Evaluation of the impact of the uncertainties on environmental data for far-field propagation in shallow water with Split-Step Padé PE

Stéphane Lesoinne, Alexander Barth
GHER, University of Liège, Belgium.

Xavier Kaiser, Jean-Jacques Embrechts
INTELSIG, University of Liège, Acoustics laboratory, Belgium.

Audrey Gillet, Robrecht Moelans
G-tec S.A., Liège, Belgium

Summary
In offshore wind farms, the installation of a wind turbine is commonly done by driving a pile into the seabed, generating high energetic impulsive noise with possible negative impact on the marine fauna. The assessment of the environmental impact of pile driving has becomed an important challenge. In conjunction with numerical models of the sound source (pile driven by hammer), numerical underwater sound propagation models can be used to predict the sound pressure levels evolution over the distance from the pile. However, those models depend on environmental input data which are marred by uncertainties that can affect the simulation results. In this paper, the impact of those uncertainties on far-field propagation transmission losses is studied using an elastic parabolic equation (RAMS) on a test case in the English Channel. The sensitivity of the model is given for the estimated maximum boundaries on the data uncertainties.

PACS no. 43.30.+m

1. Introduction

Offshore wind farm installation is commonly done using hydraulic hammers to drive hollow steel piles (typically 4-8 m in diameter) into the seabed. The pile driving generates high energetic impulsive noise that have possible negative impacts on the marine fauna over long ranges [1, 2]. In conjunction with numerical models of the sound source (pile driven by hammer), numerical underwater sound propagation models can be used to predict the pressure levels evolution over the distance from the pile. In the far-field, this can be achieved using a standard underwater acoustic propagation method such as parabolic equation (PE) [3] (Complex hybrid approaches can be also used [4, 5]). Because the pile driving happens in shallow water (water column height $<$ 200m), sound wave interactions with the seabed are important [6]. However, the environmental parameters are subject to uncertainties that will affect the simulation results. Then two questions should be answered: which parameters need to be measured in priority and which one must be adjusted to calibrate the acoustic wave propagation model. Recently, Lippert and al. [9] studied the impact of uncertainties for an hybrid model (finite-element/wavenumber). In this paper, this will be evaluated with an elastic PE model RAMS [7, 8] (Range-dependent Acoustsic Model which accounts for Shear waves in the ocean bottom) of underwater acoustic propagation. The test case used here is located in the English Channel near Saint-Vaast-La-Hougue (SVH), France, with a slowly varying bathymetry composed of a sediment layer over a marne-calcareous hard bottom. In this context, the results of uncertainties impact will be used in subsequent validation steps. This study is a part of the broader project MINOWIN (Modelling the Impact of Noise generated by Offshore Wind turbines) which is intended to model the hammer-driven pile as an array of point sources to predict the pile driving impact on marine fauna.

2. Sound propagation modeling

In the MINOWIN project, the pile will be modeled as an array of point sources and many simulations will be needed for one pile. So the processing cost is an important factor. A parabolic equation model has then been selected because PE is renowned to be the fastest family of model. Amongst these models, RAMS is a commonly used and open-source implementation of a fast and wide-angle (split-step Padé) elastic parabolic equation where:

- The ocean surface is assumed to be a perfect reflector due to the high impedance difference between air and water.
- The bottom materials are caracterized by their P and S-waves sound speeds (c_p and c_s) and attenuations (α_p and α_s), and their density over depth and range.
- The model operates in the frequency domain by marching the depth solution outward in range in a step-by-step manner over a range and depth discretization grid. It has the capability of treating forward propagation (thus neglecting the backscatered energy which is a good approximation in our case) in ocean waveguides where the material properties vary weakly along the range and abruptly over depth [10].

2.1. Configuration

The grid steps are selected accordingly to the wavelength of the acoustical wave in the water column. The source emission is set to wide-angle by selecting a number of Padé terms $n_p = 8$. The sediment layer used with the model is parallel to the bathymetry with a constant thickness equal to the averaged value over the transect.

2.2. Stability

With elastic PE models, stability problems can occur [11, 12] at low frequencies for small thickness sediment layers with small shear speed. In this study, this was the case at very low frequencies and this problem was solved by considering only the frequency bands above 50 Hz.

3. SVH area environment

The test area is situated in the English Channel near Saint-Vaast-la-Hougue (France). The site has slowly varying bathymetry and water sound speed. The RAMS environmental input data for this area were obtained from different sources: in-situ measurements, material geo-acoustic parameters from near-site measurements and from Hamilton's empirical model [13]. To simplify the analysis in this study, an assumption is made: water and material geo-acoustic parameters are constant over the depth.

3.1. In-situ and near-site measurements

The in-situ data are known with a good precision at the measurement spot but uncertainties increase with distance from those spots. For near-site measurements, a good equivalence with the test site has been assumed and they are supposed to obey the same precision as the in-situ measurements. Moreover, the materials properties used are mean values of the material samples and are then considered constant over the entire area.

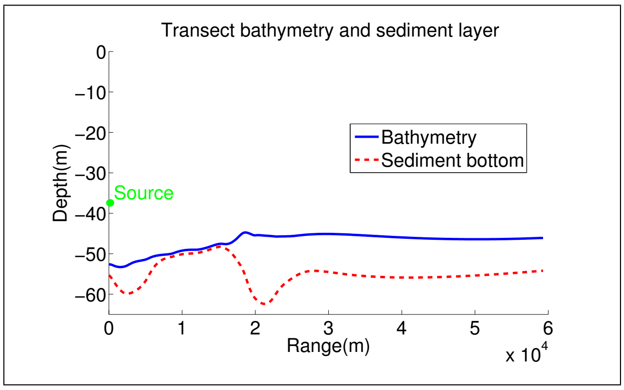

Figure 1. Transect bathymetry and sediment layer over range.

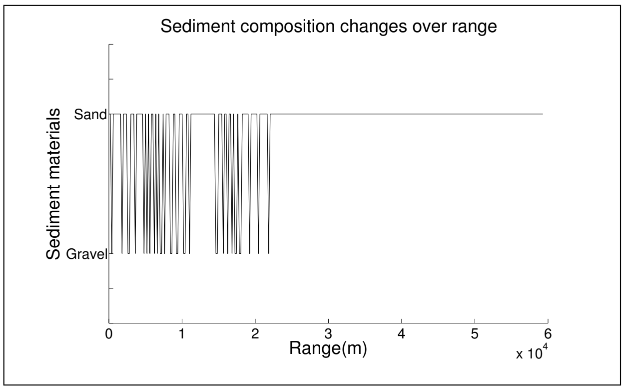

Figure 2. Transect sediment layer composition over range.

3.2. Selected transect

The selected transect extends from West to East on a 25 km range and has been artificially extended up to 60 km by copying the Eastern bathymetry values to have a sufficiently long range propagation. The transect bathymetry and sediment width are represented in Figure 1 while the sediment layer composition is illustrated in Figure 2. The near-site measured geo-acoustic parameters are similar for gravel and sand, so they share the same values. A measurement campaign was also conducted along this transect with an airgun as the noise source to serve in a first validation step of the propagation framework.

3.3. Source and receiver positions

During the campaign, the hydrophone was at a fixed position at 38 m depth and the airgun was moved along the transect at 10 m depth. For the simulations,

Table I. Bottom material geo-acoustic parameters values. Sound speeds are given in m/s, densities ρ in g/cm^3 and attenuations α in dB/m. Attenuations vary according to frequency f in kHz.

Geo-acoustic parameters					
Material	c_p	c_s	ρ	α_p	α_s
Sand	1700	52	1.88	0.65f	13f
Gravel	1700	52	1.88	0.65f	13f
Chalk	2300	1780	2.04	0.03f	0.1f

the source is fixed and source and receiver depths have been inverted accordingly to the reciprocity principle.

3.4. Environmental and geo-acoustic parameters

The environment modeling uses data coming from various sources which are summarized below, while their values are summarized in Table I:

- Water sound speed: measured over depth at the receiver position and at ranges 1, 2, 3, 4, 5, 10, 15 km from the hydrophone position;
- Bathymetry: spatial sampling measures along parallel lines separated by 500 m;
- Sediment layer thickness : spatial sampling measures along parallel lines with various spacing (from 100m to 500 m) and precision;
- Sediments (sand and gravel):
  - Near-site measurements: c_p, ρ;
  - Hamilton's model: c_s, α_p, α_s;
- Cretaceous chalk:
  - Near-site measurements: c_p, c_s, ρ;
  - Hamilton's model: α_p, α_s;

For each parameter, the data source type and measurement spacing will dictate its estimated uncertainty.

3.5. Uncertainties

The main causes of uncertainties come from:

- The measurement technique/apparatus;
- The spatial sampling;
- The delay between the moment where measurements were made and the moment at which the propagation is supposed to take place;
- The absence of measurements for the environment. Then, the data come from:
  - A supposedly similar environment;
  - A theoretical model;
- The data representation hypothesis such as: a sediment layer with constant thickness or considering the sediment geoacoustic parameters constant over depth.

Estimation of the uncertainties will be based on the data source uncertainty plus a factor to take the spatial sampling into account. Moreover, when the data comes from a model, its uncertainty will be expressed as a percentage of the data value. Estimated values for uncertainties are summarized in Tables II, III. These uncertainties have been evaluated as follow:

- The bathymetry uncertainty was taken equal to 1m which is the uncertainity of values found in databases;
- For the water sound speed it has been taken equal to its variation (10 m/s) over the measured data set;
- The sediment thickness uncertainty is hard to determine as it comes from two data with various precision which varies over the area and with the thickness value. So, to made it simple, it has been decided to evaluate the uncertainty on the sediment thickness with the variance over the entire area which is equal to 3.4 m. As this could lead to a negative value for an arbitrary transect, a relative value to the transect thickness (of 35%) has been used for subtracted perturbation (equal to 2.8m).
- The sediment geoacoustic parameters:
  - c_p positive and negative perturbation values have been chosen so that perturbed values stay in sand and gravel plausible values;
  - The ρ uncertainty is taken to 10% which is, more or less, its variation around its mean value;
  - Values generated with the Hamilton's model should be the mose uncertain values and their uncertainty has been fixed at 50 %.

Table II. Estimated uncertainties of geo-acoustic parameters.

Uncertainties on geo-acoustic parameters					
Material	$c_p(m/s)$	$c_s(\%)$	$\rho(\%)$	$\alpha_p(\%)$	$\alpha_s(\%)$
Sand	+150	+50	+10	+50	+50
Sand	-100	-50	-10	-50	-50
Gravel	+150	+50	+10	+50	+50
Gravel	-100	-50	-10	-50	-50
Chalk	+(-)150	10	10	50	50

Table III. Estimated uncertainties on environmental parameters.

Parameter	Uncertainty
Bathymetry	+(-)1 (m)
c_w	+(-)10 (m/s)
Sediment thickness	+3.4 (m)
Sediment thickness	-2.8 (m)

4. Sensibility to uncertainties - estimation method

The reference simulation is executed within the SVH reference environment with the parameters values shown in Table I and compared to simulations using modified environments. The modified environments are obtained with the modification of one parameter at once by subtraction or addition of its uncertainty. Each material geo-acoustic parameter will be varied independently.

4.1. Perturbed parameters

As the perturbations are constant and do not have a spatial structure, the derived sensitivities represent an upper bound. As an example, for sediment thickness, the same estimated uncertainty is applied over the transect which results in a maximum uncertainty boundary but the real value should be lower. The selected approach is nonetheless usefull to establish a classification of the parameters that have the highest probababilty of impacting the results.

5. Processing of results

Simulation results are available in the form of transmission loss (TL) over depth and range at discrete frequencies. The TL is defined as the ratio in decibels between the acoustic intensity at a field point and the intensity at 1 m distance from the source [6]. The difference between the reference and perturbed environments TL will be evaluated at a fixed depth over range (as illustrated in Figure 3). On this figure, it appears that the TL increase quickly over the first five kilometers and at a constant (smaller) rate after. To evaluate the impact of the uncertainties on the TL, the following procedure is applied:

- Grouping of the results into frequency bands as specified later;
- Spatial averaging of the TL;
- Computation of the Mean Square Error (MSE) between the reference and perturbed data set TLs;
- Classification of the parameters by decreasing order of TL variation;

5.1. MSE

The differences between two curves are measured classicaly by computing the MSE of the two curves. The MSE won't be computed over the entire range but over the following two range intervals: [1 - 5000 m] and [5 km - 60 km]. This is done because most of the differences consist in a slope variation of the TL curve over the [5 - 60 km] range interval.

5.2. Spatial averaging

Looking at the TL curve in Figure 3, it appears that high frequency variations can highly impact the MSE even if both curves are pretty similar in shape and decrease rate. So to reject those fast variations while keeping the main characteristics of the curves, a spatial averaging of the TL with a Savitzky-Golay moving average filter [14] (window size of 2.5 km) is applied before the MSE computation.

5.3. Frequency processing

The problem adressed here concerns the [50 Hz, 10 kHz] frequency band processing. As measurements are given per third-octave band, it seems natural to process the simulation results within those bands. Then, each band will be constructed by grouping the results obtained at 16 equally spaced frequencies. By grouping results into third-octave bands, the 496 results to analyse become 31, which is lower but still too high. To ease the comparison process a second grouping will be done into 3 bands: Low (LF), Medium (MF) and High (HF) frequency bands. These bands will be chosen based on the hearing threshold of fishes [15] in order to define three zones of maximum disturbance sensibility.

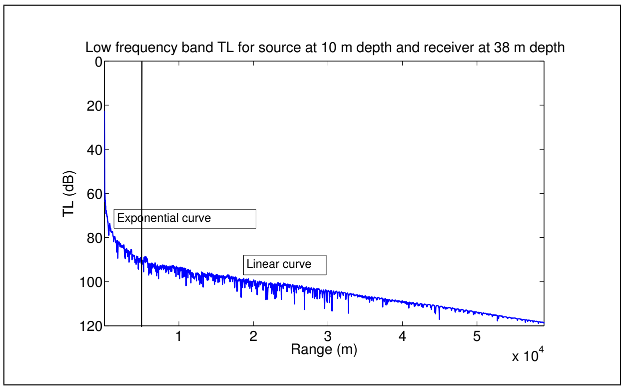

Figure 3. Illusration of exponential and linear parts of the TL curves.

6. Results

Nineteen environments have been compared and only the main results will be presented here. From the comparison of MSE for both range intervals at LF, MF and HF, it appears that the data sensitivity to uncertainties is higher at LF than MF and than HF. It was nearly negligible at HF. Similarly, the most affected range interval was the [5 - 60 km] with slope variations while the area up to 5 km was almost never strongly affected (except for high sediment thickness reduction).

6.1. Most sensitive parameters

The most sensitive parameters in our transect are:

- The sediment thickness, see Figure 4;
- The sediment P-wave speed (sand), see Figure 5;
- The sediment P-wave attenuation (sand), see Figure 6.

The MSE for these environments are given in Tables IV, V. The sand parameters appear more sensitive than the gravel ones only because it is the main component of the sediment layer. As expected, the sediment S-wave parameters have no important impact (since the wave speed is really small). From these results obtained in a particular case, it appears that the hard bottom uncertainties have a low impact on the results, probably due to the high differences between

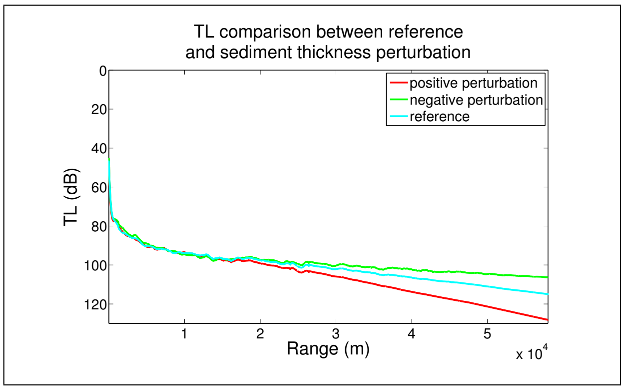

Figure 4. Sediment thickness increased by 3.4 m and decreased by 2.8 m.

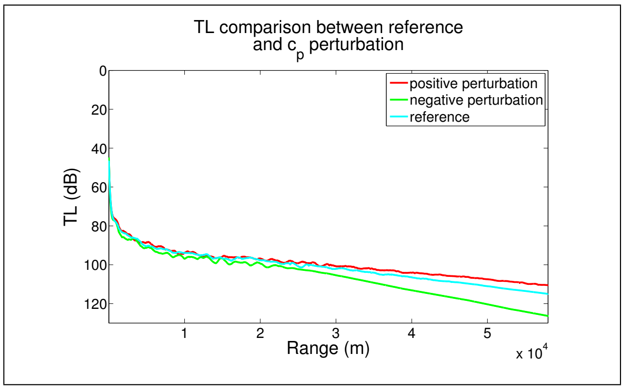

Figure 5. Sand P-wave sound speed increased by 150 m/s and decreased by 100 m/s.

the acoustical impedances of the sediment and the hard bottom.

6.2. Discussion

It has to be noted that the sediment layer thickness is considered constant over the range. Considering the uncertainties impact, this choice could be reconsidered to take into account the local variations at the expense of implementing a new PE model such as [16] to allow correct processing of a variable sediment thickness. For these simulations, the P-wave speed and attenuation have been kept constant over the depth and again, this choice should probably be reconsidered. The selected geo-acoustic model for sand poses the hypothesis that the frequency dependance of P-wave attenuation is linear but this hypothesis is controversial as other authors conclude differently [17], [18]. Identification and usage of a more realistic model could be envisaged.

7. Conclusions

The goal of this study was to determine the impact of the uncertitainties on environmental parameters used for the simulation and validation of a transect test case. It appears that the uncertainties on some parameters could have a significant impact and are prone to influence a comparison between measured and computed noise levels. These parameters are the sediments layer thickness and P-wave parameters. Those results should be valid in similar test cases, i.e.: mixed shallow water column over a narrow sandy sediment layer overlying a hard calcareous layer. This hypothesis should nonetheless be verified during further measurements campaign. While those results depends on the uncertainties evaluation, they can be used to select the parameters to vary in priority during the calibration and validation steps of the model. According to these results, it could be interesting to use a variable sediment layer thickness over the range and to search for a more reliable geo-acoustic model for the P-wave attenuation factor.

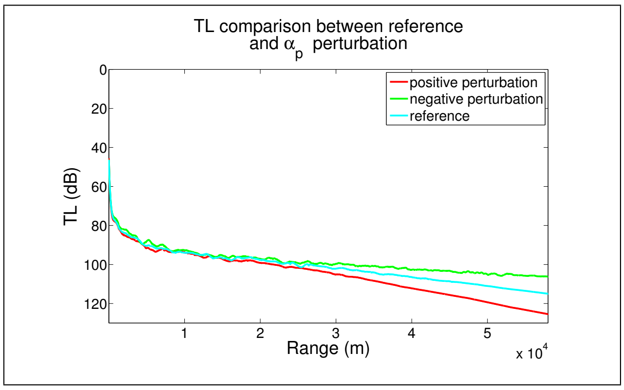

Figure 6. Sand P-wave attenuation increased and decreased by 50%.

Table IV. MSE (dB^2) for range interval [5 - 60 km] and low frequency band.

Parameter	MSE $r > 5km$
Sed. thick. +3.4 m	35
Sed. thick. -35 %	18
Sand c_p + 150 m/s	16
Sand c_p -100 m/s	38
Sand α_p +50%	36
Sand α_p -50%	18

Table V. MSE (dB^2) for range interval [1m - 5 km] and low frequency band.

Parameter	MSE $r < 5km$
Sed. thick. +3.4 m	35
Sed. thick. -35 %	1.9

Acknowledgement

The research project Minowin is supported by the regional Government of Wallonia (Belgium), by the Convention number 1217922.

References

[1] H. Bailey, B. Senior, D. Simmons, J. Rusin, G. Picken, and P.M. Thompson: Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals. Marine Poll. Bull 60 (2010), 888-897.

[2] A.N. Popper, M.C. Hastings: The effects of antrhopogenic sources of sound on fishes. Journal of Fish Biology 95(3) (2009) 455-489.

[3] C. Erbe: Underwater noise from pile driving in Moreton Bay, Qld. Acoustics Australia 37(3) (2009) 87-92.

[4] M. Zampolli, M.J.J. Nijhof, C.A.F. de Jong, M.A. Ainslie, E.H.W. Jansen, and B.A.J. Quesson: Validation of finite element computations for the quantitative prediction of underwater noise for impact pile driving. J. Acoust. Soc. Am. 133(1) (2013) 72-81.

[5] T. Lippert and O. von Estorff: On a hybrid model for the prediction of pile driving noise from offshore wind farms. Acta Acust. 100(2) (2014) 244-253.

[6] F.B. Jensen: Computational ocean acoustics. Springer (2011).

[7] M.D. Collins: A split-step Padé solution for the parabolic equation method. J. Acoust. Soc. Am. 93(4) (1993) 1736-1742.

[8] M.D. Collins: An energy-conserving parabolic equation for elastic media. J. Acoust. Soc. Am. 94(2) (1993) 975-982.

[9] T. Lippert, K. Heitmann, M. Ruhnau, S. Lippert, and O. von Estorff: On the estimation of prediction accuracy in numerical offshore pile driving noise modelling. Proc. Inter-noise2014 5068-5074.

[10] M.D. Collins: A two-way parabolic equation for elastic media. J. Acoust. Soc. Am 93(4) (1993) 1815-1825.

[11] F. Gilbert: Elastic waves in a transitional solid with arbitrarily small rigidity. Geophys. J. Int. 133(2) (1998) 230-232.

[12] J.M. Collis, A.M. Metzler: Seismo-acoustic propagation near thin and low-shear speed ocean bottom sediments using a massive elastic interface. J. Acoust. Soc. Am. 135(1) (2014) 115-123.

[13] E.L. Hamilton: Geoacoustic modeling of the sea floor. J. Acoust. Soc. Am. 68(5) (1980) 1313-1340.

[14] A. Savitzky, M.J.E. Golay: Smoothing and Differentiation of Data by Simplified Least Squares Procedures, Analytical Chemistry 36(8) (1964) 1627-1639.

[15] J. Nedwell, B. Edwards, A. Turnpenny, and J. Gordon, Fish and Marine Mammal Audiograms: A summary of available information, Subacoustech environmental, Subacoustech report 534R0214, sept. 2004.

[16] J.M. Collis, W.L. Siegmann, F.B. Jensen, M. Zampolli, E.T. Kusel, and M.D. Collins: Parabolic equation solution of seismo-acoustics problems involving variations in bathymetry and sediment thickness, J. Acoust. Soc. Am. 123(1) (2008) 51-55.

[17] K.L. Williams, D.R. Jackson, E.I. Thorsos, D. Tang, and S.G. Schock: Comparison of sound speed and attenuation measured in a sandy sediment to prediction based on the Biot theory of porous media, IEEE Journal of oceanic engineering, 27(3) (2002) 413-428.

[18] J.-X. Zhou, X.-Z. Zhang, and D.P. Knobles: Low-frequency geoacoustic model for the effective properties of sandy seabottoms, J. Acoust. Soc. Am. 125(5) (2009) 2847-2866.