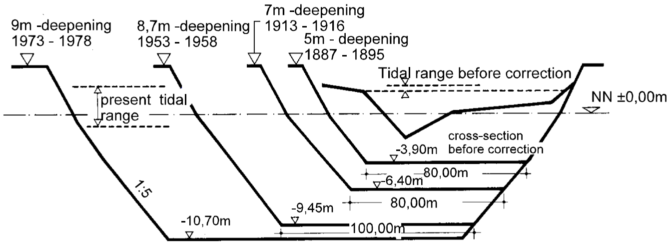


Figure 44. Cross-sections in the Lower Weser close downstream of Bremen since 1885 [WETZEL 1988]

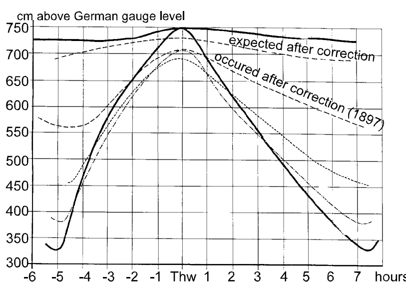


Figure 45. Tidal curves of the Lower Weser in Bremen between 1885 and 1978 [ROHDE 1970, 1980]

about 30.000 tdw to go upstream to Bremen harbor by adapting their traveling to the higher part of the tidal wave (Fig. 44). When FRANZIUS started his correction the tidal range in Bremen was about 0.3 m. As a result of the five successive deepenings tidal range has increased to about 4 m at Bremen (Fig. 45). Honesty requires us to admit that nevertheless the number of ships traveling to Bremen has been reduced in recent years and ecologists complain about the effects of the subsequent corrections demanding a restructuring of the Lower Weser to a more natural river [BUSCH et al. 1989].

Already in 1890 the growing passenger ships from the North Atlantic routes required engineering impacts in the Outer Weser which was carried out also by FRANZIUS [1895]. But this measure was less successful than the correction of the Lower Weser. The maintenance of the existing waterway required increasing efforts without gaining sufficient stability. The multiple channel system remained migrating with a tendency of changing cross-sections in its branches due to variations of local tidal volumes.

Already in 1825 the waterway had been shifted from the most westward situated channel to the eastern one. Another shift to the then deepening one was regarded by FRANZIUS as favorable, but not carried out in respect of the necessary high efforts. In 1921 PLATE [1927] started to shift the waterway from the 'Wurster Arm' in the eastern part to the central one 'Fedderwarder Arm' (Fig. 46) and fixed the then implemented system by groynes and training walls. His work was the basis for later improvements of the navigability of the Outer Weser (Fig. 46) [HOVERS 1975; WETZEL 1988] and still continues in present days for an adaption to the requirements for container vessels of the fourth generation for which a specific analysis of necessary waterway dimensions in respect of the design vessel was carried out [DIETZE 1990].

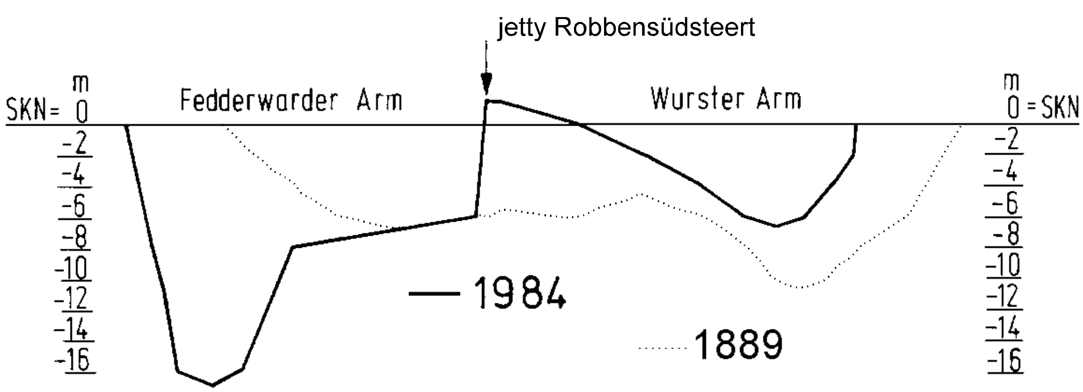


Figure 46. Cross-sections of the Outer Weser waterway in 1889 and 1984 [WETZEL 1988]

ELBE

In the beginning of the 19th century the increasing size of seagoing vessels led to difficulties in the Elbe waterway downstream of Hamburg harbor. In order to achieve a sound basis for engineering impacts HÜBBE [1842] started systematic hydrodynamical investigations. He installed e. g. permanent measuring tidal gauges in Cuxhaven at the estuarine mouth and in Hamburg between 1841 and 1843 [ROHDE 1975] which data highlighted the necessity of levelings in order to get a sound reference for the measured tidal water levels. This requirement was later fulfilled by LENTZ. River sections being critical in respect of navigability were streamlined by training walls and groynes in order to concentrate tidal flow in the navigation channel and to keep it away from tributary ones. Additionally steam dredgers were used to achieve the goal [HÜBBE 1853]. HÜBBE [1861] investigated also intensively the morphological development of the river he had to deal with; remarkable are his observations on bedforms which he already distinguished in the four classes: ripples, dunes, tidal ridges and shoals. Additionally he used tracers in order to study the migration of bedforms (Fig. 47).

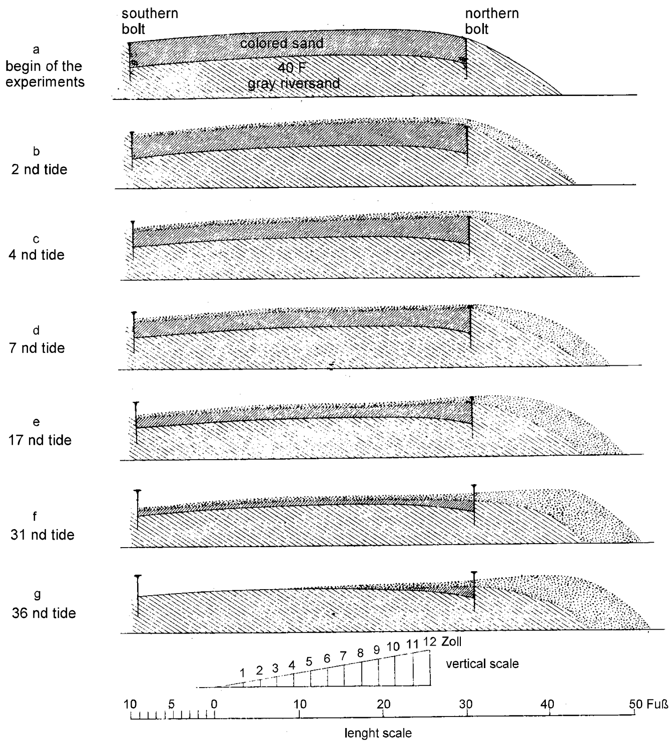


Figure 47. Results of a field experiment on bedform migration by tracer on an intertidal shoal [HÜBBE 1861]

His successor DALMANN [1856] studied the contemporary experience in coastal waterway engineering available in the neighbor countries England, France and the Netherlands. His consequence for further improvement of navigability and maintenance in the Elbe river was focussing on dredging and restriction of groyne and training wall construction on specific sections.

The increasing draft of seagoing vessels required at least dredging in the Elbe estuary, even seaward of the city of Cuxhaven [ROHDE 1971]. For the stabilization of that estuarine section between 1948 and 1966 a training wall with a length of 9.2 km was erected at the western edge of the waterway seaward of Cuxhaven due to a recommendation of HENSEN [1941]. After the 2nd World War four subsequent deepenings of the Elbe waterway have taken place. The planning for a fifth one in respect of the demands of large container vessels is presently finished [SCHLÜTER 1993]. A comparison of present and planned navigational water depths in the Elbe estuary with historical ones [ROHDE 1971] highlights the enormous changes the regime has experienced by coastal engineering interference (Fig. 48). In the meantime there had been plans to erect a deep water port at the estuarine entrance seaward of Cuxhaven. This prospects have been abandoned for economical and ecological reasons [LAUCHT 1982]. The intensive preinvestigations for that project delivered a remarkable amount of information being generally valuable for coastal engineering problems.

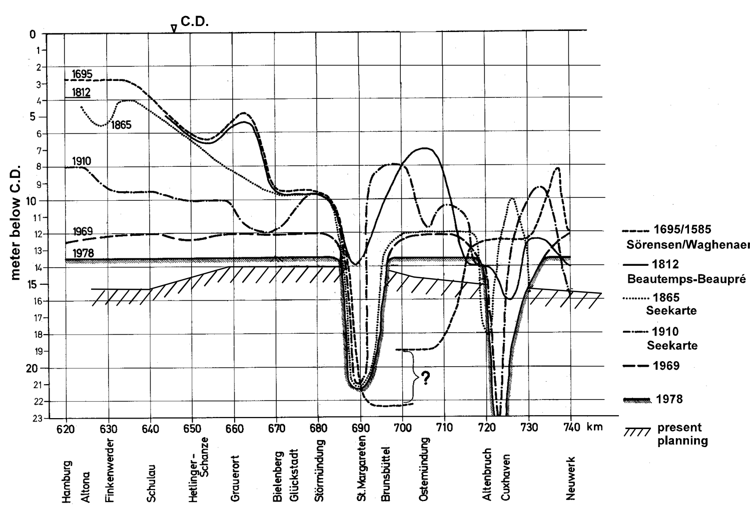


Figure 48. Change of navigational depth in the Elbe estuary and planned deepening; earlier situations adapted from ROHDE [1971]

Table 1. Coastal waterways at the German Coasts

Waterway	between	length	depth below C. D.	maximum vessel	maintenance dredging volume	1994 number of vessels	1994 cargo volume
		km	m	tdw	10^6 m^3		10^6 t
Elbe	North Sea-Brunsbüttel	70	13.5	110000	13.0	58450	81.5
	Brunsbüttel-Hamburg	64	13.5	100000			
Weser	North Sea-Bremerhaven	60	12.0	80000	1.3	29600	16.2
	North Sea-Brake	85	10.0	45000			6.6
	Bremerhaven-Bremen	60	9.0	35000			14.7
Jade	North Sea-Wilhelms-haven	55	18.5	250000	13.4	2760	34.5
Ems	North Sea-Emden	70	8.5	40000	10.6	1970	2.0
Trave	Baltic Sea - Lübeck (Stadt)	25	9.5	14000	0.02	23500	20.3
Warnow	Baltic Sea-Rostock	11	13.0	60000	0.06	23150	15.8

TRAVE

At the beginning of the 19th century sedimentation in the Lower Trave had led to a reduction of water depth allowing only ships with a draft of about 2 m traveling to the harbor of Lübeck. The necessary information for navigation was delivered by a gauge the data of which since 1826 are still available [JENSEN & TÖPPE 1986]. In order to improve navigability in the Lower Trave in 1835 dredging was started and in 1840 a channel passing through its barrier was established. The first river correction between 1850 and 1854 enabled vessels with a draft of about 4 m to enter the harbor of Lübeck. During the periods from 1879 to 1883 and from 1899 to 1907 the second and third correction were carried out due to plans of REHDER [1898], who was then in charge of waterway and harbor engineering. Major means were: reduction of river length by cutting bows, erection of groynes and deepening by dredging. Afterwards the waterway was navigable for vessels until Travemünde at the mouth with a draft of 8.5 m and until Lübeck with a draft of 7.5 m. After the fourth (1908 - 1961) and the fifth (1961 - 1982) correction the harbor of Lübeck is accessible by ships with a draft of 9.5m.

WARNOW

The harbor of Rostock was until the World War II of minor importance in comparison with other German harbors at the Baltic coast such as Lübeck and particularly Stettin. Nevertheless already in the course of the 19th century the waterway was step by step dredged up to a water depth of about 5 m. In 1903 the railway connection between Berlin and Copenhagen was closed by a railway ferry service between Warnemünde at the mouth and the Danish island of Falster. Therefore a new access channel to the Baltic Sea was established being fixed by new jetties. The navigable draft for vessels increased due to those and accompanying impacts afterwards to 7 m until Warnemünde and 6 m until Rostock. After the World War II the former G.D.R. decided to establish a basis for its sea trade in Rostock. At the southern shore of a bay connected with the Lower Warnow new harbor facilities were erected. The seaward access channel was shifted eastward of the existing jetty system with a depth of about 10,5 m and a width increasing from 60 m to 120 m at its seaward end. On its eastern bank a new breakwater with a length of 655 m was additionally established. In 1977 the water depth was increased to 13 m. Nowadays a further deepening for bulk carriers is planned including deepening to a water depth of 14,5 m and a reshaping of the existing breakwater and jetty system.

Present situation

The efforts in the past have created an effective system of harbors and waterways for sea trade being an important contribution to nation's welfare. They provide furthermore a sound basis for future development in respect of changing requirements of modern cargo vessels and new techniques of sea transport. Table 1 makes evident the navigable water depths on the major German waterways and the accessability of its ports. A major problem is already the deposition of dredged material, particularly in those areas where it has been contaminated by human waste water. Moreover major ports such as Hamburg and Bremen are located far upstream from the sea: as well the economical as the ecological limitations in respect of further adaptions to increasing seagoing vessels have been be achieved or will be soon.

EDUCATION, RESEARCH AND COOPERATION

The manuals on coastal engineering by BRAHMS [1754, 1757] and HAGEN [1863] highlighted the impressive level then available for further education. Though the predecessors of the later Universities of Technology were mostly founded in the first decades of the 19th century, no profiled school of coastal engineering was established before this century. Particularly between World War I and II Otto FRANZIUS at Hanover, WINKEL at Danzig, and DE THIERRY and AGATZ in Berlin established a widely accepted education of coastal engineering. After World War II the FRANZIUS-Institute for Hydraulic Engineering at the University of Technology in Hanover became under the directorate of HENSEN the most prominent school of coastal engineering in Germany attracting most of those students with specific interest in coastal engineering and providing German coastal engineering with a respectable number of splendid graduates. Nowadays in Germany two specific institutes for coastal engineering exist: at the Universities of Hannover and Brunswick. Furthermore coastal engineering is part of the education in hydraulic engineering at the Universities of Technology at Berlin, Darmstadt, Dresden and Rostock-Wismar.

Research has a respectable tradition at German universities, particularly in hydraulic modeling. For example, the FRANZIUS-Institute has carried out hundreds of model tests dealing with coastal problems in Germany or abroad. But also others operate in this field. For example model tests for the closure works of the Zuiderzee in the Netherlands were carried out at the Theodor-Rehbock Laboratory of the University of Karlsruhe. German coastal engineering has been provided with a unique tool by the German Research Foundation (DFG) in the 1980s: the Large Wave Flume at Hanover, a joint institution of the Universities of Hanover and Brunswick.

Traditionally, applied research has been carried out also by specific institutes belonging to administrations being responsible for coastal engineering. Before World War II the most prominent ones have been the Naval Waterway Engineering Department at Wilhelmshaven, the Prussian Hydraulic Laboratory in Berlin and the Prussian Coastal Research Stations at Büsum, Husum and Norderney. The Coastal Research Stations focused on field investigations, the Naval Waterway Department carried out both hydraulic modeling and field research. Nowadays there are still two governmental agencies for consultancy and research in the field of coastal engineering existing: the Coastal Branch of the Federal Institute for Waterway Engineering at Hamburg and the Coastal Research Station of the Lower Saxonian Central State Board for Ecology at Norderney/East Frisia.

The Naval Waterway Department became particularly under the directorate of KRÜGER the center of German coastal engineering research at the North Sea coast. KRÜGER pursued not only cooperation among coastal engineers but also with other disciplines such as geology and biology leading to integrated coastal research. He initiated as a platform for scientific discussion on coastal research the ‘Annual meetings of Northwestern German Geologists' with contributions of all fields of coastal research with coastal engineering in a - still existing - prominent position. In order to establish exchange of information he initiated with colleagues from neighboring countries the International Association of Hydraulic Research (IAHR), its first congress took place in Berlin 1937.

After World War II the division of the country enforced also a separation of the coastal engineering community. In West Germany coastal researchers of all disciplines founded the Coastal Council North and Baltic Sea (Küstenausschuß Nord- und Ostsee) which served as a platform both for exchange of information and cooperation. In 1973 it was replaced by the German Committee on Coastal Engineering Research (KFKI: Kuratorium für Forschung im Küsteningenieurwesen) which has been established by a formal agreement between the Federal Government and the coastal states being both represented in the Committee which coordinates the applied research in German coastal engineering. The Committee is supported by a research coordinator and an advisory group which might be regarded as an institution in which existing knowledge is transferred between generations of coastal engineers.

The first contribution of a German colleague at an International Coastal Engineering Conference took place in 1960 [KRAMER 1960]. In 1970 for the first time a group of German coastal engineers attended the 12th ICCE at Washington/DC and presented 11 contributions. The chairman of the German group suggested celebrating the 16th ICCE in Germany in 1978. The suggestion was appreciated though not already fixed [RAMACHER 1971]. The decision was made by the Coastal Engineering Research Council at the following 13th ICCE at Vancouver/Canada on the basis of a formal invitation by the Coastal Council North and Baltic Sea, the German Harbor Engineering Association and the City of Hamburg [PARTENSCKY 1973]. In 1978 the 16th ICCE took place in Hamburg. That location enabled a large number of German coastal engineers to attend, particularly the younger ones. Both information and even more the impressions initiated in the German coastal engineering society increasing research efforts and interest in international cooperation. A lot of those who attended then for the first time an ICCE have been motivated to participate in the unique exchange of information being offered at the following ones until today.

SUMMARY AND OUTLOOK

The tracing back of the contemporary state of the art in German coastal engineering makes evident that beside a historical development a remarkable amount of knowledge has been inherited from our professional predecessors. Furthermore, many of their projects provide still a sound basis for further developments. Taking present tools and their effectiveness into consideration, a comparison with the performance of former coastal engineers reduces the scaling of present products significantly requiring moderation. Emphasis should be laid on the message that the looking back in a profession with a remarkable empirical component is mostly worthwhile and more effective than the ‘reinventing of the wheel’ which often ends up as repeating a blunder. Particularly, but not only, our younger colleagues are encouraged to make more intensive use of the heritage of our professional history.

LITERATURE

ALW [1984]: Masterplan coastal protection island of Sylt. Amt f. Land- u. Wasserwirtschaft Husum (in German)

ARENDS, F. [1833]: Description of the storm surges between February 3rd and 5th 1825. Comission W.Kaiser, Bremen (in German)

ASTER, D.; JÜRGENS, H.H.; WEITZEL, H. [1990]: Construction of groynes on the island of Borkum. Jb. Hafenbautechn. Ges. 1989, 43 (in German)

BAENSCH, J. [1875]: The storm surges at November 12th and 13th 1872 at the Baltic coasts of Prussia. Zeitschr. f. Bauwesen 25, Berlin (in German)

BRAHMS, A. [1754]: Basic arts in dyke construction and hydraulic engineering, part I, Verl. H. Tapper, Aurich/Ostfriesland (in German)

BRAHMS, A. [1757]: Basic arts in dyke construction and hydraulic engineering, part II. Verl. H. Tapper, Aurich/Ostfriesland (in German)

BRAUN, J.; WITTE, H.H. [1979]: Enlargement and marking of the Jade waterway. Jb. Hafenbautechn. Ges. 1977/78, 36 (in German)

BOTHMANN, W.; KATTENBUSCH, E,; LORENZEN, J.M.; LÜDERS, K.; SCHAUBERGER, H.; SNUIS, H.; THILO, R. (Arbeitsgruppe Küstenschutz im Küstenausschuß Nord- und Ostsee) [1955]: General recommendations for coastal protection in Germany. Die Küste, 4 (in German)

BUSCH, D.; SCHIRMER, M.; SCHUCHARDT, B.; ULLRICH, P. [1989]: Historical changes of the river Weser. in: G.E. Petts (ed.): Historical changes of large alluvial rivers: Western Europe. J. Wiley & Sons, London

CARSJENS, R.; CLASMEIER, H.D. [1986]: Project Dollart Harbor: technical presentation. Jb. Hafenbautechn. Ges. 1985/86, 41 (in German)

DALMANN, J. [1856]: On river corrections in tidal areas. Hamburg (reprint: Die Küste, 46, 1988) (in German)

DETTE, H.H.; FÜHRBÖTER, A. [1975]: Field investigations in surf zones. Proc. 14th Int. Conf. Coast. Eng. Copenhagen/Denmark, ASCE, New York

DIETZE, W. [1990]: Expertise on the dimensions of the Outer Weser waterway for tide-independent access of container vessels. Wasser- u. Schiffahrtsdirektion Nordwest, Aurich/Ostfriesland (unpubl. in German)

EIBEN, H. [1983]: Specific hydrological conditions at the southwestern Baltic Coast. Amt f. Land- u. Wasserwirtschaft Kiel (unpubl. In German)

EIBEN, H. [1989]: Wind, water levels and waves at the Baltic coast of Schleswig-Holstein during the stormy periods in winter 1986/87. Die Küste, 50 (in German)

EIBEN, H. [1992a]: Specific hydrological conditions at the Baltic Coast. in DVWK: Historical coastal protection. Wittwer-Verl. Stuttgart (in German)

EIBEN, H. [1992b]: Coastal protection at the Baltic Coast of Schleswig-Holstein. in DVWK: Historical coastal protection. Wittwer-Verl. Stuttgart (in German)

ERCHINGER, H.F. [1970]: Coastal protection by salt marsh reclamation, dyke construction and maintenance in East Frisia. Die Küste, 19 (in German)

ERCHINGER, H.F. [1985]: Beach fill by turning the course of sandbars. Proc. 19th Int. Conf. Coast. Eng. Houston/Tx., USA, ASCE, New York

FLÜGEL, H. [1988]: Correction of the Lower Weser and harbour extension in Bremen during the last hundred years. Jb. Hafenbautechn. Ges. 1987, 42 (in German)

FRANZIUS, L. [1888]: The correction of the Lower Weser estuary. Bremen (reprint: Die Küste, 51, 1991) (in German)

FRANZIUS, L. [1895]: The correction of the Lower Weser and a project for the correction of the Outer Weser estuary. Leipzig (in German)

FÜHRBÖTER, A. [1974]: Some results from field investigations in surf zones. Mitt. Leichtweiß-Inst., 40 (in German)

FÜHRBÖTER, A. [1979]: Duration of wave energy impacts. Mitt. Leichtweiß-Inst., 65 (in German)

FÜHRBÖTER, A. [1992]: Wave impacts on dyke- and revetment-slopes. Jb. Hafenbautechn. Ges. 1991, 46 (in German)

FÜHRBÖTER, A.; KÖSTER, R.; KRAMER, J.; SCHWITTERS, J.; SINDERN, J. [1974]: A sand groyne for beach preservation on the island of Sylt. Die Küste, 23 (in German)

FÜLSCHER, J. [1905]: On protection structures for the preservation of the East and North Frisian Islands. Zeitschr. f. Bauwesen, Verl. Ernst & Sohn, Berlin (in German)

GÄTJEN, B. [1979]: Storm surge barriers at the German North Sea coast. Tasks, planning and construction. Jb. Hafenbautechn. Ges. 1977/78, 36 (in German)

GARSCHINA; PANSE [1898]: Hydrological investigations in the area of the East Frisian Islands. Part 1: Tidal inlet of Norderney. Wasserbauinspection Norden/Ostfriesland (unpubl. in German)

GAYE, J. [1951]: Changes of water levels in the Baltic and the North Sea during the last hundred years. Die Wasserwirtschaft, Sonderheft Vorträge gewässerkundl. Tag. (in German)

GAYE, J.; HENSEN, W.; LORENZEN, J.M.; LÜDERS, K.; PLATE, L. ;ROLLMANN, A.; SCHUMACHER,W.; WALTHER, F.: (Küstenausschuß Nord- und Ostsee, Arbeitsgruppe Norderney) [1952]: Expertise on the investigations concerning beach erosion at the western and northwestern shores of the island of Norderney and the recommended engineering measures for the protection of the island. Die Küste 1, 1 (in German)

GAYE, J.; WALTHER, F. [1935]: Migration of ebb delta shoals along the East Frisian Islands. Die Bautechnik, 13, 41 (in German)

GEINITZ, E. [1903]: Land losses at the coast of Mecklenburg. Mitt. Großherzogl. Geol. Landesanst. 15 (in German)

GERHARDT, P. [1900]: Manual on dune stabilization in Germany. Berlin (in German)

GERMELMANN [1904]: Expertise on necessary protection measures at the bluff coasts of Alt-Graatz, Heiligenhafen, Graal, Müritz and Wustrow. Berlin (unpubl. in German)

GEYER[1962]: Basin oscillations and water exchange in the Bay of Eckernförde under specific consideration of the storm at December 5th and 6th, 1961. Kieler Meeresforsch., 20 (in German)

GÖHREN, H. [1975]: Dynamics and morphology of sand banks in the surf zone of outer tidal flats. Proc. 14th Int. Conf. Coast. Eng. Copenhagen/Denmark, ASCE, New York

HAGEN, G. [1856]: On the tides and soil of the Prussian Jade area. Monatsber. Königl. Akad. Wiss., Berlin (reprint: Die Küste, 51, 1991) (in German)

HAGEN, G. [1863]: Marine and harbor engineering. in: Manual of hydraulic engineering. 3rd Part: The sea, Vol. 1. Verl. v. Ernst & Korn, Berlin (in German)

HAYES, M.O. [1979]: Barrier island morphology as a function of tidal and wave regime. in: S.P. Leatherman: Barrier islands. Academic Press, New York

HEISER, H. [1932]: Shore protection at coasts with and without dominant sediment transport. Die Bautechnik, 10, 40 (in German)

HEISER, H. [1933]: Coastal preservation and land reclamation at the German North Sea coast. Die Bautechnik, 11, 13 (in German)

HENSEN, W. [1941]: The development of navigability in the Outer Elbe estuary. Jb. Hafenbautechn. Ges. 1940/41, 18 (in German)

HENSEN, W. [1954]: Model tests on the impact of dyke shaping on wave run-up. Mitt. Franzius-Inst., 7 (in German)

HOMEIER, H. [1962]: Reconstructed historical morphology 1:50000 of the Lower Saxonian coast. Jber. 1961 Forsch.-Stelle f. Insel- u. Küstenschutz, 13 (in German)

HOMEIER, H. [1965]: Historical-morphological investigations at the Coastal Research Station on long-term developments at the Lower Saxonian coast. Jber. 1964 Forsch.-Stelle f. Insel- u. Küstenschutz, 16 (in German)

HOMEIER, H. [1969]: Changing shape of the East Frisian Coast in the course of centuries. in: J. Ohling (ed.): East Frisia in the shelter of the dyke, 2, Deichacht Krummhörn, Pewsum /Ostfriesland (in German)

HOMEIER, H. [1976]: Effects of severe storm surges on beaches and dunes on East Frisian Islands. Jber. 1975 Forsch.-Stelle f. Insel- u. Küstenschutz, 27 (in German)

HOMEIER, H.; LUCK, G. [1971]: Investigations on the morphological development of the tidal inlet Accumer Ee as a basis for the future behavior of beaches and dunes on the western and northwestern shore of the island of Langeoog. Jber. 1970 Forsch.-Stelle f. Insel- u. Küstenschutz, 22 (in German)
HOVERS, G. [1975]: Morphological changes in a fine sand tidal estuary after measures of river improvement. Proc. 14th Int. Conf. Coast. Eng. Copenhagen/Denmark, ASCE, New York
HÜBBE, H. [1842]: Some observations of water levels in the tidal area of the Elbe river. Hamburg (reprint: Die Küste, 46, 1988) (in German)
HÜBBE, H. [1853]: Experience and observations in the field of river engineering, part I. Hamburg (reprint: Die Küste, 46, 1988) (in German)
HÜBBE, H. [1861]: On the state and on the behavior of sand. Zeitschr. F. Bauwesen, Verl. Ernst & Sohn, Berlin (reprint: Die Küste, 46, 1988) (in German)
HUNDT, C. [1954]: Design storm surge levels for dimensioning of dykes at the western coast of Schleswig-Holstein. Die Küste, 3, 1/2 (in German)
JENSEN, J.; HOFSTEDE, J.L.A.; KUNZ, H.; DE RONDE, J.; HEINEN, P.F.; SIEFERT, W. [1993]: Long term water level observations and variations. in: R. Hillen & H.J. Verhagen: Coastlines of the southern North Sea. Proc. Coastal Zone '93
JENSEN, J.; TÖPPE, A. [1986]: Compilation and evaluation of measurements at the gauge Travemünde. Deutsche Gewässerk. Mitt., 30, 4 (in German)
JENSEN, J.; TÖPPE, A. [1990]: Investigations on storm surges of the Baltic Sea under specific consideration of the gauge Travemünde. Deutsche Gewässerk. Mitt., 34, 1/2 (in German)
KANNENBERG, E.G. [1955]: The surge from January 1st 1954 at the German Belt Coast. Urania, 18, 1, Leipzig/Jena (in German)
KLAUS, J.; SCMIDTKE, R.F. [1990]: Valuation expertise for dyke construction planning at the mainland coast -model area Wesermarsch -.. Bundesmin. Ernähr., Landw. u. Forsten, Bonn (in German)
KÖSTER, R. [1979]: Sediments at the Probstei coast. Mitt. Leichtweiß-Inst. 65
KOLP, O. [1955]: Endangering of the German coast between the rivers Trave and Swine by storm surges. Seehydrograph. Dienst der DDR (in German)
KRAATZ, D. [1966]: Beach and shoreline changes at the west coast of the island of Sylt and the impact of technical measures. Marschenbauamt Husum (unpubl. in German)
KRAMER, J. [1960]: Beach rehabilitation by use of beach fills and further plans for the protection of the island of Norderney. Proc. 7th Conf. Coast. Eng. Berkeley/Ca., USA, ASCE, New York
KRAMER, J. [1977]: Safety of sea dykes against storm surges. Die Küste, 31 (in German)
KREY, H. [1906]: On protection structures for the preservation of the East and North Frisian Islands. Zentralbl. Bauverw., 26, 54 (in German)
KREY, H. [1918]: Wadden Sea, marschlands and marshy islets at the North Sea coast of Schleswig-Holstein. Zentralbl. Bauverw., 38, 89, 93, 95, 96 (in German)
KRÜGER, G. [1910]: On storm surges at the German coasts in the western part of the Baltic Sea under specific consideration of the storm surge at December 30th and 31st 1904. Jber. Geograph. Ges. Greifswald (in German)
KRÜGER, W. [1911]: Sea and coast in the area of the island of Wangeroog and the forces acting on their shaping. Zeitschr. f. Bauwesen, Verl. Ernst & Sohn, Berlin (reprint: Die Küste, 51, 1991) (in German)
KRÜGER, W. [1922]: The Jade inlet, waterway of Wilhelmshaven, its genesis and state. Jb. Hafenbautechn. Ges. 1921, 4 (in German)
KRÜGER, W. [1937]: Migration of ebb delta shoals close to the island of Wangeroog. Abh. Naturw. Ver. Bremen, 30, 1/2 (in German)
KRÜGER, W. [1938]: Coastal subsidence in the Jade area. Der Bauingenieur, 19, 7/8 (in German)
KUNZ, H. [1991]: Artificial beach nourishment on Norderney, a case study. Proc. 22nd Int. Conf. Coast. Eng. Delft/The Netherlands, ASCE, New York
KURZAK, G.; LINKE, O.; DECHEND, W.; KRAUSE, H.; THILO, R. [1949]: Causes for erosion of the western and northwestern shores of the island of Norderney. Jber. 1949 Forsch.-Stelle f. Insel- u. Küstenschutz, 1 (in German)

LAMPRECHT, H.O. [1955]: Surf and shore variations at the west coast of the island of Sylt. Mitt. Franzius-Inst., 8 (in German)

LASSEN, H.; SIEFERT, W. [1991]: Mean tidal water levels in the southeastern North Sea and secular trend. Die Küste, 52 (in German)

LAUCHT, H. [1982]: Harbor project Scharhörn. Planning in reflection of time spirit. Aumühle (unpubl. in German)

LENTZ, H. [1899]: Expertise on the conservation of the Jade waterway. Unpubl. (reprint: Die Küste, 51, 1991) (in German)

LENTZ, H. [1903]: Second expertise on the Jade Waterway. Unpubl. (reprint: Die Küste, 51, 1991) (in German)

LIESE, R. [1956]: First experience with the management of the storm surge barrier of the Leda river close to the city of Leer. Wasser & Boden, 8, 6 (in German)

LOHRBERG, W. [1989]: Changes of mean tidal water levels at the North Sea coast. Deutsche Gewässerk. Mitt., 33, 5,6 (in German)

LORENZEN, J. M. [1954]: Hundred years coastal protection at the North Sea. Die Küste, 3 (in German)

LUCK, G. [1975]: Impact of the protection structures on the East Frisian Islands on the morphological processes in the area of the tidal inlets and basins. Mitt. Leichtweiß-Inst., 47 (in German)

LUCK, G. [1977]: Inlet changes of the East Frisian Islands. Proc. 15th Int. Conf. Coast. Eng. Honolulu, Hawaii/USA, ASCE, New York

LUCK, G.; NIEMEYER, H.D. [1980]: Albert Brahms and the storm surge of 1717. Die Küste, 35 (in German)

LÜDERS, K. [1952]: Effect of the groyne H at the western spit of the island of Wangerooge on the tidal inlet Harle. Die Küste, 1 (in German)

LÜDERS, K. [1956]: What is a storm surge? Wasser & Boden, 8, 1 (in German)

LÜDERS, K. [1957]: The reestablishment of dyke safety at the German North Sea coast between the Dutch border and the Elbe estuary. Wasser & Boden, 9, 2 (in German)

LÜDERS, K. [1971]: On the valid time of the design water level for sea dykes at the Lower Saxonian North Sea coast. Jber. 1969 Forsch.-Stelle f. Insel- u. Küstenschutz, 21 (in German)

LÜDERS, K.; FÜHRBÖTER, A.; RODLOFF, W. [1972]: New dune and beach protection method on the island of Langeoog. Die Küste, 23 (in German)

LÜDERS, K.; LORENZEN, J.M.; RODLOFF, W.; FREISTADT, H.; TRAEGER, G.; KRAMER, J. (Küstenausschuß Nord- und Ostsee, Arbeitsgruppe Küstenschutzwerke) [1962]: Recommendations for hinterland protection by dykes after the storm surge of February 1962. Die Küste, 10, 1 (in German)

MC LAREN, C. [1842]: The glacial theory of Professor Agassiz. Am. J. Sci. & Arts, 42

METZKES, E. [1966]: Report on dyke construction and coastal protection in Lower Saxony after the storm surge of February 16th/17th 1962. Die Küste, 14, 1 (in German)

MEYER, K. [1913]: Water level variations in the Firth of Kiel. Heider Anzeiger, Heide (in German)

MIEHLCKE; O. [1956]: On the water levels at the coast of the GDR in respect of the storm surge at January 3rd and 4th 1954. Ann. Hydrographie, H. 5/6 (in German)

MUNK,W.H. [1949]: The solitary wave theory and its application to surf problems. New York Acad. O. Sc., 51

NEUMANN, G. [1941]: Basin oscillations of the Baltic Sea. Arch. dt. Seewarte & Marineobserv., 61, 4 (in German)

NIEDERMEYER, R.O.; KLIEWE, H.; JANKE, W. [1987]: The Baltic coast between Boltenhagen and Ahlbeck. Gotha (in German)

NIEDERSÄCHSISCHE HAUPTDEICHVERBÄNDE [1988]: No dyke, no land, no existence. Leaflet of the Union of the Lower Saxonian Coastal Protection Commuties (in German)

NIEMEYER, H.D. [1979]: Wave climate study in the region of the East Frisian Islands and Coast. Proc. 16th Int. Conf. Coast. Eng. Hamburg/Germany, ASCE, New York

NIEMEYER, H.D. [1983]: On the wave climate at island sheltered Wadden Sea coasts. BMFT-Forschungsber. MF 0203-83 (in German)

NIEMEYER, H.D. [1987]: On the classification and frequency of storm surges. Jber. 1986 Forsch.-Stelle Küste, 38 (in German)

NIEMEYER, H.D. [1991a]: Field measurements and analysis of wave-induced nearshore currents. Proc. 22nd Int. Conf. Coast. Eng. Delft/The Netherlands, ASCE, New York

NIEMEYER, H.D. [1991b]: Case study Ley Bay: an alternative to traditional enclosure. Proc. 3rd Conf. Coast. & Port Eng. i. Devel. Countr., Mombasa/Kenya

NIEMEYER, H.D. [1995]: Long-term morphodynamical development of the East Frisian Islands and Coast. Proc. 24th Int. Conf. Coast. Eng. Kobe/Japan, ASCE, New York

NIEMEYER, H.D.; KAISER, R.; DEN ADEL, J.D. [1995a]: Application of the mathematical wave model HISWA on Wadden Sea areas. Die Küste, 57 (in German)

NIEMEYER, H.D.; GÄRTNER, J.; KAISER, R.; PETERS, K.H.; SCHNEIDER, O. [1995b]: The estimation of design wave run-up on sea dykes in consideration of overtopping security by using benchmarks of flotsam. Proc. 4th Conf. Coast. & Port Eng. i. Devel. Countr., Rio de Janeiro/Brazil

NIEMEYER, H.D.; BIEGEL, E.; KAISER, R.; KNAACK, H.; LAUSTRUP, C.; MULDER, J.P.M.; SPANNHOF, R.; TOXVIG, H. [1995c]: General aims of the NOURTEC-project -Effectiveness and execution of beach and shore face nourishments-. Proc. 4th Conf. Coast. & Port Eng. i. Devel. Countr., Rio de Janeiro/Brazil

O'BRIEN, M.P. [1931]: Estuary tidal prisms related to entrance areas. Civ. Eng., 1, no.8, ASCE, New York

O'BRIEN, M.P. [1967]: Equilibrium flow areas of tidal inlets on sandy coasts. Proc. 10th Int. Conf. Coast. Eng., ASCE, New York

PARTENSCKY, H.W. [1973]: 13th International Conference on Coastal Engineering in Vancouver/ Canada from July 10th to 14th 1972. Die Küste, 24 (in German)

PETERSEN, M. [1952]: Erosion and protection of the bluff coasts at the eastern coast of Schleswig-Holstein. Die Küste, 1, 2 (in German)

PETERSEN, M. [1954]: On the basics for the design of dykes in Schleswig-Holstein. Die Küste, 3, 1/2 (in German)

PETERSEN, M. [1961]: German literature about groynes at sandy coasts. Die Küste, 9 (in German)

PLATE, L. [1927]: Deepening of the Outer Weser waterway by adaption of the gully Fedderwarder Arm. Jb. Hafenbautechn. Ges. 1926, 9 (in German)

PRALLE [1875]: Observations of the Baltic Sea storm surge from November 13th 1872. Zeitschr. Arch. & Ing. Vereins Kngr. Hannover, Neue Folge d. Not-Bl., 21, 4 (in German)

PUTNAM, J.A.; MUNK, W.H.; TRAYLOR, M.A. [1949]: Prediction of long shore currents. Trans. Am. Geophys. Un., 30

RAMACHER, H. [1971]: The Coastal Engineering Conference 1970 at Washington. Die Küste, 21 (in German)

RAGUTZKI, G. [1976]: Effects of the storm surges of January 1976 on the protection structures on the island of Norderney. Jber. 1975 Forsch.-Stelle f. Insel- u. Küstenschutz, 27 (in German)

REHDER, P. [1898]: Report for the Engineering Council of the City of Lübeck on the deepening of the Trave river to 7.5 m water depth. Lübeck (unpubl. in German)

REINHARD, H. [1949]: The storm surge at the Baltic coast of Mecklenburg on March 1st and 2nd 1949. Zeitschr. Meteorol. 3, 7, Potsdam (in German)

REINKE, J.T. [1787]: On observations of ebb and flood tide in the Elbe river. Hamb. Adr.-Comptoir-Nachr. (reprint: Die Küste, 46, 1988) (in German)

RODLOFF, W. [1972]: Hydrological analysis of the Baltic Sea storm surge at November 13th 1872. Deutsche Gewässerk. Mitt., 16, 6 (in German)

ROHDE, H. [1970]: Development of waterways at the German North Sea coast. Die Küste, 20 (in German)

ROHDE, H. [1971]: On the development of the Elbe tidal river as a waterway. Mitt. Franzius-Inst., 36 (in German)

ROHDE, H. [1975]: Water level measurements at the German North Sea coast before the middle of the 19th century. Die Küste, 28 (in German)

ROHDE, H. [1977]: Storm surge levels and secular rise of water levels at the German North Sea coast. Die Küste, 30 (in German)
ROHDE, H. [1980]: Problems concerning enlargements of tidal river waterways. in: DVWK: Course enlargements of waters. Goslar (in German)
ROHDE, H.; TIMON, A. [1967]: Preinvestigations for a solution of the problems in the Eider estuary. Wasserwirtschaft, 57, 5 (in German)
SCHUBERT; K. [1970]: Ems and Jade. Die Küste, 19 (in German)
SCHLÜTER, K. [1993]: Basics of the adaption of the Elbe waterway. Hansa, 130, 4 (in German)
SCHÜTTE, H. [1908]: Holocene subsidence effects at our North Sea coast. Jb. Oldenburger Ver. Altertumskde. Landesgeschichte, 16 (in German)
SHEPARD, F.P.; INMAN, D.L. [1951]: Nearshore circulation. Beach Eros. Board, T.M. 26.
SIEFERT, W. [1974]: On waves in shallow water. Mitt. Leichtweiß-Inst., 40 (in German)
SIEFERT, W.; KRAUSE, G.; PROBST, B.; SCHERENBERG, R. [1988]: Design water levels in the Elbe estuary. Die Küste, 47 (in German)
STARK, E. [1952]: High water levels in the Lübeck Bight between 1885 and 1949. Die Küste, 1, 2 (in German)
STREIF, H. [1990]: The coastal areas of East Frisia - North Sea, islands, tidal flats and marshlands. Set of geological guides, 57, Gebr. Bornträger, Berlin/Stuttgart (in German)
STREIF, H. ; KÖSTER, R. [1978]: The geology of the German North Sea coast. Die Küste, 32
THILO, R.; KURZAK, G. [1952]: The causes for the erosion of the western and northwestern beaches of the island of Norderney. Die Küste, 1,1 (in German)
TOLLE, A. [1864]: Beach protection structures on the island of Norderney. Zeitschr. Arch. & Ing. Vereins Kngr. Hannover, Neue Folge d. Not-Bl., 10, 1 + 2 (in German)
VAN RONZELEN, J.J. [1857]: Description of the construction of the Bremen lighthouse replacing the Bremen beacon at the entrance of the Weser estuary. Commission L. v. Vangerow, Bremerhaven (reprint: Die Küste, 51, 1991) (in German)
VEENSTRA, H. [1976]: Structure and dynamics of the tidal area. in: J. Abrahamse et al.: Wadden Sea. K. Wacholtz, Neumünster (in German)
WALTHER, F. [1934]: Die Gezeiten und Meeresströmungen im Norderneyer Seegat. Die Bautechnik, 12, 13 (in German)
WASSING, F. [1957]: Model investigations of wave run-up on dikes carried out in the Netherlands during the past twenty years. Proc. 6th Conf. Coast. Eng.
WEINHOLDT, E.; BAHR, M. [1952]: The sedimentation in the Eider estuary - causes and countermeasures. Wasserwirtschaft, 42, 8 (in German)
WEISS, D. (1992): Coastal protection in Mecklenburg-Vorpommern. in DVWK: Historical coastal protection. Wittwer-Verl. Stuttgart (in German)
WETZEL, V. [1988]: Improvement of the Weser waterway between 1921 and today. Jb. Hafenbautechn. Ges. 1987, 42 (in German)
WIEDECKE, W.; EIBEN, H.; DETLEFSEN, G. [1979]: History of the protection of the Probstei lowland against Baltic Sea surges. Mitt. Leichtweiß-Inst., 65 (in German)
WILDVANG, D. [1915]: The alluvial age between Ley and northern Dollart coast. Aurich/Ostfriesland (in German)
WOEBCKEN, C. [1924]: Dykes and storm surges at the German North Sea coast. Friesen-Verl., Bremen-Wilhelmshaven (in German)
WOLTMANN, R. [1790]: Theory and use of the hydrometric impeller, or a reliable method to observe wind and water velocities. Hoffmann, Hamburg (in German)
WYRTKI, C. [1953]: Long shore transport balance in the surfzone. Deutsche Hydrogr. Zeitschr. 6 (in German)