Budapest University of Technology and Economics
Faculty of Civil Engineering
Department of Hydraulic and Water Resources Engineering

PhD thesis book

Investigation and modelling of wind induced waves in shallow water

Krisztián Homoródi

Supervisor: Prof. János Józsa

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Preliminaries

Shallow lakes are valuable but also vulnerable ecosystems. The variety of bird species in the reed zone is one of the many reasons why they are important in environmental protection point of view. A huge number of human activities belong to these lakes like fishing, recreation or reed production so these lakes are also important for the national economy. But because of the large surface area and long shore line compare to their volume, these lakes are particularly vulnerable to perturbations in the water balance. In addition, the typically low throughflow rate yields that if something gets into the lake it will stay there for longer time with high probability comparing with rivers. Hence the responsibility of releasing contaminants into a shallow lake increases compared to rivers. In general the wisely management of these lakes and also their catchments is very important to enable a sustainable human use for activities such as fishing, recreation and reed production.

Besides the fact that vertical extension of the lake is much larger than the horizontal extension shallowness means that the effect of the surface forces reaches the bottom and the effect of the bottom forces also reaches the surface. Wind-induced surface waves and the consequent periodic motion of the water column are known to play an important role in shallow lakes hydro- and sediment dynamics, e.g. in bed material stirring-up or wave loading on beach protection works. In shallow lakes wind generated wave have significant effect on the currents thought several processes like wave-enchanged bottom friction, Stokes drift, radiation stresses and wave-induced surface turbulence. The wave induced turbulence near the bottom also causes stir up of the fine sediment. This process has effect not only on the sediment transport processes of the lake but also on the alga growth by the resuspension of the nutrients from the sediment and the limitation of the light penetration into the water.

Field measurements and their detailed analysis are still essential to obtain a more realistic insight into hydrodynamic features in shallow conditions. The systematic research of the hydrodynamic conditions of Lake Neusiedl was started in 1990 in the Fertőrákosi Bay and then continued in the Austrian part of the lake in a Hungarian-Austrian-Finnish research cooperation. The main goal was to understand the wind driven current structures from lake-wide to bay-wide scale. Wave measurements were conducted in Lake Neusiedl from the beginning of the 21st century both in Fertőrákosi Bay and in the Austrian part of the lake. I could have joined as a student in the processing of these data.

Most of the widely used field measurement methods can give information about the wave properties only at single point, which is usually not enough for spatial characterisation. For the spatial extension of the description of the hydrodynamic state a choice is to apply some analytical estimation formulas or numerical models. By means of wave estimation formulae or numerical models it becomes then, possible to extend our knowledge also about the wave properties to the whole investigated lake. Before using any estimation method it must be checked whether it can reproduce the measured wave data sufficiently well. As to semi-analytical approaches, the Shore Protection Manual (SPM) contains widely used formulas for the estimation of significant wave height and average wave period in shallow water. In spite of their simplicity these formulas showed decent agreement with measurements e.g. in Lake Balaton. As to numerical modelling tools, I focused on SWAN (standing for Simulating Waves Nearshore) which is a 2D spectral wave model developed for the simulation of wind generated waves from the nearshore to the surf-zone.

The detailed description of the inhomogeneity in the wind field which generates the surfaces waves can be made only with simultaneous measurements at a huge number of locations. Usually it is not possible, but the fetch dependent wind field caused by the abrupt variation of the surface roughness at the land-water and reed-water interfaces can be modelled by an atmospheric internal boundary layer (IBL) model. This IBL model was verified with field measurements and it was shown that this IBL-based wind variability has significant effect on hydrodynamic processes in shallow lakes and it was taken into account in the hydrodynamic modelling of Lake Neusiedl. The effect of IBL-based wind variability on wave properties was investigated by van Vledder, who concluded that this effect is not, but those investigations were made in conditions deeper than Lake Neusiedl. I investigated if there is a significant effect of the wind field variability on the wave properties and sediment transport processes in water as shallow as Lake Neusiedl.

Objectives

The overall aim of this thesis is to obtain a realistic insight into wave features in shallow conditions. To achieve this overall aim, the objectives of the thesis are given next.

- Improve the processing method of the pressure based wave measurements to reduce or eliminate the effect of turbulence and measurement noise and subtract all available information from the raw pressure data.
- To develop and verify a possible methodology to reconstruct wave features (also propagation direction) from 3D velocity measurements. Subtract the velocity component belong to the orbital motion due to waves and reconstruct the surface displacement time series and the wave properties from that.
- To extend our knowledge about wave properties from the measurement point to the whole lake verify an appropriate empirical wave estimation method or setup a 2D numerical wave model calibrate and validate it.
- With the validated numerical wave model of the lake investigate the effect of the fetch dependent wind field desricbed with the IBL model on the wave properties and sediment transport processes.

New scientific results

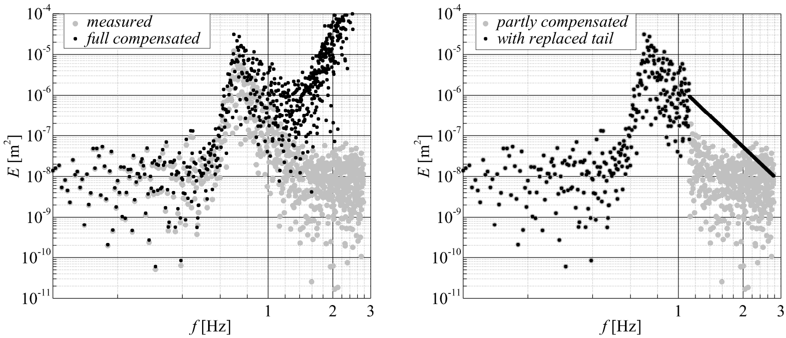
As a summary of this work the main new results and conclusions are reported in the form of theses. The 1st and 2nd theses are related to the wave measurement and the 3rd and 4th theses are related to the wave modelling.

The surface wave motion causes pressure fluctuation in water. For a monochromatic progressive wave the pressure field can be described based on the linear wave theory. The wave-induced pressure fluctuations are attenuated with depth and this attenuation depends on the frequency of the wave. To reconstruct the surface displacement time series from pressure data a compensation procedure has to be applied due to this exponential attenuation of wave-induced pressure fluctuations with depth. The higher the frequency, the larger the attenuation.

In nature the surface displacement time series is the sum of large number of monochromatic wave components with different frequency. As attenuation depends on wave frequency, the compensation has to be carried out by spectral decomposition instead of time domain analysis. Due to the attenuation the high frequency range of the spectrum is not likely to be related to the wave motion, instead, it is expected to represent the energy in turbulence, along with some possible measurement noise. That is why the wave-related compensation is not applicable here. To avoid this, an upper threshold for the frequencies to be compensated has to be chosen. Wave components beyond the threshold frequency still play a role in determining the bulk wave parameters (e.g. average wave height and period) but are absent in the original spectrum.

Thesis 1: Further improvement of the processing of the measured data

I introduced a method to improve the processing of the measured wave data, applicable both for pressure- and velocity-based measurements. I demonstrated that replacing the turbulence-dominated tail of the spectrum with a fitted analytical power function causes considerable difference in the derived bulk wave parameters so this procedure is worth doing. Investigating a great number of burst data from Lake Neusiedl, I found the average integer value of the best fitting exponent of the power function to be –5. [1, 3]



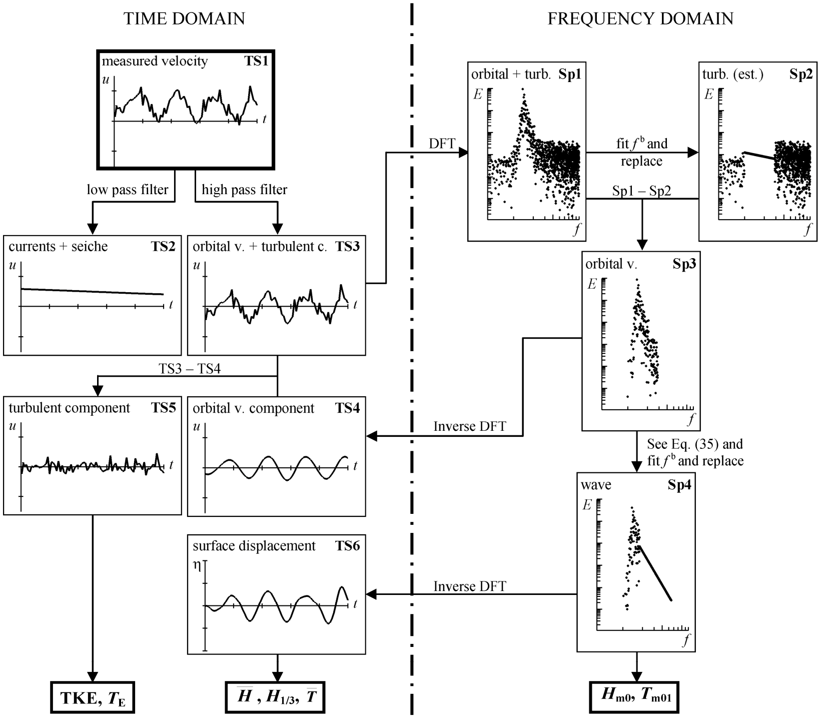
Original energy spectrum of a typical 5-min burst (gray dots) with its compensation over the full frequency range and under a threshold frequency with the replaced tail (black dots).

As many other measurement methods, the pressure-based wave measurement has a deficiency because it is not able to provide information about the direction of the waves, though in addition to the wave height direction is another relevant parameter in e.g. beach protection or harbour planning. Using several synchronised gauges it is possible to derive some kind of directional data but this is far from being a general solution. In turn, 3D velocity measurement data inherently contain directional information.

Thesis 2: Reconstruction of the wave properties from 3D velocity measurements

I developed an appropriate technique to obtain wave features from 3D velocity time series which can also contain larger time scale components such as circulatory currents or seiche and smaller time scale components such as turbulence. I proved the applicability of the presented velocity-based estimation method by simultaneous pressure and 3D velocity measurements in Stagnone di Marsala lagoon, furthermore by synchronised velocity measurements carried out at two different depths at the same horizontal location in Lake Neusiedl. [1, 3, 4]

By using suitable velocity decomposition technique we could obtain the components representing turbulence accompanying the wave motion, giving room for estimating some of its traditional parameters.

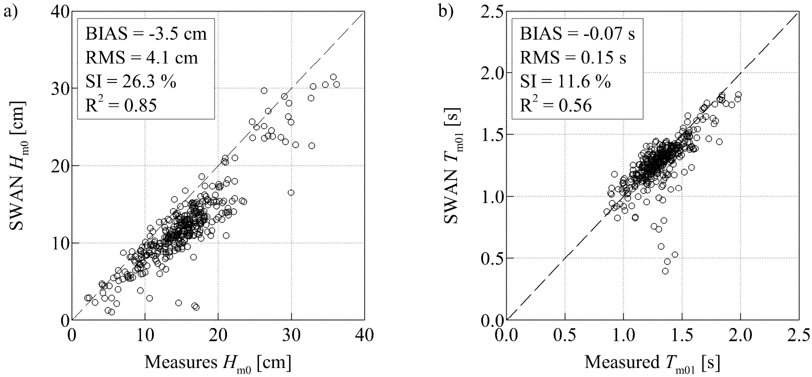


The flowchart describing the reconstruction of the wave and turbulence features from 3D velocity time series.

Most of the widely used field measurement methods can give information about the wave properties only at single point, which is usually not enough for spatial characterisation or as a snapshot which is usually not enough for the long term statistical analysis. For the spatial or time extension of the description of the wave properties to the whole investigated lake a choice is to apply some analytical estimation formulas or numerical models.

Thesis 3: Numerical wave modelling in shallow lakes

I proved the validity of the 2D spectral wave model SWAN on lakes as extremely shallow as Lake Neusiedl. I verified that the calibrated model can sufficiently reproduce the measured properties of the locally generated wind waves. [2]



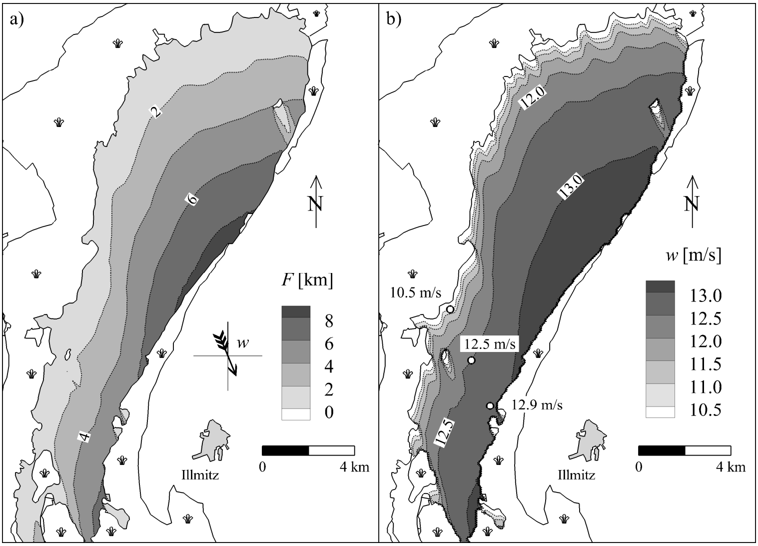
Scatter diagram of wave height (a) and period (b) for the validation period. The dashed diagonal represents an exact match.

The abrupt variation of the roughness at the land-water and reed-water interfaces results in an inhomogeneous, fetch-dependent wind speed distribution over the lake. This spatial inhomogeneity of the wind speed can be modelled by an IBL model. This IBL model was verified with field measurements and it was shown that this IBL-based wind variability has significant effect on hydrodynamic processes in shallow lakes and it was taken into account in the hydrodynamic modelling of Lake Neusiedl. The effect of IBL-based wind variability on wave properties was investigated by van Vledder, who concluded that this effect is not significant but those investigations were made in conditions deeper than Lake Neusiedl.

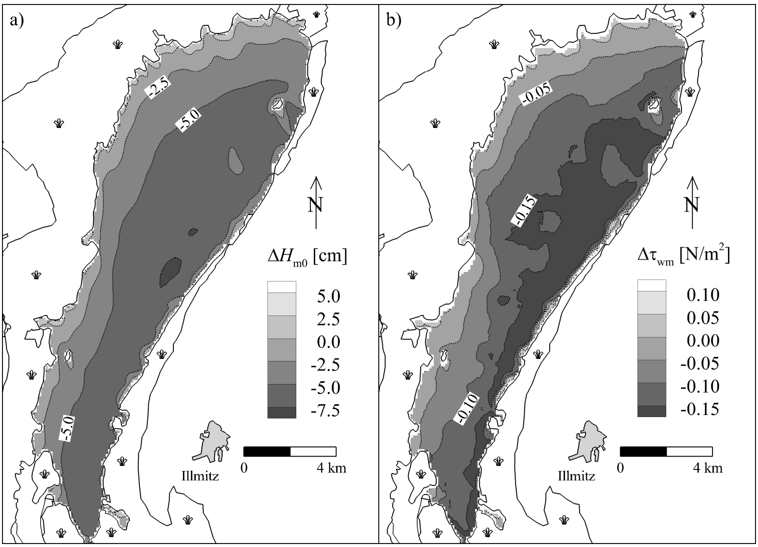
Thesis 4: Wave modelling in consideration of the fetch dependence of the wind speed field

I showed that the fetch-dependent wind field described by an internal boundary layer model of the neutral atmosphere has a significant effect on the wave properties in waters as shallow as Lake Neusiedl. I demonstrated that this effect – the rate of which also changes along the fetch – is the most pronounced on the wave induced bottom shear stress. I proved that one can find equivalent uniform wind speeds which reproduce the wave properties with decent agreement, but they are not the same for all wave properties. [2]

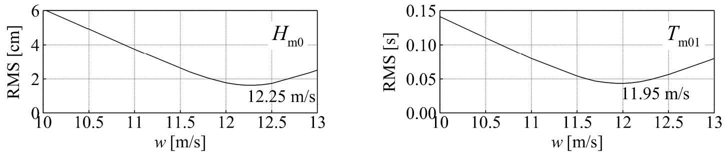
In conclusion, in fetch-limited lakes it is potentially wrong to force a wave model uniformly with wind data directly measured overland or onshore, regardless of whether it is on the upwind or downwind shore. I therefore advocate the use of micrometeorological models for distributing the wind shear stress, and the inclusion of offshore wind stations in field campaigns. At larger horizontal scales, say above 20 km, meso- and synoptic scale variations become important and atmospheric circulation models are needed to properly account for the variability of the wind input in wave models.



Distribution of fetch (a) and IBL-based wind speed (b) over Lake Neusiedl. Wind direction is NNW as shown in plot a.



H_{m0} (a) and τ_{wm} (b) differences of the uniform wind speeds, w = 10.5 m/s from IBL-based wind speed fitted to 10 m/s at the upwind shore.



The root-mean-square error of the H_{m0} (a) and T_{m01} (b) of different uniform wind speeds from IBL-based wind speed fitted to 10 m/s at the upwind shore.

Application and direction of future reseach

In this thesis I demonstrated that a 2D numerical wave model can be adapted to lakes as extremely shallow as Lake Neusiedl. It was also shown that the correct description of the fetch dependent wind speed distribution must be used for the appropriate estimation of the wave-induced bottom shear stress. During the investigations for simplicity wind generated currents were left out of consideration. But as it was mentioned above in shallow water wind generated waves have effect on the currents thought several processes like wave-enchanged bottom friction and ambient currents have effect on the growth and decay of waves. These interaction processes can be taken into account with the coupled modelling of waves and currents. The calibrated wave model of Lake Neusiedl can be used for these investigations.

The building of a hydrodynamic forecasting system for Lake Balaton was started recently. It seems to be necessary to take into account of the effects of waves estimated with a spectral numerical model on the currents. Based on these results it is possible to setup a 2D numerical wave model on Lake Balaton which is needed for the forecasting system. Further wave measurements in Lake Balaton are needed for the calibration and validation of this model.

Moreover, the measurement and estimation of the main wave and turbulence parameters should be extended also to the reed zone, where the exploration of their attenuation tendency could improve the description of the siltation processes in the nearshore interface region. A possible way to express the wave energy dissipation due to vegetation is the cylinder approach. To the calibration and validation of this method wave measurements must be conducted simultaneously at different locations in the reed zone. The described 3D velocity based wave measurement is applicable for wave measurements in the reed zone. This can be the part of a complex investigation to describe the processes at the interface of the pelagic and littoral zone.

List of publications related to the thesis

1. Homoródi, K., J. Józsa, T. Krámer, G. Ciraolo, and C. Nasello (2012): Identifying wave and turbulence components in wind-driven shallow basins, *Periodica Polytechnica Civil Engineering 56*(1), 87–95.

2. Homoródi, K., J. Józsa and T. Krámer (2012): On the 2D modelling of wind-induced waves is shallow, fetch-limited lakes, *Periodica Polytechnica Civil Engineering*, accepted for publication.

3. Homoródi K., T. Krámer and J. Józsa (2009): Analysis of high-frequency correction in shallow water wave reconstruction and parameter estimation. In: *Proceeding of the 33rd IAHR Congress: Water Engineering for a Sustainable Environment*, 9-14 August, Vancouver, Canada, pp. 6139-6145. Paper ID: 11100, (on CD-ROM).

4. Homoródi K., T. Krámer and J. Józsa (2010): Analysis of wave and turbulence measurements in wind-driven shallow basins. In *Proceeding of the First IAHR European Congress*, 4–6 May, Edinburgh, UK, Paper ID: FMIVc, (on CD–ROM).