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Storm Surge Protection Walls in Germany

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1. Introduction

Storm surge protection walls (SPW) are vertical or almost vertical walls used to prevent flooding of low-lying areas during storm surges with extremely high water levels. They are often built on top of revetments, sea dikes or simply as plain vertical walls in harbour areas. Hence, both their utilization and type of construction is manifold. Next to the classic green dikes, SPWs are considered fundamental storm surge protection measures in Germany many of them can be found in Lower Saxony, Schleswig-Holstein, Bremen, Hamburg and Mecklenburg-Vorpommern.

In Mecklenburg-Vorpommern, 27 assets with a total length of 9.5 km (sheet pile walls, cantilever retaining wall and gravity walls) can be found. The longest construction is about 1.2 km and 6 gates are also part o the defence line. In Lower Saxony there are no figures at hand to provide an overview of these constructions since numerous walls may be found along the major estuaries of the rivers Ems, Weser and Elbe. Additionally, sea wall constructions with vertical walls are also used as coastal protection schemes on some of the major East Frisian Islands.

In Hamburg, there are two storm surge protection units which are the public storm surge protection installations and the private protection assets (private polders in the harbour). The total length of the public storm surge protection assets is about 103 km, 25 km of which are built as protection walls. Additionally, 33 gates, six sluices, and six barriers can be found in the public storm surge protection area. The total length of the private polder protection walls in the harbour is about 100 km. The walls are disposed in 45 assets. For operational harbour business reasons 886 gates are also part of the private storm surge protection system.

This chapter provides an overview of the various types of vertical storm surge protection assets which can be found in the various states along the North and Baltic Sea coast in Germany. The chapter starts with some examples of typical vertical wall constructions, illustrated by photos and cross sectional drawings. Furthermore, some details of the history of this type of wall are given before a summary of the main design steps for assessing wave overtopping and wave loading at these walls is given. Finally, maintenance aspects of vertical walls are briefly discussed and some future design aspects for an improved stability and safety of these structures are introduced.

2. Types of Vertical Coastal Defence Structures in Germany

Numerous types of vertical wall constructions are being used for coastal or harbour protection in Germany. In this chapter, some typical examples of structures – recently built or renewed and with the associated documentation available – are shown. They are of the following type (Fig. 1 to Fig. 4):

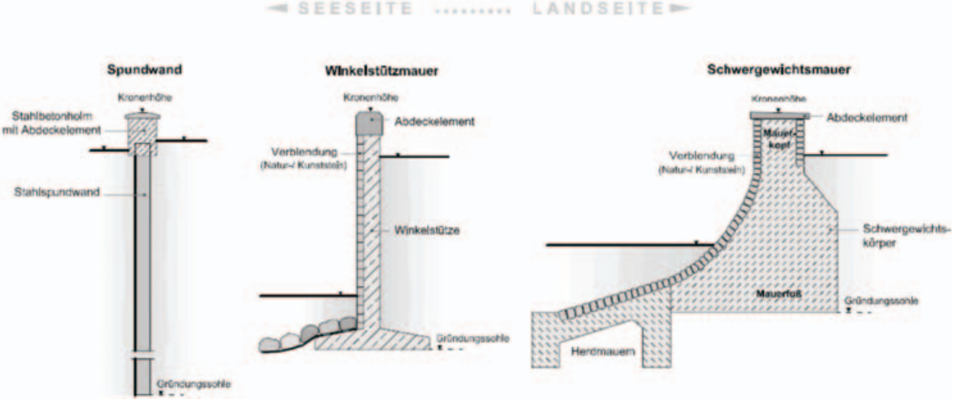

Fig. 1: Examples of storm surge protection walls

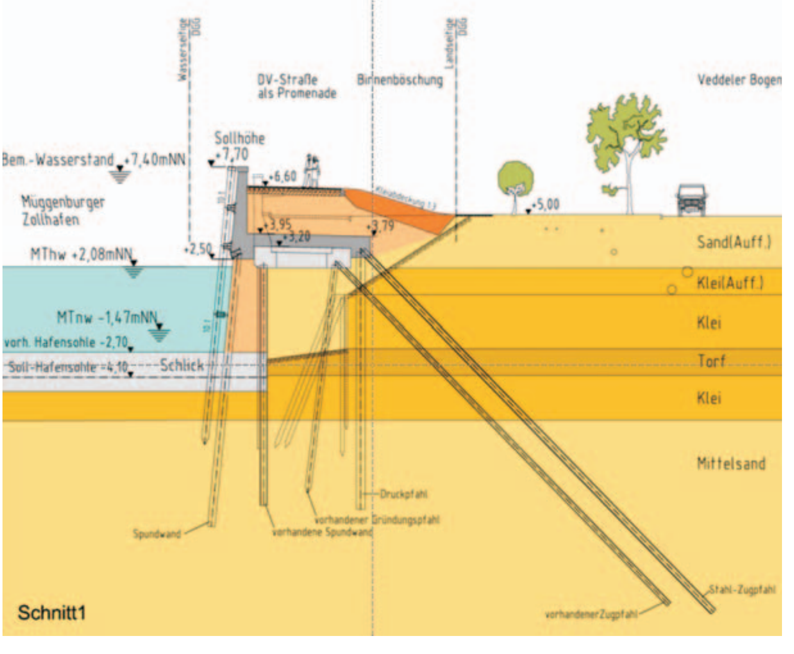

Fig. 2: Example of combined cantilever retaining wall (Hamburg)

Fig. 3: Typical example of a gravity type wall in Nienhagen (Baltic Sea)

Fig. 4: Sheet pile wall with concrete cap (Karlshagen, left; length: 183 m) and cantilever retaining wall (Heiligendamm, right)

- sheet pile walls (with or without concrete caps) (Spundwände);
- gravity walls (Schwergewichtsmauern);
- cantilever retaining walls (Winkelstützmauern);
- brick and stone walls (Steinmauern)
- combined cantilever retaining walls on sheet-pile foundations (Winkelstützmauern auf Spundbohlen), primary defence type in Hamburg

There is a wide spectrum of functionality of these walls comprising flood and storm surge protection, mooring abilities for ships, stability for embankments or revetment constructions and many more. Moreover, flood gates can be also considered as vertical walls. This may also include existing mobile flood protection walls such as stop-logs or bulkheads which need to be designed in a similar way. Size and length of these constructions may vary substantially, depending on where they were built and which purposes they serve. Usually, their height ranges from some decimetres to several meters, whereas lengths may be between a couple of meters and several kilometres.

A typical gravity wall may be found in Nienhagen (Baltic Sea coast), as shown in Fig. 3. Other examples in Fig. 4 show a sheet-pile wall with a concrete cap (left) and a cantilever retaining wall (right). All examples were taken from the Baltic Sea coast.

A new and innovative vertical storm surge protection wall is being built in Hamburg St. Pauli (Fig. 5). Due to space limitations, limitations of inclination of the access bridge and other restrictions, the existing building on the right hand side of Fig. 5 (Brückenhaus) serves as an elevated part of the storm surge protection scheme. The extension above the design water level is partially made of armoured glass in order to provide the public with a view from the building onto the harbour area.

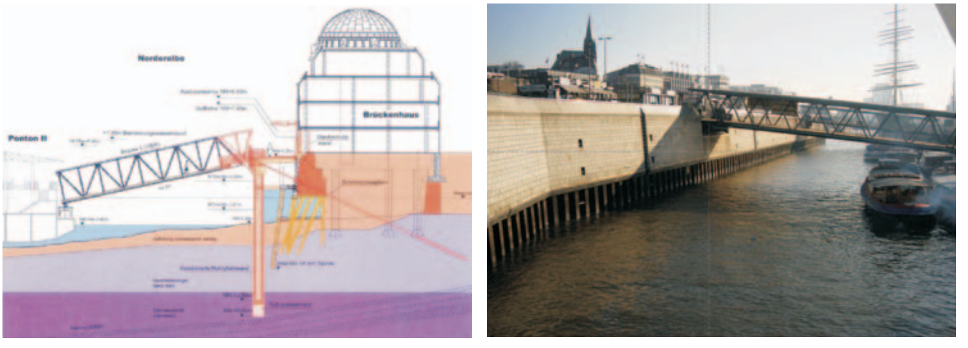

Fig. 5: Cross-section and photo of the public storm surge protection wall at 'Landungsbrücken, St. Pauli' Hamburg (photos: LSBG)

A major reconstruction of storm surge protection walls was built in 2003 at Großmarkt in Hamburg. Fig. 6 shows the overall extension of this wall of Großmarkt (left). The right side of Fig. 6 shows the storm surge protection wall from the water side. It can be seen that these walls are massive constructions which may reach considerable heights.

Fig. 6: Public storm surge protection wall at Großmarkt in Hamburg (left: aerial view; right: wall as seen from the water) (photos: LSBG, 2003)

Fig. 7 shows part of the Bostelbeker main dike which comprises a sheet-pile wall integrated in the dike line. The construction combines a classical green dike (seen from the landside in the left part of Fig. 7) with a vertical sheet-pile wall on top. Usually, space limitations and/or shortage of building material such as sand and clay are the key reasons for building vertical walls rather than sloped dike structures. Although the construction is relatively simple, other possible problems such as the structure's life time, deterioration maintenance

Fig. 7: Public storm surge protection: Bostelbeker main dike (left, length: 770 m) and sheet pile wall section at Bostelbeker main dike (right) (photos: HPA, 2007)

problems, ecological aspects, and costs have to be considered when selecting the type of protective structure. Other examples of sheet-pile walls can be found downtown in the city of Hamburg and near Finkenwerder (newly built sheet-pile walls protecting the Airbus production facility against storm surges).

In addition to vertical walls, Hamburg and other cities along the North and Baltic Sea coast maintain various other structures (gates, weirs, sluices) to prevent inhabited areas from being flooded. Examples of such structures are given in Fig. 8 with both, a mobile lift gate

Fig. 8: Use of a flood protection lift gate (left side) and a flap gate for flood protection (right side) as part of the public storm surge protection (photos: LSBG, 2007)

Fig. 9: Use of different protection gates (bulkhead gate in front and revolving gate, rear) at Dradenau main dike along the northern head of the port railway station "Alte Süderelbe" as part of the public storm surge protection (photo: HPA, 2006)

(left side) and a permanently installed flap gate (right side). In Fig. 9, another two types of gates (bulkhead and revolving gate) are depicted. Gates and mobile walls are also considered to be flood or storm surge protection structures.

All gates in Hamburg as part of the public flood protection are built following the "double safety/redundancy" concept which means that (i) there are two gates behind each other; (ii) there is always an alternative possibility to close the gate; and (iii) there are additional mechanical tools to open and close the gates. For gates, this usually means that they can either be operated by usual machinery or hydraulic engines but also by hand or emergency operation systems.

A standard type wall as part of the private flood protection has been constructed at Köhlfleet (Fig. 10). It shows an anchored sheet-pile wall with a vertical front and a back side construction with two pedestrian walkways and housing in the immediate vicinity.

Fig. 10: Public storm surge protection wall 'Köhlfleet', Hamburg
(graphics and photo: HPA, 2002)

In the private polders in the harbour, a multitude of types of storm surge protection wall is being used at various locations such as Predöhlkai (sheet-pile wall, also used as a quay wall) or Köhlfleethafen (cantilever retaining wall, Fig. 11). In the right part of the figure, the SPW is shown during construction. The different crest elevations illustrate the difference between old (crest elevation at NN + 7.50 m) and new design (crest elevation at NN + 9.50 m), which was derived from wave overtopping considerations for this part of the harbour.

Fig. 11: Private storm surge protection in Köhlfleethafen: (left: new cantilever retaining wall; right: difference between old SPW at NN + 7.50 m and new SPW at NN + 9.30 m) (photos: HPA, 2008)

3. History of Storm Surge Protection Wall Design

Whereas the history of dikes, being earthen structures, in Germany and The Netherlands is rather long (see chapter on sea dikes in this book) references to the design of storm surge protection walls are scarce, since most of these structures are either built of concrete or steel. On the other hand, there is proof that sea walls in the UK and elsewhere are dating back until Roman times and even earlier (see e.g. THOMAS and HALL, 1992). Ancient sea walls were built back to Egyptian and Constantinople times where rudiments these walls are still visible today. While these structures were made of brick or big stone blocks, modern walls use steel and reinforced concrete.

In Germany, the storm surge of 1962 has caused many dike breaches and more than 300 casualties, particularly along the Elbe estuary and in Hamburg. However, in the harbour of Hamburg where the storm surge reached NN + 5.70 m, old wharf-type structures that were built up to the same elevation were not severely affected by the storm surge. The catastrophe of 1962 triggered intensive re-design and construction of new and adapted public storm surge protection schemes, including new dikes and protection walls. The latter, rather unknown until then, were built at high speed, including the existing quay structures. It was only after the storm surge of January 3, 1976, where the highest water level ever was recorded in Hamburg (NN + 6.45 m), when the intensive design and construction of private storm surge protection walls started in the harbour of Hamburg. The private storm surge protection facilities had been previously designed for a height of NN + 7.50 m and protected major parts of the city against flooding.

At present, the public flood protection walls are being re-designed and adapted to new design water levels. Hence, the crest elevation of most of these walls is being increased or the structures are completely being replaced by new ones. New crest elevations of those structures in Hamburg are between NN + 7.50 m and NN + 9.25 m, depending on the design water level and the wave climate at the respective location. Costs for a storm surge protection wall in Hamburg may range from 20.000 to 50.000 €/running meter.

4. Present Design Practice

Presently, storm surge protection walls are being designed regarding the following parameters:

- wave overtopping over the wall crest to determine its height;
- wave induced loads on the walls;
- geotechnical aspects for wall stability.

While the geotechnical aspects of the subsoil are not considered here, both wave overtopping and wave induced loads will be briefly discussed in the following:

The crest elevation of walls is usually determined by a maximum acceptable overtopping rate under wave attack. This may be either defined based on the maximum volume of water which can be drained free of damage in the rear of the wall or on the stability of the wall or its foundation under overtopping waves. Recommendations for assessing the overtopping quantity are given in the 'Recommendations for Storm Surge Protection Walls in Hamburg' (Freie und Hansestadt Hamburg, 2007) or in the new 'Wave Overtopping Manual' (http://www.overtopping-manual.com/manual.html).

Considering wave induced loading on such walls, there is a range of different design method for a specific type of wall, none of which is really 'globally' accepted. Possible sources to design storm surge protection walls based on other parameters of influence are as follows:

- Empfehlungen des Arbeitsausschuss Ufereinfassungen (EAU, 2004 or EAU, 1996)
- Design method for vertical walls (Goda, 2000)
- Zusätzliche Technische Vertragsbedingungen – Wasserbau (ZTV-W) der Wasser- und Schifffahrtsverwaltung des Bundes

While the EAU contains design recommendations for different types of walls (e.g. sheetpile walls and gravity walls), including some recommendations for different types of wave loading and soil failures, Goda (2000) proposes design loads for vertical wall breakwaters, a method which has been found to be transferable to other vertical structures (Kortenhaus et al., 2001). The design recommendations for storm surge protection walls in Hamburg (Freie und Hansestadt Hamburg, 2007) comprise different methods for different types of loading of the wall. They also propose different measures on how to reduce the wave overtopping such as parapets and underwater sills, and they discuss the consequences of using such measures.

In addition to these general design recommendations, some of the following more practical design rules might apply:

- There should be infrastructural installations for the inspection and defence of the wall such as a road as a direct access (Deichverteidigungsweg). Elevation of the road should such as to overview the wall.
- The type of structure should be planned according to various aspects such as vibrations, noise, available space, material and equipment supply, etc.

- It might be advantageous to include in the design an option of raising the wall crest in the future.
- The use of wave dissipation systems in front of the wall should be considered in order to reduce wave heights and, consequently, loads.
- Open chambers or caviltles underneath the structure should be avoided since they have to be inspected frequently. If unavoidable, inspection possibilities have to be provided in the design.
- If sheet-pile walls are in contact with air, corrosion protection should be applied up to 0.50 m underneath soil surface. Locks should be sealed to avoid corrosion.
- To avoid erosion behind storm surge protection walls, the surface behind the wall should be armoured.
- Cable crossings should be arranged above the structure, if possible. Wherever this is not possible, cables should be bundled and pipelines carrying fluids should be equipped with additional valves.

5. Maintenance Aspects of Storm Surge Protection Walls

Storm surge protection structures are exposed to exceptional conditions under which they are required to perform their protection function, whilst they are continuously exposed to deteriorating processes. The technical demands on such structures are compounded by economic pressures and constraints on their maintenance. Since their proper functioning is not directly related to operational requirements, the allocation of sufficient budgets and resources for maintenance is problematical.

The effects of deterioration are structure and site specific. Concerning structural strength, the main deterioration processes are corrosion and fatigue. Typical indications of deterioration are spalling, cracking, and degraded surface conditions. A majority of concrete structures in the marine environment under hydraulic loads shows signs of degradation due to corrosion of the reinforcement. Beside the influence of the marine environment, other factors are responsible for the corrosion, such as: poor construction quality, inadequate standards based on prescriptive measures; and poor design as a result of insufficient information about the most important parameters that influence the degradation process.

Maintenance may be defined as "all activities aimed at retaining an object's technical state or at reverting it back to this state, which is considered a necessary condition for the object to carry out its function." This definition includes the repair of the structural strength, back to the starting level, and also any inspections. The following types of maintenance can be distinguished (JCSS, 2001):

- Corrective maintenance: there will be no inspection and repair is done after failure has occurred (this will be done if the cost of failure is low and the inspection costs are high);
- Preventive maintenance: no inspection but maintenance (repair) is done at a time no failure has occurred (this will be done when failure costs are high and failure is predictable;
- Condition based maintenance: inspections are planned and some measurable parameters are no longer fitting specific maintenance criteria (inspection intervals are fixed or depending to measured conditions)

There are two phases of a structure's life cycle in which it can be useful to apply maintenance optimisation techniques: the design phase and the serviceability phase. In the design phase, one might obtain an optimum balance between the initial costs of a structure and the future costs of maintenance and failure. In the serviceability phase, it might be possible to minimise the costs of inspection, repair, replacement, and failure. In Germany, responsibilities for maintenance works are usually laid down in the state regulation plans for the German coastal states (NLWKN, 2008; BEZIRKSREGIERUNG WESER-EMS, 2002; MLR, 2001).

To manage flood defences and structures, the maintenance has to be optimised and renewal and replacement of assets should be based on performance and effectiveness. That encourages maximum return on investment through whole-lifecycle costing. Based on such a "Performance-Based Asset Management System", critical assets will be protected from breakdown. Such a management system will lead to the following benefits:

- Asset management activity can be focused on priority areas (in terms of flood probability and consequences);
- It will enable the Authorities to assess flood risk arising from a range of asset management options, and to select cost effective maintenance/repair options;
- It will limit or stop activities that are not justified, in terms of reducing flood risk;
- Assets will be managed based on evidence of their performance and risk, accounting for climate change;
- Risk and uncertainty-based approach will allow better planning for future uncertainties.

Performance based management should be applied to all flood defence assets like embankments, walls, rivers, and tidal and sea defences. It also should be applied to structures which have a primary flood defence function such as gates, locks, sluices and pumps.

The following key problems will need to be addressed by further research (MARENGWA, 2007):

- The flood defence system is complex, with multiple components contributing to the structure's performance (or reliability) during a flood event.
- It is difficult to obtain meaningful indicators of asset performance by visual inspection alone.
- Assessing the improvement in performance resulting from management interventions (ranging from routine maintenance to major renovations) is difficult.
- Whole life asset management will need closer integration of maintenance and capital decision-making with good representation of performance over the asset's life.

6. Future Aspects of Vertical Wall Design in Germany

There is still a fundamental gap in understanding the physics of wave impacts on vertical and/or almost vertical walls (BRUCE et al., 2007). A consistent method is needed to distinguish the key loading cases for vertical or almost vertical walls (standing, slightly breaking, impact, already broken waves). Even though, after having solved this, the design for wave loads is still not simple and straightforward. So far, the key recommendation is to avoid direct wave impact on walls whereever possible. However, where that is unavoidable, a system analysis should describe the interactions between waves, structure and soil and the dynamic amplification factors for the time-dependent wave loads to be determined on this basis (CUOMO, 2005).

A new design of storm surge protection walls might be devised and considered for practical applications. This should not include the use of parapets (PEARSON et al., 2004, for a start), but also consideration of new shapes and mobile elements or even entire mobile walls.

Advantages and disadvantages of these new types of walls should be drafted and further discussed.

Further research on storm surge protection walls should deal with uncertainties related to wave loads and the methods used for design. Presently, recommendations on how to use uncertainties in design are elaborated on within a working group of EAK. Further research has also been recommended recently (KORTENHAUS et al., 2007).

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