Predictions of the effects of elastic seabed on noise radiated during marine pile driving

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Abstract

In this paper, numerical simulations are carried out to assess the effects of an elastic seabed on noise generated by impact pile driving. In the simulation, a steel pile of dimensions 25 m long, 1 m external radius and 5 cm wall thickness was used in an underwater channel of 10 m depth, with a fluid sediment layer above a semi-infinite elastic sub-seabed. The near field of the acoustic source was calculated using a finite element approach with the PAFEC software package, the results of which were coupled into a wave number integration programme (OASES) for propagation to greater ranges.

The results are compared with a fluid seabed to illustrate the effects of varying the acoustic properties of the elastic seabed on the peak pressure level and sound exposure level at long distances.

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1. Introduction

Pile driving noise in an underwater channel has the potential for detrimental effects to marine life, in the vicinity of the noise source, ranging from hearing damage to disturbance. Pile driving has been used during the construction of many large-scale offshore windfarms which have been built in recent years, with many more planned in areas such as the North Sea.

Pile driving is typically carried out in shallow water. The acoustic field generated by pile driving has been studied extensively in order to understand the mechanism of the noise radiation and to the requirements for mitigating the effects on marine life [1-3]. It is typical to treat the problem as a steel pile of cylindrical shell inserted into an infinitely deep sediment below the water column. The driving force is an impulsive impact on the top of the pile resulting in a bulge of the pile wall that travels down at a compressional sound speed of the steel from the point of impact. This generates a pressure wave, or "Mach Wave" in water, that propagates with a wave front angle determined by the sound speed in water and the compressional sound speed of the steel [1].

There is also a wave generated in the sediment by the bulge in the pile, in contact with the sediment. This wave travels with a wave front angle steeper than that of the Mach wave in water due to the higher sound speed in sediment.

It has been demonstrated that the acoustic field generated in the water column stays in the water channel, while the field generated in the sediment stays in sediment [2]. In this case, the sound field in the underwater channel is then dominated by the sound generated by the part of the pile in contact with the water.

Sound propagation in a shallow underwater channel, where pile-driving is commonly used, is determined by the conditions of the sea surface and bottom. In this case, where the dominant frequency of interest is in low hundreds of hertz, it is realistic to assume that the surface is a flat pressure release boundary. The sound propagation then becomes critically dependent on the properties of the seabed. The simplest seabed which can be considered is a flat, fluid sediment which is infinitely deep.

In practice, the seabed is more complicated, for example, with varying bathymetry, varying sediment layers below the sea floor, with different acoustic properties as a function of depth, and bedrock beneath the sediment layer. The acoustic wave propagating in the water column is subject to interaction with the seabed and is influenced by its properties. The effects of various acoustic properties on the uncertainty of underwater noise predictions, in relation to marine pile-driving, have been investigated for a fluid seabed [4].

In this paper, a preliminary study is presented which was carried out to quantify the effects of an elastic seabed on the acoustic field in the water column, resulting from pile-driving. In this case, an underwater acoustic channel was assumed, with a fluid sediment layer above a bedrock substrate of infinite vertical extent. The problem is based on Compile case 1 [5]. Various acoustical properties and depths of the bedrock, below the sea floor, were used to investigate the effects of the elastic substrate on the predicted sound exposure level (SEL) and sound pressure level (SPL) in the water column. The acoustic near field was calculated by PAFEC [6], and the far field was calculated with OASES [7,8]. The results of the simulations are presented in this paper.

2. Piling problem with an elastic substrate

The underwater channel for the modelling of pile driving is typically treated as a water column on a seabed of sediment. Many underwater noise assessments for marine pile driving use a fluid sea-bed to predict transmission loss from the source. The bathymetry and acoustic properties of the seabed, such as sound speed in the water column and seabed, density of water and sediment, attenuation in water and sediment, determine the transmission loss and consequently the level of the acoustic field for a known source level.

In practice, the sediment is always on bedrock. For the frequencies generated during pile driving, the acoustic wave can easily penetrate the sediment layer to reach the bedrock. It is therefore necessary to quantify the effects of the bedrock on the acoustic propagation. The Compile case 1 is used here as a base for numerical simulations of acoustic fields with different seabed properties.
To simplify the problem, this study focusses on the offshore bedrock predominantly present around UK. Although the bedrocks are very complex with a large range of different types, the most common bedrocks are chalk, mudstone and sandstone. It should be noted that it is unlikely that bedrocks are flat at the interface between the sediment and the rock. Like the Compile case 1, this study considers only a flat rock bed beneath a fluid sediment layer, as shown in Figure 1. In the calculation, a steel pile is inserted in a flat bottom underwater channel, with a sediment layer above an infinitely deep rock substrate. The dimensions of the pile and channel are described in Table I.

Table I. Pile and channel dimensions (m)

L	*D*	*d*	*H*	*Hs*
25	2	0.05	10	∞/15/0

As shown in Figure 1, the top end of the pile is flush with the water surface, with the top part of the pile in water and bottom part of the pile in the sediment. In order to compare the effect of the rock substrate on the sound field, three distances

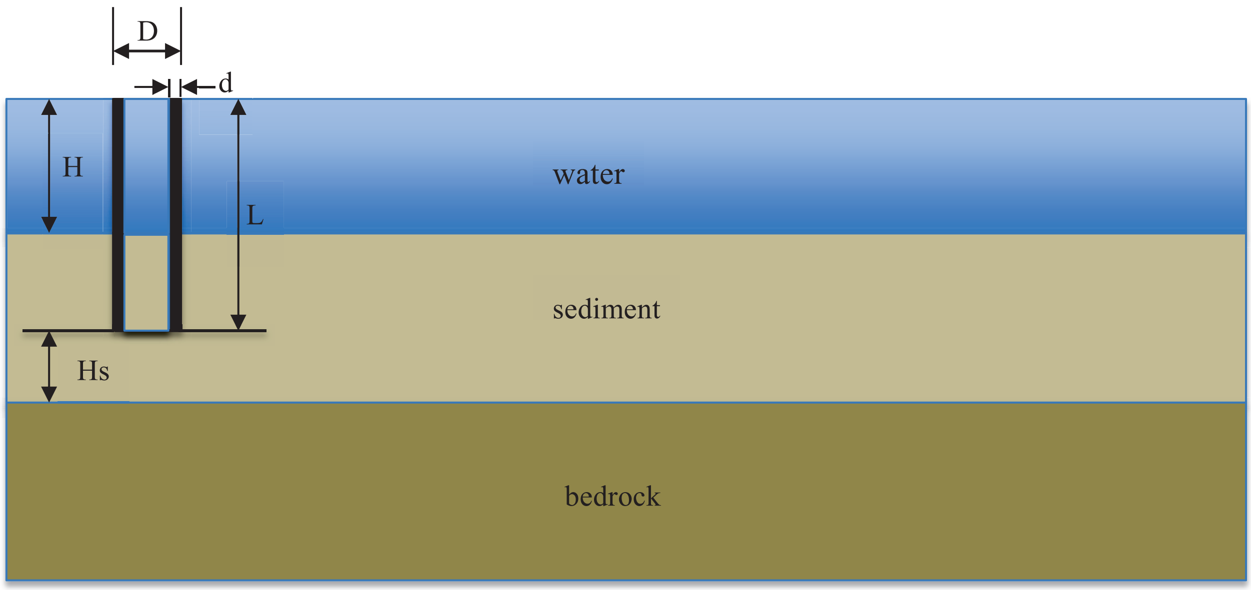

Figure 1 Piling in an underwater channel with an elastic substrate (bedrock)

from the bottom of the pile to the top of the rock are modelled, for both chalk and sandstone bedrock layers. Considering an infinitely distant bedrock (i.e. a sediment layer of infinite vertical extent), Hs=∞, is consistent with the Compile case 1. When Hs=0, the pile is in contact with the bedrock. For the intermediate case, the rock is 15 m below the bottom of the pile. To account for energy loss due to sediment friction, an equivalent damping factor is applied to the part of the pile in the sediment, while the part is water is un-damped.

The pile is driven by an impulsive force described by a function

$$F = \begin{cases} F_p \frac{t}{t_r} & t \le t_r \\ F_p e^{-\frac{t-t_r}{t_d}} & t > t_r \end{cases} \quad (1)$$

where the parameters are given in table III.

The frequency range used for all of the calculations is from 1 Hz to 2.5 kHz, with a step of 1 Hz. The frequency range is considered adequate to cover the most important part of the spectrum of piling noise, and the frequency step is fine enough to capture the time window of the pulse duration.

Table II. Parameters for the force function

	Symbol	*Unit*	*value*
Peak force	*Fp*	*MN*	*20*
Rise time	t_r	ms	0.2
Decay time	t_d	ms	1.6

The acoustic properties of the pile, the sea water, the sediment and the bedrocks are provided in Tables III and IV.

3. Numerical simulation

3.1. PAFEC

PAFEC solves acoustical vibration problems with finite/boundary element methods. It was employed here to predict the pressure field in the vicinity of the pile in response to the driving force given by Eq. (1). Although a time domain solution is available within PAFEC, which is extremely fast, the frequency domain solution was used for the data presented here to enable the inclusion of damping effects. This is not possible in the time domain solution. Hysteretic damping was applied to the part of the pile in sediment, and the bedrock to account for the attenuation by the media. The time domain waveform at various receiver positions was obtained using an inverse FFT of the frequency domain results.

PAFEC, like other finite/boundary element and time domain finite difference models, can predict sound pressure, particle velocity/displacement in the water column close to the pile. However, the requirements of very large storage and CPU time prevent it from being practically applied to distances in excess of 100 wavelengths from the source, at the highest frequencies of interest.

For longer range acoustic propagation, from a few hundreds to well over thousands of wavelengths, different modelling methods have to be used. The most commonly used methods are parabolic equation, normal mode and wave number integration [9], for the frequency of interest and shallow water channels. The sound field produced by close range solutions such as PAFEC can be coupled to such propagation models to provide a solution at long distance from the pile.

In the simulation presented here, the pressure on the exterior surface of the pile was calculated using PAFEC at steps of 0.25 m from the water surface to the bottom to form a virtual source array with 40 elements. This was used as the input to a wavenumber integration propagation model (OASES) to calculate the acoustic field resulting from the pile driving at distances beyond that practically possible with the finite element solution. The contribution from the part of the pile in sediment was not included since its contribution to the acoustic field in water is considered to be very small in comparison with the part from the water column.

3.2. OASES

OASES is a general purpose computer code for modeling seismo-acoustic propagation in horizontally stratified waveguides using a wavenumber integration solution in combination with the Direct Global Matrix solution technique [7,8]. It is particularly useful for sound propagation problem in underwater channels with many layers of seabed, which are either fluid or elastic.

The transfer function from a point source was calculated, and the time waveforms of received signals at long ranges were obtained by convolution of the pressure waveform at the source and the transfer function. The total field is the sum

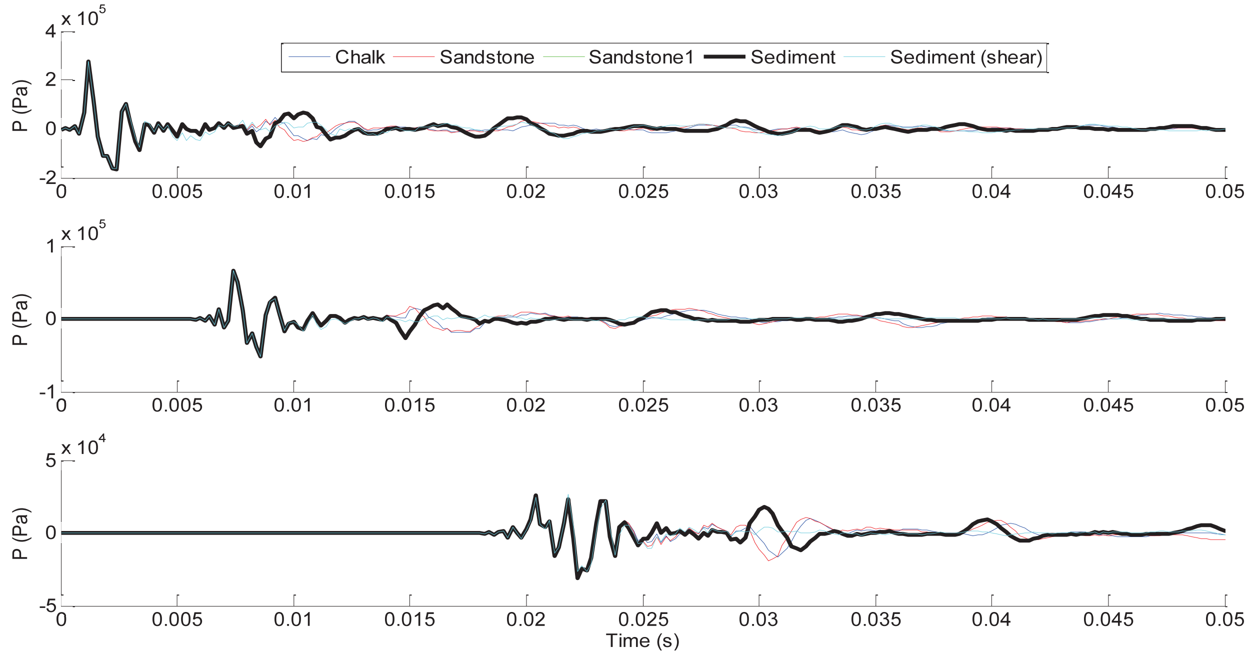

Figure 2 Near field pressure with various bottom properties at 1 m, 11 m and 31 m from the centre of the pile

of the contributions from all the sources of the virtual source array obtained using PAFEC.

The sources for the propagation model are effectively rings of the same diameter as the pile, with a height of 0.25 m. These were applied directly to the propagation model and a scaling factor was applied to convert the energy from the ring sources to equivalent spherical sources.

4. Results

The acoustic output parameters used presented are sound exposure level (SEL) and peak sound pressure level (SPL). These were calculated for receivers at various ranges and depths.

4.1. Near field results

The acoustic parameters were calculated in the near field over the frequency band of interest using PAFEC with a depth step size of 0.125 m and range step size of 0.163 m. The results were obtained at selected depths of 1, 5 and 9 m below water surface and ranges of 1, 11 and 31 m from the centre of the pile. Figure 2 shows the pressure waveforms with different seabed properties. The black line is for the Compile case 1. The blue line is for chalk substrate, red for sandstone, green for sandstone 15 m below the bottom of the pile, and cyan is for sediment supporting a shear wave. The initial part the waveforms for the 1 and 11 m distances is not affected by the bottom properties since it represents the direct path of the signal without interference from other paths. The effect of multipath arrivals becomes apparent at the 31 m range.

The waveforms are different once the acoustic wave is reflected from the seabed with different acoustic properties. It is noticed that the multipath arrivals are smaller for all the seabed types when compared with the fluid sediment (black line). This means that there is less acoustic energy in the water channel with elastic seabed properties, in the near field region of the source.

4.2. Far field results

The acoustic parameters were calculated in the far field using OASES at ranges of 0.75, 1.5, 10, 20, 30, 40 and 50 km for three depths, 1, 5 and 9 m from water surface. The differences between the Compile case 1 and the other seabed types is shown to demonstrate the effect of the seabed properties on the acoustic field, in the far field region of the source. Figure 3 shows the results for chalk, sandstone with initial attenuation in sediment and, sandstone with lower attenuation, and sediment supporting shear wave. The difference in the SELs is quite small for the channels with bedrock, the maximum value being around 1.5 dB. The differences become smaller at longer ranges with bedrocks, indicating that the bedrocks have quite a weak influence on the SEL in this case. The greatest difference is about 3 dB between the fluid sediment and sediment with shear wave.

Table III. Material property of steel used in modelling

Material property	Unit	Value
Steel		
Young's modulus	GPa	210
Poisson ratio	-	0.30
Density	$kg\cdot m^{-3}$	7850
Absorption coefficient of p-wave	$Np\cdot m^{-1}\cdot Hz^{-1}$	3×10^{-5}
Absorption coefficient of s-wave	$Np\cdot m^{-1}\cdot Hz^{-1}$	11×10^{-5}

Table IV Material property used in modelling

		water	Sediment (shear)	Chalk	Sandstone
Material property	Unit		Value	Value	Value
Sound speed p-wave	$m\cdot s^{-1}$	1500	1800	2450	3500
Sound speed s-wave	$m\cdot s^{-1}$		0 (125)	1200	1800
Density	$kg\cdot m^{-3}$	1025	2000	2450	2450
Absorption coefficient of p-wave	$Np\cdot m^{-1}\cdot Hz^{-1}$	[10]	3×10^{-5}	3.5×10^{-5}	3.5×10^{-5}
Absorption coefficient of s-wave	$Np\cdot m^{-1}\cdot Hz^{-1}$		$0\ (1.7\times10^{-3})$	10×10^{-5}	10×10^{-5}

Figure 4 shows the differences in the SPLs between the fluid sediment seabed and the other seabed types. The differences are greater than the corresponding differences between the SELs, with a maximum difference of more than 2 dB at a range of less than 10 km for the bedrock cases. The peak levels fluctuate around the value for the fluid sediment case. The bedrock in these cases modifies the shape of the signal waveform. There is only a small loss of total energy of the signal due to the bedrock; however, the peak level of signal can be either higher or lower. Once again, the effects of the bedrock are less at long ranges. The peak level of the signal is always lower for the channel supporting shear wave in the sediment. This is simply because the acoustic energy of the signal is converted into a shear wave during the propagation process and the shear wave propagates away from the water column, resulting in additional loss of energy.

5. Conclusions

A preliminary study has been carried out to examine the effects of bedrock underneath a sediment layer on the acoustic field in the water column, for the case of pile-driving. It has been shown that an elastic substrate will change the level of the acoustic field in the water column and that it depends critically on the attenuation of the sediment, sound speed density ratio between the water and sediment, and the layer thickness of the sediment. Further work is required to identify the properties of the sediment and bedrock that introduce the most prominent effects on the sound field in the water column. The results of the work will help to select propagation tools for the assessment of the levels of underwater noise resulting from pile-driving and its effect on marine life.

Acknowledgement

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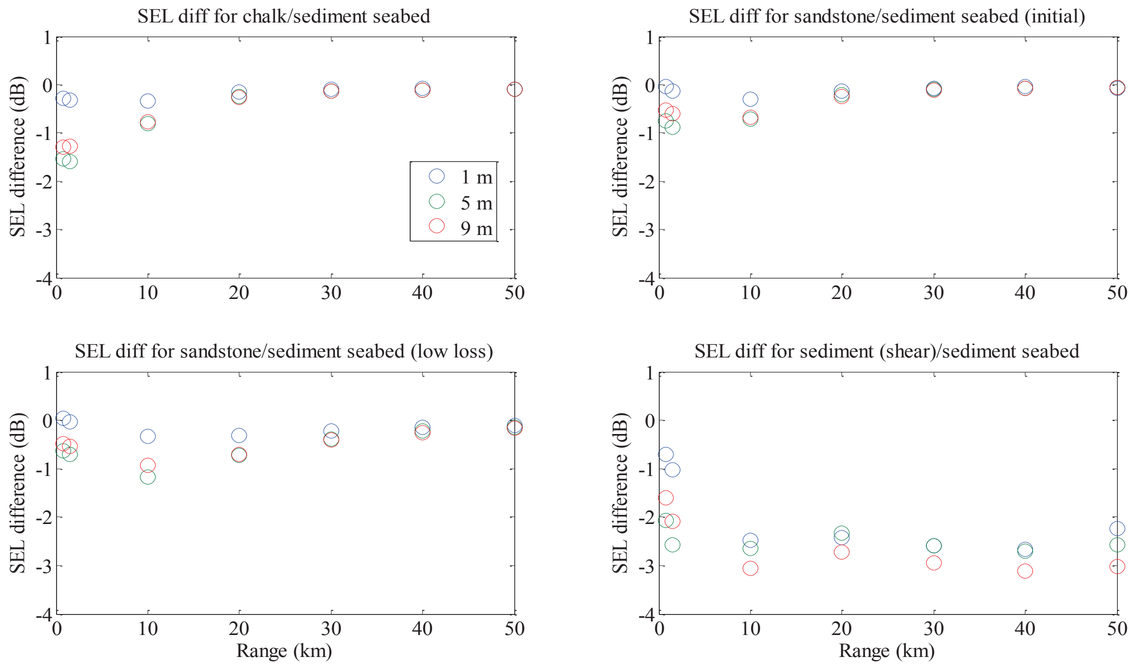

Figure 3 Differences of SELs for different sea beds against the sediment

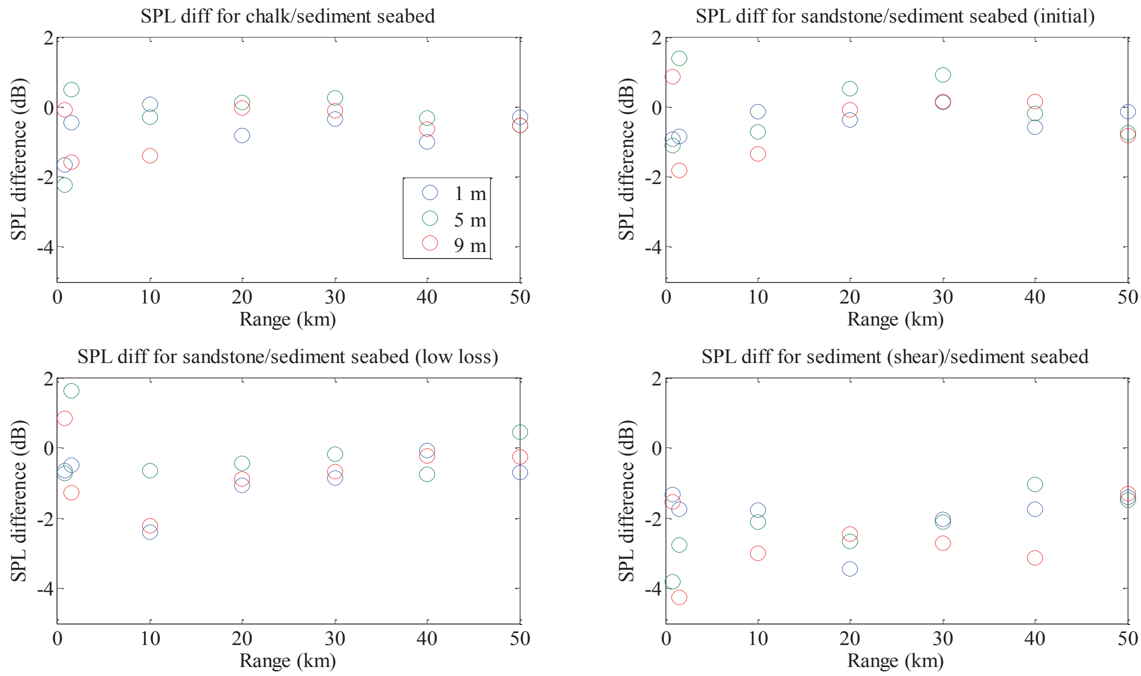

Figure 4 Differences of SPLs for different sea beds against the sediment

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