

PROPERTIES OF FLUID MUD AND PREVENTION OF SEDIMENTATION

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ABSTRACT

The open tidal harbours of Emden, Bremerhaven and Brunsbuettel on the German North-Sea Coast, are situated in the brackish zone of the tidal rivers Ems, Weser and Elbe. In these zones the intermixture of fresh water coming from inland with salt water coming from the North-Sea results in high concentrations of fine cohesive sediments. In these harbours fluid mud layers can reach a thickness of up to several metres in areas with low current intensity. The annual rates of sedimentation are an order of magnitude higher than in the harbours of Bremen and Hamburg, both situated upstream of the seawater influence. The causes for the accumulation of solid material are the superposition of tidal and density currents.

A research project was initiated (German Ministry of Education and Research, BMBF, registration: 03 KIS 051) to explore the sedimentological and rheological fluid mud properties of different brackish water harbours at the German North-Sea Coast.

The analysis of dual frequency echo soundings (210 kHz and 15 kHz) have shown that the fluid mud volumes in the outer harbours of Emden, Bremerhaven and Brunsbuettel are nearly constant over a period of years. The key for the creation of fluid mud is the presence of a bar at the harbour entrances.

The paper will present results of the in situ measurements and methods for prevention of sedimentation in harbours. The behaviour of the cohesive sediments is determined not only by physical but also by chemical and micro-biological processes. With changing rheological properties (viscosity and shear strength) fluid mud adopts increasing plastic attributes inside a transition zone.

With the knowledge of the current and morphological conditions strategies have been developed with water injections or remedial dredging to Keep the Sediment in the System (KSIS). Management of fluid mud is possible either by Keep the Sediment Moving (KSM) or Keep the Sediment Navigable (KSN).

With these measures conventional dredging in the outer harbours has been reduced to zero, saving costly deposition or dumping of dredged material.

Keywords: fluid mud pattern, navigability, solid matter, ignition loss, density, viscosity.

INTRODUCTION

Harbour basins adjoining tidal rivers in the brackish zone suffer from high rates of sedimentation. On the German North-Sea Coast this is the case in Emden, Bremerhaven and Brunsbuettel (fig.1). In these harbours the rates of sedimentation are an order of magnitude higher compared to the harbours of Bremen and Hamburg, both of which are situated upstream of the salt water influence (Nasner, 1992; Christiansen & Haar, 1996).

The sediment influx into brackish water harbours is caused by the superposition of flood current orientated eddy and density currents. Figure 2 illustrates the schematic current pattern derived from in situ current measurements in outer harbours on the Rivers Ems, Weser and Elbe. The measurements were carried out as part of a KFKI research project (03 KIS 019) funded by the German Federal Ministry of Research (BMBF) (Nasner, 2004). During the flood tide the suspended sediment is carried into the harbour basin via near bed density currents separating from the eddy. During the ebb tide the current directions are reversed, but not so intensive,

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thus leading to an accumulation of solid material in the basin. This is why there is a positive sediment budget in brackish harbour basins.

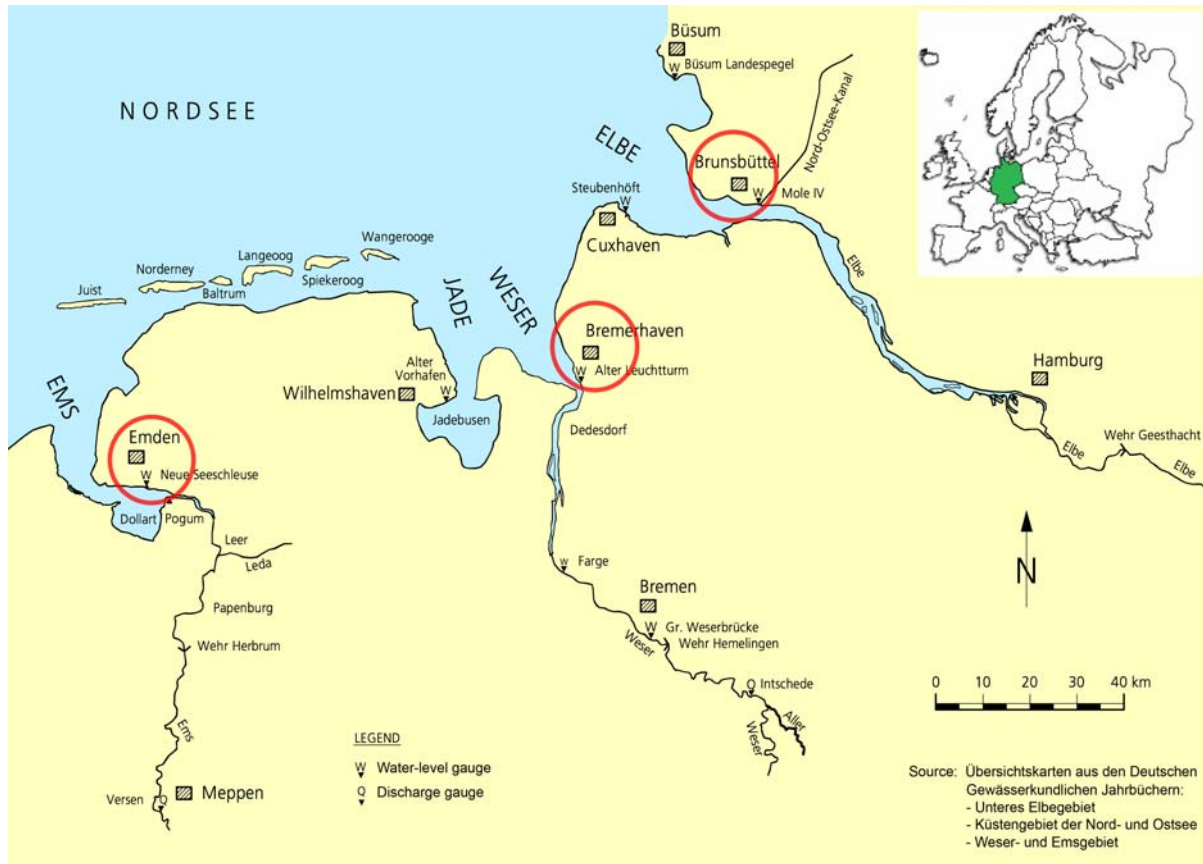


Figure 1. Map of the German North-Sea Coast.

The fine sediments, driven as suspended load into the harbour by the currents, consist mainly of silt and clay with a high organic content. They are a pre-stage of fluid mud. The particular sediment properties cause the formation of fluid mud layers in the basin which can reach a thickness of several metres.

A current research project was initiated (BMBF, registration 03 KIS 051) to explore the sedimentological and rheological fluid mud properties of different brackish water harbours on the German North-Sea Coast. Samples were taken from the fluid mud layers to analyse ignition losses, density, viscosity and the solid matter.

Microbial slimes that are produced by micro-organisms give the fluid mud buoyancy. Sedimentation tests in our institute have shown that fluid mud takes more than 14 days to settle under laboratory conditions which, owing to tidal currents and ship movement, are not found in situ.

Fluid mud is not comparable with firm sediment layers. This material consolidates only very slowly above the solid bed. Fluid mud has a very low density and viscosity and consists mainly of water. This makes it navigable. It is important that the aerobic state is maintained for the micro organisms to survive. Detailed investigations have been carried out into fluid mud in the Emden Outer Harbour (Greiser et al., 1992; Wurpts, 1997, 2003, 2005)

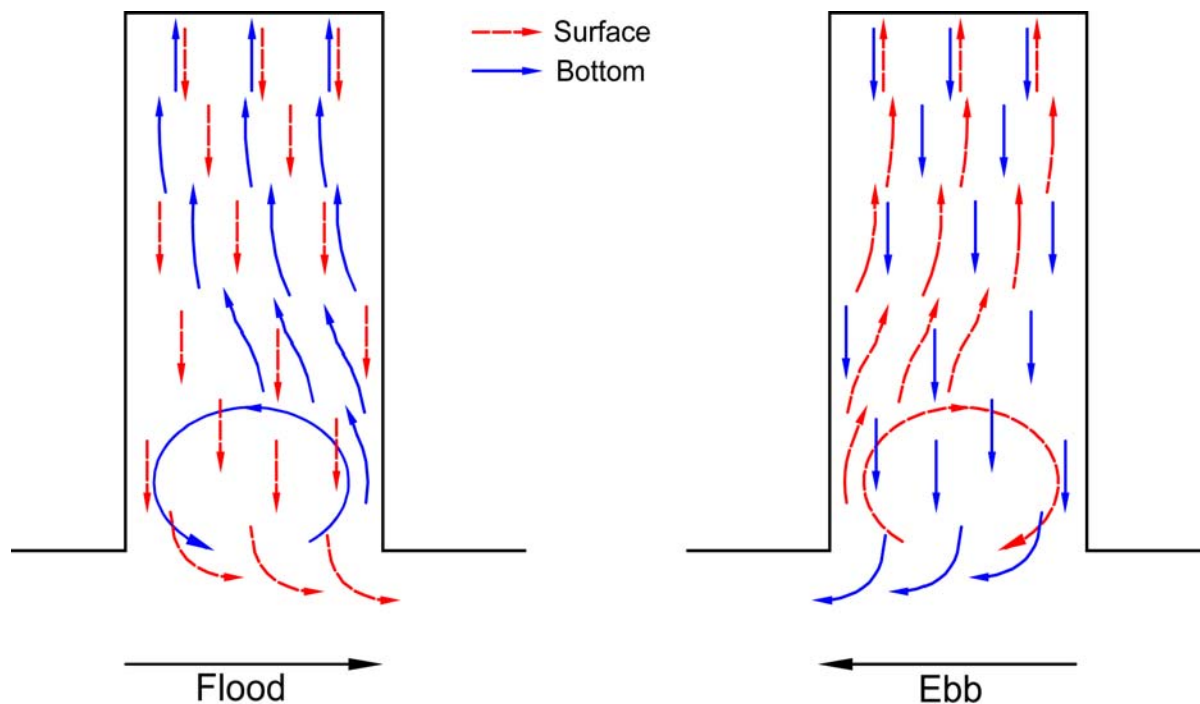


Figure 2. Superposition of Current and Density Effect (Schematic).

ANALYSES OF SOUNDINGS

The analysis of dual frequency soundings can give an insight into the fluid mud patterns in brackish water harbours. In the following, examples of low frequency soundings (15 kHz) together with difference maps showing the fluid mud volumes in the outer harbours of Emden, Bremerhaven and Brunsbuettel will be explained.

Emden

The Outer Harbours of Emden are deeper than the adjoining River Ems (fig. 3). The nominal depth for the Ems fairway is 8.5 m below SKN (SKN = Chart Datum).

The analysis of soundings covering a period of two years has shown that there is an average fluid mud volume of $V \approx 662\,000\text{ m}^3$ in front of the locks. This volume varies by less than 20 % at the most i.e. it is a highly stable layer (Wurpts, 2003). This is obtained by a special dredging method that maintains the nautical depth while keeping the fluid mud in situ.

The sounding from April 2005 shows that the volume of the open harbours is $V \approx 708\,000\text{ m}^3$ and $V \approx 852\,000\text{ m}^3$ in the impounded harbours (fig. 3). The highest differences of up to $\Delta h \approx 5\text{ m}$ are in the deepest areas of the tide influenced harbour basins in front of the sea locks. The average thickness of the fluid mud layer is $\Delta h \approx 3.4\text{ m}$ in the Aussenhafen and $\Delta h \approx 2.4\text{ m}$ in the Vorhafen.

The fluidity of fluid mud becomes clear by regarding the fluid mud pattern in the inner harbour. Fluid mud flows into the deeper areas. Differences of 3 to 4 metres can be found in areas with depths greater than 9 m below SKN.

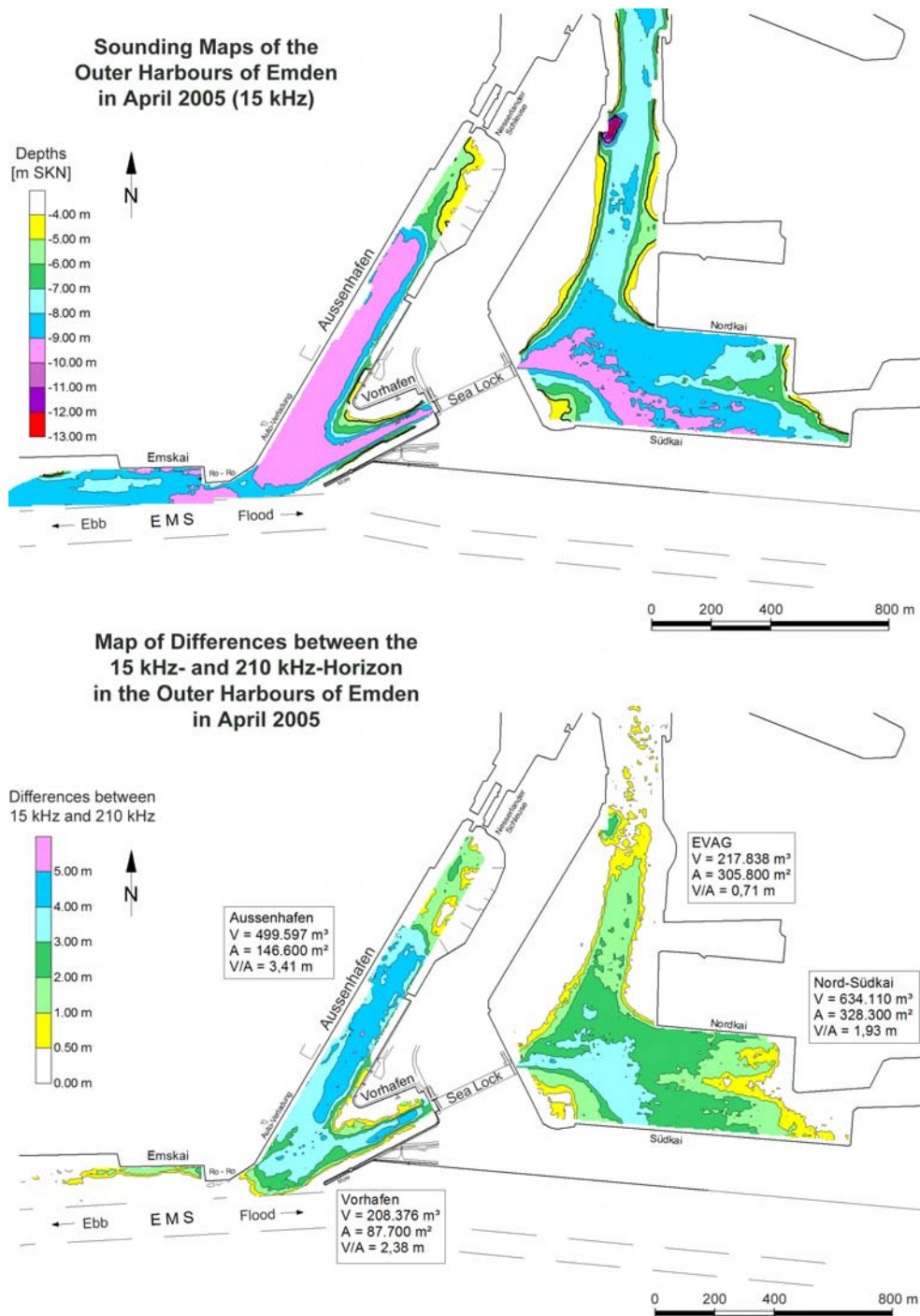


Figure 3. 15 kHz Sounding from Emden and Map of Differences in April 2005.

Bremerhaven

Fishery Harbour Lock

The soundings from January/February 2002 show the situation in the approach to the Fishery Harbour Lock (fig. 4). It is similar to the morphological situation in Emden. The bar in the entrances blocks the natural gradient to the River Weser (15 kHz in fig. 4).

The analysis of soundings covering a period of four years (2001/2004) has resulted in a calculated average fluid mud volume of $V \approx 116\,000\text{ m}^3$ in the outer harbour. This is also a stable layer that varied by only 20 % during the period of investigation.

Like in Emden the higher differences can be found in the deepest areas. The highest values of $\Delta h \approx 3$ m are in front of the outer gate of the sea lock. This documents the fluidity of fluid mud. Lock operations allow large amounts of highly concentrated sediment suspensions to enter the inner harbour through the lock chamber.

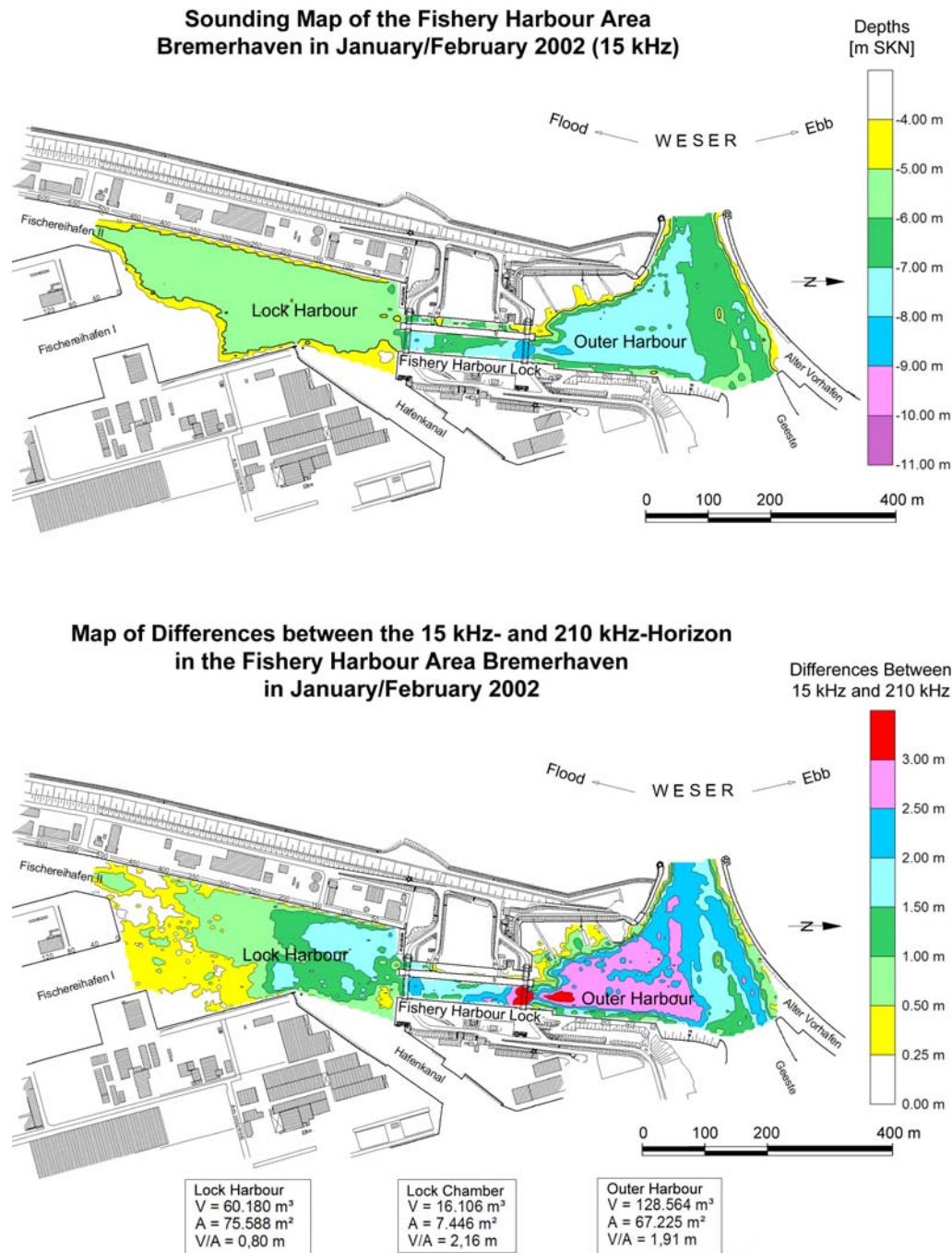


Figure 4. 15 kHz Sounding from Bremerhaven Fishery Harbour Lock and Map of Differences in January/February 2002.

Kaiser Lock

The nominal depth of the Outer Harbour of the Kaiser Lock lies about 7 m above the Weser bed. Despite of this high incline the current effects lead to the formation of a bar in the entrance (fig. 5 top). Fluid mud is formed in the trough with a difference up to $\Delta h \approx 2$ m (fig. 5 bottom). The bottom gradient away from the outer gate of the Kaiser Lock reduces the density induced near bed sediment transport into the lock chamber. In the deeper turning basin the fine sediments are displaced by ship induced currents.

Owing to reversed gradients the boundary conditions for the lock chamber of the Fishery Harbour Lock are completely different (see fig. 4).

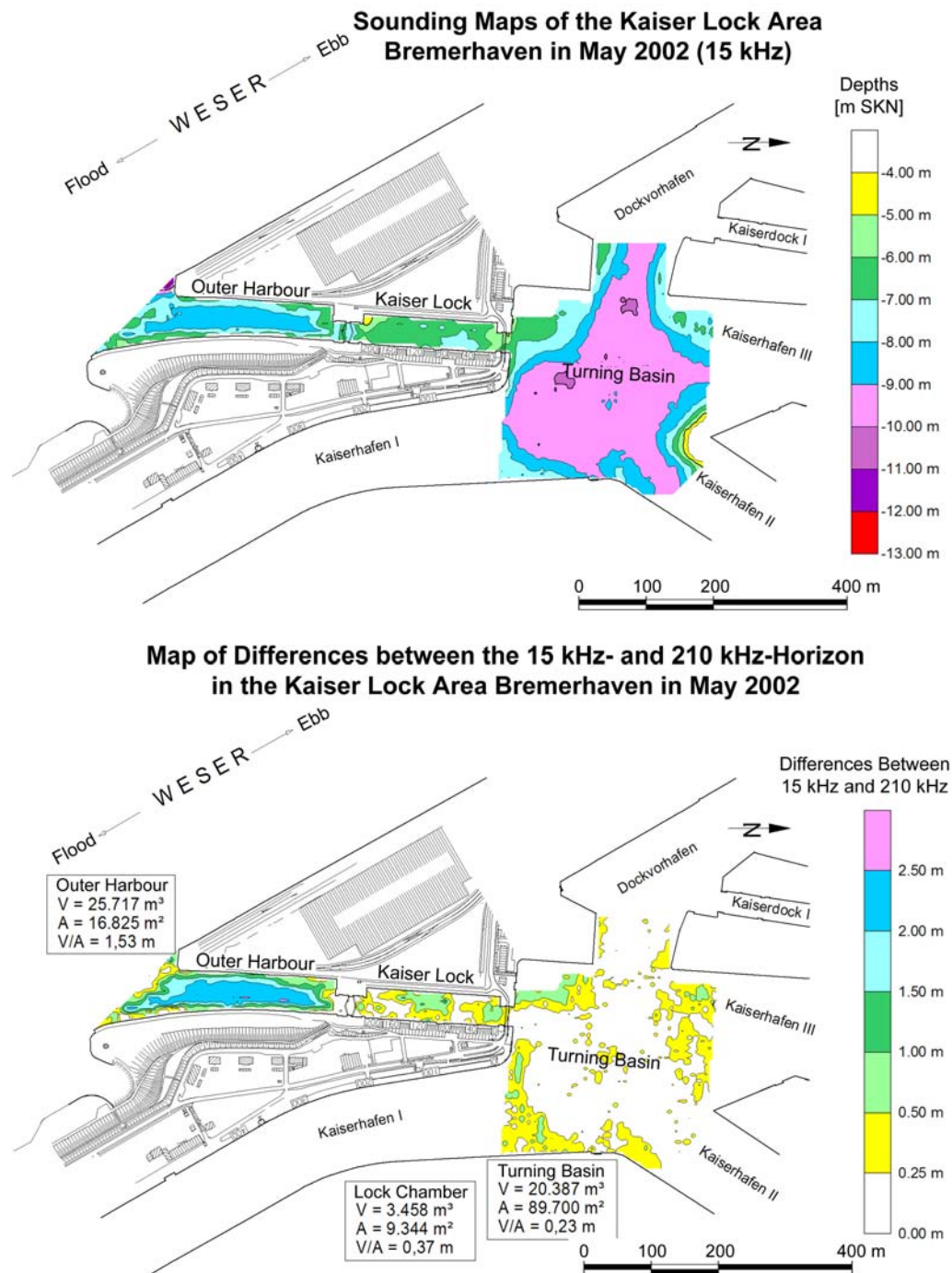


Figure 5. 15 kHz Sounding from Bremerhaven Kaiser Lock and Map of Differences in May 2002.

North Lock

The nominal depth of the Outer Harbour of the North Lock is about 3 m above the Weser bed. The sounding from January 2004 in figure 6 illustrates how a gradient away from the lock towards the river can prevent the formation of fluid mud (KSM). The density induced outward sediment transport is increased during ebb tide, while during flood tide less sediment enters the outer harbour. That is the reason why there are no significant differences (i.e. no fluid mud) in the outer harbour and lock chamber.

The higher differences of over 1.5 m can be found in the turning basin behind the lock. These result from sediment displacement caused by propeller scour and ship movement.

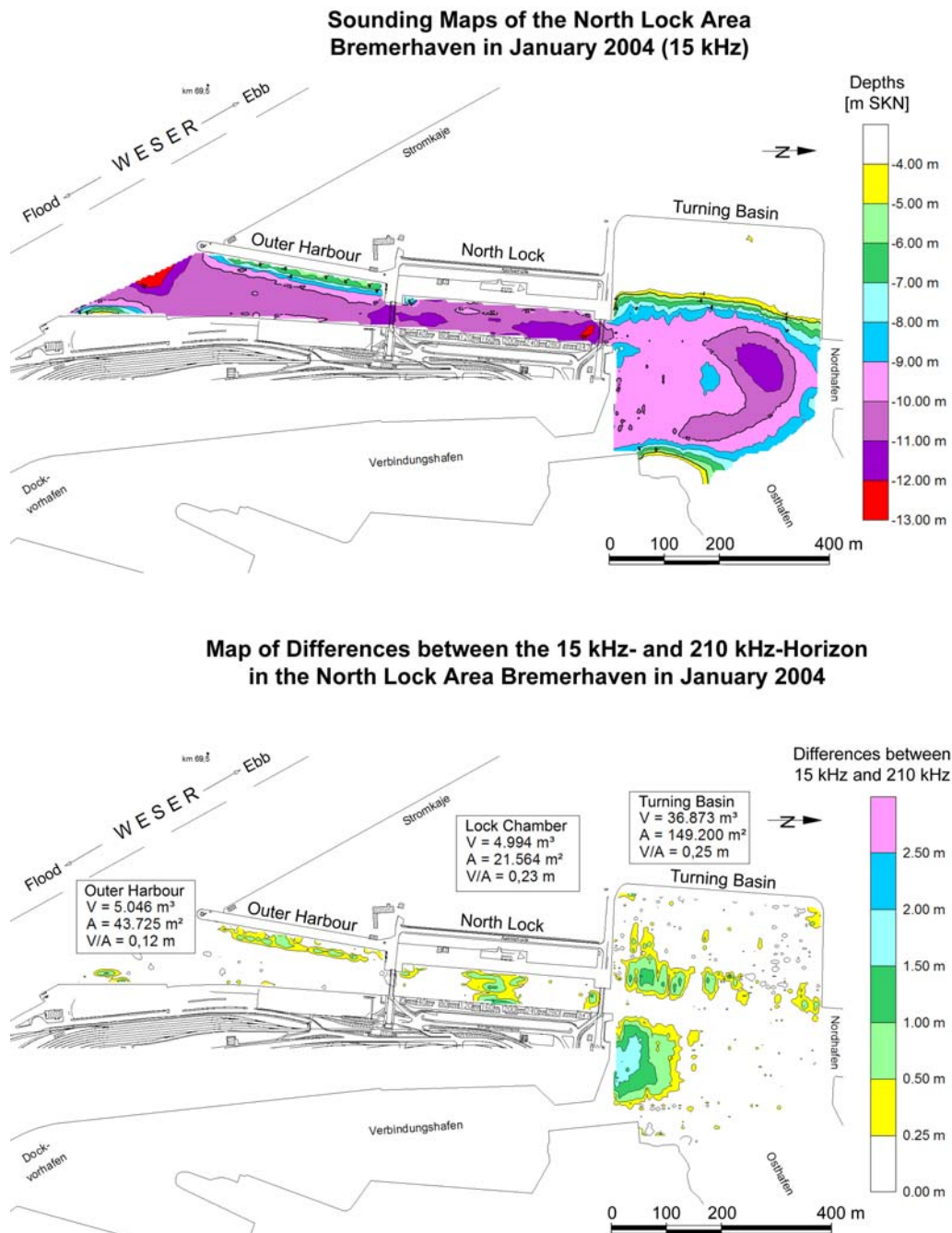


Figure 6. 15 kHz Sounding from Bremerhaven North Lock and Map of Differences in January 2004.

Brunsbuettel

The outer harbours of the Kiel-Canal in Brunsbuettel are also separated by a bar from the River Elbe (fig. 7). The results from the analysis of soundings from 2003 to 2005 have shown average volumes between the 100 kHz and 15 kHz horizons of $V \approx 337\,000\text{ m}^3$ in the New Outer Harbour and $V \approx 121\,000\text{ m}^3$ in the smaller and shallower Old Outer Harbour. The variances around the average are higher than in Emden and Bremerhaven Fishery Harbour Lock. The reason for this is the conventional dredging method applied in Brunsbuettel. Also in Brunsbuettel, owing to the fluid mud's fluidity, the highest layer thicknesses (differences) are found where the 15 kHz echo shows the greatest depth. This is a general result for all the harbours in the brackish zone on the German North-Sea Coast.



Figure 7. 15 kHz Sounding from Bruntsbuettel New and Old Outer Harbour and Map of Differences in January 2003.

PROPERTIES OF FLUID MUD

In order to analyse fluid mud, samples were taken with a Ruttner sampler that has a height of 50 cm and weighs 5 kg. The upper fluid mud limit is defined as the sudden changeover in sediment concentration at the high frequency echo, the lutocline (s. fig. 8).



Figure 8. Ruttner-Sampler with a Sample from the Lutocline.

The van Veen sampler has been weighed down with lead plates giving it a weight of 12.5 kg so that it reaches the 15 kHz horizon where plastic bed material is found (s. fig. 9).



Figure 9. Van Veen Bed Sample taken from the 15 kHz-Horizon in Bremerhaven on 15/03/2006.

The Ruttner samples were taken from the upper, middle and bottom fluid mud layer. The crossover from a Newtonian medium to a Bingham medium is in the bottom fluid mud layer. The sample depths in the fluid mud layer can be seen in figure 10.

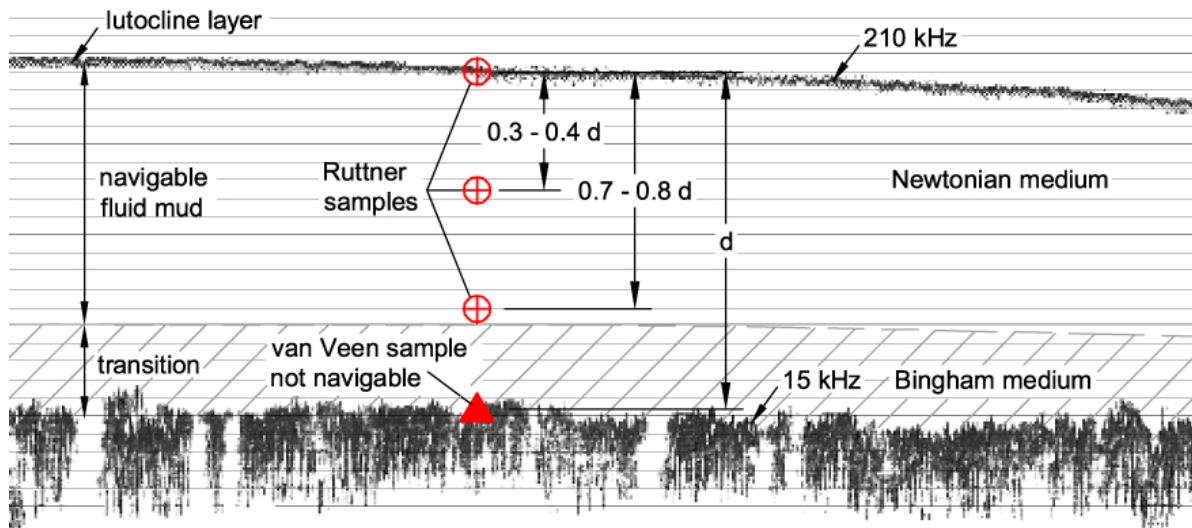


Figure 10. Sketch of Sample Positions in the Fluid Mud Layer (Sounding from December 2006 in Emden).

The results of the field trip in March 2006 is briefly summarized in the following:

The water and the bed samples from all the outer harbours have high ignition losses (fig. 11). The highest organic content was found in Emden, the lowest in Brunsbuettel. The trend decreases from the lutocline to the 15 kHz horizon.



Figure 11. Ignition Losses in the Different Layers and Harbours.

Below the lutocline there is a significant increase of solid material from about 40 to 90 g/l [kg/m³] up to 140 to 220 g/l (fig. 12). The corresponding dynamic viscosities are remarkably low. They are only 0.1 to 3 Pa•s in the upper and middle fluid mud layers (fig. 13). In the lower fluid mud layer the viscosities vary between 1 and

approx. 60 Pa·s and the densities are about 1.1 t/m³ in all harbours (fig. 14), which are navigable dimensions (navigable mud).

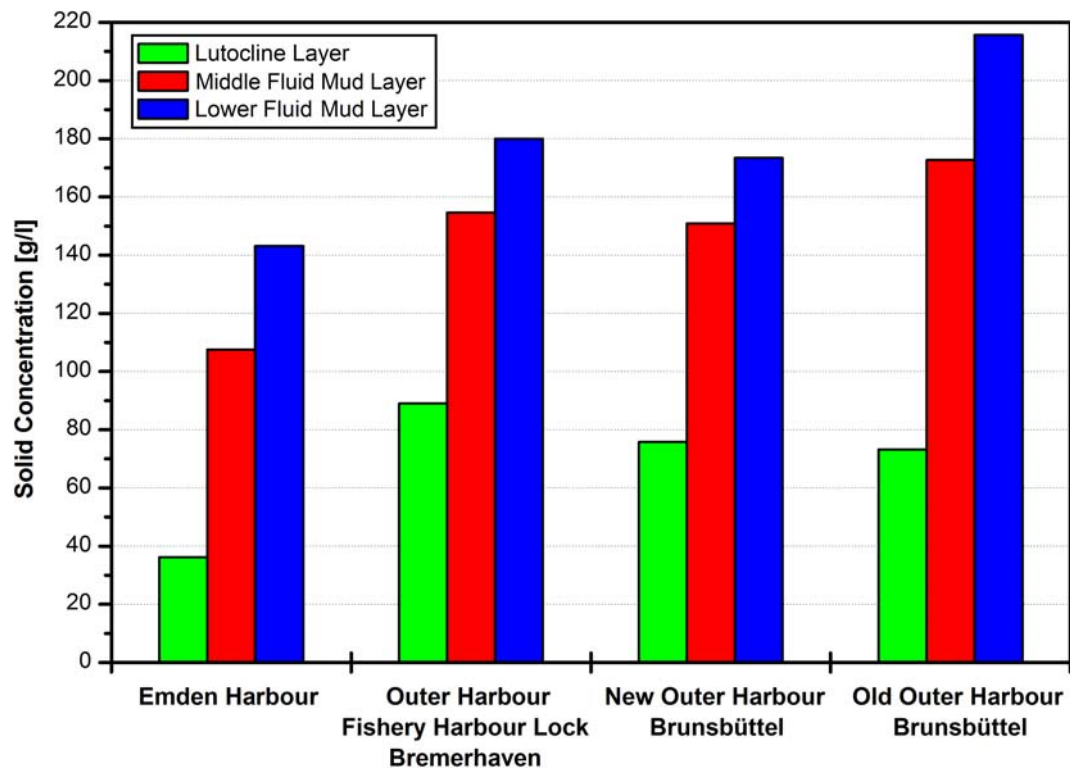


Figure 12. Concentration of Solids in the Different Layers and Harbours.

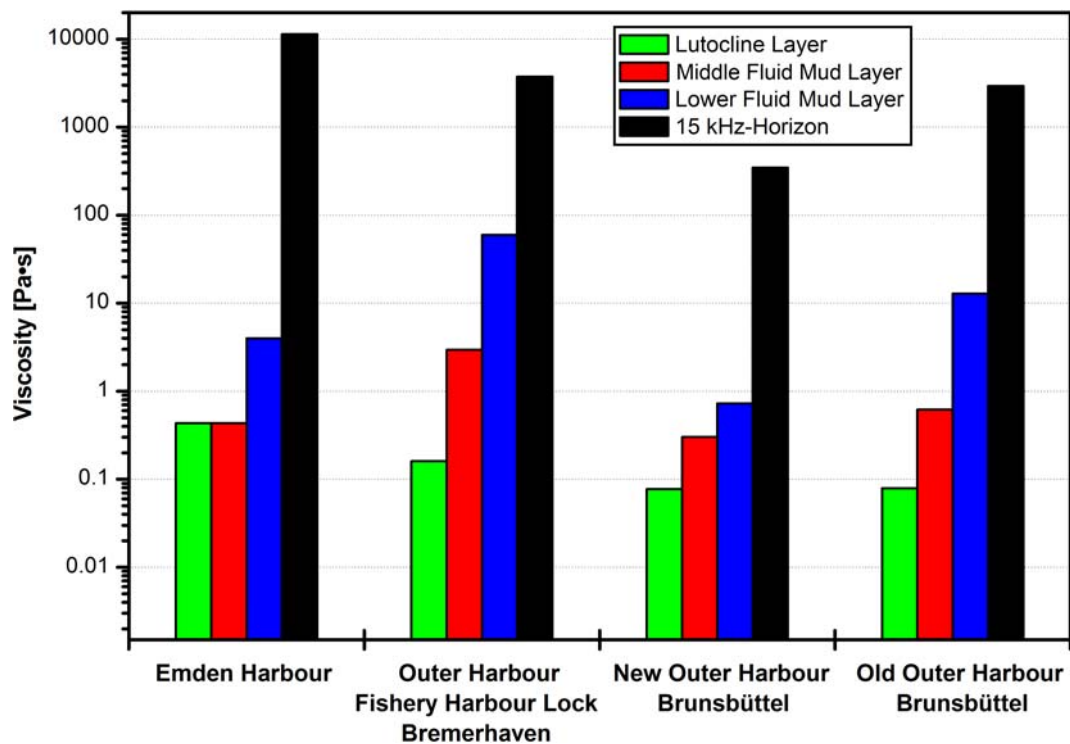


Figure 13. Dynamic Viscosities in the Different Layers and Harbours.

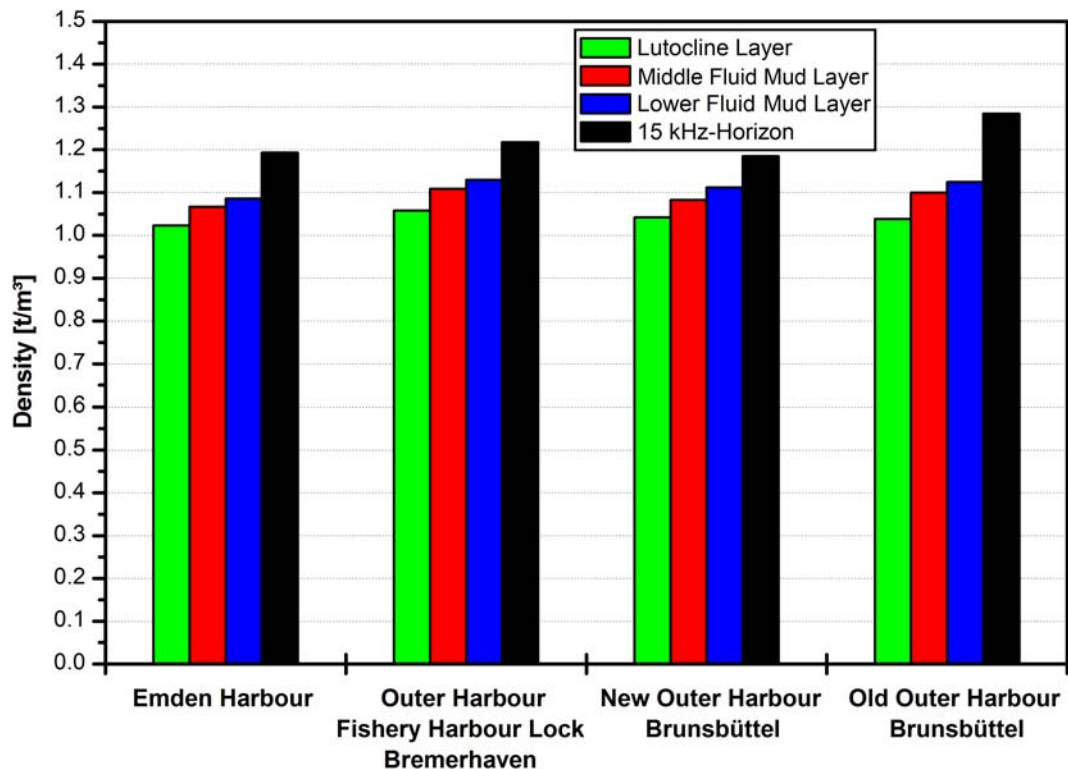


Figure 14. Densities in the Different Layers and Harbours.

The 15 kHz horizon with viscosities $\gg 100 \text{ Pa}\cdot\text{s}$ and densities of the plastic mud $\geq 1.2 \text{ t/m}^3$ is not navigable. The in situ measurements show that the limit of the nautical depth is the 15 kHz zone.

MAINTENANCE WORK

Up to the 1980's an average of about 4.0 million m^3 of fluid mud was dredged in the Harbour of Emden. This had to be deposited on flushing fields (Wurpts, 1997). Active investigations into the rheologic characteristic of fluid mud in the Outer Harbours of Emden have led to a different dredging strategy. The sedimentation process is prevented by means of selective recirculation by a hopper dredge with an under water pump that infrequently raises, oxydizes and re-deposits the fluid mud. By this method (KSN = Keep Sediment Navigable) the nautical depth is maintained. The displacement of dredged spoil has become no longer necessary.

As in Emden the outer harbour to the Fishery Lock is situated in a trough behind a bar. The analysis of dual frequency soundings covering periods of several years have shown that the fluid mud volume in Emden and the Outer Fishery Harbour in Bremerhaven are highly stable. The volume varied by less than 20 % at the most. Neither monthly tidal variations nor varying annual fresh water discharge have had any effect. Since 1994 the aerobic conditions in the fluid mud layer are achieved with the supply of oxygen by water injections (KSN). Before about 0,4 million m^3 was dredged in the outer harbours of Bremerhaven and dumped in the Weser.

The nominal depths in the front of the outer harbours of the North and Kaiser Lock are about 3 m and 7 m above the Weser bottom. The above example of the North Lock in Bremerhaven demonstrates that a bottom slope away from the lock towards the river can successfully prevent fluid mud from forming (KSM-method, Keep Sediment Moving or KSO-method, Keep Sediment Out). By increasing the density current toward the River Weser during the ebb current phase it is possible to remove the material that came into the harbour during the flood current phase.

Next to the economic advantages such as low investment and maintenance costs for water injections, there are no costs for dumping or even depositing the spoil on land.

CONCLUDING REMARKS

This paper has described the sedimentation process in brackish harbours on the Rivers Ems, Weser and Elbe. The measurements have given valuable knowledge for minimising or preventing sedimentation of fluid mud and have helped to optimize maintenance costs.

Fluid mud has a high organic content, low density and viscosity and it settles very slowly. The settling process is retarded by micro biological activity. Bacteria that are attached to the fine sediments produce slimes that prevent the highly concentrated suspension from settling and consolidating. Navigability is ensured as long as fluid mud is kept in an aerobic state.

In Emden and Bremerhaven innovative maintenance methods have been developed to prevent sedimentation and consolidation of fluid mud. In Emden fluid mud is lifted to the surface and brought into contact with oxygen, while in the Bremerhaven Fishery Harbour oxygen is driven in to the fluid mud layer by injecting surface water. Both methods are KSN. The prevention of fluid mud from forming in the outer harbours of the Kaiser and North Locks in Bremerhaven in the first place is achieved by successfully applying a KSM or KSO method by dredging the bar and creating a bottom slope to the river. All these measures have resulted in substantial cost savings. Expensive dumping or deposition on land can be saved.

Finally, the methods mentioned above keep the sediments in the tidal regime (KSIS, Keep Sediment In the System) and the supply of oxygen has a positive effect on polluted sediments.

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