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Uncertainty quantification of soil properties in offshore pile-driving noise predictions with the air-bubble curtain system

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Abstract: *Offshore wind turbines supply a significant source of sustainable energy. Installation of foundation piles in offshore wind leads to underwater noise emissions, which can harm the marine ecosystem. Although several noise control strategies exist to reduce the sound levels to within acceptable limits, the air-bubble curtain system is one of the most widely applied sound mitigation systems. Modeling the underwater noise emissions is quite challenging due to the large uncertainty in the identification of the dynamic properties of the marine sediment over a wide frequency range. In this paper, a probabilistic framework is adopted to determine the best-fit probability distributions of the soil variables. A copula-based multivariate probabilistic model is then used to analyze the dependencies between multiple soil variables. The developed probabilistic framework is integrated to an existing computational model for the noise prediction due to impact piling which includes the noise reduction module of an air bubble curtain. A case study is discussed in which predicted sound levels are utilized to identify correlations between seabed properties and noise levels. Given the large uncertainty in the soil characterization, a systematic approach is proposed to quantify the performance of the air-bubble curtain.*

Keywords: *underwater noise, marine sediment, probabilistic model, air-bubble curtain.*

1. MODEL DESCRIPTION

Offshore wind farms are recognized as a significant solution for increasing the renewable energy. However, the continuous impulsive noise generated during impact pile driving poses a threat to marine mammals, fish, crustaceans, and invertebrates [1, 2, 3]. Consequently, regulators and researchers have raised concerns regarding this issue. To address these concerns, many countries have implemented strict noise thresholds and require thorough assessment of potential sound levels and noise impact prior to installation. Near-field and far-field noise mitigation systems, including the widely adopted bubble curtain system, are often employed to reduce sound levels [1, 4].

To assess the noise prior to installation, the prediction of the noise become critical and remain challenge due to the uncertainies involved in the modelling of sound radiation from pile driving. Many models have been developed for the noise prediction [5, 6, 7, 8, 9, 10, 11]. The noise are expected to exceed the regulated sound levels without the application of the noise abatement system. To examine the performance of an air-bubble curtain system, a semi-analytical model was developed in [12]. The finite element (FE) model developed in [13] uses a simplified approach by modeling the air bubble curtain with a fully absorbing layer. A model based on the hydrodynamic behavior of bubble breakup and coalescence is developed by Bohne et al. [14]. A semi-analytical model [15] is developed where the hydrodynamic module for describing the bubble formation process is coupled to the vibroacoustic model for noise prediction from pile driving through a boundary integral formulation. However, the uncertainty and the sensitivity of the soil parameters on mitigated sound field has not been examined.

As the geometry of the pile and the bathymetry can be obatined easily, the main uncertainty in the input parameters comes from the soil properties. The data from the cone penetration test (CPT) in offshore geotechnical survey can be used to estimate the shear wave speed and density of the soil through emprical formulas. However, in order to determine the compressional wave speed of the soil layer, the Poisson's ratio is often to be estimated. Obtaining data from CPT, estimation of the density, shear and compressional wavespeed all result in large uncertainties in the modelling of sound. To address the challenges posed by variability and errors in measuring and estimating the soil parameters, probabilistic and statistical methodologies can be applied in noise prediction modelling [16, 17]. These approaches offer several advantages due to their ability to effectively account for uncertainty in the soil. To the author's knowledge, the various approaches available have mainly focused on the accurate numerical solution for unmitigated field. A sensitivity of the noise levels due to the uncertainties of environmental parameters has not yet been fully investigated [18]. However, the variation in soil properties not only impacts the vibration of the pile but also affects the propagation paths of waves through the fluid and sediment layers. The application of noise mitigation systems, such as an air-bubble curtain, can be significantly influenced by the soil, affecting the overall effectiveness of the system. When the system is in place, it primarily mitigates the noise path within the fluid medium.

In this paper, the focus is on investigating the input parameters associated with the material properties of the seabed. The influence of the soil properties on the sound levels in impact pile driving is examined through the uncertainty quantification including the modeling of noise mitigation using the air-bubble curtain system. Based on the uncertainties in the input soil pram-eters, the distribution of the sound levels is determined. In Section2, ~~the description of the pile driving model with the use of air-bubble curtain system is given together with the governing equations and the method of the solution~~. In Section 3, the probabilistic framework is established. In Section 4, a case study is analysed and discussion of the results is presented. Finally, Section 5 gives an overview of the main conclusions of the paper.

2. MODELLING PILE DRIVING NOISE WITH AIR-BUBBLE CURTAIN SYSTEM

The prediction model for impact pile driving using the air-bubble curtain system is used in this uncertainty analysis [15]. The flow of the modeling activity is shown in Figure 1.

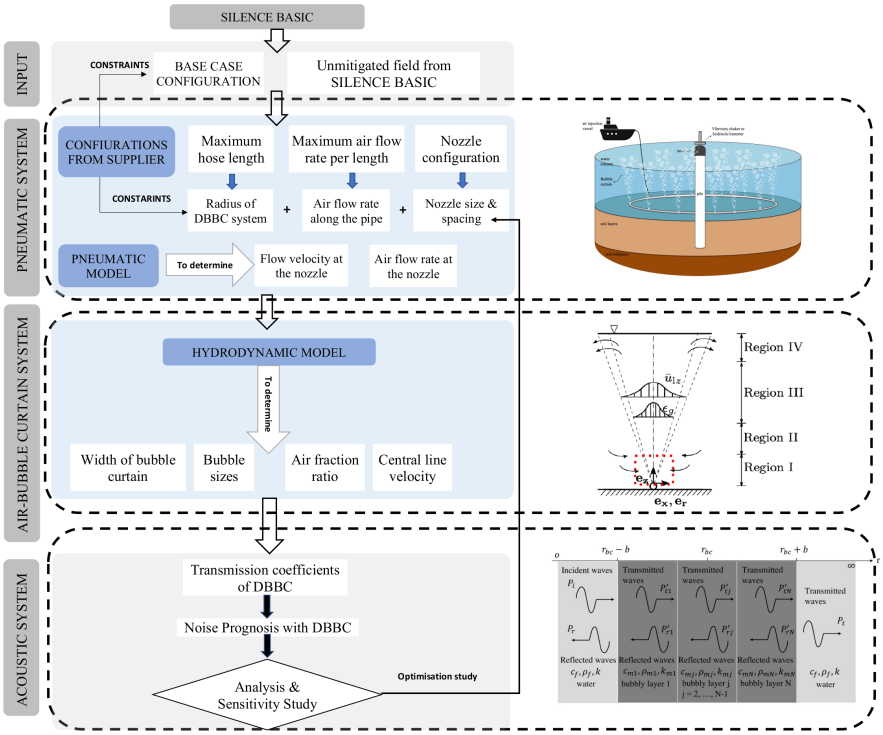

Figure 1: Activity flow of the complete model: 1) define the input of the model; 2) modelling of the pneumatic system; 3) modelling of the air-bubble curtain system; 4) modelling of the mitigated sound field with the use of DBBC.

An engineering model is being developed using compressible flow theory to predict the operational parameters of a given hose-nozzle configuration used for bubble curtain generation. Given teh flow velocities obtaine din the compressible flow model, the hydrodynamic model aims to capture the characteristics of bubble generation and development. The modeling of the bubble formation is based on an existing model developed by [14].

The acoustic model is developed for the depth- and frequency-dependent transmission coefficients of each bubble curtain configuration. Given the bubble characteristics obtained from the hydrodynamic model, the distribution of the local effective wavenumbers $k_m(\omega, z, r)$ is determined over the entire water depth as described in [15]. The transmission coefficients $\widetilde{H}(z, \omega)$ are then determined per z-coordinate and are constant within the vertical step size Δz of the integration.

The noise prediction module comprises a pile modeled as a linear elastic thin shell and surrounding media modeled as horizontally stratified acousto-elastic half-space as discussed in detail in [11, 15]. The direct boundary element method (BEM) is deployed to couple the noise prediction model for non-mitigated field and the acoustic model for the air-bubble curtain. The response functions from the noise prediction model are coupled to the sound propagation module through a boundary integral formulation on the cylindrical boundary surface $r = r_{bc}$. The complete solution for the acousto-elastic domain reads:

$$\begin{aligned}\tilde{u}_\alpha^\Xi(\mathbf{r},\omega) =&\tilde{u}_\alpha^{\Xi,f}(\mathbf{r},\omega) + \tilde{u}_\alpha^{\Xi,s}(\mathbf{r},\omega)\\ &= \sum_{\beta=r,z}\int_{S^s}\left(\widetilde{U}_{\alpha\beta}^{\Xi s}(\mathbf{r},\mathbf{r}_{bc},\omega)\cdot\tilde{t}_\beta^{\mathbf{n}}(\mathbf{r}_{bc},\omega) - \widetilde{T}_{\alpha\beta}^{\mathbf{n},\Xi s}(\mathbf{r},\mathbf{r}_{bc},\omega)\cdot\tilde{u}_\beta(\mathbf{r}_{bc},\omega)\right)dS^s(\mathbf{r}_{bc})\\ &\quad + \int_{S^f}\widetilde{H}(z,\omega)\Bigg(\widetilde{U}_{\alpha r}^{\Xi f}(\mathbf{r},\mathbf{r}_{bc},\omega)\cdot\tilde{p}(\mathbf{r}_s,\omega) -\\ &\quad \widetilde{T}_{\alpha r}^{\mathbf{n},\Xi f}(\mathbf{r},\mathbf{r}_s,\omega)\cdot\tilde{u}_r(\mathbf{r}_{bc},\omega)\Bigg)dS^f(\mathbf{r}_{bc}), \quad \mathbf{r}\in V\end{aligned} \tag{1}$$

in which the fundamental solutions of Green's displacement tensors $\widetilde{U}_{\alpha\beta}^{\Xi\xi}(\mathbf{r},\mathbf{r}_s,\omega)$ are derived from the potential functions given the receiver point at $\mathbf{r} = (r,z)$ (in medium Ξ) in α-direction due to a unit impulse at source, $\mathbf{r}_s = (r_{bc}, z_s)$ (in medium ξ) in β-direction $\mathbf{n}$ is the outward normal to the cylindrical boundary.

3. SATISTICAL MODELLING OF SOIL PARAMETERS

Geotechnical investigations conducted in ocean environments often lack comprehensive descriptions of the dynamic properties of the soil. These properties include soil density, Poisson's ratio, shear and compressional wave speeds, and damping. By utilizing empirical relationships derived from the standard Cone Penetration Test (CPT), it is possible to estimate the shear wave speed. Furthermore, assumptions are made regarding the relationships between shear wave speed and soil density. However, the absence of Poisson's ratio and the reliance on estimated values for shear wave velocity and density can lead to inaccuracies in defining the soil characteristics. Consequently, these inaccuracies introduce additional uncertainties in the model inputs. In this section, the input of soil properties are generated for the probabilistic analysis.

3.1. THE ANALYSIS OF SOIL STRATIFICATION

The analysis of variance (ANOVA) is used for the soil stratification to evaluate two or more set of data groups. Depending on the amount of independent variables involved in the various sam-ples, ANOVA can be single, double or triple factor. The aim of the analysis is to tell if at least one of the groups considered presents a high difference with respect to the others. The sum of the squares (SS) is used to evaluate to determine the F ratio, which can be divided in two parts, one referring to the model variability, and one due to casual error.

$$SS_{total} = SS_{model} + SS_{error} \tag{2}$$

$$\sum_{i=1}^{a}\sum_{j=1}^{b}(X_{ij} - \bar{\bar{X}})^2 = \sum_{j=1}^{b} a(\bar{X}_j - \bar{\bar{X}})^2 + \sum_{i=1}^{a}\sum_{j=1}^{b}(X_{ij} - \bar{X})^2 \tag{3}$$

in which X_{ij} is the i^{th} observation of the j^{th} layer, $\bar{\bar{X}}$ is the mean of all layers, $\bar{X}_j$ is the mean of the j^{th} layer, a is number of elements and b is the number of groups.

$$F = \frac{SS_{model}/(b-1)}{SS_{error}/(N-1)} \tag{4}$$

Once the F ratio is obtained, particular tables allow to evaluate the probability of the null hypothesis, that is then called p-value. The choice for the depth is made upon the minimum p-value obtained. Given the ANOVA results, it has been preferred to use for all the simulation.

3.2. PROBABILITY DISTRIBUTION

In this section a practical framework for determining the optimal parameters for the distributions considered (Maximum Likelihood Estimator) is presented. These will be then compared, and the one best representing the available data will be chosen using AIC criterion. The likelihood is a function of the distribution coefficients and represents the joint probability of the n recordings, and is obtained by multiplying their probability density function:

$$L(\theta|x) = \Pi_{i=1}^{n} f(x_i|\theta) \tag{5}$$

The Akaike Information criterion (AIC) estimates their error as information loss, and performs a trade-off between their goodness of fit (represented by the likelihood) and their simplicity,

$$AIC = 2k - 2ln(L(\theta|x)) \tag{6}$$

In which k is the standard deviation of the distribution. When AIC becomes lower and the Likelihood is higher, a better representation of the actual data sets can be expected.

3.3. GENERATION OF INPUT SOIL SAMPLES

The Copula model, based on the rank methods, is used to investigate the dependence between several random variables [17]. The main advantage provided by this approach is that the selection of an appropriate model for the dependence between data sets, represented by the copula, can then proceed independently from the choice of the distributions. The Spearman's rank coefficient instead addresses more in general monotonic correlation, therefore simply investigate whether the occurrence of high values of one variable are paired with high or low values of another. The Pearson's classical correlation coefficient can be defined as,

$$r_{x,y} = \frac{12}{n(n+1)(n-1)} \sum_{i=1}^{n} R_i S_i - 3\frac{n+1}{n-1} \tag{7}$$

in which R_i and S_i are the pair of rank of the original data samples, x and y indicate the index of the parameters in the soil.

Based on the soil stratification and its probabilistic distribution, the correlation matrix is derived as:

$$C_{c_p,c_s,\rho} = \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & & & & & \\ r_{2,1} & r_{2,2} & r_{2,3} & & \cdots & & 0 & \\ r_{3,1} & r_{3,2} & r_{3,3} & & & & & \\ & & & r_{4,4} & r_{4,5} & r_{4,6} & & \\ & \vdots & & r_{5,4} & r_{5,5} & r_{5,6} & \vdots & \\ & & & r_{6,4} & r_{6,5} & r_{6,6} & & \\ & 0 & & & \cdots & & r_{N-1,N-1} & \\ & & & & & & & r_{N,N} \end{bmatrix} \tag{8}$$

When the correlation coefficient vanishes, it indicates that the variables are independent. In this analysis, the independence of parameters between the soil layers is assumed.

4. STATISTICAL ANALYSIS OF NOISE PREDICTION

In this Section, the case examined is based on an offshore wind farm foundation installation campaign in 2018 [15, 11]. The mean soil properties, other material properties and the geometry of the model are summarised in Table 2 in [15].The soil samples for the input parameters are generated based on the Copula models with the number of cases being 100. The forcing function is defined as the smoothed exponential impulse as shown in Figure 2 (a), which results in approximately 2000kJ input energy into the pile. The seabed at this foundation consists of a thin marine sediment layer overlaying a stiff bottom soil half-space. The configuration of the DBBC system is presented in Table 1 in [15]. The inner bubble curtain is positioned at 105m from the pile and the outer bubble curtain is positioned at 145m from the pile. In Fig. 2 (b), the evolution of the pressure field in time for one realisation is shown. As can be seen, the arrival of the pressure cones is at around 0.5 s after the impact of the pile, which is in line with the expectations regarding the arrival time of the direct sound waves traveling with the speed of sound in the water at the distance of 750m from the pile. The comparison between the probabilistic distribution of modeled sound levels and the recorded measurements are presented in Figure 3. A deviation of ±2 dB is taken into account to accommodate potential errors in the measurements

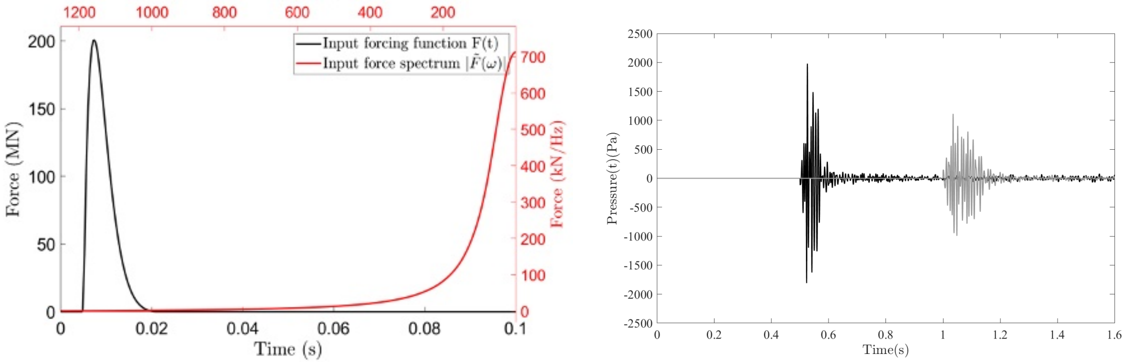

Figure 2: OWF foundation: (a) input forcing function in time and frequency domain; (b) evolution of the pressure field for the mitigated field with the use of DBBC system at 750m (black line) and 1500m (grey line) from the pile.

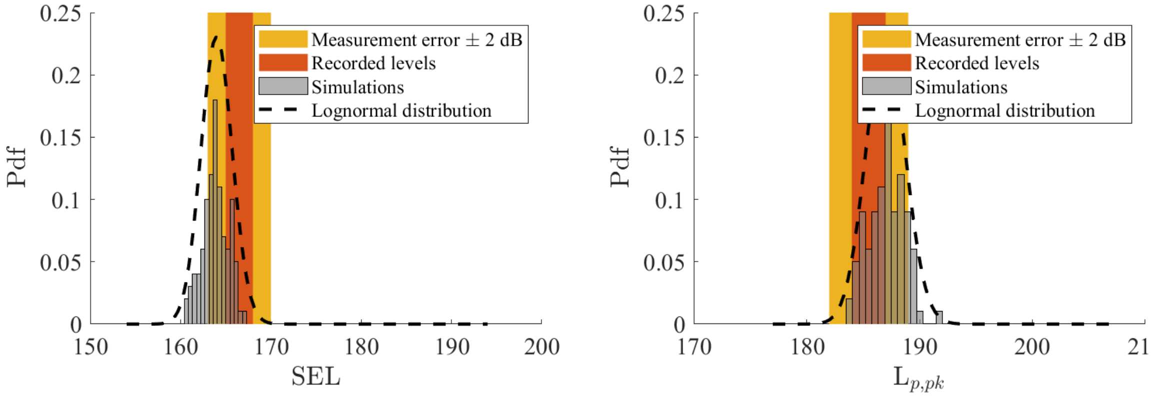

Figure 3: Probabilistic density function of SEL and $L_{p,pk}$ at 750m from the pile and 2 m above the seabed with comparison to the range of data from the measurement.

at the site. By comparing the measured sound levels, it indicates that the average Sound Exposure Level (SEL) falls within the range of accuracy accounted for by the measurement error. It is worth noting that there is a substantial variation in the reduced sound levels observed in both noise metrics. This variation emphasizes the importance of considering uncertainties in the soil properties, which can potentially lead to the exeedence of the noise thresholds.

5. CONCLUSION

This paper primarily focused on investigating the uncertainties associated with soil modeling and their impact on the predicted noise levels withe the use of air-buble curtain system. A comprehensive framework that integrates a range of statistical and probabilistic methodologies is introduced, while utilizing an computatonally efficient pile driving model with noise mitigation system. By conducting a case study on a foundation pile in the German North Sea, the results revealed significant variations in the predicted sound levels due to the uncertainties stemming from the seabed characteristics. Consequently, future recommendations can be made to identify specific soil properties and their influence on accurately predicting pile driving noise. Additionally, the study highlights the importance of considering the mitigating effects of the air bubble curtain system on noise levels, which can be used for noise reduction strategies in installation of the foundation piles for offshore wind farm.

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