Numerical simulation on the noise reduction of underwater pile-driving using a bubble curtain

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Abstract. Aiming at the problem of heavy noise pollution caused by underwater piling operation and, to protect the marine ecosystem near the construction site, this paper discusses the attenuation effect of bubble curtain system on underwater noise generated by piling operations, basing on the previous research on underwater bubble sound attenuation and the attenuation characteristics of sound propagation of different media. Using COMSOL Multiphysics finite element analysis software, the noise field of underwater piling and the model of underwater bubble curtain are established to study the influence of the bubble curtain on the pressure peak values at different depths generated by the same noise source, and the attenuation effect of the bubble curtain on underwater noise is discussed. The results show that the peak sound pressure level of underwater noise can be attenuated by about 8 dB using the bubble curtain.

1. Introduction

The ocean covers 71% of the earth's surface. With the progress of science and technology, the number of deep-sea operations and scientific research projects has been increasing. For example, in the process of the installation and fixation of offshore wind farm jackets, noise generated from piling can cause damage to the auditory system of marine mammals such as white dolphins. In order to reduce the impact of piling construction noise, methods like bubble curtain noise reduction, isolation casing noise reduction, cofferdam noise reduction and underwater acoustic damper are usually used. Compared with other methods, the research on the principles, design, use and effects of bubble curtain is more abundant and widely used.

The bubble curtain technology was first proposed by the engineer Adolph [1], and used in the underwater blasting construction of Canada's Ordario hydropower station. Later, Brasher [2] using the attenuation effect of bubbles on waves, applied the bubble curtain technology to wave attenuation of breakwater. Strietman [3] prevented sound waves from propagating in water using the reflection and absorption of sound by the gas-liquid two-phase flow curtain formed by jet flow in water. Bubbles generated due to different factors in the ocean are an important part of ocean acoustics. A large number of studies have proved that underwater bubbles can absorb and scatter sound waves. Reasonable use of bubbles in the ocean can greatly reduce the underwater noise. With the bubble curtain system, an underwater pipeline system is arranged around the construction area, and the air compressor leads the air into the pipeline. The bubbles rising from the opening of the pipeline form a relatively thick gas-
liquid two-phase flow. Due to different air and water densities, the bubble curtain produces high damping losses and scattering in the noise transmission, and brings the noise out of the water surface. According to the practical experience, the noise of offshore piling is about 160-200dB, which can be reduced by 8dB-10dB [4] with the bubble curtain, which can protect the marine ecological environment.

Based on this background, this paper will use the finite element analysis method to simulate the underwater noise field during pile-driving. First, the underwater pile-driving model is established to calculate the sound field within 30m from the noise source, and then the underwater bubble curtain model is established to compare the changes of the peak sound pressure in different depths before and after the bubble curtain, so as to provide references for the practical application of underwater bubble curtain.

2. Description of the model and working condition

When LNG receiving terminal is being built on the sea, pile driving is needed in the process of steel jacket installation and fixation. The process of pile driving is a complex nonlinear dynamic engineering. When the impulse force acts on the pile, it will produce great noise instantly. In order to study the acoustic radiation caused by the action of pile hammer on the pile, this paper takes a single pile as an example to establish a pile-driving model and a bubble curtain model.

2.1. Modelling pile-driving

The finite element analysis method is used to model the typical foundation pile [5] and its surrounding media. The average water depth of the construction site is 16m. Because the pile body and surrounding media of the pile driving model are axisymmetric. The three-dimensional model can be simplified to two-dimensional axisymmetric model, as shown in Fig.1 (a). The axis of symmetry of the hollow tubular structure pile is taken as the symmetry axis of the two-dimensional model, that is, \( r = 0 \). The acoustic medium model around the pile is composed of the air layer, water layer and sand layer from the top to the bottom. The variation of the total sound pressure field within 30m from the noise source is studied. The boundary condition is set as a perfectly matched layer. The specific parameter values of the pile and surrounding medium are shown in Table 1.

| Parameter | Value | Unit | Note |
|-----------|-------|------|------|
| D         | 6.5   | m    | Pile diameter |
| H         | 73.5  | m    | Pile height   |
| d         | 65    | mm   | Wall thickness |
| z         | 16    | m    | Depth of water |
| \( \rho_w \) | 1000 | kg/m³ | Water density |
| \( c_w \) | 1485 | m/s  | Sound velocity in water |
| t         | 30    | m    | Sand thickness |
| \( \rho_s \) | 1900 | Kg/m³ | Sand density |
| \( c_s \) | 1625 | m/s  | Sound velocity in sand |
| \( \rho_a \) | 1.293 | Kg/m³ | Air density |
| \( c_a \) | 343   | m/s  | Sound velocity in air |
| \( c_p \) | 5900  | m/s  | Pressure wave velocity |
| \( c_t \) | 3230  | m/s  | Shear wave velocity |
Assuming that the impact force of the pile hammer is perpendicular to the pile, the time-dependent spectrum of the impact force [6] is shown in Fig.2. In order to analyze the wavelength, the whole model is meshed. About 708000 elements are used to discretize the solution domain, and the mesh generation is shown in Fig.3. The transient solver of acoustic structure interaction is used, calculated the variation of sound using 0.1ms the time step within 0.04s.
2.2. Modelling bubble curtain

Underwater noise propagation is usually divided into two types. One is the underwater noise propagation in deep water and, the other is that in shallow water. Shallow water generally means that the water depth is less than 100m. Most piling projects, only require shallow water operations. The water depth of this model is \( Z = 16 \text{m} \), which accords with the condition of shallow water noise propagation.

When the incident sound wave in the form of plane wave reaches the bubble surface, the bubble will vibrate and radiate the secondary sound wave in the form of spherical waves, which is called the acoustic scattering phenomenon. When the frequency of the incident sound wave is close to the resonance frequency of the bubble, the resonance phenomenon will occur between the incident sound wave and the bubble, and the bubble resonance will convert a large amount of incident sound energy into a higher harmonic energy and other energies. Moreover, the sound velocity of the incident sound wave is greatly reduced, and the equivalent elastic coefficient of the water body with bubbles is also reduced. The incident sound wave is greatly attenuated, which is what we call the sound absorption phenomenon.

The incident acoustic wave length is longer than the bubble radius and the amplitude of the acoustic wave is very small, so the bubble curtain is simulated as a uniform layer with effective acoustic characteristics \([7]\). The bubble curtain model adopted in this paper is based on the effective compressibility method, and the existing formula is modified accordingly. The medium density is determined by calculating the volume fraction of bubbles in the liquid (formula 1), and the sound velocity is determined by calculating the change of compressibility \([8]\) (formula 2). According to the compressibility of a single bubble, the total bubble volume is integrated without considering the interaction between bubbles. Assuming that there are \( N \) equally sized bubbles in the bubble curtain, the effective compressibility \( K_e \) and mixture density \( \rho_e \) are defined as

\[
K_e = (1 - V_a)K_w + \Delta K
\]

\[
\rho_e = (1 - V_a)\rho_w + V_a\rho_a
\]

Where \( V_a \) is the volume fraction of air and \( K_w \) is the compressibility coefficient of water

\[
K_w = \frac{1}{c_w^2 \rho_w}
\]

Where \( c_w \) is the sound velocity in water, \( \rho_w \) is the density of water, and the values are shown in Table 1. For the bubble curtain with \( N \) constant radius \( \alpha \), the change of effective compressibility caused by the existence of bubbles can be expressed as

\[
\Delta K = \frac{1}{\rho_w \pi f^2} \frac{\alpha N}{((\frac{f}{f^*)}^2 - 1 + i\zeta)}
\]

\( f^* \) is the bubble resonance frequency (formula 5), \( \zeta \) is the damping coefficient (formula 6), and its value is taken from Hall's \([9]\) research results.

\[
f^* = \frac{3.25 \times 10^6}{\alpha} \sqrt{\frac{z}{1 + \frac{z}{10}}}
\]

\[
\zeta = \zeta_t + \zeta_v + \zeta_f
\]
\( \zeta_r \) is the damping due to re-radiation, \( \zeta_s \) is due to shear viscosity and \( \zeta_t \) is due to thermal conductivity. The velocity of sound in the bubble curtain is

\[
c_s = \sqrt{(K/\rho)}
\]  

(7)

In this model, the volume fraction of bubbles \( V_v = 1\% \), and the typical radius of bubbles \( \alpha = 1\) mm. The acoustic characteristic parameters of the bubble curtain are as follow: the density \( \rho_v = 990\) kg/m\(^3\), the sound velocity \( c_s = 218\) m/s. The bubble curtain with the thickness of \( d = 1 \) m is set at the distance of \( r = 10 \) m from the noise source, as is shown in Fig.1 (b).

3. Results and analysis

According to the pile driving model and underwater bubble curtain model, this paper discusses the total sound pressure field at several typical time points, and analyzes in the time domain and the frequency domain the total sound pressure values at different depths at the same distance from the noise source, so as to explore the propagation law of pile driving noise field and the noise reduction effect of the bubble curtain.

3.1. The total sound pressure field

In this paper, the pictures of the total sound pressure field at five different times are obtained, and the attenuation effect of the bubble curtain on sound wave is discussed.

Figure 4. Sound pressure field without bubble curtain

Figure 5. Sound pressure field with bubble curtain
When t = 0.0101s, the compression wave generated by the pile hammer force propagates downward in the pile, and the sound wave reaches the water sand interface. Due to the impedance difference between the two media, the sound wave is reflected upward in the form of conical Mach wave and penetrates into the water, and the Mach angle formed by it is \( \varphi_m = \sin^{-1}(c_s/c_p) \). At this time, the sound wave does not propagate to the bubble curtain, so the bubble curtain does not affect the sound wave propagation. When t = 0.0151s, the sound wave continues to propagate downward, and the top of the Mach cone angle reaches the bottom of the pile to form a point sound source, creating a new Mach cone angle \( \varphi_m = \sin^{-1}(c_s/c_p) \). Then the point source moves upward along the pile. At this moment, the sound wave propagates to the front of the bubble curtain \( r = 10m \), and the bubble curtain blocks part of the direct sound wave in the water and the reflected sound wave from the sediment. According to what is shown in Fig. 4(b) and Fig. 5(b), the sound field has obvious changed. When t = 0.0199s, due to the absorption and reflection of the bubble curtain of the sound wave, Fig. 4(c) and Fig. 5(c) can be compared. In front of the bubble curtain, that is, in the region of \( r < 10m \), the sound pressure in Fig. 5 is significantly higher than that in Fig. 4 which is caused by the reflection of the bubble curtain on the sound wave. Behind the bubble curtain, that is, in the region of \( r > 10m \), the bubble curtain slows down the propagation of sound wave, and causes the time lag of the peak sound pressure. When t = 0.0253s, the Mach cone wave keeps the same angle against the pile and continues to propagate forward. It continuously reflects at the interface of the medium. Because the model medium with the bubble curtain device is more complex, the reflection times are more than that without bubble curtain, but it can be clearly observed that the sound pressure field in the region \( r > 10m \) in Fig. 5(d) is obviously weaker than that in Fig. 4(d). When t = 0.0369, the acoustic wave continues to propagate further, and the energy of Mach cone wave gradually weakens, which is close to the energy of reflected acoustic waves. The perfectly matched layer boundary condition in the model blocks the reflection of acoustic waves. Compared with Fig. 4(e) and Fig. 5(e), the total underwater sound pressure field of the model with bubble curtain is significantly reduced. Therefore, by comparing and analyzing the distribution of the total sound pressure field at different times, it is found that the bubble curtain can block part of the propagation of sound waves, and can make the sound waves reflect many times in different media, which has attenuative effects on the noise.

3.2. Time domain analysis

Three points near the seabed (\( z = 1m \)), the middle of the water depth (\( z = 8m \)) and near the sea level (\( z = 15m \)) are chosen respectively to observe the change of the peak sound pressure before and after noise reduction. In Fig. 6(a), when \( z = 1m \), the peak value of sound pressure appears at \( t = 0.0335s \), which is \( |P_{(z=1)}| = 7.8 \times 10^4 \) Pa. When \( z = 8m \), the peak value of sound pressure appears at \( t = 0.0322s \), which is \( |P_{(z=8)}| = 1.4 \times 10^5 \) Pa. when \( z = 15m \), the peak value of sound pressure appears at \( t = 0.0194s \), which is \( |P_{(z=15)}| = 2.25 \times 10^5 \) Pa. In Fig. 6(b), when \( z = 1m \), the peak value of sound pressure appears at \( t = 0.0194s \), which is \( |P_{(z=1)}| = 2.25 \times 10^5 \) Pa. When \( z = 8m \), the peak value of sound pressure appears at \( t = 0.0372s \), which is about \( |P_{(z=8)}| = 5.5 \times 10^4 \) Pa. When \( z = 15m \), the first peak value of sound pressure appears at \( t = 0.0231s \), which is about \( |P_{(z=15)}| = 8.5 \times 10^4 \) Pa.

By comparing the two groups of data, it is found that: under the parameter setting in this paper, the existence of the bubble curtain causes time lag of milliseconds in the appearance of the peak sound pressure. It is because when the sound wave propagates in different media, the scattering effect of bubble curtain on the sound wave accelerates its energy loss, and it takes longer to achieve energy accumulation to reach the peak value at the same point. The existence of the bubble curtain makes the peak value of the sound pressure decrease notably, which is due to the reflection effect of the bubble curtain on the sound wave. The effect blocks part of the sound wave propagation and reflects the sound wave to the area in front of the bubble curtain.
3.3. Frequency domain analysis

In order to analyze the frequency-domain distribution of the piling noise field and the noise reduction effect of the bubble curtain in different frequency domains, the MATLAB software is used to create a program, and the time-domain signal obtained by the transient solver is transformed into a frequency-domain signal through Fourier transform, as is shown in Fig. 7.

![Figure 6. Time domain sound pressure (a) without bubble curtain (b) with bubble curtain](image)

![Figure 7. Frequency domain sound pressure (a) without bubble curtain (b) with bubble curtain](image)

It can be seen from Fig. 7 that at the peak sound pressure of piling noise is concentrated in the range of 0-1000Hz, which belongs to medium-and-low frequency noise. This is consistent with the conclusion of other studies[10]. In order to analyze the noise reduction effect of the bubble curtain in different frequency bands, the signal in the 0-1000Hz frequency band is amplified, and the change of the peak sound pressure with and without bubble curtain are compared, as is shown in Fig. 8. When \( z = 1 \) m, the peak sound pressure is \( 0.425 \times 10^4 \) Pa without bubble curtain and \( 0.175 \times 10^4 \) Pa with it. When \( z = 8 \) m, the peak sound pressure is \( 1.75 \times 10^4 \) Pa without the bubble curtain and \( 0.7 \times 10^4 \) Pa with it. When \( z = 15 \) m, the peak sound pressure is \( 3.5 \times 10^4 \) Pa without the bubble curtain and \( 1.75 \times 10^4 \) Pa with it.
3.4. Peak sound pressure level

In order to see the noise reduction effect of underwater bubble curtain intuitively, the peak sound pressure level $SPL$ is used to describe the piling noise. The performance of the sound pressure in the sampling data of pile driving noise is the amplitude value of the waveform generated by a single impact, and the peak sound pressure is the maximum absolute value of the impact signal amplitude. The peak sound pressure level in time domain is listed in Table 2, and the peak sound pressure level in frequency domain is listed in Table 3.

$$SPL = 20 \log \left( \frac{|P(t)|}{P_{ref}} \right)$$

(8)

$P_{ref} = 1 \mu Pa$ is the reference sound pressure of water.

| Table 2. Time domain sound pressure level |
|------------------------------------------|
| SPL (dB) | 1m       | 8m        | 15m       |
|----------|----------|-----------|-----------|
| Bubble curtain OFF | 218.12   | 223.08    | 227.22    |
| Bubble curtain ON | 210.77   | 214.87    | 218.55    |
| Attenuation    | 7.35     | 8.11      | 8.61      |
Table 3. Frequency domain sound pressure level

|                   | SPL (dB) | 1m    | 8m    | 15m   |
|-------------------|----------|-------|-------|-------|
| Bubble curtain OFF| 192.55   | 204.86| 211.01|       |
| Bubble curtain ON | 185.34   | 196.90| 204.86|       |
| Attenuation       | 7.21     | 7.96  | 6.14  |       |

By comparing the time-domain sound pressure level with the frequency-domain sound pressure level, it can be proved that the bubble curtain has attenuation effect on underwater piling noises. Throughout the whole time of calculation, the noise can be attenuated by about 8dB in total, and the noise in the middle-and-low frequency band (0-1000Hz) can be attenuated by about 7dB.

4. Conclusion

In this paper, on the basis of the finite element analysis method, the noise field model of underwater piling and the underwater bubble curtain model are established. With a single large pile with the working water depth of 16m, the height of 73.5m and the diameter of 6.5m as the example, the variation of the total sound pressure within 0.04s from the piling noise source r=30m is studied. The results show that when the impulse force acts on the top of the pile, the compression wave will be generated in the pile and propagate downward at a certain Mach cone angle. When the Mach wave reaches the bottom of the sediment, it will reflect upward at a certain angle. In the process of propagation, it will be reflected many times when passing through the interface of different media, and its wave front will diffuse in the form of spherical wave.

In order to reduce the underwater noise and protect the marine ecological environment, the acoustic parameters of the bubble curtain are obtained basing on the effective compressibility method, and the bubble curtain model is established. When there is a bubble curtain, the sound wave will scatter at which makes the peak sound pressure lag for several milliseconds. Because of the reflection effect of the bubble curtain on the sound wave, it can block part of the sound wave propagation, and the peak value of sound pressure decrease. According to the parameters set in this paper, a bubble curtain with a thickness of 1m is placed 10m away from the noise source. The peak sound pressure level of the measuring point at 20m away from the noise source attenuates about 8dB in time-domain and about 7dB in frequency-domain (0-1000Hz). On the whole, this paper studies the noise reduction effect of the underwater bubble curtain, in order to provide references for the practical application in engineering to protect the marine ecological environment.

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