Bed Mobility in the Weser Estuary Turbidity Zone

Mud in its unconsolidated, highly dynamic, fluid state may complicate problems arising from other detection difficulties in estimating water depth in estuarine channels with mobile bed deposits. This study presents new results on riverbed mobility in the turbidity reach of the Weser estuary based on datasets from an Innomar sediment echo sounder (SES-2000) and combined fluid mud sampling.

leading to highly dynamic mud deposits and large bed-forms such as sub-aqueous dunes is a characteristic feature of tidal estuaries. Often their presence poses navigation risks due to considerable reduction in nautical depth. To secure navigability, especially for the increasing draught of new and larger container vessels, many estuaries are highly engineered. Determining the forcing parameter and processes driving the formation and mobility of estuarine sediments is thus an important prerequisite to improving maintenance strategies for these waterways.

The Weser Estuary

The Weser river mouth is one of the strongest anthropogenically influenced tidal estuaries along the North Sea coast, mainly because of repeated deepening and straightening of the main navigation channel (Figures 1a-b). As a consequence the range of the semidiurnal tide has increased dramatically, for example, at Bremen from 0.2m to 4m. Although the construction of groins, sheet pilings and sub-aqueous embankments canalise the tidal current to reduce sediment deposition in the navigation channel, frequent dredging is still required. Particularly within the turbidity zone, distinctive flocculation processes of suspended particulate matter triggered by salt and fresh water mixture result in considerable accumulation of fine-grained deposits. However, the unmistakable detection of such deposits using conventional echo sounders is difficult, especially in the initial weakly consolidated state of their development, as so-called Â¡Â®fluid mudÂ¡Â¯. The definition of true nautical depth is thus often problematical.

An Acoustic Approach

To overcome the shortcomings of conventional echo sounders in detecting fluid mud, a parametric sediment echo sounder (SES-2000), provided by Innomar Technology GmbH Rostock, was deployed in the Weser estuary (Figures 1a-c). In principle, sound waves of two slightly differing frequencies, around 100kHz, are transmitted under high sound pressure. The sound propagates non-linearly while these different frequencies interact; as a consequence, secondary low frequencies of 4-15kHz are also generated. The latter are used for sub-bottom profiling, having the same footprint as the high frequency. The advantage of this device is, amongst others, precise detection of the sediment surface (high frequency Â¨C 100kHz) as well as internal sediment structures (low frequency Â¨C selectable 4-15kHz) with a high layer resolution (Â¡Ã6cm) and accuracy (e.g. 100kHz / 10kHz: 2cm / 4cm + 0.02% of water depth).

Sediment Sampling

Gravity cores (Rumohr type) were used to ground-truth acoustic information from the SES-2000 data. For highly vertical resolved sediment samplings the transparent core barrels were fitted with holes 2cm in diameter and spaced at 10cm-intervals down-core. The holes were taped before deployment and then reopened stepwise for sampling after recovery. The corer sampled the lower few metres of the water column and a short section of the upper, solid riverbed.

Ground-truthing

The SES-2000 was deployed in the navigation channel of the Weser estuary at different tidal stages. Weak acoustic impedance was observed up to a few metres above the solid riverbed within the turbidity zone during slack water (Figures 1a, 2a). Cores taken simultaneously showed an abrupt rise in the concentration of suspended particulate matter near the riverbed (Figures 2b-c). Below this discontinuity layer the concentration of the suspended sediment increased progressively down-core to reach maximum values above 100g/l. The total thickness of these layers coincided with the distance between the first acoustic impedance and the solid riverbed (Figures 2a-c). These results prove that highly dynamic fluid mud temporarily occurs in the Weser estuary. They also demonstrate the high-resolution detection capability of the SES-2000, even of sediment suspensions and weakly consolidated fine-grained deposits.

Spatial Occurrence

The SES-2000 data reveal fluid mud deposits temporally covering the Â¡Â®solidÂ¡Â¯ riverbed at various places within the turbidity reach of the estuary, thereby levelling the bed morphology by filling in depressions and draping bed-forms. A complete coverage of the solid riverbed in the navigation channel by a single fluid mud body was, however, not observed. In fact, fluid mud occurrences are rather patchy, with highly variable spatial dimensions ranging from a few metres up to several hundreds of metres along the turbidity reach. Furthermore, the patches are not always found at the same localities, variability being particularly high at the up and downstream ends of the turbidity reach (Figure 1a). Depending on freshwater discharge and tidal phase, the main deposition area shifts up or downstream.

Mud in Dune Troughs

Some river sections within the turbidity reach are characterised by mud deposits. Here, there would seem to be an obvious close interrelationship between the solid riverbed and fluid mud appearance. Apart from these, sandy stretches occur where surface sediments and fluid mud cannot be easily linked. In such cases the formation of fluid mud is not evidently related to the textural nature of the bed sediment. One spectacular example is the temporary deposition of fluid mud in the troughs of several metres-high sub-aqueous dunes (Figure 2d). In this case the two sediment types normally associated with completely different hydrodynamical energy levels coexist for a short period in the course of a tidal cycle. Whereas the formation and migration of the large sub-aqueous dunes depends upon considerable current velocities, the deposition of fluid mud is limited to the calm water conditions at slack tide.

Fluid Mud Dynamics

The tide-dependant deposition of fluid mud over a dune field is shown in a longitudinal profile of about 60m length in the upstream direction, as monitored at short time intervals over a semi-tidal cycle (Figures 3a-e). Clearly visible in this time series is the absence of fluid mud during the ebb phase under moderate to high flow velocities (Figures 3a-b). Near slack water a signal of initially very weak acoustic impedance appears above the solid riverbed (Figure 3c). During lowest current velocities a roughly metre-thick deposit of fluid mud covers the underlying rippled sand bed (Figure 3d). Here nautical depth is reduced by almost a metre, as would be recorded by a normal echo sounder. An hour later the fluid mud deposit is seen to be partly in re-suspension, especially on the current-facing side of the dune trough (Figure 3e).

Mud Formation

In this context the question arises what the mechanism might be which enables the formation of fluid mud within such short time intervals. One answer is the occurrence of large flocs up to 3mm in diameter of suspended particulate matter found in the lower water column during early slack water. Based on observations of flocs in the core barrels, these settled out at velocities of up to 1.5cm/s; amounts of suspended sand were negligible. By the time the suspended particles reached the riverbed they had merged with the fluid mud (Figure 2c). This process leads to rapid accumulation, with simultaneous sediment consolidation. Although fluid mud deposits are almost completely re-suspended between two successive slack water phases, there are indications that occasionally a certain amount of material consolidates fast enough to withstand the hydrodynamic force of the returning tidal current. This is documented by small-scale inter-bedding of sand and mud as, for example, observed in sediment cores from sub-aqueous dune troughs.

Conclusions

The mobility of the riverbed within the turbidity zone of the Weser estuary is strongly affected by highly dynamic, fluid mud deposition/re-suspension processes, as representatively documented on SES-2000 records. A clear tide-dependant deposition of fluid mud is particularly obvious. These deposits can rapidly reach a few metres in thickness by fast-settling flocs of suspended particulate matter around slack water. Only during this short time interval can fluid mud reduce the nautical depth. During ebb and flood currents the fluid mud disappears almost completely. Regarding the inter-bedding sand and mud layers found in the troughs of sub-aqueous dunes: it seems most obvious that a certain amount of fluid mud occasionally transforms into solid mud and substantially reduces nautical depth. These results not only for the first time document the high dynamics of fluid mud in the navigation channel of the Weser estuary, but they also clarify the importance of knowing about the forcing parameter and processes driving the formation and mobility of estuarine sediments when planning dredging tasks.

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