TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Exact and Natural Sciences
Department of Physics

SIMULATION OF SURFACE WAVE DAMPING NEAR COAST DUE TO OFFSHORE WIND FARMS

A research

Victor Alari

Supervisor: PhD Urmas Raudsepp

Tallinn 2010

To Aelica

TABLE OF CONTENTS

1. INTRODUCTION

The ever growing need for energy and the decreasing availability of non-renewable energy sources has put the question of using alternative energy sources into high perspective. Apart from nuclear energy, which now makes up 6.5% of worlds energy need, renewable energy – solar, geothermal, water, wind and biomass – is making its way, forming now up to 13.1 % of the global energy consumption (IEA, 2007). The question today is not only in the increasing need for energy, but in the reduction of environmental effects as well; climate change due to excess CO_2 is a well documented fact (IPCC, 2007).

In Estonia up to 5.1% of energy will be produced from renewable energy sources by the end of 2010 (European Commission, 2007). This number, however, should grow in the future. Nearly 200 wind turbines are planned to be installed on the shallows near Hiiumaa. The total power of these arrays would be 600-1000 MW and the productivity 2.3-2.5 TWh/year (4energia). This is about 40% of the total need of Estonian electricity, maximally. In comparison, in the leading wind energy country Denmark only 19.7% of the domestic need is covered by wind energy (Danish Energy Agency, 2007). Apart from the mentioned 200 turbines, which in high probability would be installed in coming years, another 500 MW of arrays could be installed on some shallows in the coastal waters of the northern Estonia as well (Erm *et al.*, 2009).

Every structure which is installed in water will affect the wave and circulation regime and the sediment transport – from the viewpoint of water physics. There are plenty of studies published in scientific literature assessing the importance of scour. Only a handful of technical studies asses the impact of wind turbines or wave farms upon surface waves near the coast (DHI water and Environment, 2007; Millar *et al.*, 2007; Defra, 2005). In scientific papers, however, no studies are published which assess the importance of the whole array of wind turbines upon wind waves. The purpose of this research is to quantify the effect of these structures on wind waves, which are propagating towards the coast. The main aim is to find out how much these structures will absorb and scatter wave energy.

Wind farms are planned to be installed in the coastal waters of Estonia near Hiiumaa, the NE Baltic Sea (Figure 1a). Basically, when planning offshore wind farms, they should be located some distance away from the shore to reduce the effect on land. Construction costs can be reduced if an offshore wind farm is located on shallows. Water is relatively deep off the coast of Hiiumaa, but there are often several shallows, where water depth is less than 20 m.

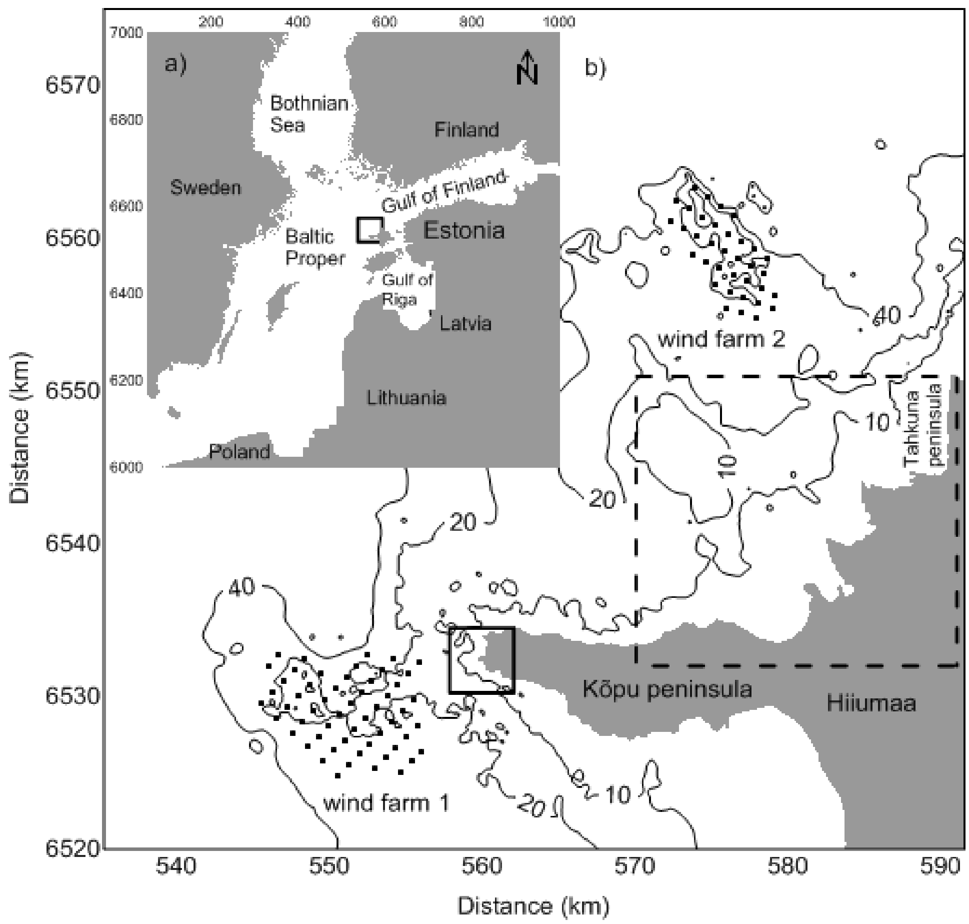

Figure 1 a) The Baltic Sea. The black box is the boundary of figure 1b; b) A detailed location of the wind farms. The black continuous box represents the impact area of the wind farm 1 and the dashed black box represents the impact area of the wind farm 2. The contour levels are the water depth in m. Every black filled circle represents a wind turbine. North up.

This study focuses on two locations – the wind farm 1, situated in the WSW from the Kõpu Peninsula (Figure 1b) and the wind farm 2, situated in the NW from Hiiumaa (Figure 1b). Coastal areas that could be under impact are the head of Kõpu Peninsula (where the so-called surf paradise is located) and the northern coast of Hiiumaa. At the wind farm 1, 55 turbines are planned to be installed in parallel rows with a minimum distance of 1000 m from each other. The closest turbines at the wind farm 1 will be 5 km from the coast (the head of Kõpu Peninsula) and the distant ones 15 km from the coast of the Kõpu Peninsula. The nearest coast from the wind farm 2 is the western part of Tahkuna Peninsula that is 13 km to the SE. The northern coast of the Kõpu Peninsula directly south from the wind farm 2 is 20 km away.

In Section 2 the model is described, set up and validated. Main findings are presented and discussed in Section 3; key conclusions are outlined in Section 4. Afterwards follows acknowledgements, summary both in English and Estonian and the work is ended with bibliography.

This study is based on the following publication, which is referred in ISI Web of Science:

Victor Alari and Urmas Raudsepp. 2010. Simulation of wave damping near coast due to offshore wind farms. Accepted for publication in *Journal of Coastal Research*.

2. METHODS

2.1 Model description

SWAN model is used to assess a potential effect of wind farms upon wave heights. SWAN is a third-generation phase averaged spectral wave model developed at the Delft University of Technology, the Netherlands (Booij *et al.*, 1999). In SWAN, waves are described with a two-dimensional wave action density spectrum, whereas the evolution of the action density, *N*, is governed by the time-dependent wave action balance equation, which in Cartesian coordinates reads:

$$\frac{\partial N}{\partial t} + \left(\vec{c}_g + \vec{U}\right) \cdot \nabla N + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}. \quad (1)$$

The first term represents the local rate of change in action density; the second term denotes the propagation of wave energy in the two-dimensional geographical space with $\vec{c}_g$ the group velocity, and $\vec{U}$ the ambient current. The third term represents the effect of shifting the relative frequency due to variations in depth and mean currents. The fourth term represents the depth-induced and current-induced refraction. The quantities c_σ and c_θ are the propagation velocities in spectral space (σ, θ) with σ and θ representing the relative frequency and the direction of propagation respectively. The right-hand side contains the source term S_{tot} that represents all physical processes that generate, dissipate or redistribute wave energy. In shallow water, six processes contribute to S_{tot}:

$$S_{tot} = S_{wind} + S_{nl3} + S_{nl4} + S_{wc} + S_{bot} + S_{db}. \quad (2)$$

These terms denote respectively the energy input by wind (S_{wind}), the non-linear transfer of wave energy through three-wave (S_{nl3}) and four-wave interactions (S_{nl4}), and the dissipation of waves due to white-capping (S_{wc}), bottom friction (S_{bot}) and depth-induced wave breaking (S_{db}).

2.2 Model setup

The model (version 40.72) was run in the 3rd generation mode with the saturation-based whitecapping model, which estimates the whitecapping of wind sea locally in the wave spectrum and gives therefore realistic estimates of peak periods (Van der Westhuysen *et al.*, 2007). In every model run, 40 frequencies distributed logarithmically on the range of 0.05-1 Hz was used and 24 spectral directions were included. The diffraction was activated only when the highest spatial resolution was used.

Steady wind speeds of 8 m/s and 15 m/s were selected. The first value is the annual average wind speed offshore (Soomere, 2003), while the second represents strong wind events that occur at least once per month in autumn and spring (Soomere and Keevallik, 2003). All presented wave fields are saturated. In case of the wind farm 1 the winds from the SW and W were selected. The head of the Kõpu Peninsula is located in the NE from the wind farm 1. Thus, waves generated by winds blowing from the N, E and S do not propagate towards the coast. Even the waves coming from the NW do not make landfall at the head of the Kõpu Peninsula.

The wind farm 2 is orientated so that the waves from the N and NW could reach the coasts of Hiiumaa. Thus, the impact of the wind farm 2 is assessed for winds blowing from those directions.

The modelling of waves at the wind farm 1 has been carried out using 5 consequently nested models. First the whole Baltic Sea with a 2000 m resolution is modelled. Getting the boundary conditions from the previous model, waters surrounding Hiiumaa are modelled with a 400 m resolution, and then 100 m, 50 m and 25 m. The same scheme applies also for the wind farm 2, but the highest model resolution is 50 m, not 25 m. The details of the grids are listed in Tables 1, 2, and the coarsest model boundaries visualized in Figure 1a.

Table 1: The location of the origin of the computational grid, number of meshes of the computational grid, mesh sizes of the computational grid for the wind farm 1 impact calculations.

	2000 m	400 m	100 m	50 m	25 m
Location of origin of x-direction [km]	50	524	535.2	541	543
Location of origin of y-direction [km]	6000	6500	6510	6521	6524
Nr. of meshes in x-direction	475	140	348	420	760
Nr. of meshes in y-direction	500	150	400	380	480

Table 2: Same as Table 1 but for the wind farm 2 impact calculations. The 2000 m grid has the same setup as described in Table 1.

	400 m	100 m	50 m
Location of origin of x-direction [km]	560	566.4	570
Location of origin of y-direction [km]	6532	6532	6532
Nr. of meshes in x-direction	90	256	420
Nr. of meshes in y-direction	110	380	700

The Baltic Sea bottom topography by Seifert *et al*. (2001) and the marine charts provided by the Estonian Maritime Administration were used to create the model topographies. The model grids are all Cartesian and the coordinate system used is UTM-34 (Universal Transverse Mercator). The scattered data were interpolated to the model grid. The land mass of Hiiumaa was blanked using a digitalized coastline that was extracted from the Google Earth. Water depths lower than 0.1 m were replaced with a value of 0.1 m. In case of the 2000 m model, some small bays in the southern Baltic Sea were artificially masked to reduce the model calculation time. It has no effect on the wave heights near Hiiumaa. Model bathymetry was smoothed at the boundaries of nested model grids to avoid spurious waves.

For every forcing situation, two calculations are made - firstly, without farms and secondly, with farms. For every wind turbine, the closest point is located in the grid and the value at that grid point is replaced with 0, e.g. it is represented as land. In SWAN the land absorbs all incoming wave energy. Here we asses the changes in significant wave height. Let Hs_1 be the calculation made without farms and Hs_2 be the calculations with farms in nodes (*i,j*). The impact is defined

$$\Delta Hs(i,j) = \frac{Hs_2(i,j) - Hs_1(i,j)}{Hs_1(i,j)} * 100\%. \qquad (3)$$

If $\Delta Hs(i,j)$<0, the impact is in terms of reduction and when $\Delta Hs(i,j)$>0, it shows an increase. The diameter of the wind mill structure (monopile) is not more than 5 m in reality. Assuming a linear dependence between the differences of calculated height, in case of a 25 m grid step, the results obtained with Eq. 3 are divided by a factor of 5 and in case of a 50 m grid size by a factor of 10.

2.3 Model validation

Sub-surface pressure sensors were deployed in the locations of the wind farms 1 and 2 in summer 2007. Although the pressure gauges remained in water for 23 days, the first 10 days were selected for the comparison. The second half of the measurements displayed a very low wave activity. Sub-surface pressure was converted to surface spectra using the method described by Alari *et al.* (2008).

The model was forced with HIRLAM wind fields (High Resolution Limited Area Model; resolutions 1’*1.6’ in latitudes and longitudes, respectively). During the verification period, wind speed did not exceed 13 m/s and wind blew mainly from the SW-W.

The temporal variability of the measured significant wave heights and peak periods are similar at both locations (Figure 2 and 3). The mean significant wave height and the mean peak period were greater at the wind farm 1 compared to the wind farm 2 (Table 3). The waves generated by the SW winds refract around the Kõpu Peninsula and loose energy. It results in a lower significant wave height and peak period at the wind farm 2 compared to the location of the wind farm 1. The simulated significant wave height matches the measurements equally well at both locations. The root mean square errors (RMSE) are

0.2 m and 0.23 m respectively, but the scatter in terms of height is smaller at the wind farm 1 (Table 3). There are time slices when significant wave height is better represented at one location than at the other. The timing of period is somewhat better represented at the wind farm 2, but the scatter is basically the same for both sites. Usually, the model fails to reproduce peak periods in both locations synchronously.

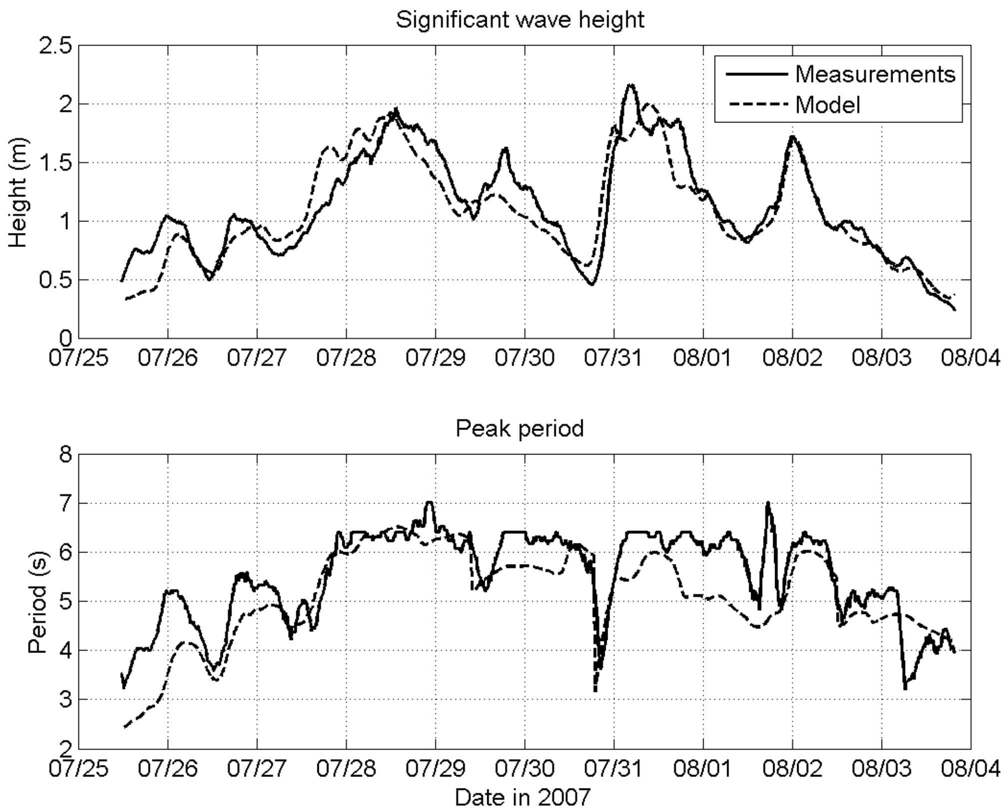

Figure 2 Model-data comparison at the location of the wind farm 1.

Table 3: The statistics of the validation of the wave model. R is the correlation coefficient, scatter index (SI) is defined as the ratio between RMSE and the mean of measurements.

	Wind farm 1	Wind farm 2
Water depth [m]	14	11
Data points	1350	1350
Hs mean [m]	1.12	0.86
Peak mean [s]	5.56	5.27

RMSE Hs [m]	0.2	0.23
RMSE Peak [s]	0.7	0.58
R Hs	0.88	0.9
R Peak	0.81	0.86
SI Hs	0.18	0.27
SI Peak	0.13	0.11

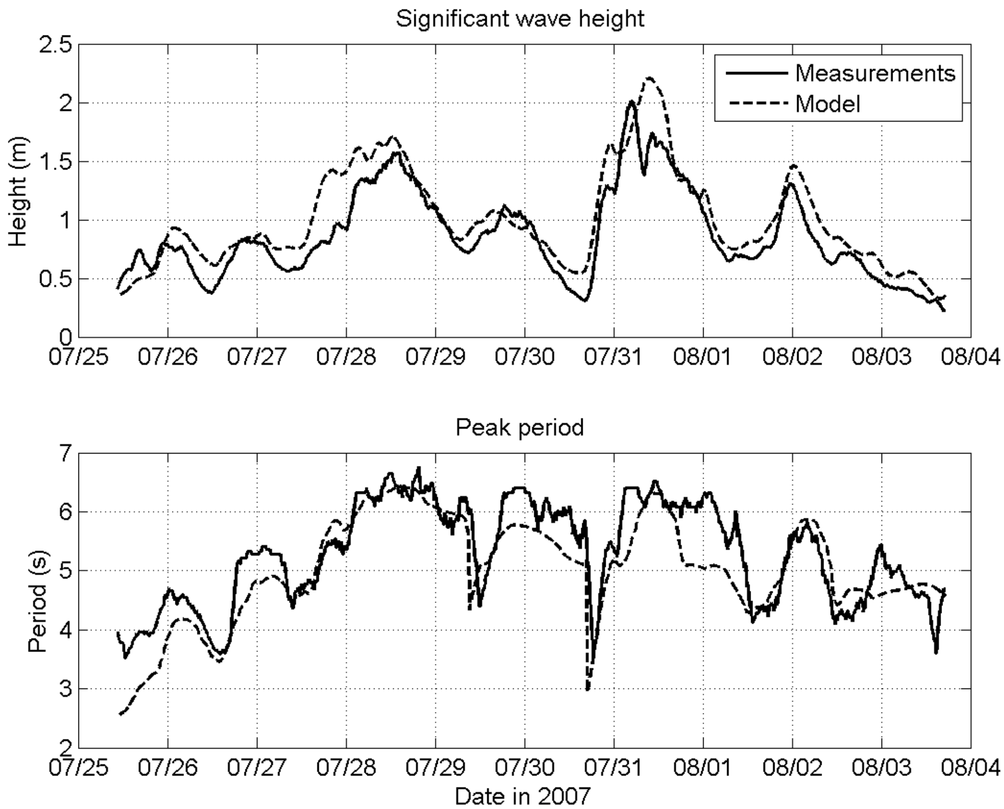

Figure 3 Model-data comparison at the location of the wind farm 2.

3. RESULTS AND DISCUSSION

It is a merit to recognize significant wave height and wavelength in the vicinity of wind turbines prior to the construction. As the fields distribution of the parameters are quite homogenous at the wind farm areas, the results are summarized in Tables 4 and 5, instead of visualizing them.

For the wind farm 1, although there is a fourfold increase of wave heights in case of doubled wind speeds and a linear increase of wave period, the 45^0 turn of the wind does not change the parameters at any significant level (Table 4). For the SW wind, significant wave height is greater only by 0.2 m compared to the W wind at the wind farm 1. The peak period is only 0.4 s greater. The resulting wavelengths display the same variability. As the fetch length for the W winds is 250 km and for the SW winds 650 km, almost the same variability means that the wave field has its full development at 250 km already.

Table 4: Modelled wave parameters at the wind farm 1 location. Hs – significant wave height; Peak – peak wave period; Wlen – wavelength corresponding to peak wave period.

	SW 8 m/s	SW 15 m/s	W 8 m/s	W 15 m/s
Hs [m]	0.9-0.95	3.2-3.8	0.88-0.94	3-3.6
Peak [s]	4.7-4.8	8.5-8.7	4.7-4.8	8.1-8.3
Wlen [m]	33-36	75-110	32-35	70-100

Table 5: Modelled wave parameters at the wind farm 2 location. Hs – significant wave height; Peak – peak wave period; Wlen – wavelength corresponding to peak wave period.

	NW 8 m/s	NW 15 m/s	N 8 m/s	N 15 m/s
Hs [m]	0.85-0.9	2.8-3.2	0.82-0.84	2.5-2.7
Peak [s]	4.4-4.6	7.4-7.7	4.1-4.2	6.5-6.7
Wlen [m]	29-31	62-84	26-28	52-66

At the wind farm 2, the turning of wind from the NW to the N reduces significant wave height up to 0.5 m and peak period up to 1 s (Table 5). The NW wind generates higher waves since the fetch is longer. However, compared to the wave parameters at the wind farm 1, the modelled values of wave parameters are lower at the wind farm 2. This is expected as the fetch length is lower in case of the wind farm 2.

As an illustration, a field distribution of significant wave heights in case of 15 m/s, the SW winds are presented in Figure 4. The variability on significant wave heights and wavelengths at the farm locations suggest that dissipation due to bottom friction occur in areas where significant wave height is lower than the mean value, but where wavelengths stay at the mean value. In places, where significant wave height is greater than the mean value and wavelengths shorter than the mean value, shoaling exceeds dissipation. The 15 m/s wind induces greater dissipation and shoaling compared to the 8 m/s wind.

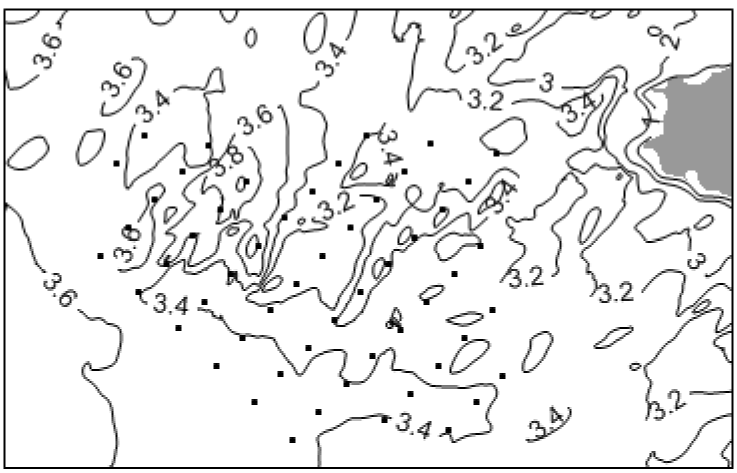

Figure 4 The field distribution of saturated wave field of significant wave height at the wave farm 1. The contour unit is in m. Every black filled circle represents a wind turbine.

In terms of significant wave height, the absolute reduction near the coast due to the wind farm 1 is not more than 2% (Figure 5). The 1% isoline is closer to the coast in case of the 8 m/s wind compared to the 15 m/s wind. The difference in terms of significant wave height does not exceed 0.5 cm and 1 cm near the coast in case of the 8 m/s and 15 m/s wind respectively. In case of the 15 m/s wind, the 1% reduction line coincides with the 10 m isobath. Compared to the impact of the wind farm 1, the reduction of significant wave height due to the wind farm 2 is even more marginal (Figure 6). The reduction is less than 0.25 % below the 10 m isobath.

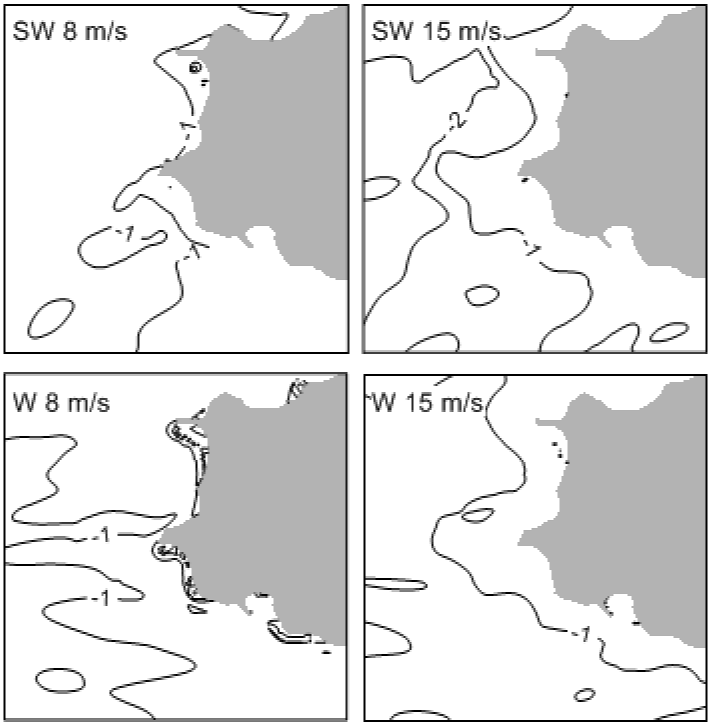

Figure 5 The impact of the wind farm 1. The contour unit is [%] and a negative value shows a decrease of significant wave height.

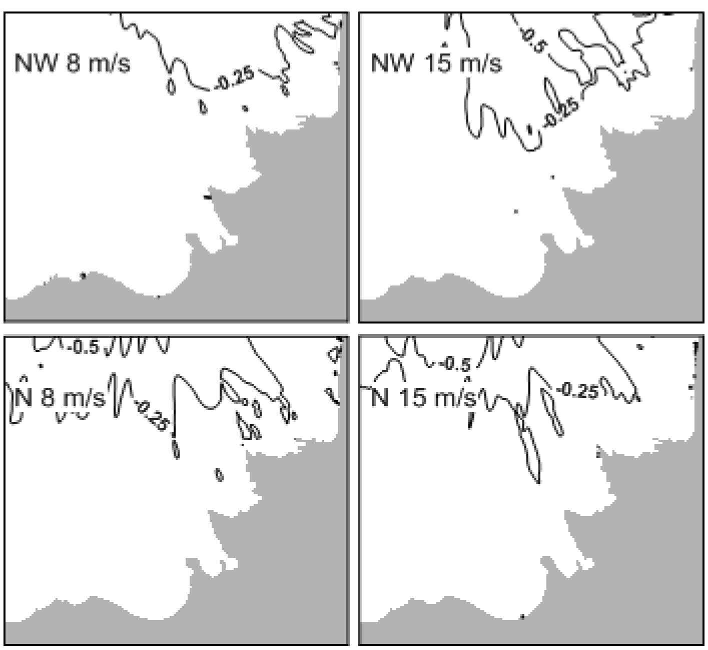

Figure 6 The impact of the wind farm 2. The contour unit is [%] and a negative value shows a decrease of significant wave height.

A very low impact is due to three factors. Firstly, waves meeting an obstacle reflect and bend around it. Only large piles change the wave field considerably. Depending on an author (see for example the Coastal Engineering Manual), the diffraction and reflection are valuated as significant for D/L >0.1 or D/L >0.2, where D is the diameter of the monopile and L is the wavelength. In case of the 8 m/s wind, the ratio is between 0.1-0.2 and in case of the 15 m/s wind, 0.05-0.08 (when the diameter is 5 m, wavelengths from Tables 4 and 5). Thus in our cases, diffraction and reflection are negligible. Secondly, the two turbines are not closer than 1 km to each other (at least 10 crests fit between) and therefore very little scatter occurs. And lastly, the wind turbines are distant from the coast (Figure 2).

A 25 m grid step might be a slight overkill for practical forecasts and hindcasts and one might consider that the results obtained with such a high resolution are not valid anymore, as the grid size is up to 4 times lower than the peak wavelength. However, when comparing the output significant wave height and wavelength with the output of the 100 m and 400 m grid, the results do not deviate (not illustrated here). The dissipation and shoaling is captured as well (of course, the 25 m grid shows more detail – Figure 4).

A question arises: is the linear scaling between 25 m to 5 m reliable? Do we get the same results with different scaling, say from between 100 m and 5 m? We also performed a numerical experiment with the 100 m grid, when the diameter of the turbine was 100 m then. After scaling it down to 5 m, e.g. dividing the impact by a factor of 20, we obtained the same result: in case of the 15 m/s W wind the reduction was 1% at 10 m isobath. However, the 100 m case displayed some 0.5 to 1% increase of the significant wave height grid point next to shore, which in reality might not exist.

The model results of this study are directly comparable with other findings from other researchers and consultancies. The loss in significant wave height due to Scorby Sands offshore wind farm was less than 2% (Defra, 2005). In the latter case a model which was based on an evolution equation solution to the mild slope equation for water waves was used. It differs from the spectral wave model. The model grid size in their experiment was 3 m. Millar *et al.* (2005) used the SWAN model in order to asses the impact of a wave farm upon wind waves. In their study the interaction of surface waves and wave farms were modelled using the so-called transmission coefficient. Applying a realistic transmission coefficient, the total reduction of significant wave height near coast was less than 2 cm. The wave damping due to Rodsand offshore wind farm was less than 1% for higher waves (DHI water and Environment, 2007). In their study the energy loss was calculated with the integral wave model WAMIT for a single turbine. The impact of the whole array was further established with the spectral wave model MIKE 21 SW.

The shortcoming of this simulation study and of the ones mentioned in the latter paragraph lies in the assumption that wind farms do not alter wind speed. In general this is not true (Christiansen and Hasager, 2006). However, establishing the exact loss of wind speed in a wind farm in the present situation needs a detailed study, which is not in the scope of this study. In our opinion the changes in the wave fields due to a 10% loss of wind behind the farm established by Christiansen and Hasager (2006) will be superimposed by the nearshore wave transformation processes.

Lastly, we have to emphasize here that although the presence of wind farms have a negligible effect on the wave field, the presence of vertical piles in water motion induces von Karman vortex shedding behind the structure. This vortex shedding provides some disturbances in the water column, particularly at the sea bottom, and may induce substantial effects on the local benthic communities at sea bottom.

4. CONCLUSION

A modelling study was undertaken in order to quantify the possible effects of offshore wind farms on the reduction of wave height near coast. The model was successfully verified against the measurements at the locations where wind turbines would be installed. The impact of wind farms was assessed by calculating the ratio of difference of significant wave height with and without wind turbines to significant wave height without turbines. It is concluded that the reduction of significant wave height near the coast below 10 m isobaths does not exceed 1%. From a practical point of view, the developers of wind farms and the habitants/tourists on the coast should not be concerned.

Acknowledgements

I would like to thank my family, especially my wife and daughter, who have always been there for me and backing my activities. I would also like to express my greatest gratitude to my supervisor Dr. Urmas Raudsepp for his patient guidance, great support and excellent advice.

Abstract

200 wind turbines with the annual productivity of 2.3 TWh, which could produce up to 40% of the Estonian energy need, are planned to be constructed on separate shallows in the NW Estonian coastal waters (the Baltic Sea), 5-20 km offshore. Using numerical modelling, a possible impact of wind farms on wave heights is established. It is concluded that the impact exists in terms of the reduction of significant wave height, but it is very marginal, not more than 1% below 10 m isobaths. This is due to a very small ratio between the turbine diameter and dominant wavelength and the favourable set-up of turbines in respect to each other and the coast.

Resümee

Hiiumaa rannikumerre on planeeritud rajada orienteeruvalt 200 tuulikuga tuulepark elektrienergia tootmiseks. Tuulikule mõjuvad hüdrodünaamilised jõud, mis on tekitatud lainetuse ja hoovuste poolt. Tuulikud omalt poolt avaldavad mõju lokaalsele lainetuse režiimile. Kuna puuduvad vastavad uuringud, ei ole selge, kui kaugele tuulikute poolt lainetusele avaldatav mõju ulatub. Tuulepargi rajamisele on eelnevalt vajalik selgitada, kas merre ehitatavad tuulikud takistavad lainete levimist Hiiumaa rannikule sedavõrd, et väheneks oluliselt lainekõrgus, mis näiteks võiks mõjutada Ristna poolsaare rannikumere kasutamist surfarite poolt.

Käesoleva uurimustöö eesmärgiks on hinnata tuulikute mõju ulatust lainetuse parameetritele konkreetselt Neupokojevi ja Vinkovi madalatele rajatavate tuuleparkide näitel. Lainetuse ruumilise muutlikkuse hindamiseks kasutatakse meetodina numbrilist modelleerimist, spektraalset lainemudelit SWAN. Esmalt modelleeritakse laineväljad kindlalt defineeritud tuulesuundade ja tuulekiiruste korral juhul kui meres tuulikuid puuduvad (praegune situatsioon). Järgmisena arvutatakse laineväljad situatsioonis, kus tuulikud paiknevad meres. Viimase ja esimese arvutuse vaheks on lainekõrguse muutus.

Modelleerimistulemused näitavad, et lainekõrguse kahanemine ranniku lähedal 10 m isobaadist madalamal ei ületa 1 %. Selline rannikuprotsessides märkamatuks jääv muutus on tingitud mitmest soodsast asjaolust. Esiteks on domineeriv lainepikkus suurusjärgu võrra suurem tuuliku diameetrist, teiseks paiknevad tuulikud üksteisest piisavalt kaugel ning kolmandaks, tuulikud paiknevad rannikust piisavalt eemal.

Literature cited

Alari, V.; Raudsepp, U., and Kõuts, T., 2008. Wind wave measurements and modelling in Küdema Bay, Estonian Archipelago Sea. *Journal of Marine Systems*, S30 - S40.

Booij, N.; Ris, R.C., and Holthuijsen, L.H., 1999. A Third – Generation wave model for coastal regions. 1. Model description and validation. *Journal of Geophysical Research*, C104, 7649 – 7666.

Christiansen, M.B., and Hasager, C.B., 2006. Using airborne and satellite SAR for wake mapping offshore. *Wind Energy*, 9(5), 437-455.

Coastal Engineering Manual., 2003. Part VI, Chapter 5, pp.242-245, Washington.

Danish Energy Agency., 2007. Energy statistics 2007. Denmark, 29 p.

Defra project nr A1227., 2005. Assessment of the significance of changes to the inshore wave regime as a consequence of an offshore wind array. 20 p.

DHI water and Environment, 2007. The effect of wind turbines on nearshore waves. 50 p.

Erm, A.; Alari, V.; Kõuts, T.; Lilover, M.-J.; and Kask, A., 2009. A pilot study of hydrodynamical and geological conditions at some possible offshore wind farms in Estonian coastal waters. *In: Proceedings of European Seminar: Offshore Wind and other marine renewable Energies in Mediterranean and European Seas, 21-23 May, Brindisi, Italy.* pp. 49 - 63.

European Commision., 2007. Estonia – Renewable energy fact sheet. 3 p.

Intergovernmental Panel on Climate Change (IPCC)., 2007. Climate change, a synthesis report. Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.) IPCC, Geneva, Switzerland. 104 p.

International Energy Agency (EIA)., 2007 Renewables in global energy supply: An IEA fact sheet. OECD/IEA, Paris, 34 p.

Millar, D.L.; Smith, H.C.M., and Reeve, D.E., 2007. Modelling analysis of the sensitivity of shoreline change to a wave farm. *Ocean Engineering*, 34, 884-901.

Seifert, T.; Kayser, B., and Tauber F., 2001. *Bathymetry data of the Baltic Sea*. Baltic Sea Research Institute, Warnemünde.

Soomere, T., 2003. Anisotropy of wind and wave regimes in the Baltic Proper. *Journal of Sea Research*, 49, 305-316.

Soomere, T., and Keevallik, S., 2003. Directional and extreme wind properties in the Gulf of Finland. *Proceeding of the Estonian Academy of Sciences, Engineering,* 9, 73–90.

The website of 4enegia, URL http://www.4energia.ee/index.php/lang/eng/article/hiiumaa-windfarm; accessed on 30 August 2010.

Van der Westhuysen, A.J.; Zijlema, M., and Battjes, J.A. 2007. Nonlinear saturation-based whitecapping dissipation in SWAN for deep and shallow water. *Coastal Engineering*, 54, 151-170.