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Numerical analysis for underwater noise caused by offshore monopile driving

Analyse numérique du bruit sous - Marin causé par l'entraînement d'un seul pieu en mer

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ABSTRACT: Impact monopile driving in offshore wind industry produces very high sound levels in water. Existed studies for marine pile diving noise always simplify the soil as an acoustic medium, which ignores the influence of shear wave in soil and surface waves along the seawater-soil interface. A numerical model considering the compressibility of water and incorporating soil elastodynamics is built in this paper to study noise generation and propagation during monopile driving. Effects of pile penetration depth into soil, water depth and soil shear modulus on the generated wave field are also obtained.

Résumé: l'entraînement par impact d'un seul pieu dans l'ingénierie éolienne offshore produira un niveau sonore élevé dans l'eau.La plupart des études existantes sur le bruit des pieux marins simplifient le sol en milieu sonore, ignorant l'influence des ondes de cisaillement dans le sol et des ondes de surface de l'interface eau - sol.Dans cet article, un modèle numérique tenant compte de la compressibilité de l'eau et de l'élasticité du sol est établi pour étudier la génération et la propagation du bruit dans le processus d'entraînement d'un seul pieu.Les effets de la profondeur du pieu, de la profondeur de l'eau et du module de cisaillement du sol sur le champ d'onde sont obtenus.

KEYWORDS: Offshore monopile driving; underwater noise; noise generation; noise propagation; numerical model.

1 INTRODUCTION.

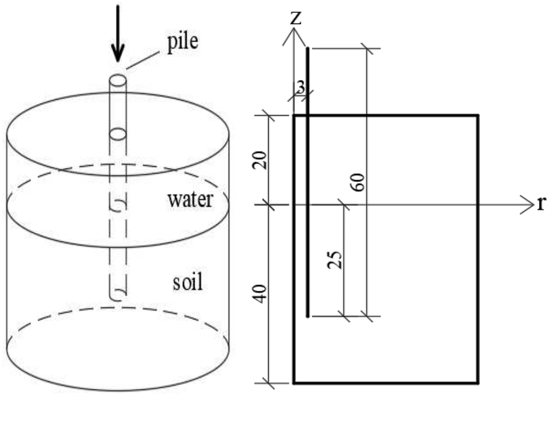
Nowadays, with the increasing scale of the project, monopile foundation is widely used in offshore wind turbine foundation. Its construction has become the main source of noise pollution in offshore environment. The transient impact pulse generated from the pile top during pile driving will make the pile vibrate strongly, and then radiate low-frequency and high-intensity underwater noise to the nearby sea area (Madsen et al. 2006; Slabbekoorn et al. 2010; Jefferson et al. 2009), which will permanently damage the hearing system of fish and marine mammals, and even lead to their death. According to the national and regional laws and regulations on animal protection, animal protection has become a necessary part of marine engineering construction (Southall et al. 2007).

Therefore, many scholars have carried out the numerical simulation of underwater noise generated during pile driving. Numerical models are mainly divided into two categories according to the simplified methods of soil. The first is to simplify soil as an acoustic medium. The generation and propagation of noise and the sound field distribution around the pile was first simulated by finite element analysis (Reinhall & Dahl 2011). It is found that when the pile top is subjected to the transient impact load, the compression wave will generate and propagate downward along the pile in the form of Mach cone. The conical wave front propagates far away in the form of cylindrical wave in water and soil. When the compression wave is reflected from the bottom of the pile, it will produce a reverse Mach cone, and the energy will be attenuated every time. The model used in this study are also adopted by many other scholars through other ways such as FEM and FD (Lippert & Lippert 2012; Zampolli et al. 2012; Lippert et al. 2013; Lippert & Estorff 2014; Nijhof et al. 2014; Gottsche et al. 2015; Wilkes et al. 2016). The second is to simplify the soil as an elastic medium. A semi-analytical model has been established (Tsouvalas & Metrikine 2014; Tsouvalas et al. 2014). It is found that the response of soil is dominated by shear waves with almost vertical polarization, which is really different from that of compression wave in an acoustic medium. In addition, surface waves are generated at the water-soil interface, which propagates forward at a very slow speed comparing with other forms of waves.

In the semi-analytical model described above, the bottom of the pile is placed at the bottom of the soil layer, while in practice, the pile will be driven to any depth of a soil layer. Therefore, in this paper, a numerical model is established. The soil is simplified as an elastic medium and different penetration depths of the pile are set to simulate the wave propagation and distribution more accurately, especially near the bottom of the pile. It can also have a reference value for vertical displacement of the pile during construction. In addition, a parametric analysis is done to study the effects of pile penetration depth, water depth and soil shear modulus on the wave fields. The generated noise levels and sound peak pressure are obtained. Noise propagation along the radical distance far away from the pile is also analyzed.

2 NUMERICAL MODEL

A dynamic axisymmetric numerical model of a monopile being driven into the soil in shallow water is created by using an implicit FE code (Comsol Multiphysics). The monopile is a hollow tubular structure, as shown in Fig. 1 (a), the vertical force acts on the top of pile. The simplified two-dimensional model is shown in Fig. 1 (b), which is composed of water layer and soil layer from top to bottom. The thickness of the soil layer is 40m, and the bottom of the soil layer is set as a fixed boundary. The initial penetration depth of the pile is 25m. In order to avoid the reflection of sound wave on the right boundary, it is set as the radiation boundary of plane wave. The geometrical and material properties of the pile and the surrounding acousto-elastic domain are summarized in Table 1.



(a) (b)

Figure 1. Monopile driving model

Table 1. Material constants and geometrical parameters of the system

Parameter	Value	Unit
R	3	m
L	60	m
h	0.05	m
E	210,000	MPa
v	0.28	-
ρ	7850	kg/m^3
G_s	50	MPa
v_s	0.3	-
ρ_s	1600	kg/m^3
H	20	m
c_f	1500	m/s
ρ_f	1000	kg/m^3

In this model, cylindrical domains of water and soil with radius of 40m are included. The marine sediment is modeled as an elastic continuum. The load applied at the pile head with no inclination to the vertical is shown in Fig. 2. The maximum input force amplitude is 200MPa and the duration of the main pulse is 0.005s. The research time in this paper is 0.1s.

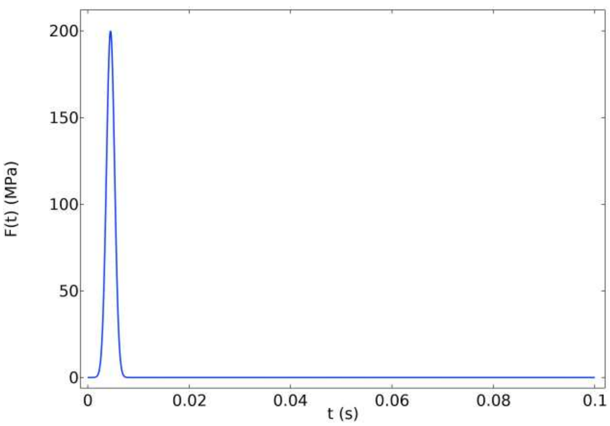


Figure 2. Input force in the time domain

3 WAVE GENERATION AND PROPAGATION

3.1 *Wave generation and propagation*

In Fig. 3, the generated wave field during impact monopile driving is shown at different time spots. The top part (in green-colored background) shows the evolution and propagation of the pressure field in the seawater, whereas the bottom part (in blue-colored background) shows the displacement in the soil continuum. After the transient load is applied on the pile top, the noise propagates downward in the form of Mach cone along the pile in the water area. Due to the change of the medium, a point source diffused in the form of spherical wave is generated at the water-soil interface. When it propagates to the soil, the vertical polarization phenomenon occurs due to the existence of shear waves. In addition, when it arrives at the bottom of the pile, a point source generates and diffuses in the form of spherical wave. Then, the wave propagates forward, and at the same time, the surface waves are produced at the water-soil interface, while its propagating speed is slower than other waves.

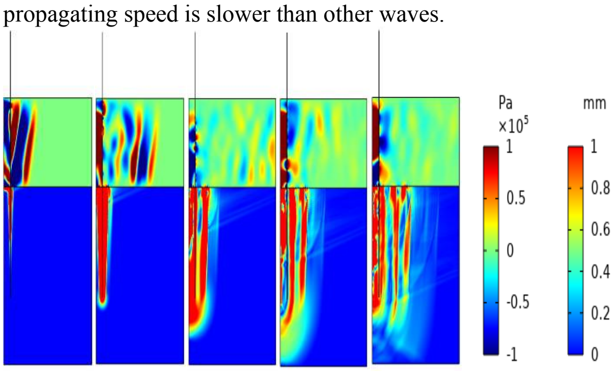


Figure 3. Pressures in the fluid and displacement in the soil. From left to the right, the time spots are given in 10^{-3}s:t=15;25;45;65;95.

3.2 *Noise levels and noise propagation*

3.2.1 *Peak Noise levels*

Sound pressure P is a basic parameter to describe underwater acoustic signal. It is an intuitive scalar of acoustic signal strength, and its unit is Pa. Peak acoustic pressure is the maximum absolute value of the shock signal amplitude, expressed as P_{peak}. Peak acoustic pressure in water area outside the wall is shown in Figure 4. Due to the large variation of sound pressure amplitude, the sound pressure value is expressed in decibels after logarithmic scaling for convenience. The sound pressure level (SPL) is defined as:

$$SPL = 20\, lg \frac{|p(t)|}{p_{ref}}$$

where p_{ref} is reference pressure in water of 1μPa.

Peak noise level can be obtained by substituting the peak acoustic pressure into the above formula. The value together with moments of occurrence and its coordinates corresponding to Fig. 4 are shown in Table 2. As can be seen from the table, the peak noise level is up to 233.2dB. It occurs close to the monopile surface near the water-soil interface at 0.06012s.

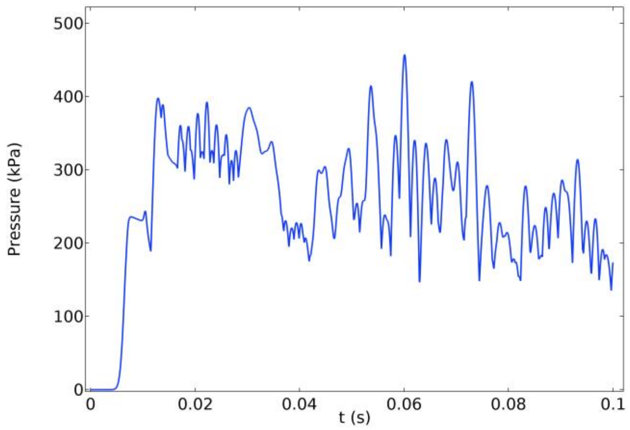


Figure 4. Peak acoustic pressure in water area outside the monopile surface

Table 2. Peak noise level

Peak acoustic pressure	457.1 kPa
Peak noise level	233.2 dB
Moments	0.06012 s
Coordinates	(3.05, 2.65)

3.2.2 *Noise propagation*

Noise propagates horizontally and vertically.In order to capture the changes, twelve fixed points is selected to be studied.

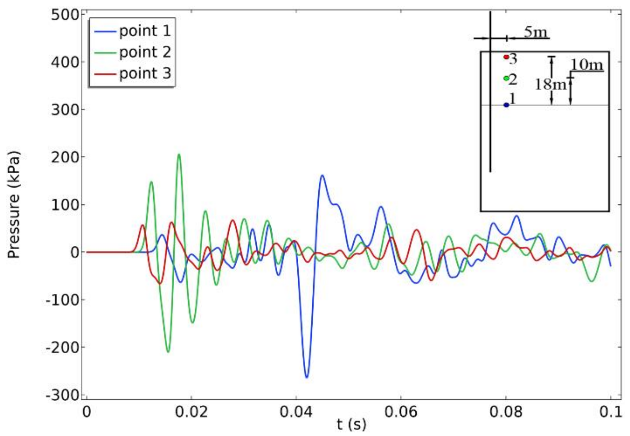


Figure 5. Acoustic pressure at points 5 m away from the monopile surface

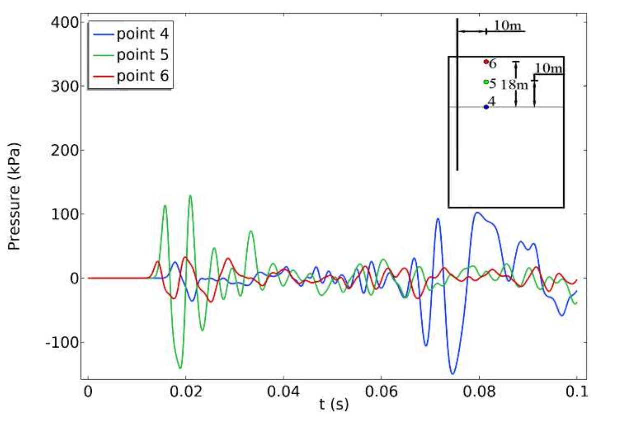


Figure 6. Acoustic pressures at points 10m away from the monopile surface

Table 3. Peak noise level

Point	Peak acoustic pressure(kPa)	Peak noise level(dB)
1	264.3	228.4
2	206.4	226.3
3	67.2	216.5
4	149.7	223.5
5	141.2	223.0
6	37.4	211.4

From figures above, it can be found that at the beginning the Mach waves propagate far away at a certain cone angle, the Mach cone first reaches the shallow position at the same horizontal distance. During this period, acoustic pressure in the middle of the water area is larger. With wave propagating forward and attenuating, acoustic pressure decreases.However, owing to the generation of surface waves, acoustic pressure at the water-soil interface increases greatly subsequently.In addition, peak acoustic pressure decreases with the increasing distance from the water-soil interface.

It can be seen that with the wave propagating downward and forward, peak acoustic pressures of points 7-12 appear in turn. Pressure close to the pile keeps a high value all through the duration. In the middle of water area, the pressure decreases immediately after the waves passing through. While at the water-soil interface, pressure still have an increasing trend owing to the existence of surface waves. From Table 4, we can also find similar results.

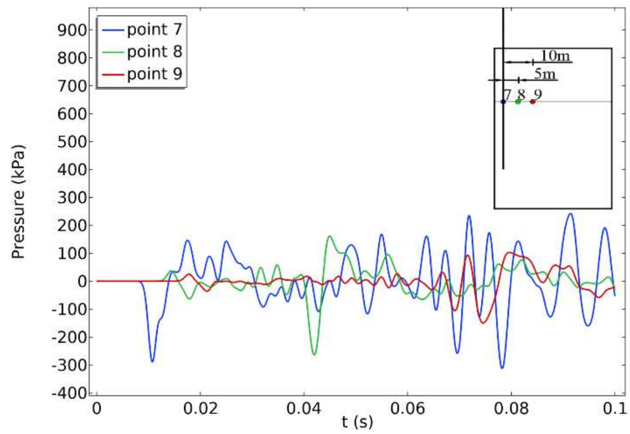


Figure 7. Acoustic pressure at water-soil interface from the monopile surface

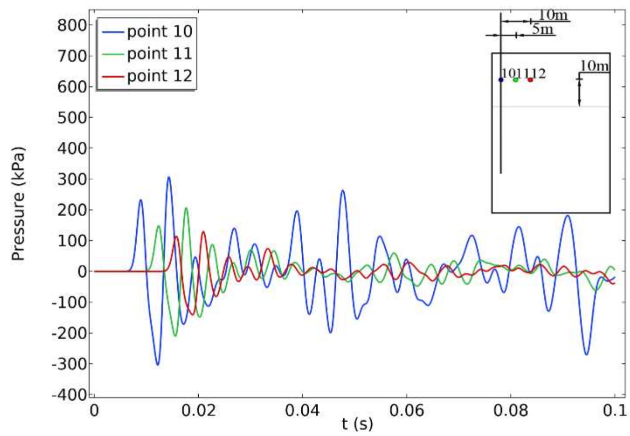


Figure 8. Acoustic pressure 10m above water-soil interface from the monopile surface

Table 4. Peak noise level

Point	Peak acousticpressure(kPa)	Peak noise level(dB)
7	313.0	229.9
8	264.3	228.4
9	149.7	223.5
10	307.0	229.7
11	210.5	226.5
12	141.2	223.0

4 A PARAMETRIC STUDY

4.1 *Pile penetration depth into soil*

4.1.1 *Wave field*

Fig. 9 shows the wave field for the case of pile penetration depth s=10m. Comparing to the results in Fig.3, it can be concluded that with the decrease of pile penetration depth, the sound pressure level in the water area is slightly larger and the angle of wave vertical polarization is smaller. In addition, due to the wave diffraction at the bottom of the pile occurs earlier, the energy of spherical wave generated near the bottom of the pile enhanced significantly.

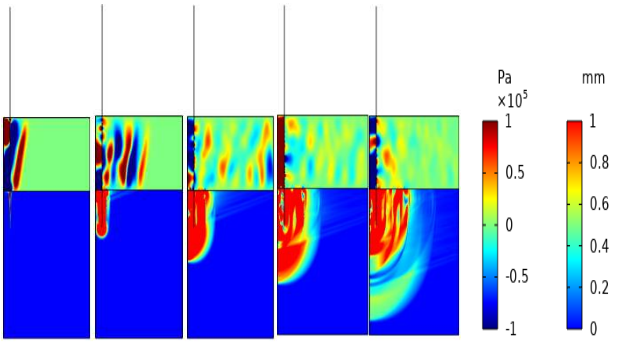


Figure 9. Pressures in the fluid and displacement in the soil for the case of s=10m. From left to the right, the time spots are given in 10^{-3}s:t=15;25;45;65;95.

4.1.2 *Noise levels*

Fig. 10 shows peak acoustic pressure in water area outside the monopile surface. With the change of penetration depth of the pile into soil from 25m to 10m, its peak noise level gets slightly smaller and its moment and position of occurrence are similar. They all occur close to the outer wall of the pile. In terms of three fixed points 5m away from the monopile surface, it can be found that with the decrease of penetration depth of the pile, peak noise level gets larger, with an increasing value within 12.5kPa, and after conversion, about 1.5dB.

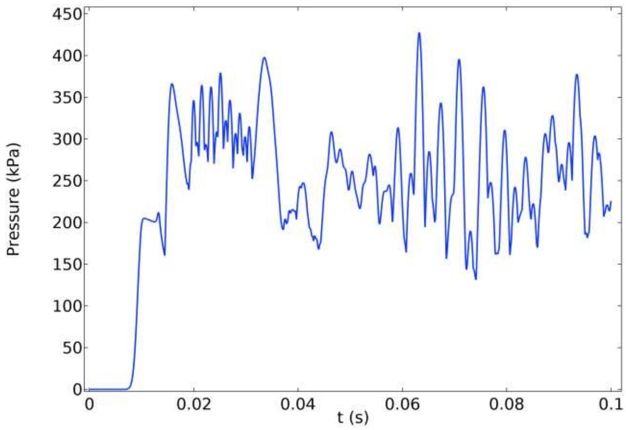


Figure 10. Peak acoustic pressure in water area outside the monopile surface

Table 5. Peak noise level

Peak acoustic pressure	427.5 kPa
Peak noise level	232.6 dB
Moments	0.06325 s
Coordinates	(3.05, 2.65)

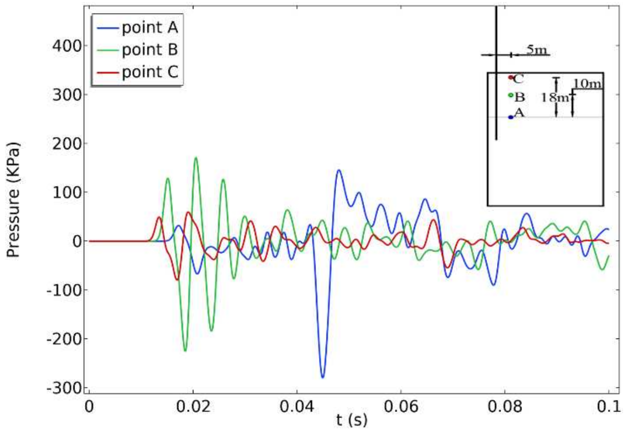


Figure 11. Acoustic pressure at points 5m away from the monopile surface

Table 6. Peak noise level

Point	Peak acoustic pressure(kPa)	Peak noise level(dB)
A	280.0	228.9
B	225.7	227.1
C	79.6	218.0

4.2 *Water depth*

4.2.1 *Wave field*

Fig. 12 shows the wave field for the case of water depth H= 10m Comparing to the results in Fig.3, it can be concluded that for shallower water depth, wave energy in water is more concentrated, which leads to the increase of noise pressure level especially at the water-soil interface near the monopile surface. Moreover, the influence width of Scholte waves increases, and the displacement of soil gets larger. The energy of spherical wave generated by the point source at the bottom of the pile also gets stronger.

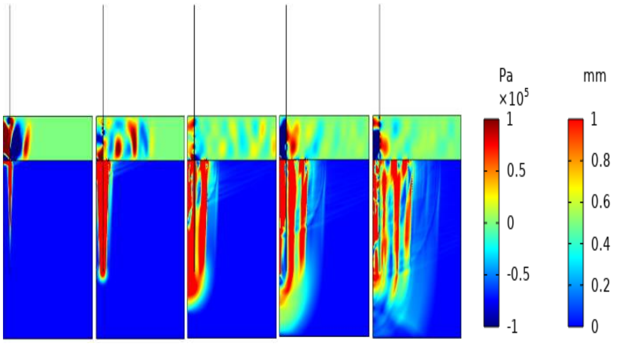


Figure 12. Pressures in the fluid and displacement in the soil for the case of H=10m. From left to the right, the time spots are given in 10^{-3}s:t=15;25;45;65;95.

4.2.2 *Noise levels*

Fig. 13 shows peak acoustic pressure in water area outside the monopile surface. With the change of water depth from 20m to 10m, its peak noise level gets slightly larger. Its position of occurrence is close to water-soil interface. In terms of three fixed points 5m away from the monopile surface, it can be found that with the decrease of water depth, peak noise level gets larger, with an increasing value within 17kPa, and after conversion, about 2dB.

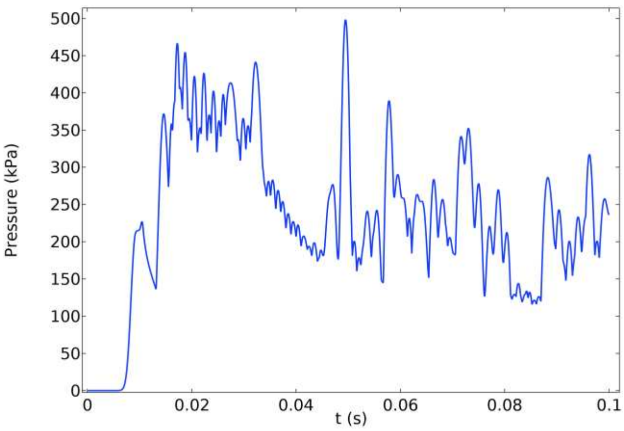


Figure13. Peak acoustic pressure in water area outside the monopile surface

Table 7. Peak noise level

Peak acoustic pressure	498.3kPa
Peak noise level	233.9dB
Moments	0.0495 s
Coordinates	(3.05, 0.10)

Table 8. Peak noise level

Point	Peak acoustic pressure(kPa)	Peak noise level(dB)
D	286.2	229.1
E	208.7	226.4
F	83.9	218.5

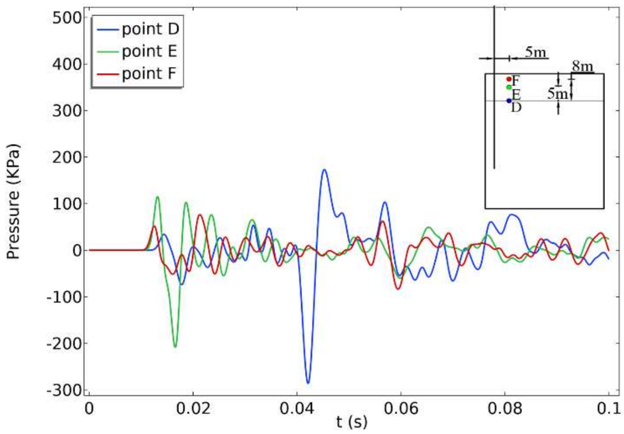


Figure 14. Acoustic pressure at points 5m away from the monopile surface

4.3 *Soil shear modulus*

4.3.1 *Wave field*

Fig. 15 shows the wave field for the case of soil shear modulus G= 200MPa.Comparing to the results in Fig.3, it can be concluded that the larger the shear modulus of soil is, the higher the sound pressure level is. Noise near the water-soil interface is obviously enhanced. Besides, the angle of wave vertical polarization increases and the attenuation of wave energy is faster.

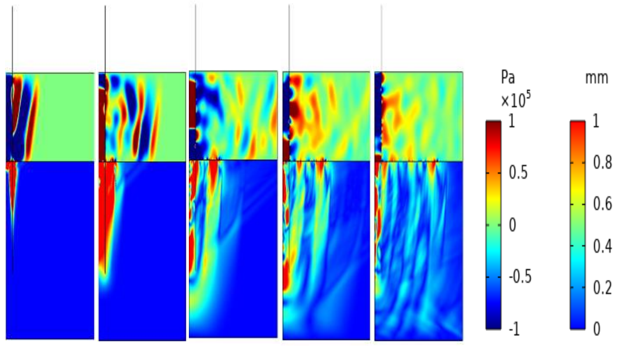


Figure 15. Pressures in the fluid and displacement in the soil for the case of G=200MPa. From left to the right, the time spots are given in 10^{-3}s:t=15;25;45;65;95.

4.3.2 *Noise levels*

Fig. 13 shows peak acoustic pressure in water area outside the monopile surface. With the change of soil shear modulus from 50MPa to 200MPa, its peak acoustic pressure increases by more than 120kPa. Its position of occurrence is close to water-soil interface. In terms of three fixed points 5m away from the monopile surface, it can be found that with the increase of soil shear modulus, point G has an increasing peak acoustic pressure of more than 200kPa comparing to point A and after conversion, it increases by 5 dB.

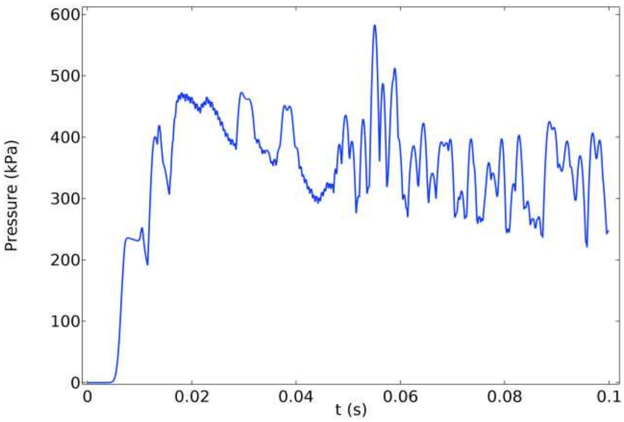


Figure 16. Peak acoustic pressure in water area outside the monopile surface

Table 9. Peak noise level

Peak acoustic pressure	583.1kPa
Peak noise level	235.3dB
Moments	0.0551 s
Coordinates	(3.05, 5.94)

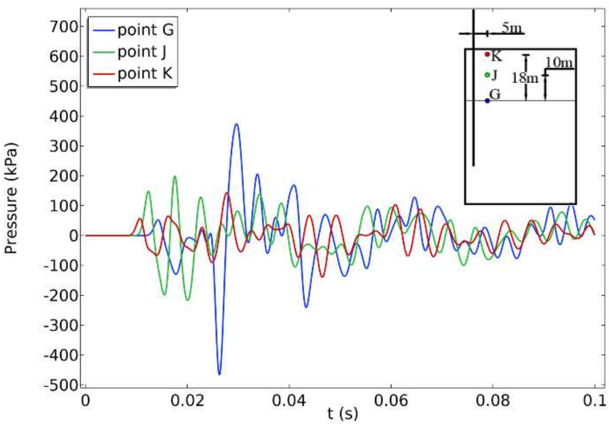


Figure 17. Acoustic pressure at points 5m away from the monopile surface

Table10. Peak noise level

Point	Peak acoustic pressure(kPa)	Peak noise level(dB)
G	466.8	233.4
J	217.1	226.7
K	143.7	223.1

5 CONCLUSIONS

In this paper, a numerical model of a monopile being driven into the soil in shallow water is created to analyze the noise generation and propagation. The results shows that when the soil is simplified as an elastic continuum, vertical polarization in soil will occur because of the existence of shear waves. Also, surface waves propagate along the water-soil interface with a much slower speed compared to other waves. Energy localized near the water-soil interface is strong and it has a less attenuation. At the water-soil interface and the bottom of the pile, it will produce a point source, which diffuses in the form of spherical wave front. Horizontal and vertical noise propagation is analyzed. Noise level at water-soil interface is higher owing to surfaces waves. With wave propagating forward, energy will attenuate gradually. Next, a parametric study is conducted where effects of pile penetration depth, water depth and soil shear modulus are analyzed. It can be concluded that noise pressure level in water and displacement in soil increase with the decrease of pile penetration depth and water depth. Besides, noise pressure level in water increases with soil shear modulus.

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