

Investigation the stability of reservoir sediments in the lab and field

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Abstract. To investigate the erosion stability of reservoir sediments, two measuring strategies were applied. Next to in situ measurements, sediment cores were extracted and analysed in the laboratory. At several sampling points at a reservoir in Germany, the in situ device was used to determine the critical bed shear stresses at the sediment surface. At the same time, sediment cores were withdrawn at each site to perform depth-orientated investigations in the hydraulic laboratory. The objective of this study is to investigate the remobilisation potential of the deposited fine sediments and to compare different methods to determine the erosion threshold. Next to critical shear stresses and erosion rates, additional sedimentary and biological parameters were examined such as bulk densities, particle size distributions, TOC-contents and chlorophyll-a concentrations. The results show generally a very low erosion stability, especially at the sediment surface and in the upper sediment layers. Deeper sediment layers are characterised by consolidation effects and show a higher erosion resistance. High clay contents result in increased stability while high sand contents show a high remobilisation potential. No significant relation to the parameters TOC-content or chlorophyll-a concentration are identified. A comparison between the different applied techniques to determine the critical bed shear stresses reveals values in the same order of magnitude; however, some significant variations occur because of different hydromorphological conditions and the different limitations for each device.

1 Introduction

Reservoir sedimentation can reduce the lifetime of a reservoir and may have negative impacts on the operation as well as on the affected downstream region. Thus, sustainable sediment management strategies are required to minimize reservoir sedimentation, to remobilize already deposited material and to restore natural sediment continuity at its best. However, successful measures can only be derived when detailed knowledge of the sediment characteristics and the sediment erosion stability as well as their mutual interaction exists. In this context, especially the description of fine sediment mixtures (clay, silt and sand) is a challenge due to their cohesive erosion behaviour [e.g. 1–5]. Complementary expertise and methods from different disciplines need to be combined to finally unravel the complex erosion and resuspension properties of cohesive sediments. The first step, however, is an appropriate determination of the sediment stability that can be expressed by the critical shear stress.

Therefore, different laboratory and in situ devices have been developed to measure the critical shear stresses and/or erosion rates (e.g., [6–14]). For some of these erosion devices, determination of fine sediment stability is restricted to the surface layer. However, once the surface layer has been eroded, the underlying sediment layers vary extremely in stability and

consolidation depending on the magnitude of influencing parameters such as particle sizes, water content, cation exchange capacity, organic substances (dead or alive), and microbially secreted polymeric substances [15]. The erosional behavior of these deeper sediments is of particular interest since many pollutants, which preferentially bind to small particles and originate from peak-inputs of the past, are immobilized in these long-deposited layers (“legacy of the past” [16]). Increased hydraulic forces such as floods or dredging activities might remobilize these old burdens to become toxic again [[17,18]. The Institute for Modelling Hydraulic and Environmental Systems (IWS, University of Stuttgart) realized a twofold strategy for a sophisticated sediment erosion risk assessment: an in situ device for determination of critical shear stresses directly in the field, and a laboratory approach where sediment cores are withdrawn and subsequently exposed to the turbulent flow within a straight erosion flume (SETEG). Along with the detection of critical shear stresses and erosion rates, further sedimentary parameters can be addressed such as particle size distribution, and bulk density as well as biochemical attributes such as TOC, Chlorophyll-a (CHL-a), cation exchange capacity (CEC) and extracellular polymeric substances (EPS).

This article presents both techniques for a selected case study to show their chances and drawbacks in evaluating the stability of reservoir sediments.

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2 Methods

2.1. Collection of undisturbed sediment samples

For the laboratory analyses, sediment cores are taken from the reservoir with a so called Frahm Sediment Sampler (“Frahm-Lot”, [19]). This device was developed at the Leibniz Institute for Baltic Sea Research (IOW). It was previously used in marine technology to close the gap between piston and gravity cores and is applied in inland waters for the first time. With the Frahm Sediment Sampler, undisturbed sediment cores with a diameter of 0.1 m and a length of up to 1.0 m can be extracted from the reservoir. The advantage is that a lid and a sideways movable clasp seal the sediment core immediately after removal from the bed. It can be operated from a floating platform that is equipped with a tripod and a winch. The maximum depth of operation is currently 50.0 m.

2.2. The SETEG-flume and PHOTOSED

To analyse the cores in the laboratory, the so called SETEG flume (with a height: 0.090 m, width: 0.142 m, and length: 8.320 m, [10,20]) is used that consists of a closed rectangular channel with pressurized flow to obtain optical access for photogrammetric measurements (Figure 1). The measuring section consists of a circular opening in the bottom of the flume where cylindrical sediment cores, with a maximum diameter of 135 mm, can be inserted and are exposed to the fully developed flow. A jack-stepping motor controls vertical movement of the sediments in the core to ensure that the sediment surface is flush with the flume bottom. This arrangement allows for different depths of the sediment core to be investigated independently to obtain depth-oriented information about the erosion behaviour. During an erosion experiment, the discharge is increased stepwise until the entrainment of sediment particles, or aggregates, can be observed. The resulting critical shear stress is determined by a hydraulic calibration function (Q - τ -relation), which was obtained by previously conducted high-resolution LDA measurements. To obtain vertical profiles along the cores, the measurements are typically conducted at depth intervals of 10 mm to 50 mm.

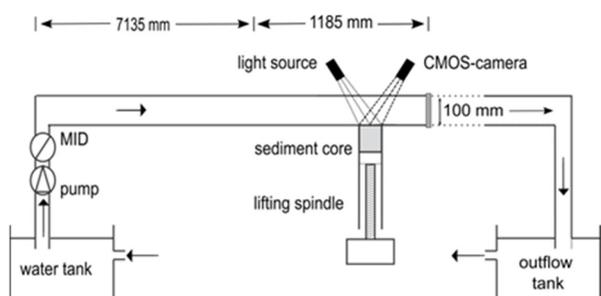


Figure 1. Schematic side-view of the SETEG-system with the light source and CMOS-camera for PHOTOSED.

For the measurements of erosion rates a photogrammetric approach, called PHOTOSED

(photogrammetric detection of sediment erosion, Figure 1) is used [21]. Therefore, the SETEG-flume is equipped with a semiconductor laser, with a diffraction optic at the light source, to project a pseudo-random pattern of approximately 24,000 light points on the 143 cm² sediment surface (based on the maximum diameter of a sediment core). In addition, a CMOS-camera (2 MP) is installed for image acquisition, with a temporal resolution of 10 Hz. The laser is mounted outside the flume, and projects down onto the sediment surface in the direction of flow at an angle of 45° while the CMOS-camera is mounted vertically above the sediment surface. PHOTOSED analyses the displacement of the projected light points for consecutive time-steps that are extracted from continuous image acquisitions of the CMOS-camera. To assess the erosion volume between two consecutive images, a Dense Optical Flow (DOF) algorithm [22] of the OpenCV library (Open Source Computer Vision) is used to evaluate the displacements of the projected light points during the erosion process. The critical shear stresses can be detected either by visual observation or by the interpolating the measured erosion rates.

2.3. The in situ erosion device

The in situ device of the IWS (Figure 2) is based on the flow-through technique with an open bottom and consists of a rectangular flume made of acrylic glass (length, 110 cm, width 10 cm, height 5 cm). The flume is placed directly on the river bed and an adjustable pump directs pressurized water through the flume. The chosen geometry of the flume enables the development of natural turbulent flow conditions. This was verified in advance by LDA-measurements allowing the application of the logarithmic formula and the development of a relationship between flow, flow velocity and bottom shear stress. The illuminated measuring area is located 70 cm behind the inflow and is monitored optically using two underwater video cameras. The flow is measured using a micropropeller located next to the measuring area. In addition turbidity sensors are used at the in- and outflow section of the flume allowing for the qualitative observation of the amount of suspended particles during the erosion experiments. By steadily increasing flow and monitoring of the measuring area the incipient motion of sediments and thus their stability can be detected. The cameras are directly connected to a laptop transferring and storing the transport behaviour of cohesive sediments.

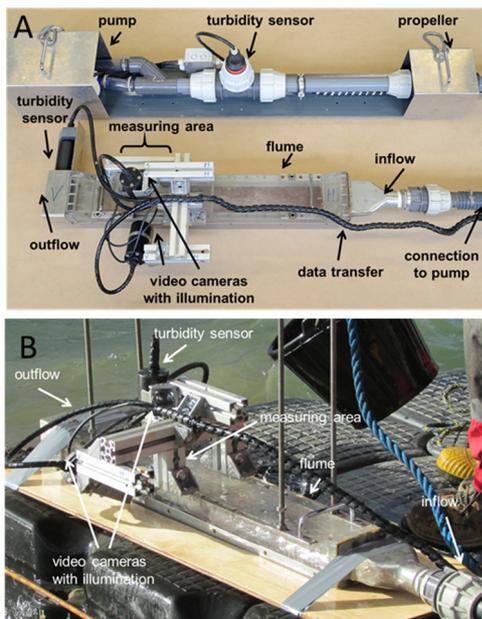


Figure 2. In situ device to determine critical bottom shear stresses at the sediment surface with submersible pump in the laboratory (A) and in the field with submerged pump (B).

3 Results and Discussion

3.1. Analysis of the laboratory measurements

In the meantime, multiple projects related to investigations of erosion stability of reservoir sediments have been conducted at our institute including several run-off river plants, reservoirs but also groyne fields. Figure 3 represents an exemplary analyses of a one sediment core at a reservoir in Germany.

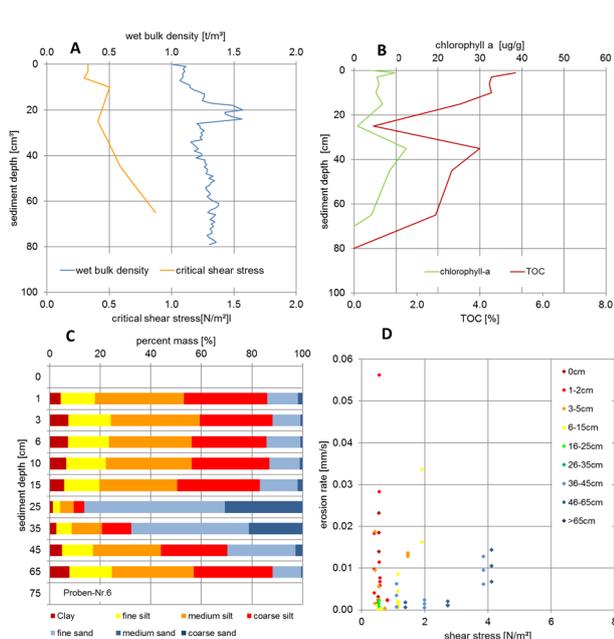


Figure 3. Exemplary analysis of one sediment core at a reservoir in Germany regarding sedimentary and biochemical parameter and erosion stability.

The critical shear stress show no uniform vertical distribution but an increasing stability with increasing sediment depth due to consolidation effects. This is confirmed by the slightly increasing wet bulk density over sediment depth. However, at a depth of 20-30 cm a sudden peak of the bulk density can be indicated with a simultaneously occurring reduction of the critical shear stress. At the same depth the TOC and CHL-a show minimum values and the particle size distribution is dominated by a high sand content (in contrast to the other sediment layers). This sandy layer explain the low values of organic material as well as the higher bulk density and the lower critical shear stress (no cohesive forces). The erosion rates over shear stress show a high remobilization potential for the upper sediment layers (0-15cm), while the deeper sediment layers are characterized by a higher variability with a clear trend towards higher erosion resistances. Such analyses are usually done for all extracted sediment cores with the overall goal to examine correlations between different parameters that are involved in the erosion process of reservoir sediments.

3.2. Analysis of the in situ measurements

While the laboratory analyses allow for depth-orientated measurements of erosion stability, the in situ measurements offer the possibility to directly repeat measurements of the erosion threshold in the field. Figure 4 shows the time series of the turbidity and the controlled shear stress at one sampling site. Based on the turbidity measurements the erosion threshold for particle erosion can be determined by a significant change of the turbidity, while mass erosion can be detected if the turbidity values differ from the background turbidity.

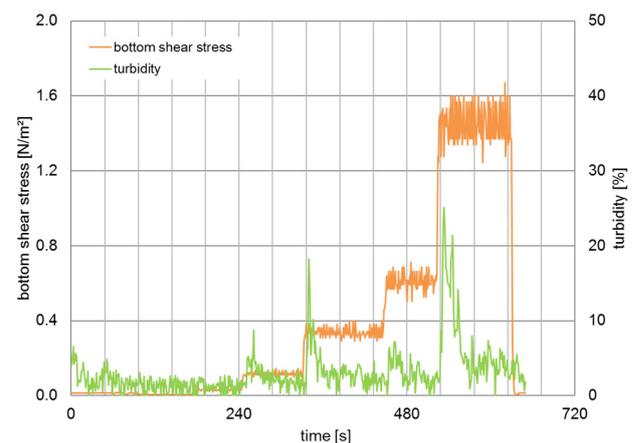


Figure 4. Exemplary time series of turbidity and the controlled bottom shear stress of the in situ device.

Next to the laboratory-based measurements of critical shear stresses based on the surface of extracted sediment cores (SETEG-flume), the in situ measurements provide two additional method to detect the erosion stability; either by visual observation or by turbidity measurements.

3.3. Comparison of in situ and laboratory measurements

Figure 5 shows a comparison of the determined critical shear stresses using the different previously described methods for 12 sampling sites.

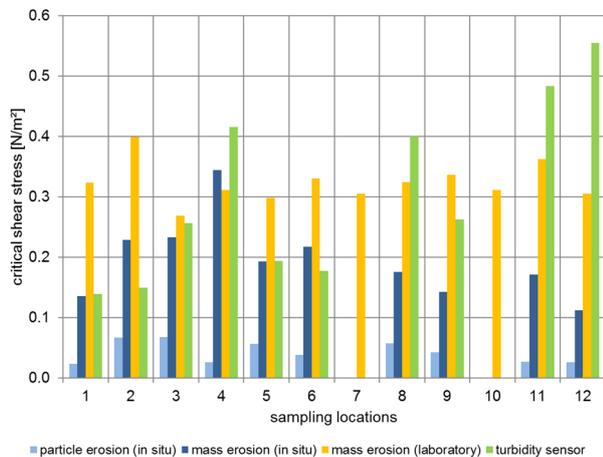


Figure 5. Comparison of the critical shear stresses detected with different devices in the laboratory and in the field.

As expected the in situ determined particle erosion for sampling sites is lower compared to the thresholds for mass erosion. However, for practical reasons such as the development of sediment management strategies, the threshold for mass erosion represents a higher relevance because the particle erosion plays only a minor role in terms of erosion stability. At several sampling locations the thresholds for mass erosion with different methods agree quite well while other locations show a severe difference. This is partly due to the minimal discharge of 5 l/s in the SETEG-flume to that time that is required to allow pressurized conditions. This means the lower limit of the laboratory investigation is 0.3 N/m². However, in the meantime the SETEG-flume was adapted to allow investigations up to 1.0 l/s (0.1 N/m²). Comparing the thresholds based on turbidity measurements and visual observations a high agreement for the sampling sites 1-6 can be indicated while the sites 8-12 show higher thresholds for the turbidity measurements. However, the different hydraulics and morphological conditions needs to be taken into account when comparing the different methods. Therefore, a comparability is only partly given.

In general, the in situ data show slightly different and often lower values as compared to the laboratory measurements. According to [23,24] these discrepancies can be explained by treatment/withdrawal, handling, transporting, and possibly storing of sediment cores, all of which might further compact the sediment to result in higher strength as compared to natural values. Moreover, the flocculent surface layer can be retained and addressed within in situ devices to give lower values of incipient motion while being washed away during sediment withdrawal for the laboratory, thereby exposing more consolidated layers beneath. The most important drawbacks of the in situ device are the limited capability of doing vertical investigations of the erosional behaviour and sediment characteristics such as bulk density, etc. Especially when considering the risk to

remobilize pollutants of the past (“old burden”), the stability of deeper layers, where most of the contaminated sediments are deposited long ago, is of high importance [25].

The withdrawal of sediment cores allows, beside depth-dependent analyses, for an examination of additional sedimentary parameters, which may influence the incipient motion and erosion rates of cohesive sediments.

4 Conclusions

This study presents the investigation of erosion stability of reservoir sediments. Therefore, both in situ measurements and laboratory measuring methods were applied. Particularly, the measuring techniques in the laboratory are of high importance because they allow for investigations on additional relevant stability parameters and for depth-orientated profiles of these parameters. Hence, the deposition history can also be considered. In agreement with the scientific literature, the results show a significant influence of the particle size distribution on erosion stability, especially the sand and clay content are important fractions that determine the erosion potential of the deposited sediments. While sandy layers are characterized by a high erosion potential, high clay contents lead to an increased erosion stability. The bulk densities show a weak trend towards consolidation with increasing sediment depth and no biostabilization processes are observed. A systematic analysis regarding correlations between the measured parameters (particle size distribution, bulk density, TOC-content, chlorophyll-a concentration) need to be done in future to unravel the interactions among the involved parameter further. The results of the presented study can be used to develop computational approaches for the erosion behaviour of cohesive sediments. This allows for detailed simulations of the temporal and spatial erosion processes reservoirs and for development of sediment management strategies.

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