Research Article

Numerical Study of Wave- and Current-Induced Oscillatory Seabed Response near a Fully Buried Subsea Pipeline

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To investigate the wave- and current-induced seabed response near a fully buried subsea pipeline, a two-dimensional coupled model for fluid-seabed-pipeline interaction (FSPI-2D) is developed within the framework of COMSOL multiphysics. Different from previous studies, both the wave-current interaction and the nonlinear pipeline-soil contacts are considered in the present model. In this paper, Biot’s consolidation mode is used to govern the fluid-induced seabed response, and combined Reynolds averaged Navier–Stokes (RANS) equation with the $k$-$\varepsilon$ turbulence model is employed to simulate the fluid propagation. Meanwhile, the pipeline is treated as a linear elasticity. Firstly, the effectiveness of the new model is verified by laboratory experiments from previous reports. Then, the numerical model is employed to examine the effects of nonlinear pipeline-seabed contacts and fluid characteristics on the seabed response around the structure. Finally, the momentary liquefaction near the fully buried pipeline is studied based on the 2D coupled model.

1. Introduction

Subsea pipeline is an engineering facility for long-distance transportation of oil and gas, and it is the main component of the offshore oil (gas) production system. At present, in situ stability of subsea pipeline due to the seabed dynamic response has become the main focus for engineers in the field of offshore geotechnical engineering [1–4]. In the marine environment, the wave-induced cyclic pressures at the seabed surface might lead to the seabed liquefaction [5–9]. Once the seabed liquefies, it will lose bearing capacity and show fluid-like properties, which could cause the sinking or flotation [10] of the subsea pipeline due to the seabed liquefaction caused by pore pressure variations [11, 12]. Therefore, investigating the fluid-induced seabed dynamic response near the structure is very significant for offshore geotechnical engineers to predict the stability of the subsea pipeline.

Over the past few decades, many efforts have been devoted to the problem of wave-seabed interactions. Based on Biot’s consolidation model [13], Yamamoto et al. proposed the analytical solution to wave-induced dynamic response of an isotropic, poro-elastic, and infinite seabed [14]. Whereafter, Hsu and Jeng further extended the analytical solution to an unsaturated, isotropic seabed with finite thickness due to three-dimensional, short-crested wave loadings [15]. As an extension of Biot’s poro-elastic theory, Zienkiewicz et al. proposed the $u$-$p$ approximate solution for one-dimensional wave propagation in porous media [16]. Later, Jeng et al., Jeng and Rahman, and Ulker et al. further extended the $u$-$p$ approximation to the two-dimensional cases to examine the dynamic response of porous seabed [17–19]. Meanwhile, Ulker et al. summarized the application scope of three different Biot’s fluid-structure coupled models [19]. Using the finite element model, Ye and Jeng studied the influences of fluid shear stress on the seabed dynamic response and
concluded that the fluid shear stress can greatly affect the stresses and pore pressure developments within the seabed [20]. In recent years, relevant researchers further investigated the dynamic response of seabed caused by wave loadings using laboratory experiments [21, 22], analytical methods [23], and numerical models [24, 25].

In real oceanic environment, the wave and current normally co-exist, and their interaction process is very complex, which can bring great difficulty to the analysis of fluid-induced seabed response. However, some investigations have still been carried out through different methods. Among these, Zhou et al. studied the wave- and current-induced seabed dynamic response through flume experiments and found that the current could aggravate the liquefaction of the sandy seabed [26]. Ye and Jeng investigated the seabed dynamic response due to combined wave and current loadings and concluded that the maximum error of the pore pressure can reach 25% unless the wave-current interaction is not considered [27]. Liao et al. proposed the analytical solution to the pore pressure response within the infinite seabed and derived that current would change the dynamic response of a near-saturated soil, under the wave loadings with a long wave period and shallow water depth. With the three-dimensional numerical model [28], Wen et al. studied the wave- and current-induced seabed response and found that the existence of following current would increase the pore pressure response in the seabed [29]. Based on the flume tests, Qi et al. studied the seabed response induced by wave and current loadings and clarified that the fluid-induced pore pressure increased for the following-current case, but reduced for the opposing-current case [30].

The phenomenon of wave-structure-seabed interactions (WSSI) has attracted great attention in the field of offshore geotechnical engineering involving the design of subsea pipelines [31]. In the 1980s, Wagner et al. firstly proposed the pipeline-soil interaction model [32, 33]. Similarly, Brennonden et al. proposed an energy-based pipe-soil interaction model based on physical experiments [34]. Later, based on Biot’s model [13], Magda and Jeng employed the finite element model to investigate the wave-induce pore pressure around buried pipelines [35, 36]. Teh et al. and Sumer et al. conducted Flume experiments to investigate the wave-induced seabed response and the stability of subsea pipeline [37, 38]. By means of finite element model, the influences of pipeline-seabed contact effects and inertial effects on the wave-induced seabed response near the pipeline were examined by [39]. Later, Fredsøe reviewed the research process of pipeline-seabed interaction and pointed out the future research direction for pipeline stability in marine environment [2]. Recently, Gao revealed the coupled mechanism of fluid-pipeline-seabed [40]. Chen et al. studied the pipeline-soil interaction using the finite element model and concluded that the existence of pipeline can accelerate the accumulation of pore pressure at the top and side of pipeline [41]. The aforementioned studies can deepen the understanding of seabed response near the buried pipeline. However, most of the existing studies did not consider the effects of fluid shear stress at the seabed surface while examining the seabed dynamic response. Moreover, previous studies normally used different numerical methods to solve fluid submodel and seabed submodel, respectively, which may affect the accuracy of the numerical results.

The purpose of this study is to investigate the fluid-induced dynamic response of seabed near the fully buried pipeline. Therefore, a two-dimensional fully coupled model for fluid-seabed-structure interaction is proposed within the framework of COMSOL multiphysics, where both the wave-current interaction and the fluid shear stress at the seabed surface are considered. Using the new model, the effects of the nonlinear pipeline-seabed contacts and the fluid characteristics on seabed dynamic response near the fully buried subsea pipeline are studied.

2. Methods

This paper mainly studies the fluid-induced transient dynamic response of seabed near the fully buried subsea pipeline, based on a two-dimensional numerical model built in the framework of COMSOL multiphysics, where the dynamic calculation is adopted. The quadrilateral mesh is used and the minimum size of the mesh is 0.01 m in this study. The new model mainly includes the fluid submodel, the seabed submodel, and the pipeline submodel. The fluid submodel and the seabed submodel are adopted to govern the fluid motions and the seabed dynamic response near the subsea pipeline. Meanwhile, the pipeline submodel is employed to describe the fluid-induced pipeline dynamic response.

The diagram of fluid-seabed-pipeline interaction (FSSI-2D) is shown in Figure 1, where $L$ is the length of the calculated area, $h$ is the depth of the seabed, $L$ is the wave length, $d$ is the depth of the water, $e$ is the thickness of the pipeline cover, $U$ is the current velocity, $D$ is the pipeline diameter, and $B$ is a point at the pipeline bottom.

2.1. Fluid Submodel. In the fluid submodel, the Reynolds averaged Navier–Stokes (RANS) equations with the $\kappa$-$\varepsilon$ turbulence model is adopted to simulate the fluid propagations, and the level set method (LSM) is adopted to track the free water surface. As for a two-dimensional problem, the RANS equations can be expressed as follows:

$$\frac{\partial \langle \mu_i \rangle}{\partial x_i} = 0,$$

(1)

$$\frac{\partial \langle \mu_i \rangle}{\partial t} + \frac{\partial \langle \mu_i \rangle \partial \langle \mu_j \rangle}{\partial x_j} = -\left( \frac{1}{p_w} \frac{\partial \langle p_w \rangle}{\partial x_i} + \frac{1}{p_w} \frac{\partial \tau_{ij}}{\partial x_j} \right) + g_i + S_i,$$

(2)

where $x_i$ is the Cartesian coordinate, $u_i$ and $u_j$ are the ensemble averaged velocity, $p_w$ is the water pressure, $p_w$ is the water density. $g_i$ is the component of gravity acceleration, $t$ is time, and $S_i$ is a source term related to wave characteristics, which is used to generate waves. Since the model in this study is two-dimensional, thus, $S_i = 0$; $\tau_{ij}$ is the shear stress tensor including the viscous stress and the Reynolds stress, which can be expressed as
\[ \tau_{ij} = \mu_f \left[ \frac{\partial p_i}{\partial x_j} + \frac{\partial p_j}{\partial x_i} \right] - \rho u_i' u_j', \quad (3) \]

\[ -\rho u_i' u_j' \kappa = \mu \left[ \frac{\partial p_i}{\partial x_j} + \frac{\partial p_j}{\partial x_i} \right] - \frac{2}{3} \rho w \delta_{ij} \kappa, \quad (4) \]

where \( \mu_f \) is the dynamic viscosity, \( \rho u_i' u_j' \) is the Reynolds stress term, \( \kappa \) is the turbulence kinetic energy, \( \delta_{ij} \) is Kronecker Delta's sign, \( \mu_t \) is the turbulent viscosity, and \( \epsilon \) is dissipation rate of the turbulent kinetic energy. Based on (3) and (4), (2) can be written as

\[ \begin{align*}
(\frac{\partial \rho w}{\partial t} + \nabla \cdot (\rho w \mathbf{u}) ) &= -\nabla \cdot (\rho \mathbf{f} + \rho \epsilon \kappa) + \frac{2}{3} \rho w \delta_{ij} \kappa, \\
\end{align*} \]

where \( \Phi \) is the level set function, \( \epsilon_{ls} \) is the parameter that controls the interface thickness, and \( \gamma \) is the reinitialization parameter.

### 2.2 Seabed Submodel

In this paper, Biot’s poro-elastic equation is taken to govern the seabed response induced by the wave and current loadings. The governing equation should be expressed as

\[ \begin{align*}
\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_z}{\partial z^2} - \frac{\gamma_w n \beta_s}{k_s} \frac{\partial u_x}{\partial t} &= \frac{y_w}{k_s} \frac{\partial \epsilon_x}{\partial t}, \\
GV^2 u_x + \frac{G}{1 - 2\mu} \frac{\partial \epsilon_x}{\partial x} &= \frac{\partial u_x}{\partial x}, \\
GV^2 u_z + \frac{G}{1 - 2\mu} \frac{\partial \epsilon_z}{\partial z} &= \frac{\partial u_z}{\partial z},
\end{align*} \]

where \( u_x \) and \( u_z \) are the soil displacements along \( x \)- and \( z \)-directions, respectively, \( u_e \) is wave-induced pore water...
where $\sigma$, $\beta$, and $G$ can be expressed as follows:

$$\varepsilon_s = \left( \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right),$$

$$\beta_s = \frac{1}{K_w} + \frac{(1 - S_r)}{p_{w0}},$$

$$G = \frac{E}{2(1 + \mu)}$$

where $K_w$ is the true elastic modulus of water, which is taken as 2.0 GPa in this study, $S_r$ is the degree of seabed saturation, $p_{w0}$ is the absolute water pressure, $E$ is Young’s modulus, and $\mu$ is Poisson’s ratio.

2.3. Pipeline Submodel. In the pipeline submodel, the pipeline is assumed to be a linear elastomer. In other words, the relationship between the stress and strain follows Hooke’s law, which can be expressed as follows:

$$[\sigma] = [D][\varepsilon],$$

$$= [D][B][\delta]^e,$$

where $[D]$ is the elastic matrix, $[B]$ is the element strain matrix, and $[\delta]^e$ is the element node displacement matrix.

2.4. Boundary Condition. In the numerical study, the boundary conditions can significantly affect the accuracy of the numerical results. The new model of this paper includes five boundary conditions, which are the water surface boundary condition, the seabed surface boundary condition, the seabed bottom boundary condition, the pipeline-seabed interface condition, and the seabed lateral sides boundary condition.

2.4.1. Water Surface Boundary Condition. The relative pressure at the free surface of water is zero at the water surface.

2.4.2. Seabed Surface Boundary Condition. As mentioned previously, one of the new contributions in this study is that the fluid shear stress is considered while examining the seabed dynamic response. Therefore, at the seabed surface, the shear stress of the soil ($\tau_{sz}$) is equal to the fluid shear stress ($\tau_w$) and the pore pressure ($u_z$) is equal to the wave pressure acting on the seabed surface ($p_a$). Meanwhile, the normal effective stress ($\sigma'_z$) is equal to zero:

$$\mu_e = p_a,$$

$$\tau_{sz} = \tau_w,$$

$$\sigma'_z = 0.$$  

2.4.3. Seabed Bottom Boundary Condition. In this study, the seabed is assumed to be placed on a rigid bedrock. Therefore, the pore pressure gradient as well as the soil displacements are set to be $z \partial u_z/\partial z = 0$ and $u_z = \omega_z = 0$, at $z = 0$.

2.4.4. Pipeline-Seabed Interface Boundary Condition. In this paper, the interaction between the pipeline and the surrounding seabed is simulated through the pipeline-seabed interface constitutive equation, which can be expressed as follows:

$$T_t = v_f T_n + T_c,$$

where $T_t$ is the traction force, $T_n$ is the contact pressure, $T_c$ is the coherent sliding resistance, which is taken as 1 $\times$ 10$^4$ Pa, and $v_f$ is the static frictional coefficient, which is taken as 0.213 [42]. Once the traction force ($T_t$) exceeds the coherent sliding resistance, the sliding will occur. In this study, the seabed is considered to be cohesive; $T_n$ is taken as 1 $\times$ 10$^4$ Pa, and $v_f$ is taken as 0.213. It should be noted that the contact pressure ($T_n$) in the above equation should be determined considering gravity of the soil, while the gravity is not considered in the governing equation of seabed response, which would be one shortcoming of this study.

2.4.5. Seabed Lateral Sides’ Boundary Condition. The left and right sides of the seabed are assumed to be roller boundaries, and the pore pressure gradient should be zero:

$$u_z = 0,$$

$$\frac{\partial u_z}{\partial n} = 0.$$  

2.5. Model Validation. In this section, two model verifications are conducted to check the accuracy of the present numerical model, which are fluid model validation and fluid-seabed-pipeline interaction model validation.

2.5.1. Fluid Model Validation. In this section, the laboratory results from Qi and Gao [43] are applied to validate the wave-current model. The schematic diagram of the experiment is shown in Figure 2 and the input data are listed in Table 1. Meanwhile, Figure 3 illustrates the comparison results of pore pressure ($u_z$) on the seabed surface with time between the present model and laboratory experiments. As shown in above figure 3, the numerical results are nearly in accordance with the laboratory results.

2.5.2. Fluid-Seabed-Pipeline Interaction Model Validation. The experimental data from Zhai et al. [44] are applied to validate the new model in simulating fluid-induced seabed response around the pipeline. Figure 4 shows the schematic diagram of this experiment, and Figure 5 illustrates the comparison results of wave-induced dynamic pore pressure at the bottom of the pipeline with time between the present model and laboratory experiments, where the input data are
listed in Table 2. It can be observed from Figure 5 that the simulated pore pressures agree well with laboratory measurements.

Based on the above two model validation results, it can be concluded that the present numerical model can effectively simulate the wave-current-seabed-pipeline interaction process.

3. Results and Discussion

As reported in previous studies, the fluid-induced soil dynamic response is a key factor to determine the seabed stability, which has been thoroughly studied in the past. However, most previous studies ignore the fluid shear stress at the seabed surface and pipeline-seabed contact effects when examining the seabed response, although Ye and Jeng [27] pointed out that the fluid shear stress may affect the maximum of the pore pressure in the case involving wave-current interaction. To examine the effects of fluid shear stress on seabed dynamic response, Figure 6 illustrates the comparison results of the wave- and current-induced pore pressure response at the bottom of the buried pipeline over a complete wave period between the model considering the fluid shear stress and the model without considering the fluid shear stress. It can be observed from Figure 6 that the pore pressure at the bottom of the pipeline is larger for the case considering the fluid shear stress onto the seabed surface.

In this section, the effects of pipeline-soil contacts on fluid-induced seabed response are studied first. Then, the effects of fluid characteristics on seabed response and momentary liquefaction near the pipeline are fully checked. Finally, the momentary liquefaction around the buried pipeline is examined. The parameters used in the following study could refer to Table 3 unless specifically specified.

In this study, the criteria proposed by Zen and Yamazaki [45] are used to judge whether the seabed liquefies. As for these criteria, when the initial effective stress of the seabed is less than or equal to excess pore water pressure, the seabed will be considered to be liquefied:

$$\sigma_0' \leq p,$$

where $\sigma_0'$ is the initial effective stress in the soil and $p$ is the excess pressure ($p = u_e - u_a$).

3.1. The Effects of the Pipeline-Soil Contact on Seabed and Pipeline Response. The pipeline-soil interaction process is very complex, which belongs to nonlinear interface contact problem. In this section, the effects of the pipeline-soil...
contacts on fluid-induced seabed and pipeline responses are examined. Therefore, Figure 7 and Figure 8 display the distribution of the wave-current-induced seabed liquefaction and the pipeline dynamic response, where the wave trough is just passing over the pipeline.

It should be noted that the liquefaction zone, according to the criterion [45], has been removed when drawing the figures in this paper. Therefore, the white zone at the seabed surface and around the pipeline is the liquefaction zone. As shown in Figure 7, the liquefaction zone of the conode model

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**Table 2:** Parameters used in the second validation.

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| Wave period \((T)\)        | 1.2 s                      |
| Wave height \((H)\)        | 0.1 m                      |
| Soil permeability \((k_s)\) | \(3.75 \times 10^{-5}\) m/s|
| Shear modulus \((G)\)      | \(8.28 \times 10^6\) Pa    |
| Poisson’s ratio \((\mu)\)  | 0.3                        |
| Soil porosity \((n)\)      | 0.369                      |
| Degree of saturation \((S_r)\) | 0.98                        |

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**Table 3:** Parameters used in the numerical examples.

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| Wave height \((H)\)        | 4 m or various             |
| Water depth \((d)\)        | 7 m or various             |
| Wave period \((T)\)        | 8 s or various             |
| Wave length \((L)\)        | 61.39 m                    |
| Current velocity \((U)\)   | 0.4 m/s or various         |
| Seabed thickness \((h)\)   | 20 m                       |
| Shear modulus \((G)\)      | \(10^7\) N/m²              |
| Poisson’s ratio \((\mu)\)  | 0.333                      |
| Soil permeability \((k_s)\) | \(1.5 \times 10^{-3}\) m/s|
| Degree of saturation \((S_r)\) | 0.98                        |
| Seabed porosity \((n)\)    | 0.333                      |
| Density of soil \((\rho)\) | 1600 kg/m³                 |
| Density of water \((\rho_w)\) | 1000 kg/m³                |
| Acceleration of gravity \((g)\) | 9.82 m/s²               |
| Burial depth of pipeline \((e)\) | 0.5 m                     |
| Pipeline diameter \((D)\)  | 1.2 m                      |
| Thickness of pipeline      | 0.01 m                     |
near the pipeline is larger than that of the nonlinear contact model. Moreover, the liquefaction depth at the bottom of the pipeline in the conode model is 0.031 m greater than that in the nonlinear contact model (the liquefaction depth in the nonlinear contact model is 1.955 m). This phenomenon should be attributed to the over constraints of the pipeline on the surrounding seabed, which can increase the pore water pressure and enlarge the liquefaction region near the pipeline. Therefore, the nonlinear pipeline-soil contacts should be considered in the estimation of seabed response around the structure.

Based on the previous studies, the nonlinear interface contacts can greatly influence the structure dynamic response. As shown in Figure 8, the stresses of pipeline are larger at the top and the bottom of pipeline when the nonlinear pipeline-soil contact is considered. Notably, the vertical displacement of the pipeline is large. Thus, emphasis should be placed on vertical pipeline displacement in the estimation of pipeline stability.

3.2. Effects of Current Velocity on Pore Pressure Response near the Pipeline. In the marine environment, the wave and current may co-exist and affect each other. Hence, the effects of wave-current interaction on the fluid-induced seabed response near the pipeline are investigated in this section. Thus, Figure 9 displays the pore water pressure over time at the surface of seabed and at the bottom of pipeline (in which \( U < 0 \) means opposing current, \( U = 0 \) represents no current, and \( U > 0 \) means following current). As shown in Figure 9(a), the amplitude of pore pressure at the surface of seabed increases with the increasing current velocity. It is

![Figure 7: Distribution of the wave-current-induced liquefaction near the pipeline during the wave trough (\( H = 1 \) m, \( T = 8 \) s, \( d = 7 \) m, and \( U = 0.4 \) m/s): (a) the conode model; (b) the nonlinear contact model.](image)

![Figure 8: Dynamic response of the pipeline during the wave trough: (a) deformation profile of pipeline (magnified by 1000 times); (b) the distribution of stress of pipeline (\( H = 1.0 \) m, \( T = 8 \) s, \( d = 7 \) m, and \( U = 0.4 \) m/s).](image)
worth noting that the phase of waves decreases with increase of current velocity and the phase differences increase over time at different velocities. This phenomenon is due to the fact that the following current will accelerate the wave’s propagation and opposing current will reduce the wave’s propagation. Besides, the effect of currents on waves will increase with the amplitude of current velocity. It can be observed from Figure 9(b) that the amplitude of pore water pressure at the bottom of the pipeline increases with the increase of current velocity. Overall, the variation trend in Figure 9(a) is similar to that in Figure 9(b). Notably, the pore water pressure at the bottom of the pipeline for following currents is overall greater than that of the pore water pressure for opposing currents. In other words, the following current can aggravate the instability of seabed around a pipeline.

In addition, seven current velocities ($U = -1.2 \, \text{m/s}$, $-0.8 \, \text{m/s}$, $-0.4 \, \text{m/s}$, $0 \, \text{m/s}$, $+0.4 \, \text{m/s}$, $+0.8 \, \text{m/s}$, $+1.2 \, \text{m/s}$) are selected to examine the effects of current on the fluid-induced oscillatory pore water pressure responses near the pipeline. Figures 10 and 11 illustrate the distribution of pore pressure in seabed around the pipeline and the amplitude of fluid-induced pore water pressure along the outer surface of the pipeline for different current velocities, where the wave trough is just passing over the pipeline. As shown in Figure 10, the pore water pressure near a pipeline continuously increases with the increase of current velocities. Furthermore, the pore water pressure around a pipeline when $U = 1.2 \, \text{m/s}$ improved by 15% compared to that when $U = 0 \, \text{m/s}$ and the pore water pressure around a pipeline when $U = -1.2 \, \text{m/s}$ reduced by 11% relative to that when $U = 0 \, \text{m/s}$, respectively. Notably, the distribution of pore water pressure around the pipeline is dis-symmetric and this trend increases with the increase of amplitude of current velocity. This phenomenon is due to the fact that the following currents may aggravate the wave-induced seabed response and the opposing currents may reduce the wave-induced seabed response. Meanwhile, the wave-current interaction can change the phase of wave, which can further induce the phase lags of the pore pressure within the seabed.

As shown in Figure 11, the amplitude of pore water pressure at the top of the pipeline is overall larger than that at the bottom of the pipeline, and the pore water pressure at the top of the pipe increases faster than that at the bottom of the pipeline as the current velocity increases. Moreover, the pore water pressure around the pipeline increases faster with the increase of the current velocity for the case with the following current. At the top ($\theta = 90^\circ$), the lift side ($\theta = 180^\circ$), and the bottom of pipeline ($\theta = 270^\circ$), the difference of pore water pressure between when $U = 1.2 \, \text{m/s}$ and when $U = 0 \, \text{m/s}$ can reach up to 16.3%, 17.8%, and 14.6%, respectively, while the difference of the pore pressure between the case of $U = -1.2 \, \text{m/s}$ and the case of $U = 0 \, \text{m/s}$ only reaches up to 10.3%, 9.1%, and 12.4%, respectively. Consequently, the following current has a greater influence on fluid-induced seabed response near the pipeline than that of the opposing current.

3.3. Effects of Wave Parameters on Pore Pressure Response near the Pipeline. It is known that wave parameters can affect the fluid-induced dynamic pressure along the seabed surface, which may further influence the seabed instability. Among the wave parameters, the wave height ($H$) can directly affect the fluid-induced dynamic pressure on the seabed surface. The wave period ($T$) and the water depth ($d$) can indirectly affect the wave-induced dynamic pressure on the seabed surface by changing wavelength ($L$). Therefore, the effects of
Figure 10: Distribution of pore pressure in seabed around the pipeline under different current velocities during the wave trough ($H = 1\, \text{m}$, $T = 8\, \text{s}$, and $d = 7\, \text{m}$): (a) $U = -1.2\, \text{m/s}$; (b) $U = -0.8\, \text{m/s}$; (c) $U = -0.4\, \text{m/s}$; (d) $U = 0\, \text{m/s}$; (e) $U = 0.4\, \text{m/s}$; (f) $U = 0.8\, \text{m/s}$; (g) $U = 1.2\, \text{m/s}$. 

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Figure 11: Distribution of amplitude of fluid-induced pore pressure along the pipeline outer surface under various current velocities ($H = 1\ m$, $T = 8\ s$, and $d = 7\ m$).

Figure 12: Distribution of pore pressure in seabed around a pipeline under different wave heights during the wave trough ($T = 8\ s$, $d = 7\ m$, and $U = 0.4\ m/s$): (a) $H = 0.5\ m$; (b) $H = 1\ m$; (c) $H = 1.5\ m$; (d) $H = 2\ m$. 
wave height, wave period, and water depth on the fluid-induced pore water pressure are checked thoroughly based on the fully coupled model. In this section, the wave height ($H$) ranges from 0.5m to 2.0m with an interval of 0.5m, the wave period ($T$) varies from 5s to 14s with an interval of 3s, and the wave depth ($d$) varies from 7m to 16m with an interval of 3m. Figures 12–14 shows the distribution of pore water pressure in seabed around a pipeline with different wave heights ($H$), different wave periods ($T$), and different water depths ($d$), respectively, where the wave trough is just passing over the pipeline. Figure 15 displays the distribution of amplitude of wave- and current-induced pore water pressure along the pipeline outer surface.

As shown in Figure 12, the pore water pressure near the subsea pipeline overall increases as the wave height increases. At the top ($\theta = 90^\circ$), the lift side ($\theta = 180^\circ$), and the bottom ($\theta = 270^\circ$) of the pipeline, the pore water pressure increases linearly with the increase of the wave height, while the difference of pore water pressure at three locations can reach up to 47.6%, 46.3%, and 45.4% when $H = 1.0 m$, respectively. In addition, it can also be observed that the increase of pore water pressure at the top of the pipeline is larger than that at the bottom of the pipeline under the combined wave and current loadings. The difference of pore water pressure between the top ($\theta = 90^\circ$) and the bottom ($\theta = 270^\circ$) of the pipeline increases with the increase of the wave height. Therefore, the potential instability of seabed around the subsea pipeline will enhance with the increase of wave height. As shown from Figure 13, with the wave periods’ increase, the pore water pressure near the pipeline increases rapidly at first and then slows down. At the top ($\theta = 90^\circ$), the lift side ($\theta = 180^\circ$), and the bottom ($\theta = 270^\circ$) of the pipeline, the differences of pore water pressure at three different locations are 17.3%, 22.5%, and 27.2% when $T = 8.0 s$, respectively. Figure 14 shows that the pore pressure around the pipeline decreases overall as the wave depth increases. At the top ($\theta = 90^\circ$), the lift side ($\theta = 180^\circ$), and the bottom of the pipeline ($\theta = 270^\circ$), the decreased amplitude of pore water pressure can reach up to 12.1%, 9.4%, and 7.7% compared to that when $d = 7.0 m$, respectively.

3.4. Fluid-Induced Momentary Seabed Liquefaction near the Pipeline. Based on the new coupled model (FSPI-2D), the momentary liquefaction around the pipeline is examined in this section. Thus, Figure 16 illustrates the variation of fluid-induced momentary liquefaction around the pipeline in a complete wave period. As shown in Figure 16, the liquefaction zone, near the pipeline, changes constantly over the time. It is worth noting that the liquefaction region near the pipeline is greatest when the wave trough is over the pipeline head ($t = 1/4 T$), and liquefaction mainly occurs at the

![Figures 13](image1.png)

![Figures 13](image2.png)

![Figures 13](image3.png)

![Figures 13](image4.png)

**Figure 13:** Distribution of pore pressure in seabed around a pipeline under different wave periods during the wave trough ($H = 1 m$, $d = 7 m$, and $U = 0.4 m/s$): (a) $T = 5 s$; (b) $T = 8 s$; (c) $T = 11 s$; (d) $T = 14 s$. 
Figure 14: Distribution of pore pressure in seabed around the pipeline under different water depths during the wave trough ($H = 1$ m, $T = 8$ s, and $U = 0.4$ m/s): (a) $d = 7$ m; (b) $d = 10$ m; (c) $d = 13$ m; (d) $d = 16$ m.

Figure 15: Continued.
Figure 15: Distribution of the amplitude of the wave- and current-induced pore water pressure along the pipeline outer surface: (a) \( H = 0.5 \text{ m}, 1.0 \text{ m}, 1.5 \text{ m}, 2.0 \text{ m} \) (\( T = 8 \text{ s}, d = 7 \text{ m}, \text{ and } U = 0.4 \text{ m/s} \)); (b) \( T = 5 \text{ s}, 10 \text{ s}, 15 \text{ s}, 20 \text{ s} \) (\( H = 1 \text{ m}, d = 7 \text{ m}, \text{ and } U = 0.4 \text{ m/s} \)); (c) \( d = 7 \text{ m}, 10 \text{ m}, 13 \text{ m}, 16 \text{ m} \) (\( H = 1 \text{ m}, T = 8 \text{ s}, \text{ and } U = 0.4 \text{ m/s} \)).

Figure 16: Variation of the wave- and current-induced momentary liquefaction around the pipeline in a complete wave period (\( H = 1 \text{ m}, T = 8 \text{ s}, d = 7 \text{ m}, \text{ and } U = 0.4 \text{ m/s} \)): (a) \( t = 0 \), (b) \( t = 1/4 T \), (c) \( t = 1/2 T \), and (d) \( t = 3/4 T \).
surface of seabed and the top and bottom of the pipeline, which may cause the sinking or flotation of the pipeline.

4. Conclusions

In this paper, the fluid-induced oscillatory seabed response and momentary liquefaction around the fully buried pipeline are thoroughly studied based on a 2D coupled model (FSPI-2D), where both the fluid shear stress at the seabed surface and the pipeline-seabed contact effects are considered. The new model is first validated with previous experimental reports, and then, the effects of fluid characteristics on seabed dynamic response are investigated in detail. The main findings of this study can be concluded as follows:

1. The pipeline-soil interaction and the fluid shear stress can enhance the fluid-induced oscillatory pore water pressure response near the structure
2. The fluid-induced stress response of the pipeline is small while the vertical displacement is large
3. The oscillatory seabed response can be enhanced with the increases of the current velocity when the wave travels following the current
4. The wave with a large wave height, a long time period, and a shallow depth may increase the liquefaction potential of the porous seabed

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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