THE STABILITY OF THE PIPELINE LAID ON A PORO-ELASTIC SEABED

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ABSTRACT
The dynamic response of buried submarine pipeline subjected to wave must be take into account in the design. In this paper the two-dimensional finite element model has been established, the poro-elastic model has been adopted, the deformation and force condition of pipeline have been calculated under the load gravity and the combined load of weight and harmonic wave force respectively. The key issue is to simulate the interaction among flow, pipe and soil. The factors such as seabed thickness, water depth, pipe’s diameter, elastic modulus, wave period and permeability coefficient have been considered. The numerical results show that pipe’s weights, horizontal load, pipe’s diameter, water depth, elastic modulus have an important effect, but seabed thickness, wave period have little effect. The research results can provide scientific gist for the pipeline’s design.

Key words: wave loading, seabed pipeline, pipe and soil interaction, numerical analysis.

1. INTRODUCTION
Because of the ever increasing engineering activities in offshore and coastal regions, phenomena such as wave attenuation caused by percolation in seabed, seafloor instability, and wave induced soil response around submarine structures have attracted the attention from coastal and marine geotechnical engineers. Particularly, since inadequate design of marine structures and foundations can lead to costly failures such as jacking and floatation of pipeline, it is necessary to improve our knowledge on the interaction among wave, seabed and submarine structures. In general, the fluctuations of wave pressure at the surface of the seabed exert excess pore pressures and effective stresses, which have been recognized as dominant factors in analysing the instability of a seabed. Once the seabed under the pipeline becomes “unstable”, the instability of the pipeline can occur. It has also been reported that the soil supporting the pipeline may fail due to the liquefaction of the seabed, resulting in the self-burial of the entire pipeline(Bijker and Leeuwenstein[3], 1984; Sumer and Fredsoe[2], 1997);this is the reason of causing the instability of the pipeline, but another reason is that the lateral resistance of pipes on seabed can not offset against the horizontal component of the hydrodynamic force, pipe breakout occurs.

Although the importance of the wave-soil-structure interaction phenomenon has been addressed in the literature, most previous investigations have only concerned with the soil response owing to two-dimensional progressive wave or three-dimensional short-crested waves(Jeng[43],1997). Only few investigations have been carried out for the wave-soil-pipe interaction problem in recent years(Mei and Foda[44],1981). However, their research only considered the seabed response under the pipeline; Jeng[44] et al(1998) carried out the seabed response around a pipe laid on the seabed, in their research, soil permeability and shear modulus varied with the seabed depth, however, they couldn’t consider the contact surface between the pipe and seabed and didn’t describe the behavior of the pipeline on the seabed.

Gao fuping[6] has proposed an improved analysis method for the on-bottom stability of a submarine pipeline which is based on the relationship between Um/gD 0.5 and Ws/D2. The proposed analysis method may provide a helpful tool for the engineering practice of pipeline on-bottom stability design. Gao fuping[7] has employed a hydrodynamic loading method in a flow flume for simulating ocean currents induced submarine pipeline stability on a sandy seabed. The pipeline stability in currents is compared with that in waves, which indicates that the pipeline laid directly upon the sandy seabed is more laterally stable in currents than in waves.

Liu Jing[8] has simulated the interaction among flow, pipe and soil. The factors such as contact effect, frictional coefficient between pipe and soil, buried depth, pipe radius. Based on the numerical results the vertical displacement and hoop stress should are underestimated dramatically without considering the contact effect in the case of smaller buried depth. Meanwhile, porous water pressure in coarse sand attenuates slower than that in fine sand, so pipe embedded in fine sand is more stable and safer than that in coarse sand.

The object of the paper is to describe the movement behavior of the pipeline on the seabed by means of the contact surface prescribed in the general program ABAQUS. A two-dimensional finite element model has been established. Based on the model, the mechanism of the wave-induced seabed response in the vicinity of a pipeline and the behavior of the pipeline has been discussed in detail.
2. THE ESTABLISHMENT OF THE FINITE MODEL

In this study, we consider a soil column of a finite thickness (h) beneath a pipeline (with a radius R), as depicted in fig. 1.

In this study, the wave crests are assumed to propagate in the positive x-direction, the seabed is simulated by the poro-elastic model, and the pipe is considered to be fully elastic. The rectangular elements with 8 nodes and 232 elements will be used to model the pipe. The coupled pore pressure elements with 4 nodes and 2680 elements will be used to model the seabed.

The finite element model is as follows:

3. BOUNDARY VALUE PROBLEM

3.1. Governing equations

In this study, the seabed is modelled by a poro-elastic theory. The consolidation equation (Biot, 1941), extending from Terzaghi's theory, is generally accepted as the governing equation for flow of a compressible pore fluid in a compressible porous medium.

The consolidation equation is:

\[ \nabla^2 p - \gamma_w n' \beta \frac{\partial p}{\partial t} = -\gamma_w \frac{\partial \varepsilon}{\partial t} \]

In which: \( \gamma_w \) is water density, \( n' \) is porosity of soil, \( p \) is pore pressure, \( t \) is time, volumetric strain of the soil and porosity is as follows:

\[ \beta = \frac{1}{K_w} + \frac{1 - S}{P_{oc}} \quad \varepsilon = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \]

The soil skeleton is assumed to be ideal and isotropic, The equation is as follows under the plane strain:
\[\sigma_x' = 2G\left(\frac{\partial u}{\partial x} + \frac{u}{1-2u}\right)\]
\[\sigma_y' = 2G\left(\frac{\partial v}{\partial y} + \frac{u}{1-2u}\right)\]
\[\tau_{xy} = G\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) = \tau_{yx}\]
\[\varepsilon_x = \frac{\partial u}{\partial x} = -\frac{1-v^2}{E} (\sigma_x - \frac{\nu}{1-\nu} \sigma_x)\]
\[\varepsilon_z = \frac{\partial w}{\partial x} = -\frac{1-v^2}{E} (\sigma_z - \frac{\nu}{1-\nu} \sigma_z)\]

The body force is ignored, so the equilibrium equation has changed to be:
\[
\begin{align*}
\frac{\partial \sigma_x'}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} &= -\frac{\partial p}{\partial x}, \\
\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y'}{\partial y} &= -\frac{\partial p}{\partial y}, \\
GV^2 u + \frac{G}{1-2u} \frac{\partial \varepsilon}{\partial x} &= -\frac{\partial p}{\partial x}, \\
GV^2 v + \frac{G}{1-2u} \frac{\partial \varepsilon}{\partial y} &= -\frac{\partial p}{\partial y}.
\end{align*}
\]

3.2. Boundary Conditions
3.2.1. Defining the Displacement boundary conditions
The displacement of the bottom is zero, and there is no normal flow.
\[u = w = \frac{\partial p}{\partial Z} = 0, \quad y = -h\]

3.2.2. Defining the force boundary conditions
The dynamic pore pressure \(P\) has been produced because of the wave loadings, the expression is:
\[p(x,0,t) = p_0 \cos(kx - \omega t)\]
\[p_0 = \frac{\gamma_H}{2} \cosh kd\]

The dynamic pressure \(P\) is Harmonic oscillation, the \(p_0\) is the amplitude. The direction of force is positive at the wave crest, negative at the trough of wave. The stress and pore water pressure are produced because of the dynamic wave loadings. The strong dynamic water pressure can produce and accumulate superpore pressure from the medium dense soil to loose soil.

The effective stress and tangent stress disappear to zero at the seabed.
\[\sigma_y' = \tau_{xy} = 0, \quad p(x,0,t) = p_0 \cos(kx - \omega t) \text{ when } y = 0,\]

The wave pressure of the surface of the seabed is:
\[p_0 = \frac{\gamma_H}{2} \cosh kd\]

In which: \(d\) - water depth.
\(H\) - wave height
\(k\) - wave number, \(k = \frac{2\pi}{l}\)
\(\omega\) - angular speed, \(\omega = \frac{2\pi}{T}\)

Because of the pipeline’s existence, the wave will produce the turbulence. The wave force has been computed according to the Morsion Equation, the horizontal force will be imposed on the left of the pipeline, the lift force will be imposed on the bottom of the pipeline.
4. NUMERICAL RESULTS

4.1. Parameters needed

Some parameters needed are as follows:

<table>
<thead>
<tr>
<th>Table1 Parameters</th>
<th>Wave parameters</th>
<th>Soil parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wave period</td>
<td>Soil thickness</td>
</tr>
<tr>
<td></td>
<td>10.0 (s), 15.0 (s)</td>
<td>0.975-1.0</td>
</tr>
<tr>
<td></td>
<td>Water depth</td>
<td>Degree of saturation</td>
</tr>
<tr>
<td></td>
<td>20m</td>
<td>0.975-1.0</td>
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<tr>
<td></td>
<td>Wave length</td>
<td>Soil’s porosity</td>
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<tr>
<td></td>
<td>Wave height</td>
<td>Possion’s ratio</td>
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<tr>
<td></td>
<td>5.0m</td>
<td>0.4</td>
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<tr>
<td></td>
<td>Water bulk module</td>
<td>Shear stiffness</td>
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<td></td>
<td>2×10^9 N/m²</td>
<td>5×10^6 N/m²</td>
</tr>
<tr>
<td></td>
<td>Sea water density</td>
<td>Soil’s coefficient of permeability</td>
</tr>
<tr>
<td></td>
<td>1030 kg/m³</td>
<td>10^4 m/s (coarse sand) 10^3 m/s (fine sand) 10^2 m/s (gravel)</td>
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<tr>
<td></td>
<td></td>
<td>The bulk modulus of soil particles</td>
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<td>4×10^10 N/m²</td>
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<tr>
<td></td>
<td></td>
<td>The bulk modulus of soil skeleton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100×10^6 N/m²</td>
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<tr>
<td></td>
<td></td>
<td>Pipe’s diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4m</td>
</tr>
</tbody>
</table>

4.2. Numerical results

4.2.1. The effect of permeability coefficient

From the figure, it can be found that the pipe’s penetration will increase with the permeability coefficient’s decreasing, so the pipe is stable. It is because that the pipe have the penetration under the effect of pipe’s weights and horizontal load, another reason is that the water loss in the fine sand is larger than that of coarse sand under the same horizontal load, so the soil particle under the pipe is easy to be loose and it is easy to cause the penetration for the pipe, which is advantageous for the pipe’s stability.

4.2.2. The effect of the pipe’s weight

The computation has been carried out by changing pipe’s weight when pipe’s diameter is constant.
Figure 4 The relationship between pipe’s penetration and pipe’s weight

Figure 5 The relationship between pipe’s horizontal displacement and pipe’s weight

Figure 6 The relationship between lateral coefficient and pipe’s weight
From the above figure, it can be found that the pipe’s penetration will increase with pipe’s weight increasing, but horizontal displacement will be decrease, which can explain that the pipe’s stability will be increase. The average value of lateral coefficient is 0.887.

4.2.3. The effect of environmental load
In order to consider the effect of environmental load, when pipe’s diameter is 0.4, pipe’s weight is 0.656kN, the results will be figured are as follows by changing pipe’s environmental load.

Figure 7 The relationship between pipe’s penetration and environmental load
Figure 8 The relationship between horizontal displacement and environmental load

From figure 7 and 8, it can be concluded that the pipe’s horizontal displacement and penetration will increase with the horizontal load’s increasement.
4.2.4. The effect of elastic modulus

Figure 9 The relationship between pore pressure and elastic modulus

Figure 10 The relationship between x-stress and elastic modulus

Figure 11 The relationship between normal stress and elastic modulus
From the above figures, it can be concluded that the value of elastic modulus has decisive effect on the distribution the pore pressure. The pore pressure is decreasing with the elastic modulus around the seabed, but increasing when z/h is bigger than 0.5. The effective stress is increasing with the decreasing of the elastic modulus. The pipe’s penetration will decrease with the increase of elastic modulus.

4.2.5. The effect of period
Figure 15 The relationship between $x$ stress and wave period

Figure 16 The relationship between normal stress and wave period

Figure 17 The relationship between tangent stress and wave period
From the above figures, it can be found that wave period had not obvious effect on the soil’s stress and pore water pressure. The normal stress and pipe’s penetration had little increase with the increase of the wave period. The reason is that the pore pressure will increase because of the increase with wave load.

4.2.6. The effect of water depth

Figure 19 The relationship between pore pressure and water depth

Figure 20 The relationship between x-stress and water depth
Figure 21 The relationship between normal stress and water depth

Figure 22 The relationship between tangent stress and water depth

From the above figures, it can be found that the pore pressure, $x$-stress will increase with the increase of water depth but tangent stress on the contrary. The normal stress will increase with the decrease of water depth, but when $z/h$ is larger than 0.4, the normal stress will increase with the water depth.

4.2.7. The effect of seabed thickness

The results are as follows:

Figure 23 The relationship between pore pressure and seabed thickness
Figure 24 The relationship between x-stress and seabed thickness

Figure 25 The relationship between normal stress and seabed thickness

Figure 26 The relationship between tangent stress and seabed thickness
4.2.8. The effect of pipe’s diameter
The pipe’s diameter is an important parameter in pipeline’s design. The computation results are as follows:
Figure 30 The relationship between x-stress and pipe’s diameter

Figure 31 The relationship between normal stress and pipe’s diameter

Figure 32 The relationship between tangent stress and pipe’s diameter
From the above figures, it can be found that when z/h is less than 0.4, pore pressure will increase with the pipe’s decrease, but on the contrary when z/h is larger than 0.4. Tangent stress will decrease and the pipe’s penetration will increase with the increase of pipe’s diameter.

5. CONCLUSIONS
(1) The pipe’s penetration, horizontal displacement, the distribution of pore pressure can be obtained by changing the parameters of soil and horizontal load.
(2) In these parameters, pipe’s weights, horizontal load, pipe’s diameter, water depth, elastic modulus have an important effect, but seabed thickness, wave period have little effect.

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6. REFERENCES