DESIGN OF A 3D NUMERICAL MODEL OF LAKE CONSTANCE TO ASSESS POTENTIAL SEDIMENT EROSION

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Abstract

In 2011 the prehistoric pile-dwelling settlements (5000 to 500 BC) around the Alps became part of the UNESCO world heritage. Archaeological investigations nowadays show that some of them are endangered by erosion due to several reasons.

Within the project 'bank erosion and archaeological heritage protection in Lake Constance and Lake Zurich' (UED) a coupled 3D numerical model of Lake Constance is set up to determine complex hydrodynamic and morphodynamic processes in the shallow water zone. Depending on the quality of the wind input data the model is able to simulate the stratification of the lake, water levels, wave heights and current velocities sufficiently accurate. The simulation of erosion and transport of sediment particles during storm wind events is accomplished.

For calibration and adjustment of the model parameters the site is intensively sampled by different means. In 2010 water temperature distribution, wave heights, current velocities and turbidity in the shallow water zone were measured at one site in the western part of Lake Constance. To obtain the site specific information on the erosion parameters required by the morphodynamic model 13 sediment cores are retrieved. Their erosional stability is determined by the enhanced SETEG system that was developed at the University of Stuttgart and comprises of a flume to measure the erosion of aquatic sediments as a function of sediment depth and its related analyzing software. Altogether the gained data provide good insights into erosion processes and thus allow the calibration and simulation of morphodynamic processes. In future the numerical model will act as a decision support system to ensure the preservation of the UNESCO World Heritage of pile dwellings.

Introduction

The pile dwellings of Lake Constance and Lake Zurich belong to the most important archaeological cultural property in Europe and became part of the UNESCO-world heritage in June 2011. Hermetically sealed by sediments the prehistoric pile-dwelling settlements in the littoral zone of Lake Constance from Stone Age and Bronze Age could be preserved until today. However, archaeological investigations nowadays show that the pile-dwellings are increasingly endangered by erosion. Every year cultural layers are uncovered, eroded, transported and permanently lost. Obvious reasons for the increasing erosion are primarily embankment constructions, ship traffic, the long-term water table drawdown and storm wind events.

Within the framework of the European project 'bank erosion and archaeological heritage protection in Lake Constance and Lake Zurich' an international group of archaeologists and lake researchers come together to save the precious cultural layers in the shallow water zones from their complete destruction. The aim is to investigate the erosion processes with respect to wave and flow dynamics including sediment relocation, to prove ecologically compatible protection measures and to prepare a (better) long-term monitoring of the cultural artifacts under water. One field of the scientific work within the project concerns the collection and analysis of metrological data that govern the complex physical processes in the shallow water zone and their simulation with a numerical model of Lake Constance. For this purpose a coupled three-dimensional numerical model system for hydrodynamics and morphodynamics is set up. It simulates the relevant interactions of wave and flow fields, suspended sediment concentration and sediment transport in the shallow water zones of Lake Constance for short-

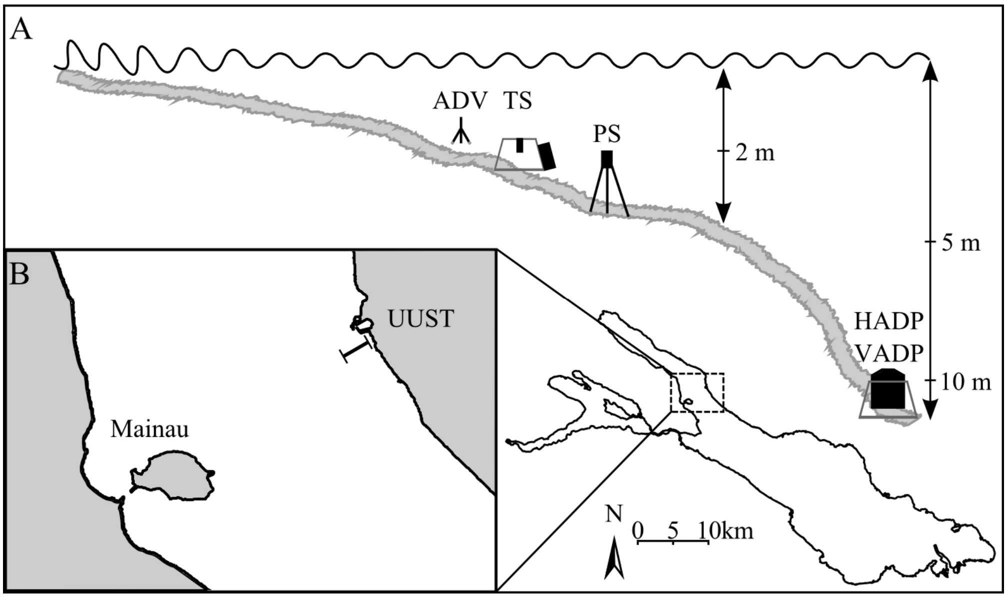

Figure 1: Experimental set-up and study site. (A) Vertical section with the position of all used devices: ADV, Acoustic Doppler Velocity meter; TS, Turbidity Sensor; PS, Pressure Sensor; HADP/VADP, high-resolution Horizontal and Vertical Acoustic Doppler Current Profiler. (B) Map of Lake Constance and transect near Unteruhldingen-Stollenwiesen (UUST).

and medium-term (days to few weeks) events. The focus lies on the impact of storm wind events on the hydrodynamics and morphodynamics around the prehistoric pile-dwelling site at Unteruhldingen-Stollenwiesen (UUST, Fig. 1B). In future this model system shall act as a decision support system to develop and interpret potential protection strategies to preserve the UNESCO World Heritage of pile dwellings.

Study site and measurements

The pre-alpine Lake Constance (surface area 535 km², volume 48 km³) located in Southern Germany adjoins to Northern Switzerland and Western Austria. It consists of two parts. The mesotrophic Untersee (Lower Lake Constance) covers 63 km² with a depth of maximum 40 m only, while the oligotrophic Obersee (Upper Lake Constance) has a maximum depth of 254 m and a surface area of 473 km². (IGKB 2004). In 2010 intensive measurements were carried out in the shallow water zone in the Western part of the Obersee (Überlinger See) close to the pile-dwelling site at Unteruhldingen-Stollenwiesen to investigate physical and sedimentological parameters. The collected data support the understanding of the shallow water erosion and serves as data base for the three-dimensional numerical model.

The littoral zone of Unteruhldingen-Stollenwiesen contains a very important archaeological site, which is threatened by surface erosion. Köninger (2005) describes an alarming erosion depth of up to 1 m within 20 years. An obvious reason for the strong erosion is the exposition to wind waves generated by southwestern winds and ship waves from ferries and passenger ships (Hofmann 2012).

Field measurements

In two intensive field campaigns in spring and autumn parameters as water temperature, significant wave height, current velocity (near bottom and profiles) and turbidity are collected in a high temporal and spatial resolution at a transect from the shore to the so-called 'Haldenkante' in approximately 10 m depth (Fig. 1A).

Laboratory measurements

To collect sedimentological parameters serving as relevant input parameters for the morphodynamic model several sediment samples (two at one site) in different water depths (0-10 m) are retrieved at the study site. While one of the two samples is used for grain size analysis the other is tested on erosional stability.

For the grain size analysis the sediment is prepared with 15 % hydrogen peroxide and the fraction >500 µm is separated. Smaller grain sizes are determined by a laser diffracometer (Micromeritics, DigiSizer 5200). The gained data is further analyzed by the program 'Gradistat' to compute single grain size classes and statistical parameters (Blott & Pye 2001).

The erosional stability analysis of the second sample is performed applying the SETEG-system constructed at the Institute for Modeling Hydraulic and Environmental Systems, University of Stuttgart. It allows the measurement of shear resistance parameters of cohesive sediments and its erosion capacity as a function of shear stress and sediment depth (Kern et al. 1999). The used flume has a rectangular cross-section (145 mm wide, 100 mm high), is about 7 m long and is operated with pressurized discharges of up to 60 L s^{-1}. Within the SETEG-system sediment samples are retrieved with tubes (inner diameter 13.5 cm) that are pressed into deposited bed material and sediments. Applying a vacuum allows the extraction of a sediment core inside the tube. For the analyzing process the tube is installed at the floor plate of the testing flume and the sediment core is moved upwards and thus exposing the sediments into the turbulent flow. Then the flow intensity is increased until the sediment particles start to erode. Due to a hydraulic calibration of the flume the shear stress can be calculated directly from the discharge. Optical equipment measures the eroded volume which helps to calculate the critical shear stress and erosion rates. The procedure is repeated at every depth of interest (e. g. based on density profiles or grain size distribution) and thus provides a vertical profile of related critical shear stresses (Kern et al. 1999, Witt 2004, Leo 2011). The erosion characteristics of very fine grained sediment compositions based on literature only are difficult to determine, as the incipient motion of cohesive sediments depends on numerous factors such as bed shear stress, shear length and physico-chemical properties (Partheniades 2009). However, in this case not only the resistance of the immediate top layer is of interest, but also changes along the depth range of sedimentary deposits. Also a possible consolidation needs to be taken into account. For an adequate quantitative estimation of the erosional behavior of cohesive sediments the experimental analysis is essential.

Results

The field data show a high potential of erosion due to wind and ship generated surface waves. Primarily high and energy-rich surface waves (wind waves) lead to a significant mobilization of sediment particles at the study site. Besides distinctive low wind conditions three storm wind events with wind speeds up to 18 m s^{-1} are observed and measured. The grain size analysis indicates a strong spatial heterogeneous sediment distribution. However, all sediment cores have a mobile top layer consisting of coarse silt and fine sand with a thickness up to 7.5 cm that is easily erodible. Additionally the analysis demonstrates that the sediments at the study site consist of a mixture of silt and fine sand with different amounts of clay intrusions depending on sediment depth and the sample's specific location. At Unteruhldingen-Stollenwiesen an overall of 13 sample cores are retrieved and analyzed with the SETEG-system resulting in 191 datasets of different depth and discharge combinations. Figure 2 shows the critical shear stress as a function of depth of two different sediment cores consisting of fine sand (Fig. 2 A) and lake marl (Fig. 2 B). It is clearly recognizable that the cohesive lake marl has a much higher erosional stability (up to 2.5 Pa) compared to the fine sand (max. 0.55 Pa). At the top the lake marl sediment core shows a highly erosive layer (approx. 0.6 Pa) composed of fine sand, coarse silt and small amount of clay.

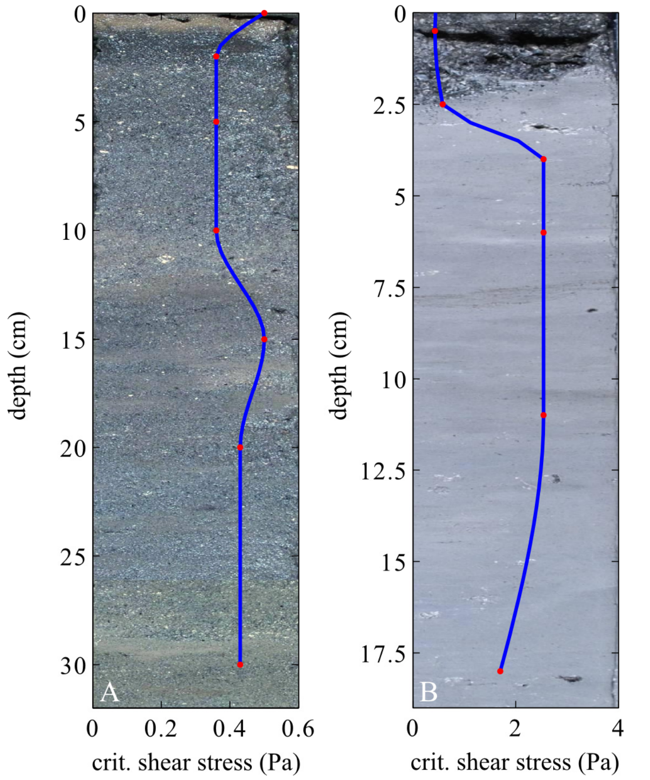

Figure 2: Critical shear stress as a function of depth of two different sediment cores consisting of fine sand (A) and lake marl (B) measured at the SETEG-system.

The effect of consolidation does not show any relevance here. The calculation of the erosion rate is based on the grain size (D50) of the depth-discharge combinations. Table 1 displays the results. The analysis shows that the fine sediment (silt, clay) has a higher erosional stability due to cohesion than coarse sediment (sand).

Table 1: Erosion rates and critical shear stresses of different sediment cores at Unteruhldingen-Stollenwiesen depending on grain size classes from investigations with the SETEG-system

D_{50} in microns	critical shear stress τ in Pa	Erosion rate in g $cm^{-2}s^{-1}$
<20	2.39	$E = 2.53 \cdot 10^{-5} \cdot (\tau/2.39 -1)$
20 - 63	1.46	$E = 2.23 \cdot 10^{-4} \cdot (\tau/1.46 -1)$
63 - 630	0.50	$E = 1.03 \cdot 10^{-3} \cdot (\tau/0.50 -1)$

In conclusion, the intensive field campaign yields to a unique data base for measurements of waves, current velocities, water temperatures and turbidities on the one hand and laboratory measurements of grain size distributions and erosional stabilities of sediments on the other hand. This data shall be used to understand the erosion process in shallow waters and for the set-up of a three-dimensional numerical model of Lake Constance.

Numerical model of Lake Constance for hydrodynamics and morphodynamics

The design of the model system is performed with the software Delft3D (Deltares, The Netherlands) that includes the simulation of all necessary physical processes. To account for wave-current interactions the internal hydrodynamic modules WAVE and FLOW3D (Deltares 2010) are coupled online. This online coupling enables the model system to account for the shear stress due to wave and current impact. Combined with high resolved measurements on grain size and critical shear stress risk maps can be derived that will show potential 'danger zones' within the pile-dwelling site of Unteruhldingen-Stollenwiesen.

The online coupling of the hydrodynamic modules with the morphodynamic module SED is not considered due to additional computational effort. This approach, neglecting the impact of suspended particles on the surrounding flow field, is appropriate when suspended sediment concentrations are below 300 mg L^{-1} (Wu 2008). The use of a model grid with a high temporal and spatial resolution at the study site allows for the simulation of complex physical processes like wave and flow dynamics along with sediment relocation in the shallow water zone. The forcing meteorology is considered by two-dimensional wind fields from different sources (BodenseeOnline, German Weather Service).

The model system and its parameterization is validated with a storm wind event (up to 18 m s^{-1}) of December 2010 taking into account that high and energy-rich surface waves have the highest potential to erode sediments.

The hydrodynamic model

The hydrodynamic model of Lake Constance shows a good adaptation to measured water levels and water temperatures in the shallow water zone at Unteruhldingen-Stollenwiesen during the storm wind event of 2010, December 8th to 14th. On the contrary the results of the calibration of significant wave heights and near bottom flow velocities indicate a strong dependence on the chosen wind input data. There are different wind field sources for the above-mentioned period:

- Wind measurements at land station (weather service Meteomedia) near the study site that are included in the model system by a homogeneous two-dimensional wind field,
- Generated two-dimensional wind fields of a wind model from the model environment of 'BodenseeOnline' (Lang & Paul 2008). It can be distinguished between a linear interpolated wind field and the so-called MCF (Mass Consistent Flow) wind field (Scheuermann et al. 2008).

A more detailed analysis of the wind input data confirms the assumption that they do not sufficiently characterize the wind situation at the Western Obersee, especially at Unteruhldingen-Stollenwiesen.

Figure 3 compares measured and modeled near bottom flow velocities (5 cm above bottom) in 2 m water depth for the storm wind event of December 8th to 12th. Aside from a few exceptions the simulated along-shore flow velocities match the measurements. The time delay of some amplitudes is caused by the wind data's large temporal resolution of 1 h and the reaction of the model system (delayed wave generation). However, there is no correlation between measured and modeled flow velocities rectangular to the shore. Obviously the horizontal grid resolution of 40x40 m chosen to limit computational efforts leads to an insufficient amount of grid cells. To solve the cross-shore components adequately a higher horizontal resolution is necessary.

The morphodynamic model

Due to the high computational effort the heterogeneity of the sediment distribution cannot be taken into account. Therefore the sediment surface at the whole study site is modeled by a 5 cm thick layer consisting of coarse silt and fine sand. Most essential input parameters of the morphodynamic model are derived or directly included from the measurement data: bulk density, critical shear stress, erosion rate and sinking velocity. As no in-situ measurements on net erosion rates and depths are available, the morphodynamic part of the model system is validated with suspended sediment concentrations derived from turbidity data. A comparison of measured and simulated significant wave heights, near bottom flow velocities and suspended sediment concentrations together with simulated maximum bottom shear stresses for the storm event of 2010, December 08th to 14th is given in Figure 4. As wave heights and flow velocities show an acceptable correlation, the modeled suspended sediment concentration is not correlated in such manner, due to two main reasons:

On the one hand the meteorological input data do not represent the correct wind situation during the storm wind event. Hence differences in the wave and flow field and subsequently in the bed shear stress occur. The other reason are the input parameters of the morphodynamic model itself. So far the assumed sinking velocity is obviously too

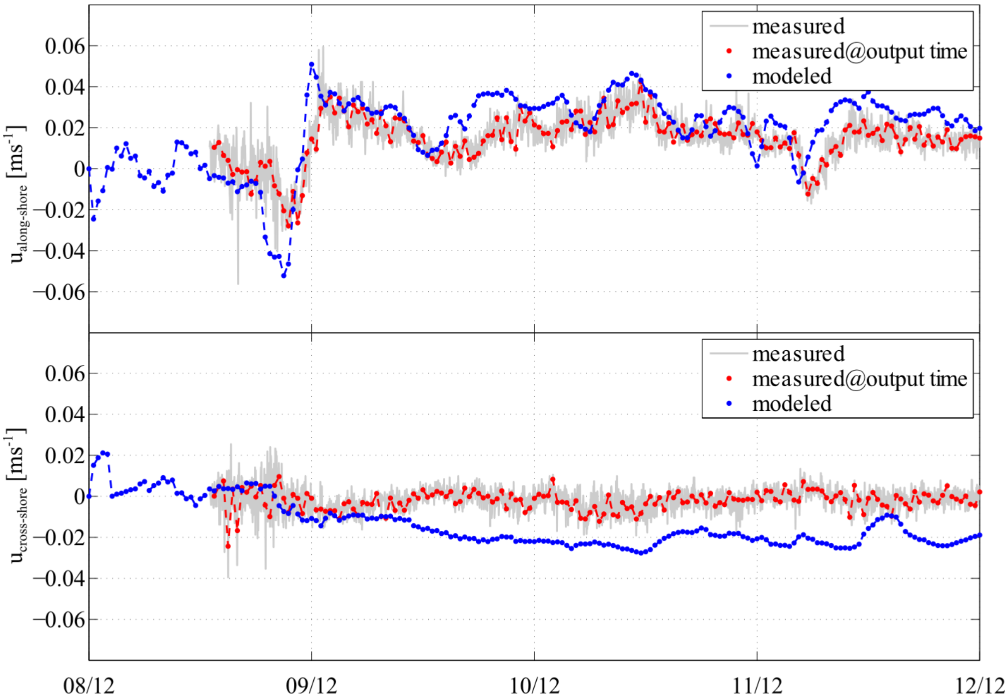

Figure 3: Measured and modeled along-shore and cross-shore flow velocity components in 2 m water depth, 5 cm above bottom during a storm event of 2010, December 08th to 12th.

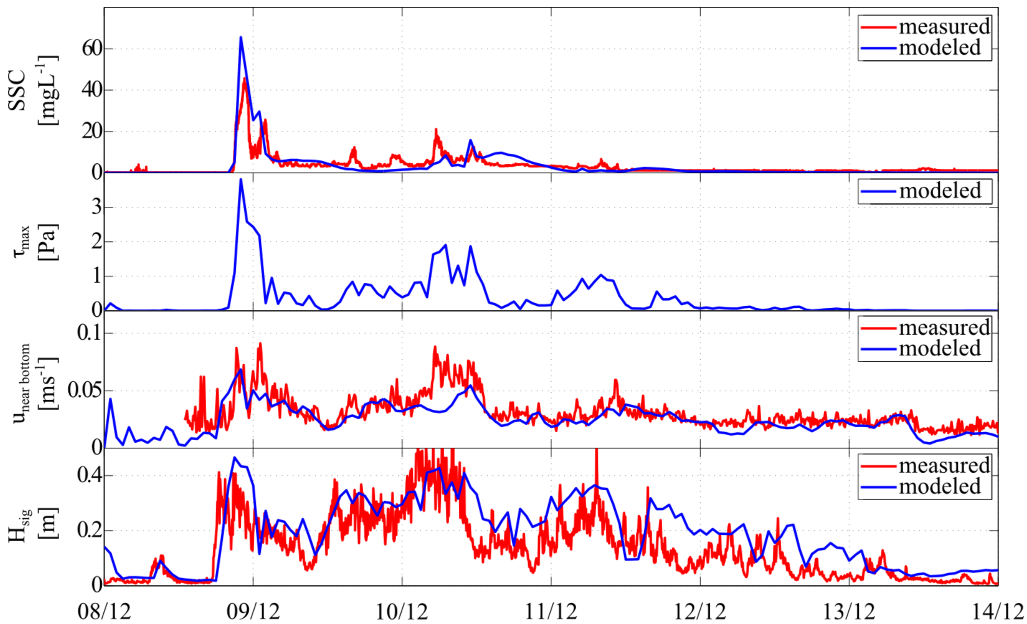

Figure 4: Measured and modeled significant wave heights H_{sig} (2 m water depth), near bottom flow velocities $u_{near\ bottom}$ (2 m water depth, 5 cm above bottom) and suspended sediment concentrations (SSC) (2 m water depth, 10 cm above bottom) together with the modeled maximum bottom shear stress τ_{max} during a storm event of 2010, December 08th to 14th.

low or the critical shear stress is too high. The smooth suspended sediment concentration curve barely following the modeled bed shear stress confirms this hypothesis.

Conclusion and outlook

The results of this current study enhance our understanding of the complexity of simulating hydrodynamics and morphodynamics in the shallow water zone of Lake Constance. Further work on the existing model system is required until it is able to reproduce sediment erosion and transport processes at the study site during the storm wind event of 2010, December 08th to 14th sufficiently. So far experience shows that a higher grid resolution is not always practical with respect to the ratio of additional computational effort and expected benefits and is subject of current research. A next step is the implementation of more detailed meteorological input data as the two-dimensional wind fields of the COSMO model provided by the German Weather Service (DWD). Additional field measurements will focus on flow velocities and suspended sediment concentrations along the total water depth. Especially the near-bed has to be in the focus so that the model can be validated more precisely. The consequences of different protection measures like honeycombed or extensive gravel coverings will be object of future simulation scenarios. The implementation of a vegetation submodule to compute the stabilizing effect of macrophytes on the sediment deposits is planned too.

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