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A PARAMETRIC STUDY ON THE INFLUENCE OF VARIOUS PARAMETERS ON THE UNDERWATER NOISE LEVELS GENERATED BY OFFSHORE PILE DRIVING

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ABSTRACT

Marine renewable energy has been growing rapidly over the last decade which results into a rapid development of offshore wind power. The construction of wind turbines commonly involves a pile-driving process, which has raised concerns about the resulting environmental impact of high sound levels on species such as fish and marine mammals. In this study, a simulation model based on the Finite Element (FE) commercial software ADINA is developed in order to determine the resulting acoustic field distribution due to the pile driving process. The pile-fluid-soil interaction model is validated and the influence of a number of parameters on the resulting sound pressures in the surrounding fluid medium is analysed. The inclination of the applied force, the position of the artificial non-reflective boundary, the diameter of the pile and the input energy of the hydraulic hammer are considered in order to examine their influence on the underwater acoustic field. The results indicate that these parameters influence the predicted sound field. The numerical analysis presented in this paper could result in potential modifications to the structure, hammer, and/or process that could reshape the temporal characteristics of the pile driving stimulus without changing structural integrity. The development of effective mitigation measures such as acoustic baffles will be aided by understanding the noise generation process. This is the only way to define zones of impact on marine species since the sound energy received by them depends not only on the pile-driving configuration, but also on the size, shape and properties of the underwater environment.

Keywords: *wind turbine, pile driving, vibro-acoustics, underwater noise.*

INTRODUCTION

The wind has been established as a source of renewable energy to generate electricity through the use of wind turbines (Gaudiosi G. 1999), (Gill A.B. 2005). The wind turbines are used to harness the kinetic energy of the moving air over the oceans and convert it to electricity. In general, three types of foundations are used to support the offshore wind turbines. These are monopile foundation, torpid foundation and gravity based caisson foundation. The majority of offshore wind energy projects in shallow waters up to a depth of 30 m use monopile type of foundation. The monopile foundation consists of a steel pile up to 6 m in diameter with a maximum wall thickness of 150 mm. Depending upon the subsurface conditions, the pile is typically driven into the seabed by either impact or vibratory hammers. In some cases the piles are grounded into the sockets drilled into rock. With the growing awareness of the potential impact of anthropogenic noise on marine life, it is important to gain an understanding of the physics of the noise generation mechanism and to examine how the sound propagation into shallow waters is affected by the input energy of the hammer, the seabed conditions and the water column characteristics. The propagation of sound in the deep ocean is well documented, but it is more complicated in the case of shallow water environments (< 200 m in depth) (Urick R.J. 1983). The large variety of sediment types as well as the repeated reflections of the generated sound waves on the surface and on the seabed level makes sound transmission difficult to model (Marsh H.W. and Schulkin M. 1962). The prediction of the underwater noise levels from offshore pile driving is complicated not only because of the complex nature of the sound source but also because of the strong interaction that takes place between sound waves propagating outwards in the water column and various types of waves travelling along the seabed-water interface.

During offshore pile driving, a hydraulic hammer produces an impact on the pile head that generates a stress wave which propagates downwards as shown in Fig. 1. Part of the energy introduced into the system is spent on the progression of pile into the soil whereas another part is irradiated directly into the water in the form of pressures waves from the vibrating surface of the pile. A third part of the energy enters the soil and generates elastic waves which propagate through the soil medium. These conditions produce a very complex sound field that does not have a simple relationship between sound pressure and particle velocity. Because of the complexity of the sound field produced in pile driving environments, relatively simple models, such as the one developed by *Dzwilewski* and *Fenton* (Dzwilewski P.T. and Fenton G. 2003), are not very useful in predicting the impact zones for aquatic animals. More detailed models of the acoustic environment are needed in order to understand the way in which sound energy is distributed among various subsystems i.e. pile, water column and soil, and to adequately predict impact zones for aquatic animals.

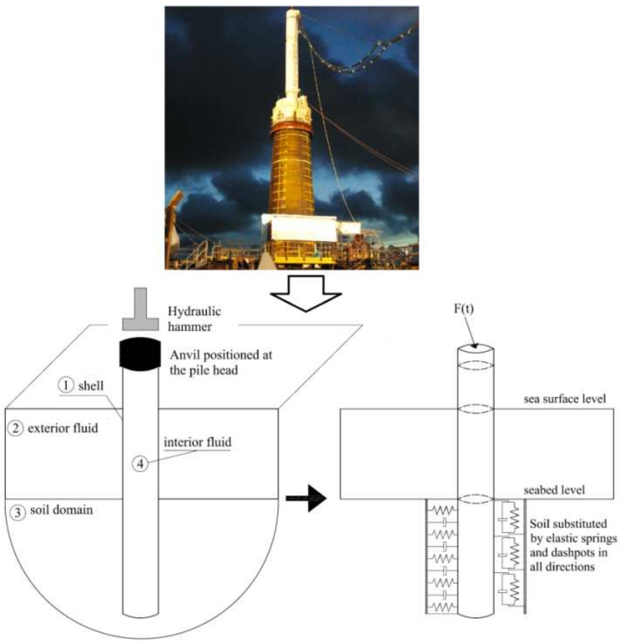

Fig.1 Representation of the real situation (top) and of a model consisting of springs and dashpots (bottom)

In this paper, the results of the simulation of underwater noise generated from offshore pile driving are presented. The simulation involves the development of a vibro-acoustic model by using the commercial FE software ADINA. The model (Fig.2) incorporates all major parts of the system. The pile is modeled as a thin circular cylindrical shell of constant thickness and of finite length. The surrounded water is described with the help of linear compressible fluid elements. The impact of the hydraulic hammer is represented by an external force which is applied at the top of the pile (A.J.Deeks and M.F.Randolph 1993). Two possibilities are explored to include the properties of the soil into the model: the first approach consists of modeling the soil with spring and dashpot elements (Gazetas G. and Dobry R. 1984) as shown in Fig. 1 while the second one comprises of modeling the soil with equivalent fluid elements (Reinhall Per G. and Peter H. Dahl 2011). The pile and fluid domains are coupled with fluid-structure interface elements and a coupled fluid-structure interaction (FSI) analysis is performed. The structure of the document is as follows. Once the model is validated, the influence of a number of parameters on the generated sound pressures in the exterior fluid is analyzed. Subsequently, the results of the finite element analysis are presented and the main characteristics of the sound field are discussed. Finally, some conclusions are given together with some points for which further research is required.

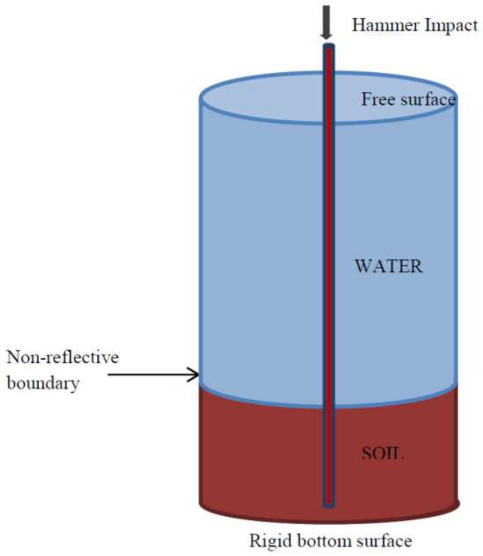

Fig.2 Schematic representation of pile-fluid-soil interaction model

MODEL DESCRIPTION

To investigate the acoustic radiation due to pile strike, a dynamic FE model of a pile driven into the soil sediment in shallow waters is developed by using FE software ADINA. The model consists of a pile with a length of 32.4 m, an inner radius of 43.7 cm and a wall thickness 2 cm. Non-reflecting boundaries, available in ADINA, are employed to prevent the reflection from artificial boundaries that truncate these domains (Fig. 2).

The material model used for the pile is based on a linear elastic formulation. The density, modulus of elasticity and Poisson ratio of the steel is 7850 kgm^{-3}, $2.1*10^{11}$ Nm^{-2} and 0.28 respectively. To model the surrounding fluid medium potential based fluid elements are used with a bulk modulus of $2.2*10^9$ Nm^{-2} and a density of 1030 kgm^{-3} resulting in a compressional wave speed of 1461 ms^{-1} for the fluid domain. The pile is assumed to be free at the top and fixed at the bottom which is a reasonable approximation for large penetration depths of the pile into the soil. At the pile-fluid interface, the fluid and structural equations are coupled with the help of fluid structure interface (FSI) elements available in ADINA. The sea surface is simulated as a free surface boundary condition, whereas the seabed is modelled with different boundary conditions; a free surface, an artificial non-reflective boundary and a rigid boundary condition. The infinite exterior (to the pile) region is truncated with the help of cylindrical infinite boundary elements available in ADINA to reduce the computational effort. The approximate pressure F(t), resulting from the impact between the hammer weight and the pile is modelled in time and in frequency domain as shown in figures 3 and 4. The assumed shape of the loading function is consistent with previously published data (A.J.Deeks and M.F.Randolph 1993). On the basis of the maximum frequency content of the applied load, the speed of sound in the water and the speed of compressional waves in the pile, 10 elements per unit of wavelength are used for the fluid and the shell. The wave propagation in the pile and the surrounding medium is modelled for 0.1 s using a typical time step of 0.1 ms.

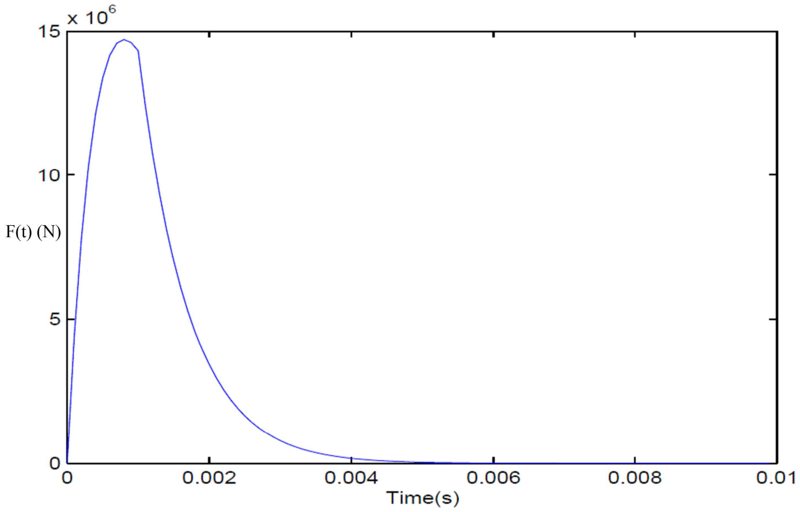

Fig.3 Variation of applied load with time

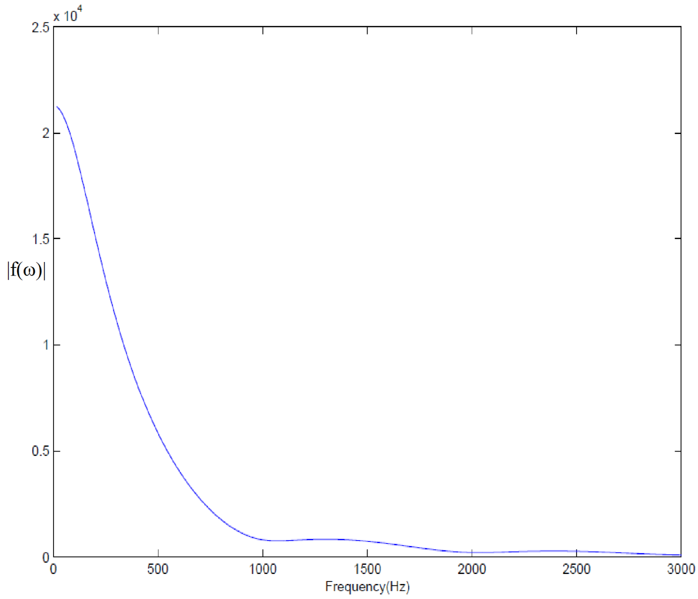

Fig.4 Frequency spectrum of the load

VALIDATION OF THE MODEL AND BASIC FEATURES OF THE SOUND FIELD

It is observed that the primary source of underwater noise originates from the downward travelling compressional wave at the pile which causes a radial displacement motion due to the effect of the Poisson's ratio of steel. The development of axisymmetric Mach cones is observed from the analysis at an angle of 17^0 with the vertical axis of the pile as shown in Fig. 5. This phenomenon is also observed by other researchers (Reinhall Per G. and Peter H. Dahl

2011) and (A. Tsouvalas and A.V. Metrikine, 2013). The angle of the cones depends only on the ratio between the compressional waves in the pile and the speed of sound in the fluid and is independent of the distance from the pile axis.

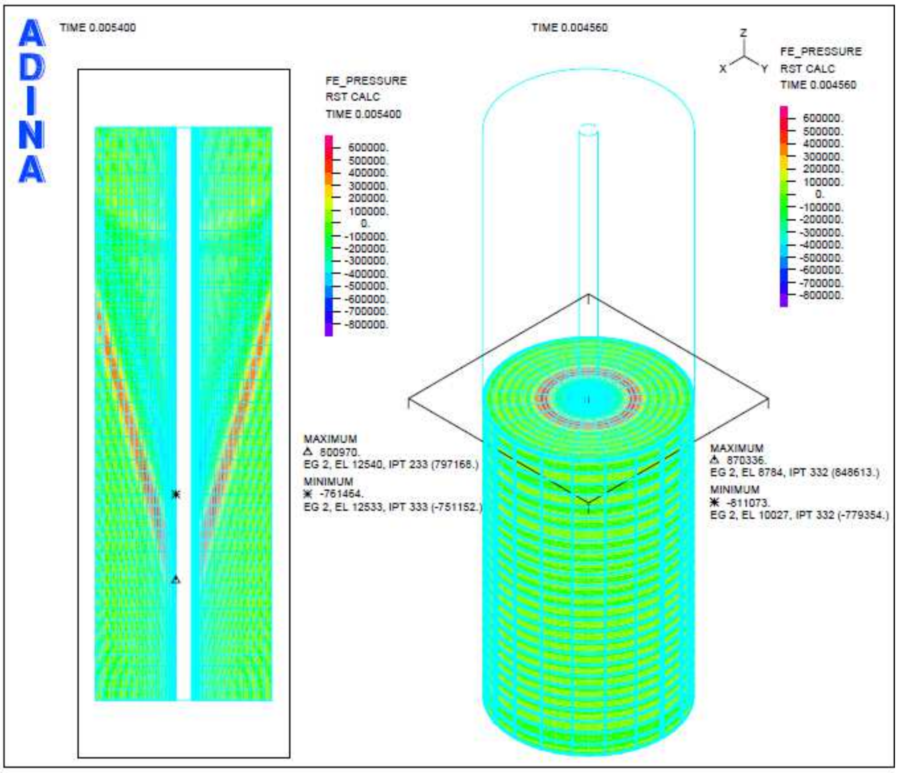

Fig.5 Development of Mach cone at an angle of 17^0 with the pile axis and the radial expansion of pressure in the surrounding fluid medium

The axial stress wave in the pile creates a spike in the radial velocity which is followed by oscillations of the pile surface. In Fig. 6, the radial velocity of the pile is plotted at three nodes, which are located at a distance of 26.56 m, 17.42 m, 1.29 m as measured from the bottom of the pile. For this analysis the soil is modelled as a fluid having the same properties with the actual water column. The propagation of the radial wave from top to bottom nodes of the pile is shown in Fig. 6. From figures 6 and 7, it can be observed that the radial velocity spike in the pile produces a corresponding spike in the acoustic pressure of the fluid elements which are adjacent to the pile nodes at the same point in time.

A comparison between a three dimensional model and an axisymmetric one has shown that both predict similar results for the case of a vertically applied force at the pile head, with the axisymmetric one being computationally very fast. Thus, for the cases in which the load is applied vertically, the axisymmetric model is preferred both in terms of accuracy and of computational speed.

The variation of the pressure development in the fluid domain with increasing depth and radial distance is studied. A strong correlation has been found between the pressure levels and the radial distance from the surface of the pile for the case of a rigid bottom. The variation is shown to be inversely proportional to $\sqrt{r}$ as shown in Fig. 8, which simply implies a cylindrical spreading of the input energy. This is expectable since the bounded waveguide formed by a pressure release surface and a rigid bottom is one of the cylindrical type. On the contrary, in Fig. 9 a clear correlation between the pressure levels and the depth of fluid zone is not observed for the near-field sound pressures. This implies that the actual pressure field at the vicinity of the pile is very complex with a strong depth variation which cannot be accurately characterized by a single pressure measurement.

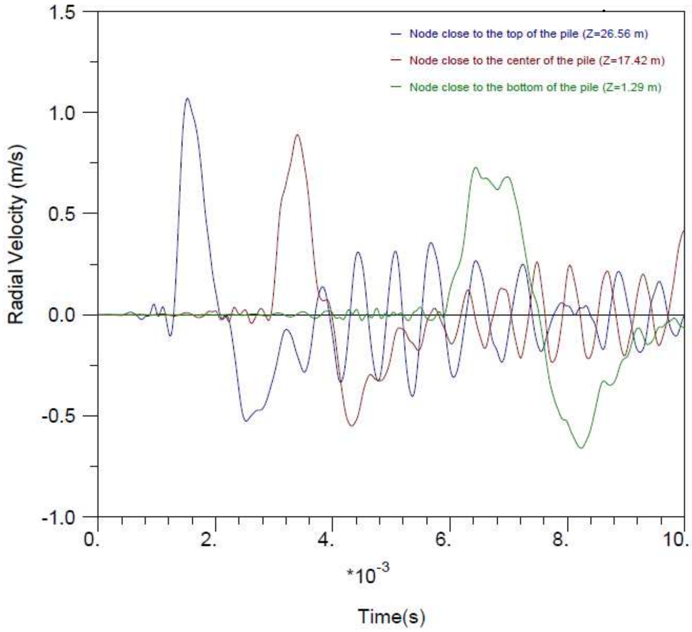

Fig.6 Radial velocity in shell element at a depth of 26.56 m, 17.42 m and 1.29 m

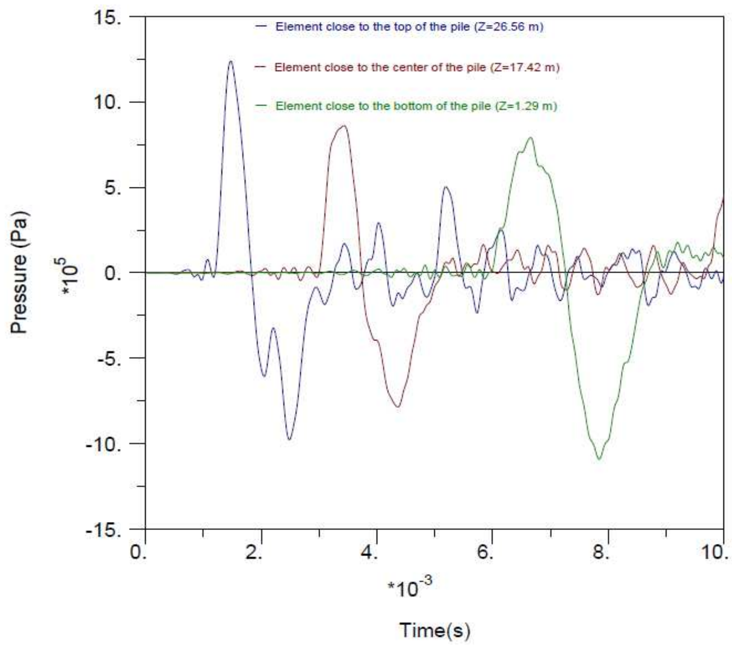

Fig.7 Finite element pressure in a fluid element located at different depths and at a radial distance of 0.45 m

PARAMETRIC STUDY

A parametric analysis of the pile-fluid model is performed. Parameters such as the position of infinite boundary(R_∞), the inclination of the external force (θ) and the diameter of the pile are considered in order to examine their influence on the generated sound field.

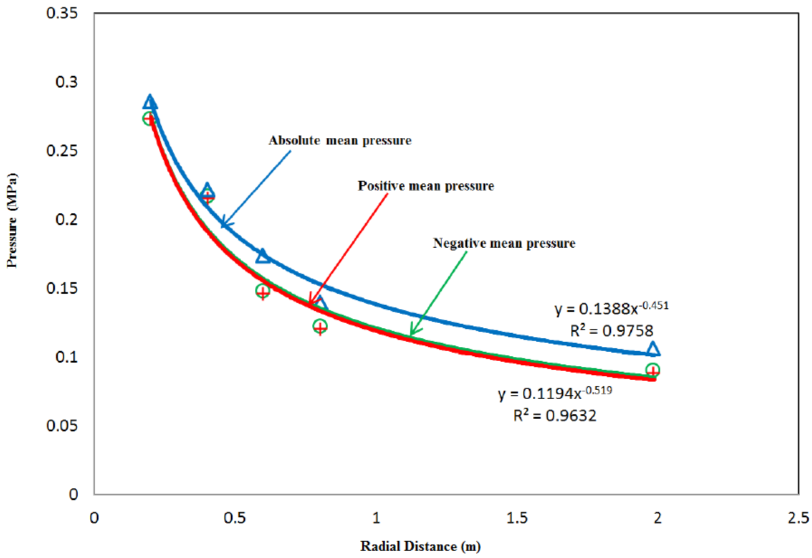

Fig.8 Variation of mean pressure level with radial distance

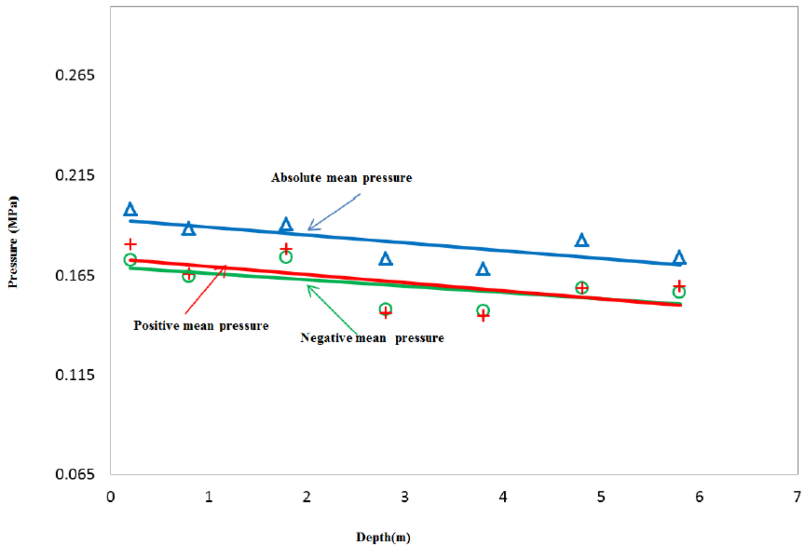

Fig.9 Variation of mean pressure level with depth

Influence of the position of non-reflective boundary

The effect of the position of the non-reflective boundary is examined and the optimum location of the absorbing boundary is found by trial and error until the desired accuracy is achieved within reasonable computational time. The non-reflective boundary is employed in the model in order to truncate the infinite domain and to reduce the computational time. However, the non-reflective boundary available in ADINA software is restricted to waves traveling normal to the boundary, whereas it is observed that wave fronts are formed at an angle of 17^0 to the vertical. In order to set the radius of non-reflective boundary, the R_∞ is increased till the variation in the pressure levels is negligible at the selected elements. The analysis is performed under the assumption that the pile is completely embedded in the fluid. An element is randomly selected at a radial distance of 1.9 m and at the middle depth in order to compare the pressure development for different radii R_∞.The pressure level in the element for different values of R_∞ is shown in Fig. 10. The pressure wave is divided into two zones: **i)** the primary pulse zone and **ii)** the secondary pulse zone.

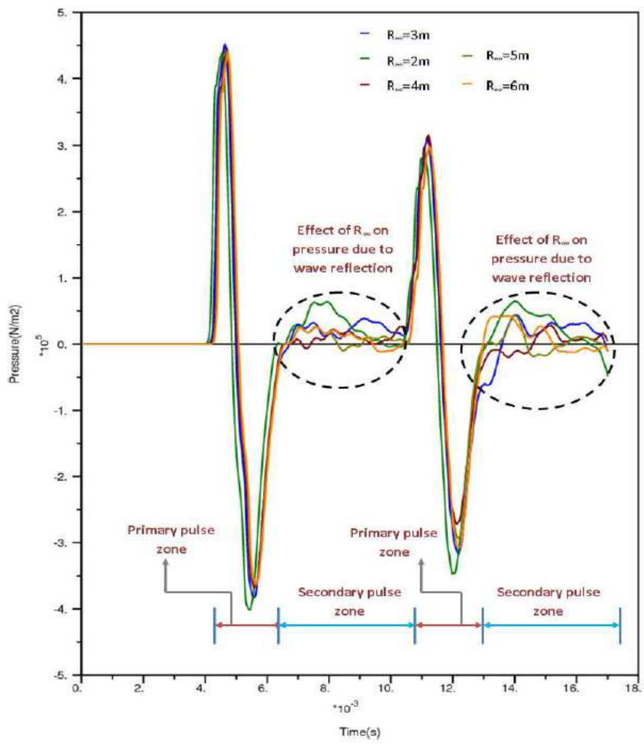

Fig.10 Influence of radius of non-reflective boundary (R_∞) on pressure development

The primary pulse zone represents the pressure development corresponding to main pulse and the secondary zone represents the resulting pressure due to vibrations of the surface of the pile after the passage of main pulse. There are two primary and two secondary pulse zones as shown in Fig. 10. The first zone corresponds to the compressional wave traveling downward at the pile and the second one is due to the reflected wave which is traveling in the opposite direction. In the primary pulse zone the differences in the pressure levels are small compared to the ones obtained in the secondary pulse zone for the different radii R_∞. The pressure levels in the secondary pulse zone are higher for R_∞ =2 m due to the reflection. The reflected energy is reduced due to the geometrical spreading loss as R_∞ increases and hence a reduction in the amplitude of the reflected waves is observed in Fig. 10 for increasing radii R_∞.The results obtained from this analysis clearly show that the position of the infinite boundary should be carefully chosen in order to minimize the reflections from artificial infinite boundaries.

Influence of inclined loading

The application of inclined loading activates the bending modes of the shell. This alters the vibro-acoustic behaviour of the coupled model. The response of the system is analysed for different inclinations of the external loading varying from 0^0 to 10^0 to the vertical. In order to analyse the effects of inclination, the ratio of the maximum pressure at an inclination θ (P_θ) and of the maximum pressure at 0^0 (P_0), i.e. vertical load, are shown for five elements at three radial distances. Plots of P_θ / P_0 against different depths are shown in the Fig. 11. At a radial distance (RD) of 0.44 m and for an inclination of 10^0, the ratio maximises. This is followed by a RD=0.44 m and θ=5^0. For RD=1.24 m and RD=1.96 m, the maximum pressure ratio is very close to unity. Hence, for an increase in the inclination of the applied load, the maximum pressure increases only at the vicinity of the pile surface.

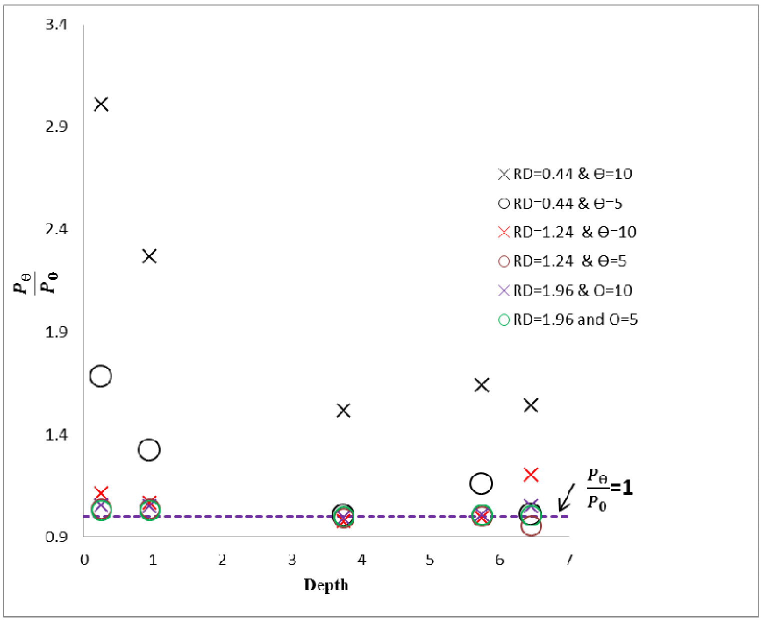

Fig.11 Pressure ratio in selected elements at different inclination of loading

Influence of pile diameter

In this section, the influence of the diameter of the pile on the acoustics is studied using an axisymmetric pile-fluid interaction model. The same load density as discussed previously is applied at the top of the pile. Note that same load density does not imply an equal total force since the increase in the total force is proportional to the increase in the radius of the pile. The radius of the pile is increased from 0.46 m to 1m and a water column of radius equal to 2 m is modelled with fluid elements. A fluid element located at 2m from the central axis of the pile is selected to compare the pressure development for different pile diameters. As shown in Fig. 12, an increase of the radius of the pile from 0.46 m to 0.80 m, results in an increase of the peak pressure of about 1.8. In a similar way an increase of the radius to 1.00 m results in an increase of the peak pressure by a factor of 2.2. Therefore it can be concluded that the increase of the peak pressure is directly proportional to the increase in the radius of the pile. That of course does not imply that the pressure field is identical in the two cases since the oscillations of the pile surface after the passage of the strong compressional front are completely different. In the corresponding figure a phase shift is observed due to reduction in the distance between the selected element and the pile surface.

CONCLUSIONS

In this study, it has been shown that the noise field generated by offshore pile driving can be affected by a large number of parameters. It has been found that the pressure field in the fluid zone varies both with depth and radial distance from the pile surface. A strong correlation is found with respect to the radial distance from the pile surface. The pressures vary inversely proportional to $\sqrt{r}$ in the case of a rigid seabed interface. However, a clear correlation with the depth of fluid zone cannot be established. The effect of the non-reflective boundary is analyzed and discussed in this paper. The position of the non-reflective boundary is obtained by trial and error till the desired accuracy was achieved within practical computational time. The study on the effect of the inclination of the force shows that an increase in the inclination of the load results in an increase of the peak pressures only at the vicinity of the pile surface. The change of the pile diameter shows that although piles of different diameter show different dynamic responses and sound radiation patterns, the increase in the peak pressure is linearly proportional to the increase of the diameter of the pile.

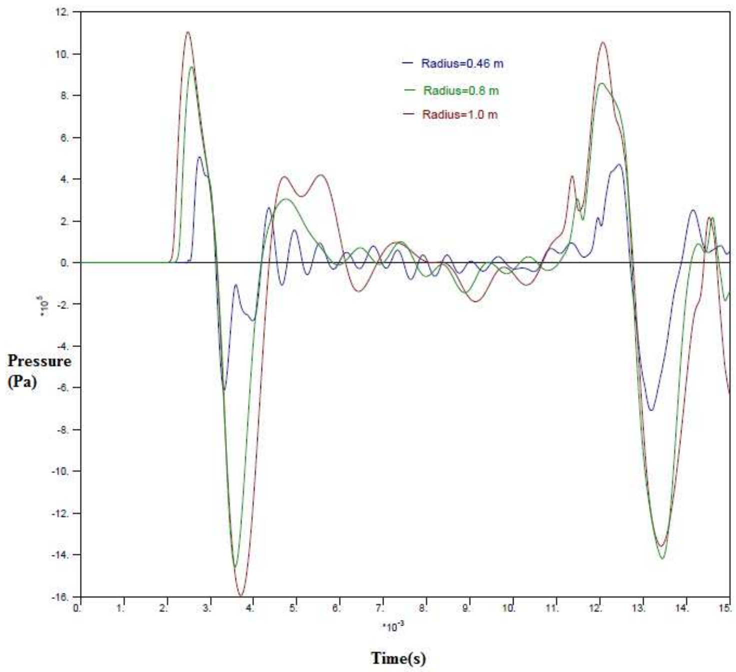

Fig.12 Effect of pile diameter on pressure development in the surrounding fluid medium.

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