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UNDERWATER NOISE GENERATED BY OFFSHORE PILE DRIVING: A PILE-SOIL-WATER VIBROACOUSTIC MODEL BASED ON A MODE MATCHING METHOD

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Abstract: *In this paper, a pile-water-soil model is developed for the prediction of sound generated due to impact piling. The complete model consists of two modules: i) a near-source module aiming at the accurate description of the pile-water-soil interaction together with the sound generation and propagation in the vicinity of the pile; and ii) a far-from-source module aiming at the propagation of the wave field at larger distances. The input to the far-from-source module is provided by the near-source module through a boundary integral formulation.*

Keywords: *underwater noise, offshore pile driving, acousto-elastic medium, mode matching, boundary integral*

1. INTRODUCTION

The underwater noise generated during the installation of foundation piles offshore has been an issue of serious concern mainly due to the rapid developments in the offshore wind industry. The noise pollution itself poses a threat to the marine fauna [1], especially when one considers the large foundation piles, i.e. pile diameters exceeding 7m and lengths of about 80m, that have been installed lately. In order to comply with the strict regulations imposed by several countries, the offshore industry strives to keep the noise levels to within acceptable limits. Various noise mitigation systems [2] have been employed to date aiming at the effective blockage of the noise transmission in the seawater while new ones are under development. To assist in the control of hydro-sound emission, underwater noise prediction becomes essential.

During the last decade, several models have been developed for noise prediction due to impact piling [3]. Reinhall and Dahl [4] were the first to examine systematically the noise generated by impact pile driving. By means of finite element (FE) simulations, they concluded that the sound waves in the seawater originate from the radial expansion of the pile surface caused by the compressional waves travelling downwards the pile at supersonic speed; the latter radiate waves in the water in the form of Mach cones. This observation was later confirmed by noise measurements [2]. Soon after, a wavenumber integration model was proposed by Lippert and Lippert [5] for the noise radiation due to pile driving, in which the pile was not modelled explicitly but substituted by a vertical array of point sources emitting sound with a phase delay trying to mimic the waves travelling downwards the pile after the hammer impact. The results were generally found to be in good qualitative agreement with those of more detailed FE simulations.

In most available models [3], a two-step approach is adopted to model the entire noise path from the noise source (pile) to the receiver, the latter often positioned at large distances from the pile. A near-source model, based on either finite elements or finite differences, is usually employed for sound generation purposes. Subsequently, a far-from-source module is used to propagate sound at larger distances based on the normal-mode method, the wavenumber integration method or the parabolic equation method. The numerical predictions by the different models are basically consistent with each other [3]. With only a few exemptions [6,7], the seabed is customarily approximated by an equivalent acoustic fluid with extra attenuation. However, it is well-known that the pile-driving sources located in the seafloor are not purely compressional in nature, but emit both compressional, shear and interface waves [8]. Next to that, a detailed description of the soil is essential to correctly capture the noise source characteristics (pile vibrations) in the first place.

In contrast to the models described above, a semi-analytical pile-water-soil interaction model was developed by Tsouvalas and Metrikine [7], which includes a three-dimensional description of the water-saturated seabed as a layered elastic medium. In this model, the significance of the seabed-water interface waves (Scholte waves) was also investigated for the first time; the model predictions were also confirmed by collected measurement data [9]. The primary noise transmission path is in the water column in the form of Mach cones, while the secondary noise path is attributed mainly to Scholte waves which propagate along the seabed-water interface and, possibly, also to waves that are reflected in deeper soil layers and leak energy back to the water column. Examining the various noise transmission paths is key to the effective blockage of the noise propagation by exploiting the proper functioning of noise mitigation systems.

In this paper, the authors present a computationally efficient method for the prediction of the generation and propagation of the sound field associated with impact piling at large (from the pile) distances. The complete model consists of two modules: i) a near-source module aiming at the accurate description of the pile-water-soil interaction together with the sound generation and propagation in the vicinity of the pile; and ii) a far-from-source module aiming at the propagation of the wave field at larger distances with high accuracy. The input to the far-from- source module is provided by the near-source module through a boundary integral formulation. The structure of the paper is as follows. In Section 2, the descriptions of the near-source module and the far-from-source module are given. In Section 3, two case studies are analysed for both near-source module and the far-from-source module. Finally, Section 4 gives an overview of the main conclusions of the paper and the future work planned.

2. DESCRIPTION OF THE MODEL

2.1. Near-source module

The pile-water-soil coupled vibroacoustic model is used for the near-field prediction of the underwater noise induced by offshore impact pile driving. It is based on a three-dimensional semi-analytical model developed by Tsouvalas and Metrikine [7]. The complete system consists of the pile interacting with a layered acousto-elastic medium as shown in Fig. 1. The shell vibration is described by a linear high-order shell theory [10]. The shell is of finite length and occupies the domain $0 \leq z \leq L$. The fluid is modelled as a three-dimensional inviscid compressible medium and occupies the domain $z_0 < z < z_1$ with a pressure release boundary at $z = z_0$. The soil is described as a three-dimensional horizontally stratified elastic continuum that occupies the domain $z_1 < z < H$ and is terminated at $z = H$ with a rigid boundary. The effect of the rigid boundary is insignificant in the near-source range

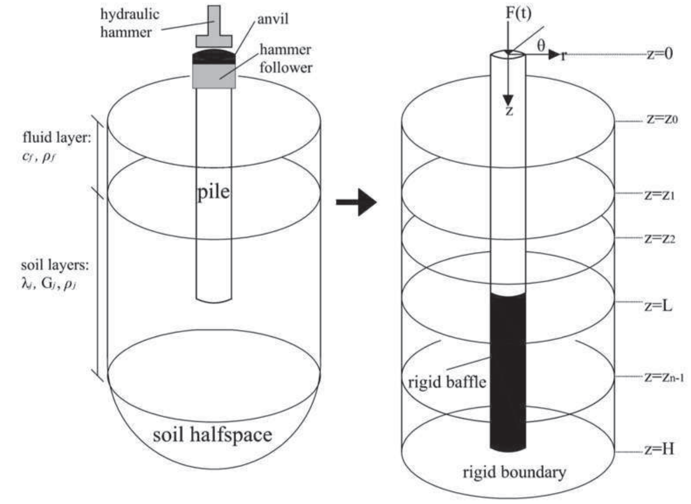


Fig. 1 Geometry depiction of the near-source model by Tsouvalas and Metrikine [9].

A modal decomposition is applied both for the shell structure and the acousto-elastic waveguide. The modal expansion of the shell structure is introduced as:

$$\tilde{u}_{p,k}(z,\omega) = \sum_{m=1}^{\infty} A_m U_{km}(z) \tag{1}$$

The vertical eigenfunctions $U_{km}(z)$ satisfy the boundary conditions at $z = 0 \sim L$. The expressions for the displacement and stress field in the waveguide, which inherently satisfy the boundary conditions and interface conditions, as well as the conditions at $r \rightarrow \infty$:

$$\tilde{p}_f(r,z,\omega) = \sum_{p=1}^{\infty} C_p H_0^{(2)}(k_r^{(p)} r)\tilde{p}_{f,p}(z) \tag{2}$$

The displacement and stress fields in the soil part of the waveguide can be expressed in the similar formulations as shown in [7], which are omitted here for the sake of brevity. The term k_r denotes the horizontal wavenumber, which is the solution of the dispersion. In Eqs. 1~2, the only unknowns are the coefficients of the modal expansions A_m and C_p. A system of infinite algebraic equations with respect to the unknown coefficients C_p can be obtained as explained in [7]:

$$\sum_{p=1}^{\infty} C_p \left(L_{qp} + k_r^{(q)} H_1^{(2)}\left(k_r^{(q)} R\right)\gamma_q \delta_{qp} - \sum_{m=1}^{\infty} \frac{R_{mq} Q_{mp}}{I_m} \right) = \sum_{m=1}^{\infty} \frac{F_m Q_{mp}}{I_m} \tag{3}$$

A detailed derivation of the terms L_{qp}, γ_q , Q_{mp}, R_{mq} and I_m introduced in Eq. 3 is given in [7] together with some explanation of the physical significance of each term. Finally, the coefficients of the shell structure are given by:

$$A_m = \frac{F_m + \sum_{p=1}^{\infty} C_p R_{mp}}{I_m} \tag{4}$$

The method presented above allows the coupling of the two sub-systems, namely the pile structure and the layered acousto-elastic medium. The solution method used in the near-source module gives great flexibility in examining various installation configurations. Due to the fact that the eigensolutions of the pile and seabed-water medium need to be solved only once for a certain location, different installations scenarios, i.e. hammer force, pile penetration depths, etc., require only part of the solution to be evaluated, i.e. Eqs. 3~4. In fact, this allows one to examine multiple configurations with minimum computational effort. By coupling the near-source module to the far-from-source module, the complete model can also treat accurately complex soil conditions over larger radial distances.

2.2. Far-from-source module

In the far-from-source module, the environment is modelled as a fluid layer overlaying a layered elastic half-space. The input to the far-from-source module is provided by the near-source module. The far-from-source module aims to propagate the wave field at larger distances including the consideration of more complex soil conditions, i.e. frequency-dependent soil attenuation, which can be important for sound predictions at large distances.

Within the assumption of a cylindrically symmetric field, the acoustic field can be expressed by the displacement potential $\tilde{\phi}_f$ for the fluid, the displacement compressional potential $\tilde{\phi}_s$ and shear potential $\tilde{\boldsymbol{\psi}}_s = [0, \tilde{\psi}_s , 0]$ for the soil in frequency domain. The wave propagation in the fluid and soil medium can be described by the following displacement potentials:

$$\left[\nabla^2 + k_\chi^2(z)\right]\tilde{\varepsilon}_\chi \,(r, z, \omega) = \tilde{S}_{\omega\chi}(r_0, z_0, \omega)\frac{\delta(r - r_0, z - z_0)}{2\pi r} \tag{5}$$

in which $\tilde{\varepsilon}_\chi$ is one of the displacement potential functions $\tilde{\phi}_f, \tilde{\phi}_s$ and $\tilde{\psi}_s$ with the index $\chi = f, s, p$, $k_\chi \,(= \frac{\omega}{c_\chi})$ are the medium wavenumbers for the fluid, the compressional or the shear potentials in the soil, respectively. The terms $\tilde{S}_{\omega\chi}$ are source strengths of the corresponding potential functions. Applying the forward Hankel transform in Eq. 5, the depth-separated wave equations in the wavenumber domain are obtained. The solutions for the displacement potentials in the wavenumber domain at each layer can be expressed as:

$$\hat{\varepsilon}_\chi(k_r, z) = \hat{S}_{\omega\chi}\frac{e^{-ik_{z,\chi}|z - z_s|}}{4\pi i k_{z,\chi}} + A_{\chi,1}(k_r)e^{ik_{z,\chi}\,Z} + A_{\chi,2}(k_r)e^{-ik_{z,\chi}\,Z} \tag{6}$$

in which the vertical wavenumbers are denoted as $k_{z,\chi} = \left(k_\chi^2 - k_r^2\right)^{1/2}$, the coefficients $A_{\chi,n}$ are the undetermined complex constants. The solutions for the potentials in the half-space consists of the particular solution to the source term and the general solution to the homogeneous equation with the waves propagating solely along the positive z-direction ensuring the radiation condition z → ∞. The condition $\Im(k_{z,p}) < 0$ and $\Im(k_{z,s}) < 0$ are imposed so that the field decays exponentially in depth [11].

Finally, the displacement potentials in frequency domain can be found by applying the inverse Hankel transform. According to the *Cauchy's* theorem and the residue theorem, the representations of the tensor of the Green's functions in both fluid and soil layers are given as:

$$\tilde{\varepsilon}^g_{\chi,k}(r, r_0, \omega) = -\pi i \sum_{m=1}^{M} Res\left(\, \hat{\varepsilon}^g_{\chi,k}(r_0, \omega)\right) H_0^{(2)}\left(k_r^{(m)} r\right) + \frac{1}{2}\int_{L_\alpha} \hat{\varepsilon}^g_{\chi,k}(r_0, \omega) H_0^{(2)}(k_r r) k_r dk_r$$
$$+\frac{1}{2}\int_{L_\beta} \hat{\varepsilon}^g_{\chi,k}(r_0, \omega) H_0^{(2)}(k_r r) k_r dk_r \tag{7}$$

in which $\tilde{\varepsilon}^g_{\chi,k}$ with the index g denotes the Green's function with $\tilde{\varepsilon}$ being one of the displacement potential function, the index $\chi(= f, s, p)$ represents the location of the receiver and the index $k(= f, s, p)$ represents the location and type of the source with f indicating the volume source in the fluid, p indicating compressional wave source and s indicating shear wave source in the soil, respectively.

Consider a cylindrical surface surrounding the pile at close proximity, and the case of a fluid layer overlaying a horizontally stratified linearly elastic half-space. The complete wave field characterized by the Green's function for the sources emitting both compressional waves and shear waves and the resulting amplitude of displacement potentials on the cylindrical surface from the pile driving, which are connected through the boundary integral equation as:

$$\tilde{\varepsilon}_{\chi}\,(\boldsymbol{r},\omega) = \sum_{k=f,s,p}\int_{S_k}\left[\tilde{\varepsilon}^{g}_{\chi,k}(\boldsymbol{r},\boldsymbol{r}_0,\omega)\frac{\partial\tilde{\varepsilon}_k(\boldsymbol{r}_0,\omega)}{\partial\boldsymbol{n}} - \tilde{\varepsilon}_k(\boldsymbol{r}_0,\omega)\frac{\partial\tilde{\varepsilon}^{g}_{\chi,k}(\boldsymbol{r},\boldsymbol{r}_0,\omega)}{\partial\boldsymbol{n}}\right]dS_0 \qquad (8)$$

in which $\tilde{\varepsilon}_k(\boldsymbol{r}_0,\omega)$ can be readily obtained from the near-source module (section 2.1).

3. CASE STUDIES

3.1. Case study 1: predictions of the near-source module

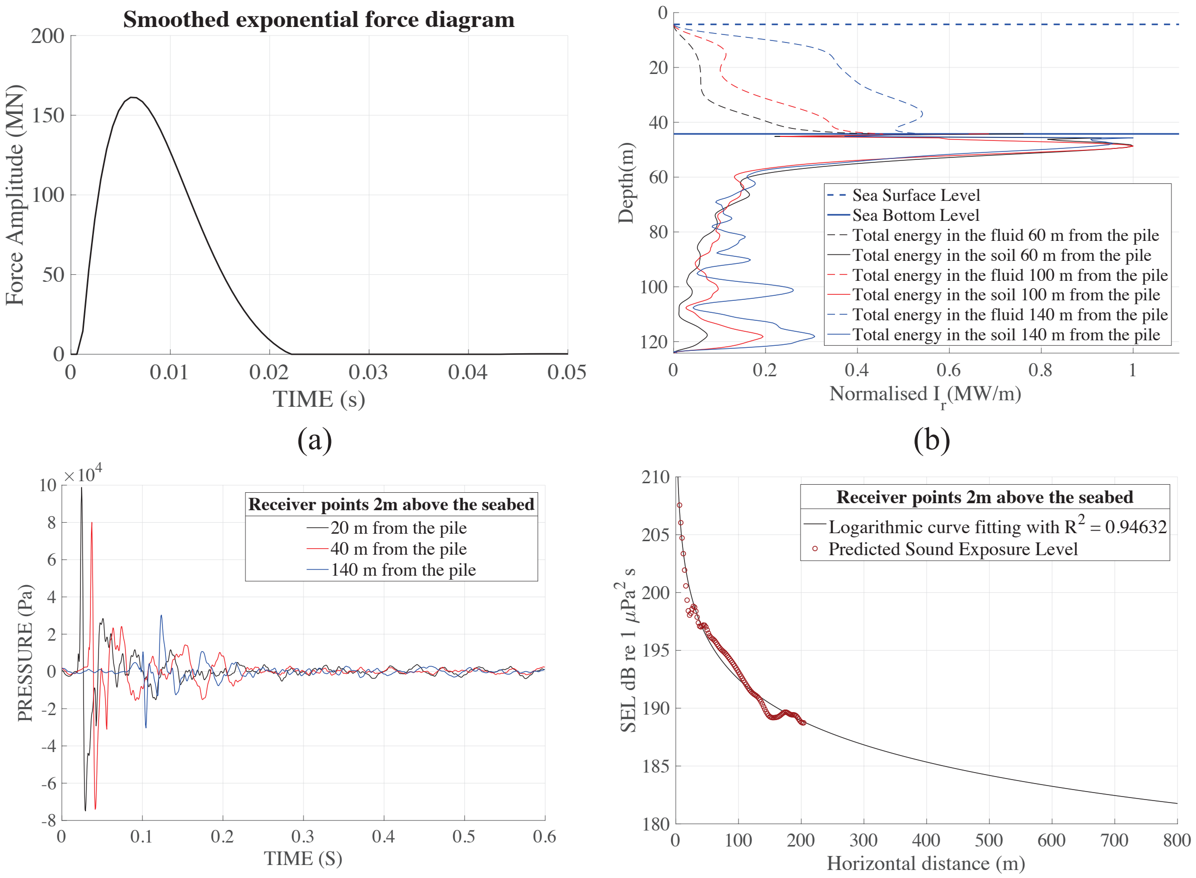
The predictions of the near-source module have been compared to data available in the literature from several measurement campaigns [8]. This section aims at examining the existence of an overlaying marine sediment layer (which is rather fluidised and thin) on the noise predictions for some typical seabed stratifications. In contrast to most other studies, which focus on the prediction of the pressure levels in the seawater region, the focus here is shifted towards an energy flux analysis which is believe to be key in the understanding of the noise transmission paths in the water and through the soil.

Case	Properties	Depth (m)	Density (kg/m^3)	c_L (m/s)	c_T (m/s)	α_p (dB/ λ)	α_s (dB/ λ)
Case study 1	Fluid	39.9	1000	1500	-	-	-
	Marine sediment	1.5	1540	1551	62	1.36	5.46
	Soil layer	78.5	1970	1967	468	0.27	1.09
Case study 2	Fluid	10	1000	1500	-	-	-
	Soil Half-space	-	1970	1845.7	130.2	1.00	2.00

Table 1: Properties of the acousto-elastic medium for case study 1 and 2.

The model consists of a pile with the length of L = 76.9 m, a diameter of D = 8 m, and a wall thickness of 90 mm, which is driven into the seabed through a water column, with the depth of H = 39.9 m, having a final penetration depth of L_p = 32.71 m. Table 1 contains all relevant properties of the system. In this analysis, the hammer and anvil are not modelled explicitly but replaced by a given smoothed exponential forcing function. As shown in Fig. 2 (a), a smoothed exponential force is used which results in approximately 1750 kJ input energy to the system which is a typical energy needed to drive piles of such dimension deep into the soil.

For the validation study, the acousto-elastic layer consists of one fluid layer and two soil layers. The marine sediment layer is described by a fluidized thin soil layer at the upper part of the seabed. In this analysis, the hammer and anvil are not modelled, but replaced by a force function applied at the pile head. In Fig. 2 (b), the total energy along the cross section of the acousto-elastic medium is normalized with the peak amplitude due to the existence of the interface waves. The results indicate the contribution of the energy in the fluid and the soil domains for different horizontal distances from the pile. The energy carried by *Scholte waves* start to decay as soon as the interface waves propagate away from the pile surface. On the contrary, the amplitude of the pressure waves in the fluid decays much slower at large distances. The energy along the vertical coordinate grows steeply at the level of transition from fluid to marine sediment layer and from thin sediment layer to the soil layer due to the abrupt change in the impedance of the medium. As can be seen from the pressure evolution in Fig. 2 (c), higher pressure levels are found in the vicinity of the pile surface. Then the pressure levels start to decay rapidly as the waves radiate away from the pile. The Sound Exposure Level (SEL) are obtained for the 100 receiver points at radial distances up to 200m. Based on the logarithmic curve fitting of sound radiation over distances, the sound pressure level at 750 m distance from the pile are predicted as 182.4 dB.



(a) (b)

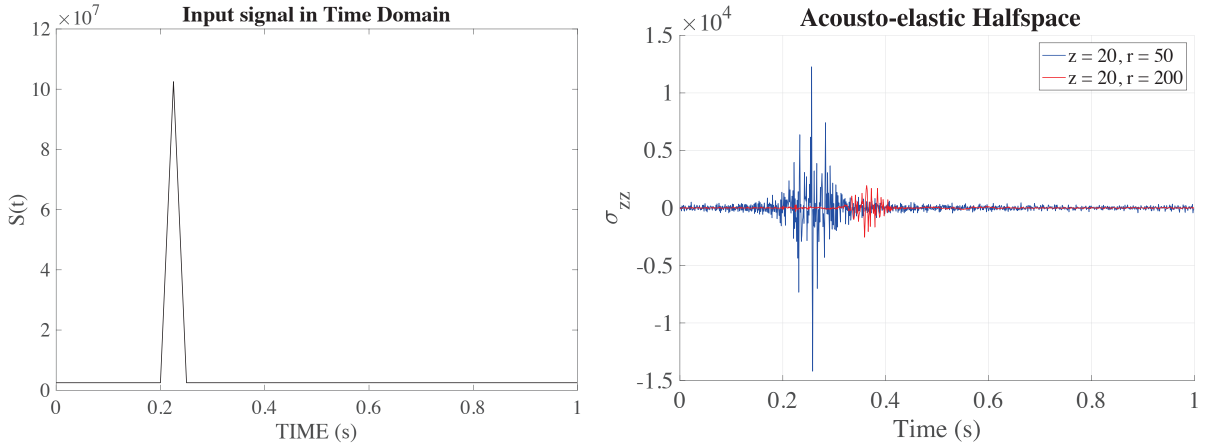
(c) (d)

Fig. 2: (a) Force diagram for the smoothed exponential force function with an estimated blow energy of around 1750 kJ; (b) normalised total energy along the cross section of the fluid-soil domain at different horizontal positions; (c) pressure evolution with time; (d) predicted Sound Exposure Level (SEL) at different radial distances from the pile.

3.2. Case study 2: predictions of the far-from-source module

In this section, the sound radiation from pile driving is reproduced by a vertical distribution of time-delayed ring sources with the method proposed by Reinhall and Dahl [4]. The time delay of the i_{th} source located at the cylindrical cross section $r_0 = 5m$ is determined by its depth and the speed of the pile bulge wave $c_b = 5080\ m/s$, as $\Delta\tau_i = z_i/c_b$.

The sources are defined as volume sources in the fluid and the soil with the source strength being the volume-injection amplitude in the unit of m^3 emitting compressional waves as shown in Fig.3 (a). In this case study, 60 ring sources at a spacing of 0.25m is distributed from the sea surface to the bottom of the pile. The penetration depth of the pile is assumed to be 5m. The ocean environment is described as one fluid layer overlaying a soil half-space. The material properties of the acousto-elastic domain and the geometry of the domain are summarised in Table 1.



(a) (b)

Fig. 3 Case study 2: (a) Input signal for the source (without time delay); (b) the normal stress σ_{zz} in the soil at 20m below the sea surface.

As shown in the Fig. 3 (b), the evolution of the pressure field in time is consistent with the appropriate arrival times of the wave fronts at different horizontal distances. The results presented here aim at solely proving the validity of the concept. In the next work, the input data from the near-source module will be inserted in Eq. 8 to propagate the wave field at large distances using the far-from-source module.

4. RESULTS AND FUTURE WORK

The paper establishes a computationally efficient method for noise predictions over large horizontal distances due to offshore pile driving. The complete model consists of a near-source module and a far-from- source module. The former aims at describing accurately the pile- soil-water interaction and the wave field generated at the surrounding acousto-elastic domain at close distances from the pile (~ 200 − 300 m). The latter module aims at the propagation of this wave field at larger distances from the pile (~ 5 − 10 km) provided that bathymetry changes are insignificant. The mathematical statement of the complete problem is presented and the adopted method of solution is described in great detail. Results from both the near-source module and far-from-source module are presented for a typical installation case encountered in the offshore wind sector. Future work will focus on the coupling of the pile-driving sources along the cylindrical surface to the far-from-source module.

5. ACKNOWLEDGEMENTS

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