



Noise reduction by the application of an air-bubble curtain in offshore pile driving

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ABSTRACT

Underwater noise pollution is a by-product of marine industrial operations. In particular, the noise generated when a foundation pile is driven into the soil with an impact hammer is considered to be harmful for the aquatic species. In an attempt to reduce the ecological footprint, several noise mitigation techniques have been investigated. Among the various solutions proposed, the air-bubble curtain is often applied due to its efficacy in noise reduction. In this paper, a model is proposed for the investigation of the sound reduction during marine piling when an air-bubble curtain is placed around the pile. The model consists of the pile, the surrounding water and soil media, and the air-bubble curtain which is positioned at a certain distance from the pile surface. The solution approach is semi-analytical and is based on the dynamic sub-structuring technique and the modal decomposition method. Two main results of the paper can be distinguished. First, a new model is proposed that can be used for predictions of the noise levels in a computationally efficient manner. Second, an analysis is presented of the principal mechanisms that are responsible for the noise reduction due to the application of the air-bubble curtain in marine piling. The understanding of these mechanisms turns to be crucial for the exploitation of the maximum efficiency of the system. It is shown that the principal mechanism of noise reduction depends strongly on the frequency content of the radiated sound and the characteristics of the bubbly medium. For piles of large diameter which radiate most of the acoustic energy at relatively low frequencies, the noise reduction is mainly attributed to the mismatch of the acoustic impedances between the seawater and the bubbly layer. On the contrary, for smaller piles and when the radiated acoustic energy is concentrated at frequencies close to, or higher than, the resonance frequency of the air bubbles, the sound absorption within the bubbly layer becomes critical.

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1. Introduction

Noise pollution in the sea environment is often a by-product of marine industrial operations. In Europe, the problem has gained considerable attention in the recent years mainly due to the acceleration in the deployment of the offshore wind industry. To meet today's increasing energy demand, a large number of offshore wind farms are planned to be constructed in the near future [1,2]. Despite the existence of several foundation concepts to support the tower of an offshore wind power generator [3], the most common and widely adopted solution is a steel foundation pile [4]. The latter is usually driven into the seabed with the help of

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large impact hammers or vibratory devices [5]. During impact hammering, the generated noise levels in the seawater can be very high, often exceeding 100 kPa within 10 m from the pile surface [6]. Naturally, such high noise levels can be harmful for the aquatic species as highlighted in several recent publications [7–11].

In order to reduce the noise levels and to comply with the strict regulations imposed by different nations [12–14], several noise mitigation concepts have been developed. For an overview of the various mitigation techniques the reader is referred to OSPAR [15] and Bellmann [16]. Despite the plethora of the available solutions, the air-bubble curtain is usually preferred due to the simplicity in its application and the efficacy in the noise reduction. The use of an air-bubble curtain is a well-established method to mitigate the underwater noise with a long-standing history [17]. It consists of rising air bubbles that encircle the pile forming thus a *closed curtain* of certain thickness [18]. The freely rising bubbles are created by compressed air that is injected through perforated pipes positioned either horizontally on the seabed level or vertically fixed at a framed structure [19]. The difference in density and compressibility between the seawater and the bubbly mixture leads to a significant mismatch in the acoustic impedances between the two media, even for very small fractions of the air volume in the bubbly medium.

In a series of previous publications by the authors [20–22], a number of models have been developed that allowed an in-depth investigation of the generation mechanisms and the propagation characteristics of the underwater sound during marine piling. In this paper, a three-dimensional model is proposed which includes the air-bubble curtain positioned around the pile. The aim is to investigate the physical mechanisms that are responsible for the noise reduction as well as their dependence on the system characteristics. This understanding will help the industry to optimise the air-bubble configuration in order to achieve the maximum noise reduction for piles of various diameters.

The semi-analytical model consists of the foundation pile, the surrounding water–soil medium and the air-bubble curtain that is placed around the pile along the depth of the water column. The bubbly layer is described as a homogeneous medium with a frequency-dependent, complex-valued compressibility [23,24]; a description which is considered to be realistic for the air–water mixture characteristics and the associated acoustic wavelengths related to marine piling. It is also assumed that the air-bubbles rise vertically from the seabed to the sea surface which implies that the air-bubble curtain is confined so that the air-bubbles are prevented from drifting away due to the presence of sea currents.

The solution approach is based on the dynamic sub-structuring technique and the modal decomposition method [25–28]. The principal idea is the division of the complete system into several sub-domains, which span the total depth of the acousto-elastic region while remaining invariant in the horizontal direction. The response of each sub-domain is expressed in terms of a complete set of orthogonal eigenfunctions which inherently satisfy the boundary and interface conditions along the depth of the waveguide. The forced vibrations of the system are obtained by an appropriate combination of the kinematic continuity and dynamic equilibrium conditions at the interfaces between the various sub-domains together with the forced equations of motion of the pile. This solution approach is similar to the one presented by Tsouvalas and Metrikine [21] but is generalised here to account for the inhomogeneity along the horizontal direction introduced by the presence of the air-bubble curtain.

A parametric study is performed in order to reveal the principal mechanisms that are responsible for the noise reduction for different system configurations. The influence of the size of the air bubbles, the volume of the air content, the thickness of the bubble curtain and its position relative to the pile surface on the predicted sound levels are investigated. It is shown that the principal mechanism of noise reduction depends strongly on the frequency content of the radiated sound and the characteristics of the bubbly medium. For piles of large diameter, the noise reduction is mainly attributed to the mismatch of the acoustic impedances between the seawater and the bubbly layer. On the contrary, for smaller piles in which the bulk of the acoustic energy is concentrated at frequencies close to, or higher than, the first omnidirectional breathing frequency of the air bubbles, the sound absorption within the bubbly layer becomes critical.

The contribution of the present paper can be regarded original with respect to the following two aspects. First, an efficient method is presented for the study of the vibroacoustic behaviour of piles embedded in continua which show vertical and horizontal inhomogeneities. Despite the fact that the treatment here is restricted to inhomogeneities of a piecewise character, the incorporation of continuous variations of the system properties along the depth of the waveguide can be included with minimum computational effort. The semi-analytical solution is computationally faster when compared to other classical modelling approaches like, for example, the finite element or the boundary element method. Second, it is shown that the mechanism of noise reduction depends strongly on the frequency content of the radiated sound. Although not surprising, the quantitative aspects of this result are new and can be useful for the offshore industry. By knowing only a few of the characteristics of the system, i.e. pile diameter, water depth, and type of input force, the settings of the air-bubble curtain can be optimised to achieve the maximum noise reduction.

The paper is structured as follows. In Section 2, the geometrical and material properties of the model are introduced. In Section 3, the mathematical description of the pile–water–soil model is given and the semi-analytical solution method is presented. Section 4 discusses the background theory used to model the dynamic behaviour of the air–water mixture. Section 5 examines the basic case of a typical foundation pile that is used in the offshore wind industry. The focus is placed on the differences in the wave field that is generated during impact hammering with and without the use of the air-bubble curtain. In Section 6, a parametric study is performed and the generated wave field for various bubble curtain configurations is analysed. Finally, Section 7 gives an overview of the results of this study together with some points that require further investigation.

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