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Design and Protection of Artificial Underwater-Sand-Depots in the Elbe Estuary

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I. Introduction

The Elbe estuary is a very important waterway for whole Germany and consists of economical, environmental, ecological and habitation spheres. The Elbe connects the important Port of Hamburg with the approx. 100 km long waterway with the North Sea (see map in Figure 1).

The Port of Hamburg belongs to the most important harbours in the world with respect to transshipment capacities and infrastructure. Especially the growing container traffic is the reason for the further increasing transshipment rates of the Port of Hamburg. Nearly 12.000 seagoing ships and 12.000 inland vessels reach and pass the Port of Hamburg every year. In the year 2005 for the first time more than 8 Million TEU [4] were transshipped at several container terminals in Hamburg. In the northern Europe Hamburg competes at the second position after Rotterdam.

So far the navigational depth of the Elbe is a limiting factor for ship traffic, especially for large container vessels. The navigational depth of the Elbe allows ships with a maximum draught of 12.5 m to reach the Port of Hamburg independent from tidal conditions. Ships with a larger draught than 12.5 m have to consider the tidal conditions [4].

With respect to the raising container transshipment especially with ports in Asia and China and the design of the next generation of container ships a deepening of the 100 km long access channel of the Elbe between the North Sea and the Port of Hamburg is intended by German federal authorities. This measure has the aim to guaranty best economical and therefor navigational conditions for future developments of the Port of Hamburg, which is competing with other European and international ports. For further information it is referred to [4].

This aim can only be gained with a detailed planning concept, where all economical and environmental aspects have to be considered. As part of this planning process a detailed hydraulic and dredging concept concerning the hydraulic conditions along the river Elbe and management of dredged materials was elaborated by the responsible project group commissioned by the responsible German Ministry (Bundesministerium für Verkehr, Bau und Stadtentwicklung, BMVBS) and the federal state Hamburg.

One aim of this concept is the deposition of dredged sand material at several locations along the river Elbe below still water level in so called underwater-sand-depots, which have a certain hydraulic function within the estuary. This concept was already applied within the last dredging measure in the last. So these underwater-depots enable on the one hand the controlled deposition of dredged material and on the other hand a softening of the daily incoming tidal energy. Figure 1 gives an overview of the proposed locations of the underwater-depots for the coming deepening measure.

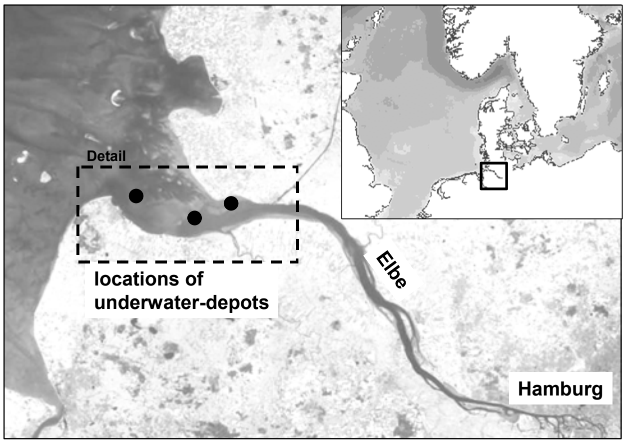

Figure 1: Map of northern Germany with the Elbe estuary and proposed locations of underwater-depots

With the placement of these underwater-depots in the western entrance of the Elbe estuary it is further intended to compensate negative consequences according to a deepening or dredging measure in the Elbe river, like reduction of the lowering of low water levels and heightening of high water levels (increase in tidal range).

This paper presents different construction methods for underwater-depots and gives explanations on their design dependent on spatial circumstances and hydraulic conditions. Finally recommendations for the construction of underwater-depots are given.

II. PAST AND PRESENT DEEPENING MEASURES IN THE ELBE ESTUARY

A. Deepening measures of the Elbe estuary in the past and hydraulic consequences

In the past the river Elbe has been deepened several times. 200 years ago Hamburg had to conduct dredging measures for increasing drafts of ships and against ongoing sedimentation in the Port of Hamburg. Since 1834 the dredging work was done by steam dredgers. Until 1897 ships with a draught of 4.3 m (7.9 m at high water) could reach Hamburg, but sedimentation was still going on. Therefor a further deepening of the Elbe of 10 m below low water level was conducted, accompanied by additional construction measures (like groins) along the river. The historical development of the deepening measures is described by Keil (1985). The latest deepening measures of the Elbe are summarized in Table 1.

TABLE 1: LATEST DEEPENING MEASURES OF THE ELBE BETWEEN HAMBURG AND THE NORTH SEA

depth below chart zero (LAT)	period of dredging works
11.0	1956 – 1961
12.0	1964 – 1969
13.5	1974 – 1978
14.5	1997 - 2000

With each dredging and deepening measure of the Elbe estuary in the past the hydraulic conditions, namely water levels and tidal range, were changed apart from natural influences and changes. The deepening measure reduces the hydraulic roughness of the estuary which leads to a reduction of tidal energy dissipation and an amplification of the tidal amplitude in the estuary. This effects generally increased tidal currents in the main river channel after dredging works, while sedimentation increased in flat areas and branches of the Elbe river caused by reduced currents and increased sedimentation. For further explanations concerning deepening measures in estuaries and their hydrodynamic effects it is referred to Flügge (2002).

B. Aim of the elaborated dredging measure and hydraulic concept

It is the aim of the elaborated dredging measure for the next dredging campaign to increase the navigational depth downstream of Hamburg for larger vessels and at the same time to reduce the consequences on hydraulic conditions to a minimum with the help of the deposition of dredged material.

The hydraulic concept proposes therefore an increased hydraulic roughness and tidal energy dissipation, which will be gained with the help of underwater-sand-depots in the western end of the Elbe estuary, and a resultant reduction of the hydraulic changes in water levels and currents along the access channel. A potential variant of underwater-depots is illustrated in Figure 2.

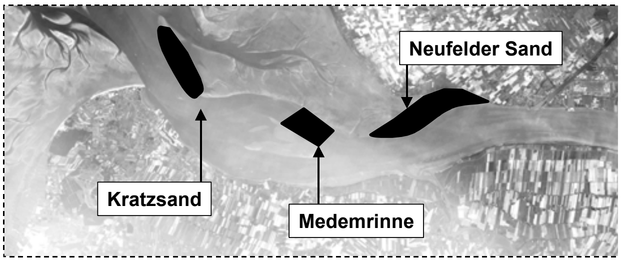

Figure 2: Location of three planned underwater-sand-depots in the Elbe estuary as detail to Figure 1

In the estuary mouth the navigational channel shifts to the southern coastline. The underwater-depots, placed closely to the access channel, reduce the cross section significantly in the entrance to the estuary, which leads to an increase of shear stresses and a loss of incoming tidal energy in upstream direction. This energy reduction results in a reduction of proposed water level changes in case of the deepened Elbe river. This effect is mostly expected with the depot *Kratzsand*.

Additionally the currents are concentrated in the deeper river channel parts. The depot *Medemrinne* will guide the flow along the navigational channel and not go apart through the *Medemrinne*, which results in increased currents in this area in the navigational channel.

The hydraulic function of the depot *Neufelder Sand* is also the guidance of the tidal flow and concentration of the currents in the main river parts in order to avoid the deflection of the tidal currents towards the tidal flats *Neufelder Sand* and *Neufelder Watt*.

III. CONSTRUCTION OF UNDERWATER-SAND-DEPOTS

A. General

With regard to the construction of the underwater-sand-depots it has to be investigated how mobile this depot has to be and is allowed to be because of its hydraulic function and durability in a morphodynamic active environment. Considering the impacting currents and waves in the Elbe estuary it is evident that an underwater-depot consisting of dredged material has to be built and protected in a certain way that its function is guarantied for a certain life time. More information on the hydraulic design conditions are given in chapter IV. In the following different construction methods are presented and discussed based on [5].

B. Construction methods for underwater-sand-depots

Underwater-depots generally change the cross section geometry of the river and influence the flow. The resulting influence on the hydraulic conditions can be minimized if the depot is adopted, smoothened and integrated into the given topography. The following construction types of underwater-depots are summarized and illustrated in Figure 3:

- natural slopes with protection layer (riprap),
- bordering dams and backfilling with protection layer and
- bordering dams with new front slope and backfilling with protection layer

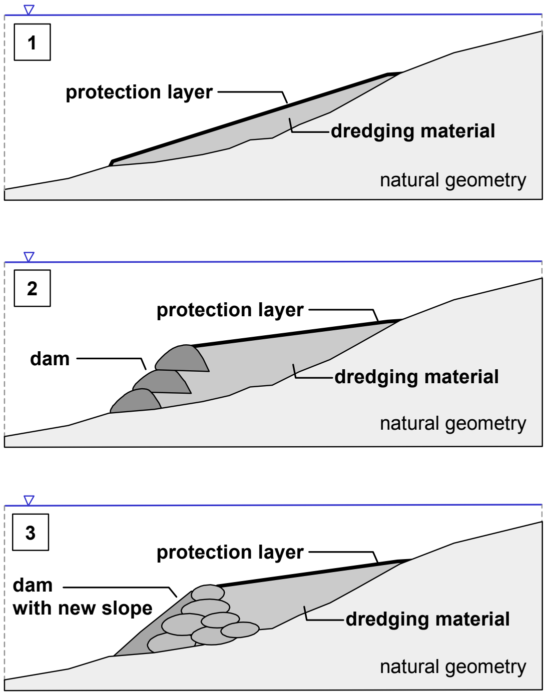

Figure 3: Construction types for underwater-depots (schematized)

If possible the dredged material can be deposited within the underwater profile (adopted to the natural geometry) without changing the cross section significantly (case 1 in Figure 3). Normally the possible volume of the material deposition is very limited. In comparison to the surface, which has to be protected dependent on the hydraulic impact, the deposition volume is quite small, which results in higher deposition costs.

In the second case (case 2 in Figure 3) bordering dams, i.e. made of stones, can be built and used during the dredging and deposition works in such a way that the backfilling material will not be transported out of the working field, which is common practice for dredging works. The material of the bordering dam varies between stones and geotextile tubes or any other stable construction element. The bordering dams have the function to define a certain stable underwater dam, which surrounds the deposition area and reduces the mobilization and transport of the deposited dredging material. The bordering dam can be constructed with a quite steep slope that the backfilling volume will be larger than in case 1 of Figure 3.

Parallel to the ongoing construction works the bordering dam is increased in height. If necessary a protection layer is finally constructed, which covers and protects the deposition area. This protection layer has the task to resist against the hydraulic impact and guaranty for the shape and geometry as well as for the hydraulic function of the underwater-depot. In case of reduced hydraulic impact or coarser grain sizes of the dredged and deposited material the protection layer can be neglected.

As a third case the bordering dam with additional front slope and backfilling with protection layer is illustrated in Figure 3. In comparison to case 2 an additional front slope covers the bordering dam. This could be necessary for geotechnical or hydraulic reason.

The volume of the dredged material, the given topography at the location as well as the hydraulic conditions have influence on the proposed geometry of the underwater-depot. If a certain hydraulic function is intended with the underwater-depot each component of the construction has to be designed for the boundary conditions.

C. Construction of the bordering dam

The bordering dam can be built with different materials and methods as summarized and illustrated in Figure 4:

- quarrystones
- gabions
- geotextile containers with filling
- geotexile tubes with sand filling
- sheet piling

Figure 4: Construction types for the bordering dam

The most common method to build a bordering dam is the use of quarrystone, because of the flexibility, the easy handling and the construction costs. Gabions are possible to use but not the common case.

In case of the use of geotextile container more effort is necessary to fill, transport and displace the container at the location. For geotextile tubes detailed experience for the filling is important.

Sheet piling is cost intensive and only economically effective if there is not enough space to build a dam or a slope.

All construction types have to be compared with regard to the suggested building, also in combination with the construction types for the protection layer in order to find the best solution. For further information it is referred to [11] and [12].

D. Construction of the protection layer

The necessity of a protection layer is a function of the hydraulic impact and the definition on the acceptable mobility of the depot material.

The protection layer has to be designed considering filter stability (geotechnical design) and erosion by hydraulic impact (hydraulic design). In general the protection layer can consist of different layers (see Figure 5) with corresponding functions as

- filter layer,
- armour layer or
- combined construction types.

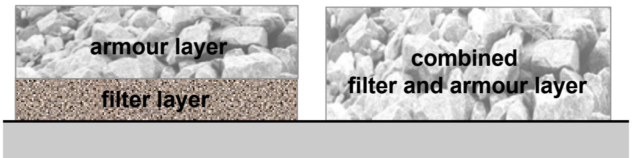

Figure 5: Construction types of the protection layer

Possible materials are stone materials with certain grading, weight and stone sizes or geotextile layers, also in combination with concrete blocks. In the following the above mentioned construction types are shortly discussed.

1) Filter layer

Filter layers consist of different natural or artificial stone mixtures with different grading. The corresponding sieving curve has to be designed for the soil material (lower border) and armour stones (upper border). The filter layer can also consist of a geotextile mattress, like illustrated in Figure 6.

Figure 6: Geotexile layer before controlled sinking process

2) Armour layer

The armour layer has the task to resist against the hydraulic impact like tidal and wave-induced shear stresses and has to be designed for this. In most cases armour stones are used for the armour layer. In cases with extreme hydraulic conditions it can be necessary to interlock the stones with underwater concrete.

Figure 7: Armour stones

3) Combined construction types

Combined construction types fulfill two requirements according to the filter and armour layer, which means filter stability against the soil and hydraulic stability against the impacting current and wave forces. Construction types can be

- single layer stone mixtures,
- geotextile mattress with sand or concrete filling,
- geotextile mattress with concrete blocks or
- material mattress made of tires

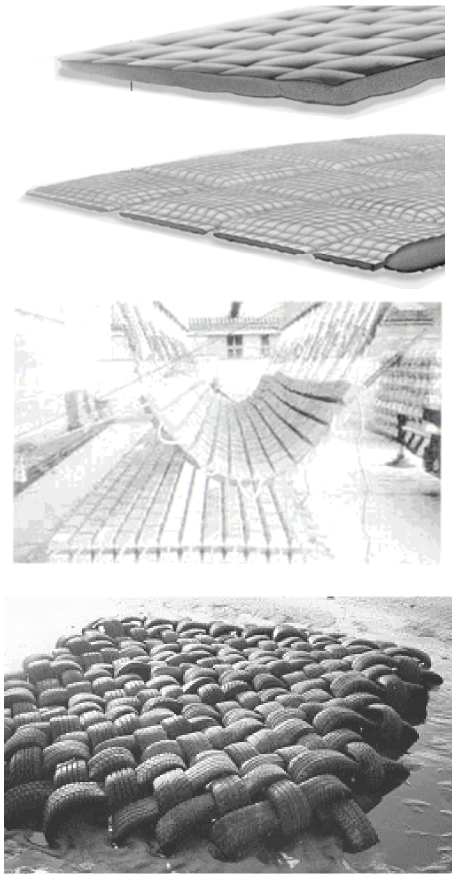

Figure 8: Combined construction types: mattress with sand/concrete filling (top), mattress with concrete blocks (middle) and mattress of tires (below)

The most used combined construction type is the single layer stone mixtures because of its flexibility, easy construction and small construction costs. For certain applications also other construction types are used as illustrated in the Figure 8.

E. Recommendations for construction of bordering dam and protection layer

For the decision of the perfect method for construction of the bordering dams and protection layer many project specific boundary conditions have to be investigated and evaluated for the project.

The decisive points are the stability of the construction under the hydraulic conditions, the flexibility in case of necessary modifications on the repositories and the economy of the chosen construction. The construction time is an important fact as well as ecological aspects and the necessary effort for maintenance of the construction.

In the specific project the criteria were weighted separately for all underwater depots (see Figure 2).

IV. Design of Underwater-Depots in the Elbe Estuary

A. Design requirements

The underwater-depots are placed in the complex area of the Elbe estuary, which underlies continues morpho-dynamic processes and resulting changes of the morphology. This depot area is open for incoming tidal movement as well as for wind and ship waves, which means that also the underwater-depots have to be designed for these hydraulic conditions.

Caused by the proposed depot geometry and position in the dynamic estuary different hydraulic impacts scenarios have to be considered for the protection design as well as requirements for the long-term stability of the depot. Therefore a detailed analysis of the hydraulic impact and the abbreviated design conditions was carried out.

As a geometrical boundary condition the top of the depot *Kratzsand* is particularly below the mean low water level in order to achieve the intended hydraulic behaviour and function.

B. Hydraulic boundary conditions

With regard to the design of the necessary protection layer of the underwater-depots numerical simulations of the wave and current conditions have been conducted by the Federal Waterways Engineering and Research Institute (BAW). The hydraulic design conditions were further extracted and defined for the design of the protection layer.

Especially the underwater-depots *Kratzsand* and *Medemrinne* located in the river mouth will be stressed by fairly high wind and ship induced waves as well as tidal currents. The depot *Medemrinne* with a schematic cross section is exemplary illustrated in Figure 9.

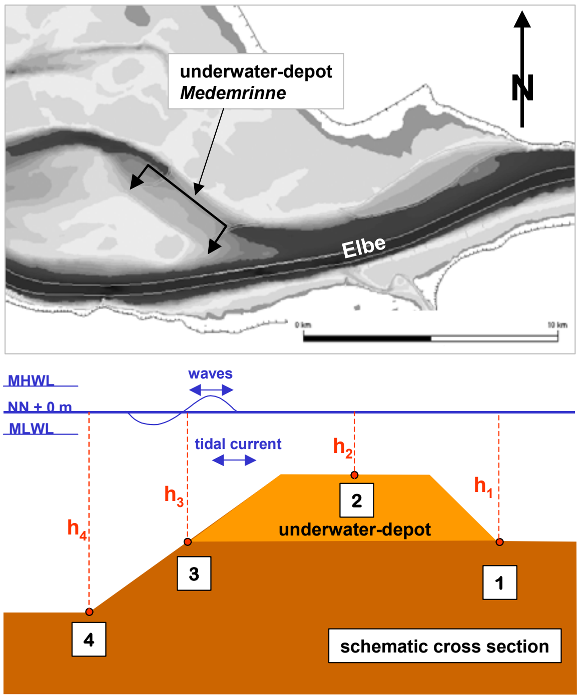

Figure 9: Underwater-depot *Medemrinne with* schematic illustration of the cross section

Investigations showed that the most relevant scenarios are low water levels in combination with relatively high waves, which resulted in highest shear stresses at the slope and the top surface of the depot. With increasing water level the resultant bed shear stresses reduce significantly compared to the shear stress increase by to increased wave parameters. Therefor the following range of design conditions have been considered for the depot *Kratzsand* and *Medemrinne* in the design scenarios :

- minimum water depth below LAT: 1.0 m – 2.0 m
- maximum tidal currents:1.6 m/s – 3.0 m/s
- max. wind waves H_s/T_m for LAT: 1.15 m / 3.7 s
- max. ship waves H_s/T_m for LAT: 1.0 m / 4.0 s
- underwater-depot slopes: 1:3 – 1:10

C. Hydraulic design

In general these underwater-depots influence the tidal dynamic of the Elbe estuary. According to the hydraulic impact mainly by waves and tidal currents an adequate protection of the underwater-depots is necessary in order to guaranty the essential local stability of the depot in the dynamic estuary and maintain the intended and corresponding hydraulic function. The most relevant design scenarios are low water levels in combination with relatively high waves.

1) Approches for protection layer design

For the design of the depot protection different engineering solutions were investigated. With regard to the preferred solution as grain filter or riprap with larger stones, if necessary, a comparison of different existing formulas and approaches for stone size design has been conducted and led to a wide bandwidth of protective measures. An overview of existing calculation methods is given in [7], [8], [9], [10], [11] and [12]. The calculated stone diameters varied with a factor of 10 to 15.

The major input for the practical use of such formulas is the correct and adequate description of the current profile and the turbulence (see Figure 10), which has a significant influence on the design of necessary stone sizes and finally the construction costs. Additionally the acceptable mobility of the stone has to be defined.

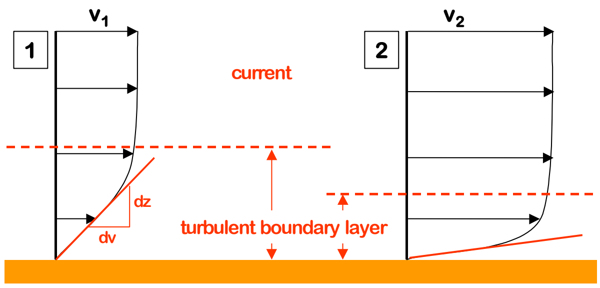

Figure 10: Current profiles with low turbulence (1) and high turbulence (2)

It has to be differentiated between current profiles with low turbulence intensity in the boundary layer and current profiles with high turbulence, which can mobilize grains or stones which would be stable under conditions with low turbulence intensity.

In case of tidal currents and undisturbed flow a current profile with low turbulence intensity is expected, which means that grains or stones at the bed have to resist a quasi constant hydraulic impact. In this case the calculation method of Shields or Hjulström (in Zanke, 1982) can be applied to calculate the necessary stone diameter against erosion.

In case of a current profile with higher turbulence intensity in the boundary layer, calculation methods of Isbash or Pilarczyk have to be applied.

2) Application of the Shields concept

While composing all information and calculation results the Shields concept was applied for the design of the scour protection of the underwater-depots in the Elbe estuary under the given hydraulic conditions considering different slopes and current impacts as well as wave induced shear stresses. For detailed description of the scientific background it is referred to Soulsby (1997), Pilarczyk (1998) or CIRIA/CUR (1991).

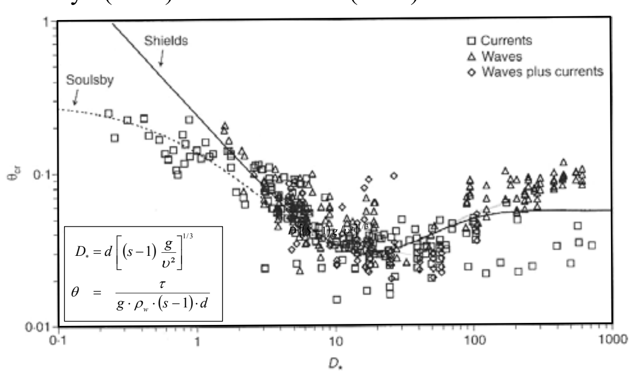

Figure 11: Critical Shields parameter as a function of the dimensionless grain size (after Soulsby, 1997)

The Shields diagram defines the critical Shields parameters for grains or stones larger than D* = 150 (equivalent to grain diameter of 7,5 mm) with a constant value of 0.055 (Soulsby, 1977) or 0.060 (Pilarczyk, 1998). For larger stones no detailed information is available to define the critical Shields parameter. It can be assumed that the critical Shields parameter increases with increasing stone diameter and angle of repose, but more research has to be done in order to gain engineering and calculation approaches.

3) Results

As a result necessary stone sizes were calculated for all underwater-depots dependent on the given boundary conditions. The protection layer was designed as single grain filter layer with the mentioned advantage that a self-armouring effect establishes which means smaller stones are carried away and larger stones of the mixture protect the dredged material. Exemplary a possible protection strategy for the underwater-depot *Medemrinne* is illustrated in Figure 12.

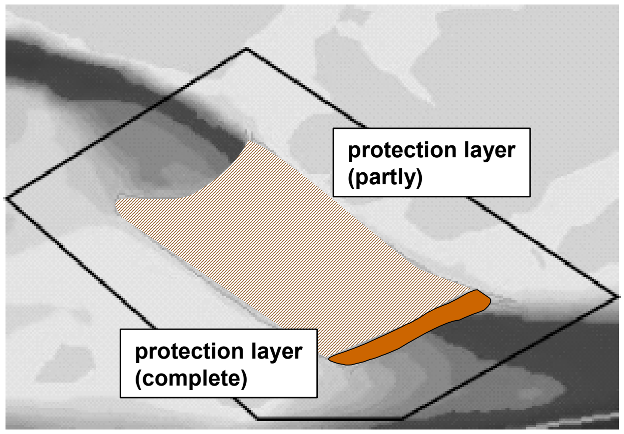

Figure 12: Possible protection strategy for the underwater-depot *Medemrinne*

V. Recommendations

For choosing the best fitting construction method for bordering dams and protection layers the hydraulic conditions have to be examined very detailed for the specific locations.

With the knowledge of the hydraulic conditions the correct design concept has to be chosen in order to find a design which is on the one hand stable for the hydraulic conditions and on the other hand as cost effective as possible.

The applied hydraulic design concept has to be verified with the expected, measured or calculated hydraulic conditions. The characterization and correct description of the flow including the turbulence intensity has to be done intensively with respect to the deposition and protection costs of the dredged material. With regard to all boundary conditions the acceptable freedom of movement of the protection layer or unprotected deposition areas has to be investigated and finally defined. Small changes in the design results have great influences on the construction costs.

With all this boundary conditions a detailed engineering and design for the repositories has to be made in order to optimize the construction.

ACKNOWLEDGMENT

Investigations on feasibility, construction and protection of underwater-depots in the Elbe estuary [5] have been conducted on behalf of the Wasser- und Schifffahrtsamt Hamburg.

REFERENCES

[1] Keil G.W. (1985) Die schrittweise Anpassung der Elbe an die Entwicklung des Seeschiffsverkehrs. Jahrbuch der Hafenbautechnischen Gesellschaft, Band 40

[2] Flügge, G. (2002) Ausbauvorhaben in Tideästuaren – Erläuterung der wirksamen hydromechanischen Prozesse. Jahrbuch der Hafenbautechnischen Gesellschaft, Band 53

[3] Soulsby, R. (1997) Dynamics of Marine Sands. Thomas Telford

[4] Projektbüro Fahrrinnenanpassung, Wasser- und Schifffahrtsamt Hamburg, www.zukunftelbe.de

[5] IMS Ingenieurgesellschaft mbH (2006) Feasibility study on underwater-depots (unpublished). On behalf of the Wasser- und Schifffahrtsamt Hamburg

[6] CIRIA/CUR (1991) Manual on the use of rock in coastal and shoreline engineering, CIRIA special publication No. 83, CUR report No. 154, Balkema

[7] Bundesanstalt für Wasserbau (2004) Grundlagen zur Bemessung von Böschungs- und Sohlensicherungen an Binnenwasserstraßen. Federal Waterways Engineering and Research Institute, Mitteilungsblatt Nr. 87

[8] Zanke (1982) Grundlagen der Sedimentbewegung. Springer Verlag

[9] DVWK (1997) Maßnahmen zur naturnahen Gewässerstabilisierung. DVWK-Schriften, Heft 118

[10] Hansen (1987) Wasserbausteine im Deckwerksbau. Westholsteinische Verlagsgesellschaft Boysen & Co.

[11] Pilarczyk, K.W. (1998) Dikes and revetments – design, maintenance and safety assessment. Balkema

[12] Przedwojski, B and Pilarczyk, K.W. (1998) River training techniques – fundamentals, design and application. Balkema

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