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Restoration of a Tidal River Embankment

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Abstract

Large container ships approaching harbours via tidal rivers create strong currents and large ship waves. In the Elbe estuary near the Port of Hamburg with a tidal range of about 2,85 m the century old protection of the embankments show undulate shape even after frequent restoration. Analysis of the origin of the deformed embankment protections was done considering wind waves, ship waves and flow conditions from varying river discharges and tidal flows by using numerical and physical models which were calibrated with local field measurements. The river discharges vary between LQ = 145 m^3/s and HQ = 3.620 m^3/s at the gauge Neu Darchau. The analysis determines different reasons for the deformed protections. One reason is the construction of the embankment protection. Most embankments in the Hamburg harbour are protected with rubble or rip-rap protections. As the basement of the protection debris of destroyed buildings and quay structures are used. These are covered by loose granite stones. Another reason is the interaction of ship and wind induced waves, because even restored and redesigned embankment protections were deformed. The interaction processes were simulated with the numerical models SWAN and ODIFLOCS. The results were verified with physical models in a small towing tank of the FRANZIUS-Institute and field investigations.

Introduction

The north embankment of the River Elbe near the Port of Hamburg is protected with rubble stone or rip-rap protections in the investigation area (Figure 1).

Figure 1 Location and area of the investigation at the River Elbe near the Port of Hamburg.

The protection is located parallel to the waterside on a sandy ground with a mixed mineral grain filter. In the last years the protection was deformed and destroyed several times, even it was re-designed after each destruction (using EAK, 1993). Photos of the embankment give impressions of large groyne fields out of rubble stones, Figure 2. Similar damages of embankment protections were not observed at other river banks, therefore this damage problem has to be considered as a complex but distinct process.

Figure 2 Deformation and undulate shape of the rubble stone or rip-rap protection.

Embankment structure

Basic Facts

The embankment protections and structures described above at the River Elbe near Nienstedten and the Port of Hamburg (river km 630 until 633) were buildt between 1952 until 1956 in its actual form. At this time the original river bank was protected with debris of destroyed buildings and quay structures from the Second World War. The riverward slope was chosen to 1 : 3 and the inner slope to 1 : 2. The crest of the debris wall was covered with old quay plates. The area behind the debris wall was filled up with sand from the river ground. The riverward slope was covered with loose granite

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stones as rubble stone or rip-rap protection. Figure 3 shows the details of the construction and gives an idea of the loads, which may force the deformations and damages of the embankment protection.

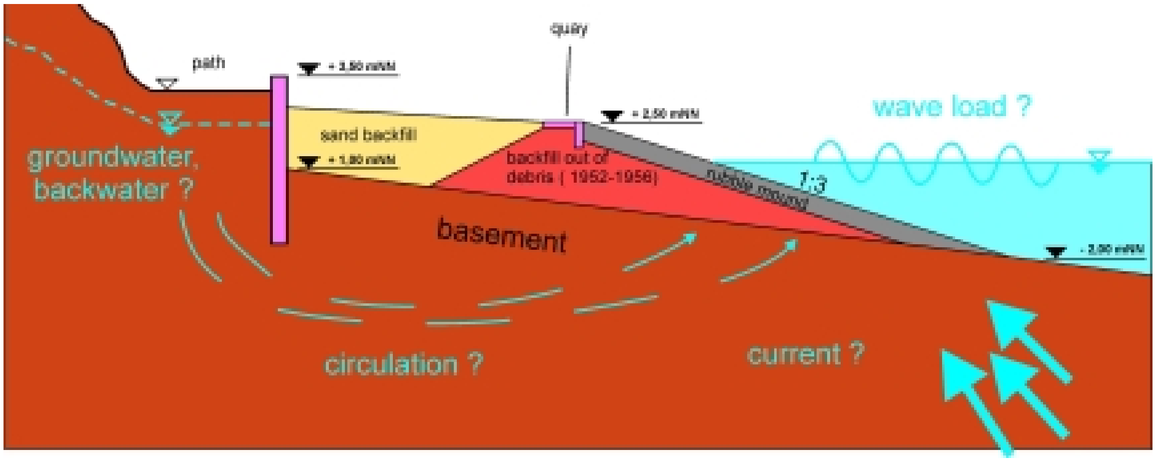

Figure 3 Cross-section of the embankment construction in the investigation area.

Geology

Only sandy and gravel river banks, which can be easily eroded require the installation of embankment protections. This kind of loose rocks must be protected with porous or nonporous protection constructions against erosion or slope failure as a result of current or wave load.

The basement of the embankment and its surrounding geology was determined in 1971 by using 18 disturbed samples of drillings in the investigation area. The location and thickness of the singular stratum can only be determined exactly for each sample drilling. The geological structure can be determined by analysing several drill samples e.g. in section A-A (Figure 1 and Figure 4). This cross-section can only give a rough impression of the strata thickness.

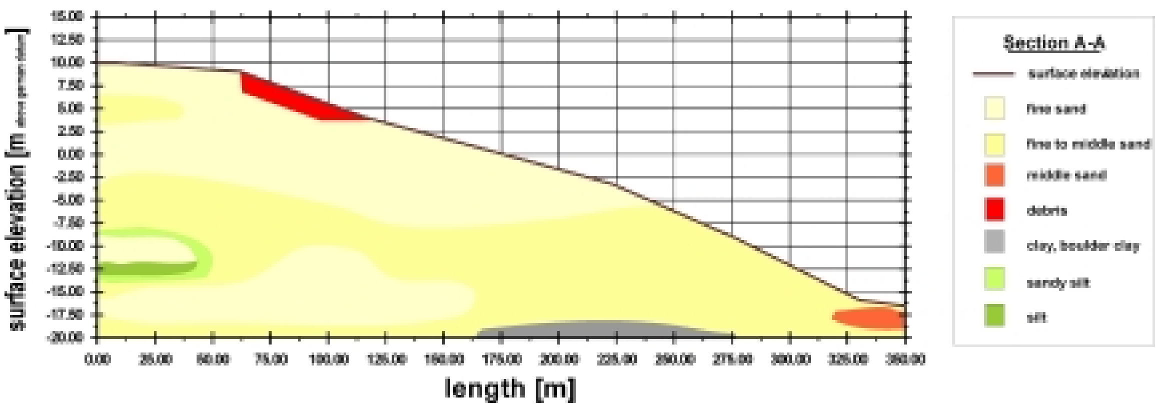

Figure 4 Geological cross-section of the river bank in the investigation area (Section A-A).

On the basis of the cross-sections it can be pointed out, that only consolidate or non-compressible stratums are situated in the investigation area. This layers can not lead to settlements or deformations of the embankment protection. Furthermore the slope and bottom of the navigation channel of the River Elbe persist of non eroding clay layers. So it can be concluded, that there is no correlation between loads of e.g. jet stream and rip-rap formations or the deformation of the river embankment.

Groundwater, Backwater

Another possible reason for the embankment deformation can be ground- or backwater and their seepage current and circulation. This inner load has an indirect impact on the stability of the protection in the form of a high hydrostatic gradient due to a fast decrease of the water surface elevation. The fast decrease of the water may be generated by ship or wind induced waves. The high hydrostatic gradient leads to water overpressure in the soil pores. Depending to the type of the soil, the velocity of the water surface depression or the soil permeability the above described overpressure can lead to a slope failure and sliding.

The groundwater level in the investigation area was explored with the help of four bearing wells. Figure 5 shows the cross-section B-B (location see Figure 1) of the ground-water level. It can be analysed that the groundwater disembogue at 0 m above German datum in the River Elbe. Even during low tide situations, these are levelled under the water surface of the River Elbe. Furthermore the ground- and backwater level is located fare under the embankment protection. Since this the ground- and backwater situated here, has no influence on the stability of the protection.

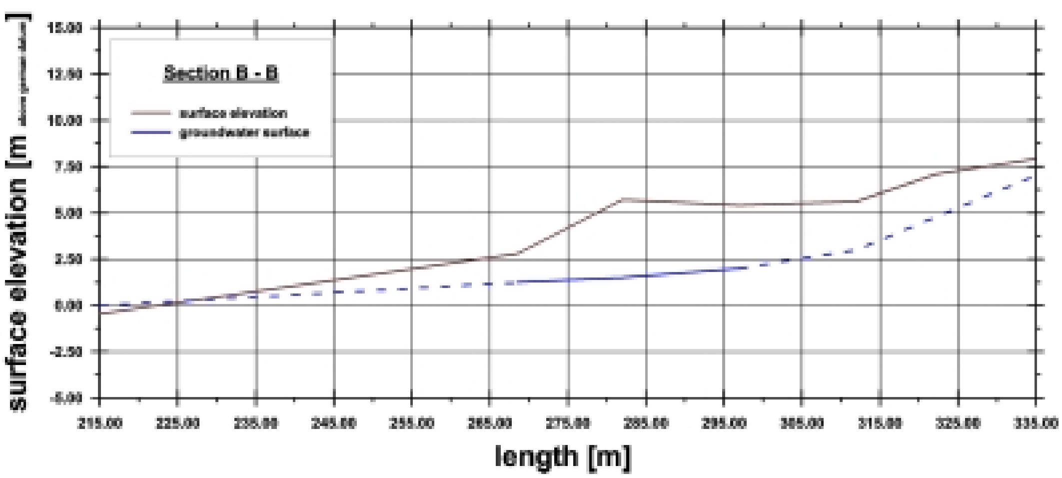

Figure 5 Cross-section of the groundwater level in the investigation area as an annual mean value (Section B-B).

Bathymetry

The bathymetry and the system geometry of the embankment protection are more relevant for the wind wave propagation and the transformation processes of wind and ship induced waves approaching the river bank. If there are shallow water conditions in the river, the bathymetry has also influence on the transforming wave processes (refraction, diffraction). These can be important factors for the design of the protection and has also influence on the choice of the design formula. During the redesign process of the last years, the HUDSON (1959) formula was used, but maybe it is better to use the formula of VAN DER MEER (1993). This equation regards also possible potential damages and the type of the protection basement.

To evaluate potential damage areas and to get an impression of the deformation it is useful to get reference bearings of the bathymetry. In order to quantify disarrangements of the river embankment protection and its surrounding bathymetry, bearings of the year 1998 were subtracted from the reference bathymetry of 1996 (Figure 6). Increased areas or aggradations are shown in red colour referring to the reference and erosions or degradations of sediment or cover stones are shown in green.

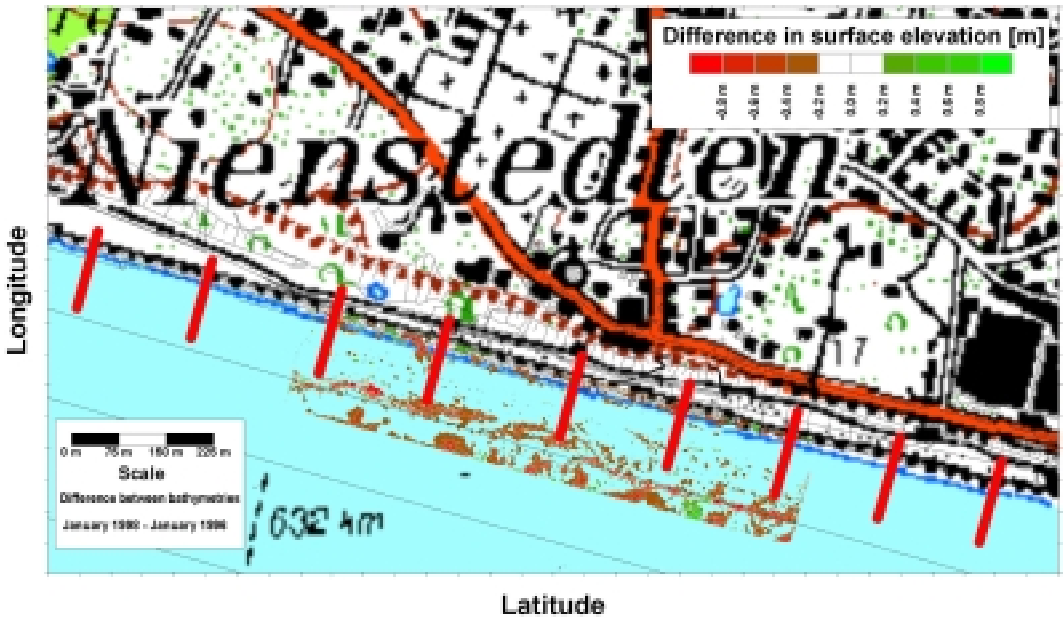

Figure 6 Difference between the reference bathymetry from January 1996 and the bathymetry from January 1998.

It's clearly visible, that a kind of groyne has been established in front of the former smooth river embankment protection, near the river km 631.8. Deformations up to 0.6 m heights took place here (vertical to the water level). During the last two years most deformations of the investigation area can be recognized in the western site. Here changes of 0.4 m height difference can be investigated.

In the eastern site less changes are visible and even those which can be detected are not significant in size. Between bearings in January 1998 and March 1998 and the reference bathymetry of 1996 not many differences are detectable. Figure 7 shows the difference between the bathymetries of January 1996, January 1998 and March 1998 at the cross-section near river km 631.8.

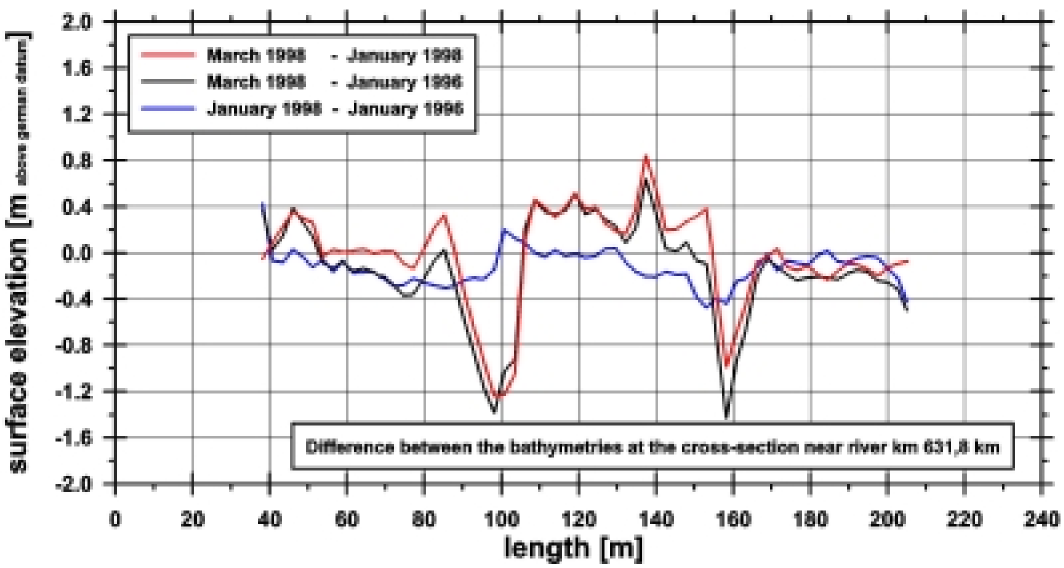

Figure 7 Difference between the bathymetries from January 1996, January 1998 and March 1998 at the cross-section near river km 631.8.

Loads from currents and waves on the embankment

Basic Facts

Direct hydraulic loads on a loose stone cover layer are only created by current processes, which are linked to a high hydrostatic gradient due to a fast decrease of the water surface elevation. This current processes are in general:

- river bank parallel directed reverse flows, often induced by ship passage.
- slope downward directed through- and overflow, caused by a fast decrease of the water surface elevation, induced by ship passage or by wind waves.

The water-flow out of the cover layer (with contents of loose stones) is, due to the flow resistance of the stones, the velocity of the water level depression and the size of the pores and cavities in the stone layer, a turbulent and delayed process. The largest flow velocities are directly linked with the sinking water level.

According to Figure 8 flows come nearly horizontal out of the cover layer, so that the stones setting directly on the sinking water level are mostly charged. The fast decrease of the water surface elevation causes turbulent flows and can therefore be treated like loose cover layers due to their erosion stability.

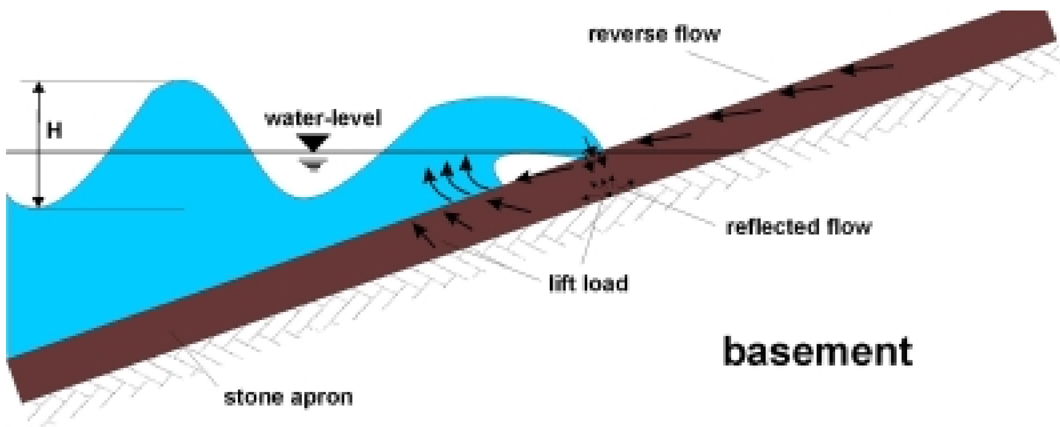

Figure 8 Currents in loose stone cover layers due to a fast decrease of the water surface elevation. [SHANK and HERBICH, 1970]

Erosions of cover layers can also be caused by direct flow influence and not only by wind and ship induced waves and flows. Here direct flow influence is less harmful considering the loosing of stones. But it is highly reasonable for the manners of diversion on cover layers.

Nevertheless direct flow can result in long-shore or cross-shore transport of already loosened stones. Periodically deformations of cover layers profiles are the result of this transport and can be seen in the investigated area (see also Figure 12).

Currents

The currents of the River Elbe were simulated with numerical model TRIM-2D by the Bundesanstalt für Wasserbau BAW, a national research organization, for the investigation area. The simulations for the investigation area between river km 630 and 633 yield to a mean flow velocity of 0.3 m/s at the river bank during ebb tide and 0.4 m/s during flood tide. During the ebb tide the flow direction is parallel to the river bank.

During the flood tide, the sheet pile at the southern side of the "Mühlenberger Loch" obviously results in a deflection of the flow direction and therefore to an oblique current attack at the western site of the embankment protection in the investigation area (Figure 9). The finite difference grid was chosen to 50 m x 50 m due to storage limitations. However this grid spacing is too large to detect the real flow direction in this area during flood tide.

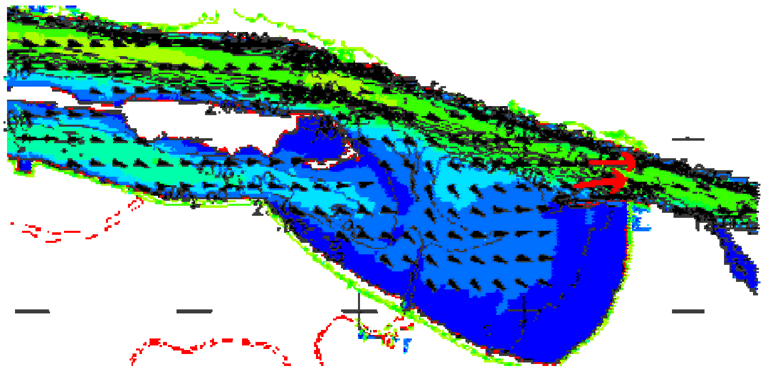

Figure 9 Simulated flow velocities during flood tide with hint of flow directions and load on the embankment protection in the investigation area. [BAW, 1996]

The simulated flow velocity poses no direct danger for the embankment protection. Using the SHIELDS (1936) diagram its not possible to lift a single stone of the embankment protection. The threshold velocity for the used cover stones (stone class II, diameter $D_{N50} = 0{,}25$ m) amounts $v_{crit.} = 2{,}5$ m/s. As also described in the MASTII (1993) research programme, the simulated flow direction and velocity can result in a long-shore transport of already loosened stones. In particular the oblique flow directions at the western site of the embankment protection can lead to periodically deformations of the cover layer , which can be observed in the investigated area.

Wave loads due to ship passage

During a ship passage different velocities with changing directions occur between ship bottom and channel bed, which are superimposed by propeller induced velocities near the stern and in the wake of the ship. In a river such velocities are superimposed to river flows, generating new velocity fields, moving with the ship. Looking for bank and bottom stability and river ecology affected from ship motions therefore requires knowledge of locally induced water level variations for analysis of pore pressure variations within bank and bottom materials together with the velocities and their directions. Figure 10 shows the system of ship induced waves.

The increase of the ship velocity leads to an increase of hydraulic impacts because of the restrictions and shallowness of waterways, resulting in increased ship-generated water level variations and reverse flow velocities.

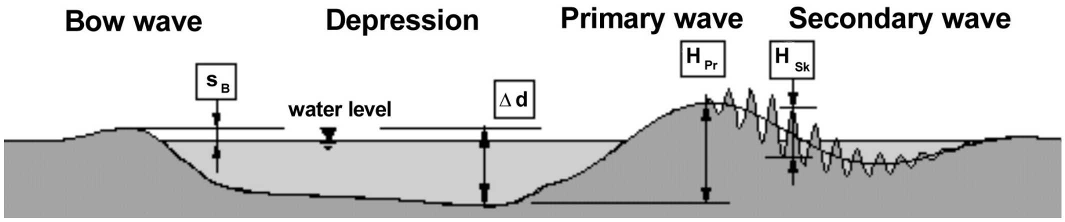

Figure 10 Schematic cross-section of a ship induced wave system. [BAW, 1996]

In order to investigate the real ship induced waves and their influence of the fast water depression, nature measurement were made. Therefore three measurement profiles were installed in the investigation area and measurement took place from 27th until 29th July 1999. At this time there were good weather conditions with nearly no winds, so that only ship induced waves were measured.

Figure 11 shows in the upper part the measured water surface elevation and the tidal water level of the River Elbe and in the lower part the water level draft and depression due to ship induced waves correlated with the ship types. In the middle of Figure 11 the daily mean maximum wave due to ship induced waves is shown. This is caused by the ship with the name “Albemarie Islands” and have a total water depression of Δd = 0.53 m, the bow wave had a height of 0.62 m and the secondary wave had a height of 0.35 m. The maximal water depression during the field measurements were investigated to 0.6 m and the period of the primary and secondary waves were determined to 5 to 10 s.

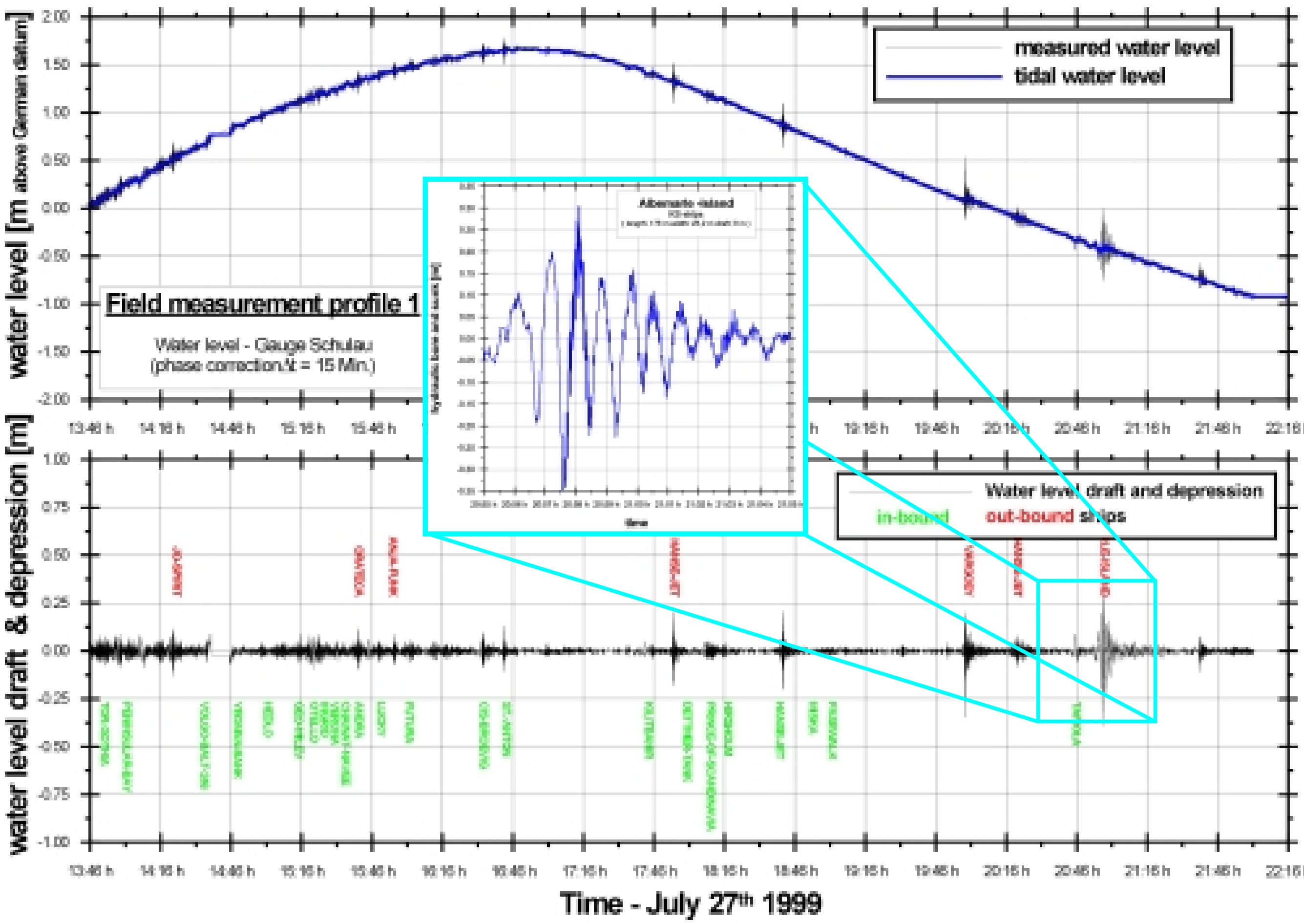

Figure 11 Field measurements at profile 1 from 27th July 1999.

Wave loads due to ship passage in the physical model

To get an impression of the deformation process at the river embankment, physical model investigations were carried out in a bed model flume without flow with a scale 1 : 45. The used cross-sections is characterising the situation of the western part of the investigation area at the River Elbe. A container ship type was used in the physical model test. The ship model was fixed to a rail carriage for quick acceleration to high speed, allowing also for a trim in the longitudinal axis.

Figure 12 show on the right site the main process for the embankment deformation. First ship and wind induced waves are loosing and lifting (red and green arrows) the cover stones and second flows due to river current and ship induced wave system (grey arrows) transporting the stones and shaping a periodic long wave (black line). The right site of Figure 12 show the results of embankment deformations in nature and physical model, after more than 1000 ship passages. By recalculating the model scale (red line in the physical model picture), comparisons between nature and physical model can been carried out.

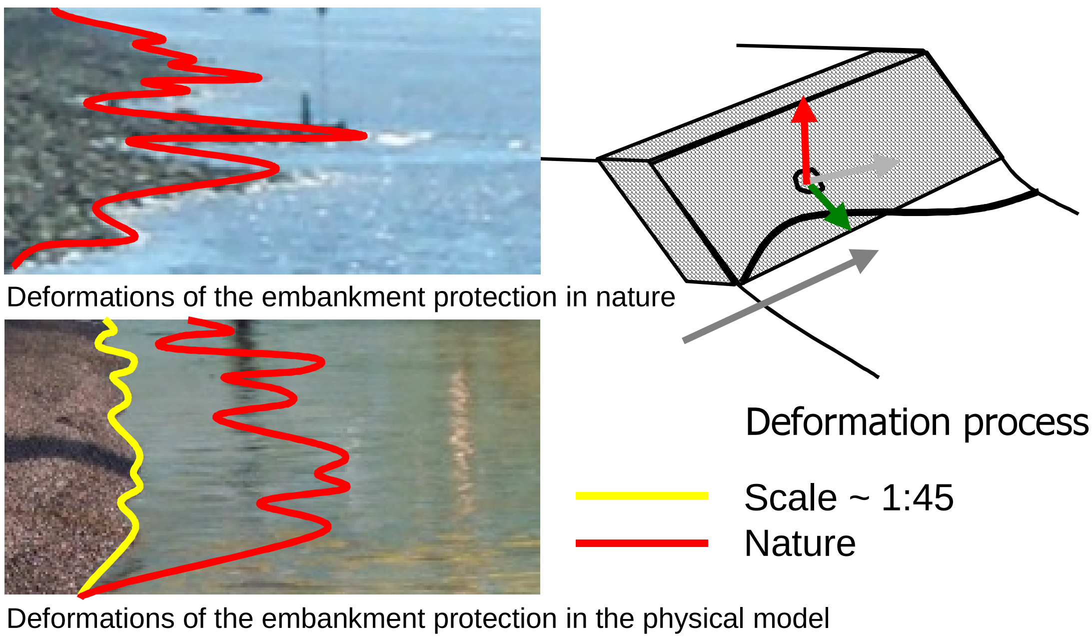

Figure 12 Deformations and their processes in nature and physical model.

Wave loads due to wind

For the embankment protection area all possible wave-propagations for different water levels, wind velocities and wind directions were calculated by the numerical wave-model SWAN, which was developed at the TU Delft and which was applied by the FRANZIUS-Institute to different investigation problems (e.g. MAI, OHLE and DAEMRICH, 1999).

In this area waves are generated by local wind fields. So the energy impact and therefore also the developing wave height are depending on the wind velocity and especially on the restricted fetch length. Winds from western directions can induce very high waves in the investigation area, since the “Mühlenberger Loch” is a wide and plane field where the wind can blow for a long distance relatively undisturbed in one direction. This is why the western site of the river embankment protection is exposed to higher waves, in the opposite to the eastern site, where the waves are lower. In this area the fetch length is short no matter for which wind direction.

Figure 1 shows the necessary bathymetry for the numerical wave-propagation of the investigated site. The grid spacing in this area was 2.5 m each in x-and y-direction. According to the simulation results it is obvious that the cover layer loads by wind wave impacts are higher than by ship waves. Also important is the amount of significant wave impacts. During each storm flood every 2-3 seconds waves with heights between 0.5 and 1 m occur, while equal ship induced waves take place only seldom during a year. As Figure 13 shows, these very high loads on the cover layer appear only with western winds and with wind velocities higher than 16 m/s.

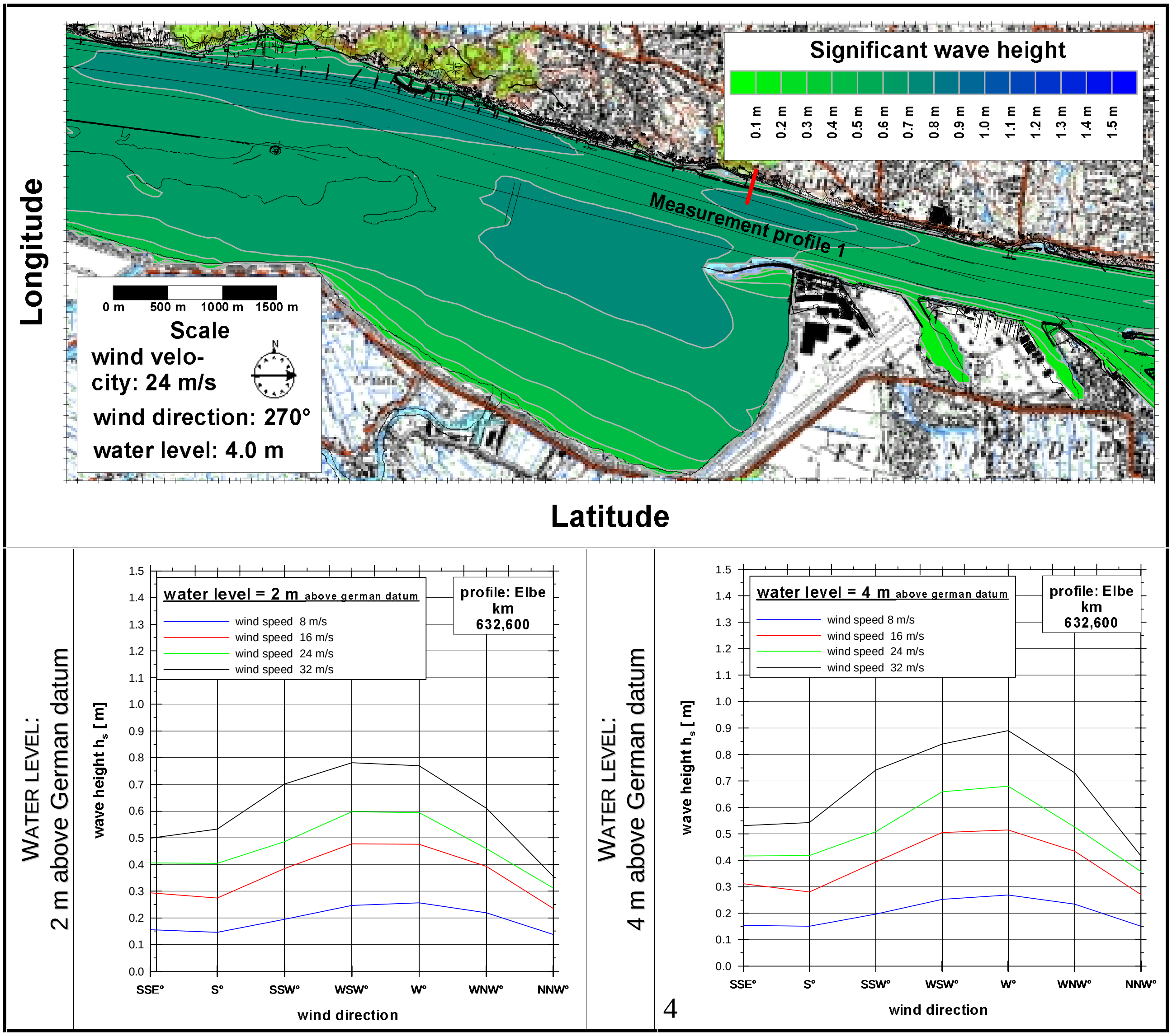

Figure 13 Significant wave height simulated with different wind situations and water levels for the whole investigation and as cross-section near river km 632.6.

Summary

The main loads on the embankment protection occur, referring to this investigation, as a result of wind wave impact, ship passage and their combination. It was pointed out that the ship velocity and the ship's distance to the river bank are the most important and only variable parameter for ship induced waves heights.

But the totality of loads and load quantity with its long periodic ship waves doesn't seem to be significant to influence the embankment protection's stability. On the opposite this investigations show that the loads due to wind induced waves during storm floods are much higher. If these loads are sufficient to cause a embankment protection deformation has to be investigated further on.

To our opinion the critical loads to deform the embankment protection are developed by the combination of ship and wind induced waves influenced by river flows. These results were used to carry out a totally new design of the embankment protection at its most threatened areas by using VAN DER MEER (1988) design proposals.

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