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Seismic Dynamics of Pipeline Buried in Dense Seabed Foundation

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Abstract: Submarine pipeline is a type of important infrastructure in petroleum industry used for transporting crude oil or natural gas. However, submarine pipelines constructed in high seismic intensity zones are vulnerable of attacks from seismic waves. It is important and meaningful in engineering design to comprehensively understand the seismic wave-induced dynamics characteristics of submarine pipelines. In this study, taking the coupled numerical model FSSI-CAS 2D as the tool, the seismic dynamics of a submarine steel pipeline buried in dense soil is investigated. Computational results indicate that submarine pipeline buried in dense seabed soil strongly responds to seismic wave. The peak acceleration could be double of that of input seismic wave. There is no residual pore pressure in the dense seabed. Significant resonance of the pipeline is observed in horizontal direction. Comparative study shows that the lateral boundary condition which can avoid wave reflection on it, such as laminar boundary and absorbing boundary should be used for seabed foundation domain in computation. Finally, it is proven that the coupled numerical model FSSI-CAS 2D is applicable to evaluate the seismic dynamics of submarine pipeline.

Keywords: submarine pipeline; dense seabed foundation; seismic dynamics; resonance of submarine pipeline; FSSI-CAS 2D

1. Introduction

Submarine pipeline is a type of important infrastructure in petroleum industry widely used in offshore area for transporting crude oil or natural gas. Nowadays, several hundred thousands of kilometers of submarine pipelines have been constructed worldwide. The stability of submarine pipelines is important and crucial for guaranteeing their normal service performance in the designed service period. However, submarine pipelines are vulnerable of attacks from extreme ocean waves or strong seismic waves. Therefore, it is necessary and meaningful to understand the responding dynamics characteristics of submarine pipeline under the dynamic loading applied by ocean wave or seismic wave.

Generally, the instability of submarine pipelines would be attributed to scouring, ocean wave applications, or seismic wave attacks. Some valuable works have been conducted on the scouring of seabed floor near the submarine pipeline to understand the process and mechanism of seabed scouring around pipeline under ocean waves and currents [1–3]. On the ocean wave-induced dynamics of submarine pipeline, a series of research works have also been conducted, and a great number of literature is available. The research method mainly includes analytical solutions, numerical computations, and laboratory wave flume tests. Previous studies mainly focused attention on the wave and current-induced pore pressure and effective stress in seabed soil, seepage force [4,5] and buoyancy [6–8] of pipeline. In the field of marine geotechnical engineering, the investigation on the response of pore pressure and effective stress in seabed foundation to ocean wave around marine pipeline was the most popular topic. On this topic, the team led by Jeng D.S. conducted a number of works. For example, Jeng and Cheng [9] proposed an analytical solution to understand the wave-induced pore pressure around a pipeline buried in poro-elastic seabed. Then, Wang et.al [10] and Jeng [11] further investigated the wave-induced pore pressure around a pipeline buried in anisotropic or nonhomogeneous seabed. Later, the effect of nonlinear wave as well as soil-pipeline contact effects on pipeline dynamics were studied [12–14]. Recently, the dynamics of a pipeline buried in a single-layer or multi-layer seabed applied by conodal wave or linear wave were studied by Zhou et al. [15] and Zhou et al. [16]. Previous studies were basically limited to two dimensions. Zhang et al. [17] studied the wave-induced dynamics of a pipeline, adopting a three-dimensional model. In above-mentioned works, the seabed soils were all described as poro-elastic medium. However, there is another type of seabed soil widely distributes in offshore area. It is loosely deposited seabed soil, in which pore pressure could build up under ocean wave loading, resulting in seabed soil liquefaction. Recently, the wave-induced dynamics of a pipeline buried in loose seabed soil was tentatively investigated [18,19] by adopting some empirical-based soil models, such as the soil model proposed by seed [20,21]. There were also few investigations [17,22] which adopted a advanced soil model, such as PZIII model proposed by Zienkiewicz et al. [23], to do such work.

On the seismic dynamics of submarine pipeline buried in seabed floor, only a few investigations have been previously conducted. Actually, researchers mainly focused on the seismic dynamics and the stability of submarine pipeline from about 1980s. At the early stage, the seismic performance of free-spanning pipelines supported by a number of upholders was the focus of engineers and scientists [24,25]. To the authors' best knowledge, Wang and Cheng [26] first investigated the axial seismic dynamics of a buried pipeline adopting a simplified quasi-static method, in which the soil-pipeline interaction was modelled by some virtual springs. After that, Datta et al. [27] further investigated the seismic dynamics of a buried pipeline, adopting a three-dimensional numerical model where the seabed foundation was described by linear elastic model, and the steel pipeline was modelled by shell elements. It was found by Datta et al. [27] that the seismic dynamics of submarine pipeline was significantly controlled by the stiffness ratio between pipeline and its surrounding soil. Later, Datta and Mashaly [28] further analyzed the seismic dynamics of a buried pipelines by performing spectral analysis, where the earthquake was considered as a partially correlated stationary random process characterized by a power spectral density function (PSDF). After the 2000s, there were also a few works performed to study the seismic dynamics of submarine pipeline adopting numerical modelling, such as Ling et al. [29], Luan et al. [30], Zhang and Han [31], and Saeedzadeh and Hataf [32]. However, these works mainly focused their attention on the pore pressure and acceleration in soil foundation. The dynamics characteristics of effective stresses in soil foundation, as well as the dynamics of pipeline itself, were basically not demonstrated, resulting in the lack of comprehensive understanding on the seismic dynamics characteristics and the instability mechanism of submarine pipelines. Over the past 10 years, several numerical modelling works were conducted to study the deformation of steel pipelines buried in seabed after faults were moved in strong earthquake events [33,34]. Their works were beneficial to improve the seismic design ability of engineers, avoiding instability of submarine pipeline in earthquake events. In addition to numerical modelling, laboratory shaking table tests in centrifuge device were also performed to study the seismic dynamics of buried pipelines [35,36]. Their test results provided engineers with insights to further understand the seismic instability mechanism of submarine pipeline.

As we know, a seismic wave is a kind of significant and nonignorable environmental loading for marine structures. It brings a great threat to the stability of offshore structures constructed in high seismic intensity zones. The seismic stability of submarine pipelines has attracted much attention in offshore petroleum industry. Some national or industry association codes, such EU code EN 1594, Canadian code CSA Z662, and ASME codes B31.4 and B31.8 suggest to design engineers that the adverse impact of seismic wave should be considered in pipeline design, and some mitigation measures should be taken. However, there is basically no further detail information on how to quantitatively perform the anti-seismic design due to the fact that the seismic dynamics characteristics of submarine pipeline is not yet comprehensively understood. In this study, taking the coupled numerical model FSSI-CAS 2D as a tool, the seismic dynamics of a submarine steel pipeline buried in dense soil is investigated. The analysis results could further improve the understanding of ocean engineers on the seismic dynamics of submarine pipeline buried in seabed foundation.

2. Coupled Numerical Model: FSSI-CAS 2D

In the offshore environment, pipeline, seabed foundation, and overlying seawater are an integrated system. There is a strong interaction between them when subjected to environmental loading-ocean waves or seismic waves. To understand the complicated interaction between fluid, offshore structures, and their seabed foundations, an integrated numerical model FSSI-CAS 2D, as well as its three-dimensional version FSSI-CAS 3D, were successfully developed by Jeng et al. [37], Ye et al. [38], and Ye et al. [39] for the problem of fluid-structures-seabed foundation interaction. In FSSI-CAS 2D, the Volume Averaged Reynolds Averaged Navier–Stokes (VARANS) equation [40] governs the wave motion and porous flow in the porous seabed, solved using the finite difference method (FDM). The dynamic Biot's equation, known as 'u-p' approximation [41], is adopted to describe the dynamic behavior of offshore structure and its seabed foundation, which is solved in the finite element framework [23]. A coupled algorithm was developed to integrate these two governing equations together, forming a coupled/integrated numerical model for the problem of fluid-structures–seabed interaction (FSSI). More detailed information on solving the VARANS equation and the dynamic Biot's equation can be found in Ye et al. [38,42] and Zienkiewicz et al. [23]. FSSI-CAS 2D has the innate advantage for the problem of fluid-structures-seabed interaction. However, the main limitation of FSSI-CAS 2D is that the displacement discontinuity cannot be guaranteed on the interface between fluid and structures/seabed.

The developed coupled model FSSI-CAS 2D has been validated by analytical solutions, a series of wave flume tests, and a centrifuge test [39]. It has also been successfully applied to investigate the dynamics of breakwater and its seabed foundation to several types of ocean waves, such as regular waves, breaking waves [43], and tsunami waves, as well as seismic waves [44]. It is indicated that the coupled numerical model FSSI-CAS 2D is applicable for the seismic dynamics of pipeline.

3. Computational Domain, Boundary Condition, Seismic Wave and Parameters

As demonstrated in Figure 1, a pipeline transporting crude oil is buried in dense seabed foundation in offshore area with a water depth d = 10 m. The diameter of pipeline is 800 mm. The buried depth is 1.0 m (distance of pipeline center to the surface of seabed). The computational domain of seabed foundation is 200 m in length and 20 m in thickness. The pipeline is placed on the symmetrical line x = 100 m.

The bottom of the seabed foundation is fixed in x and z direction. The lateral sides of the seabed foundation are set as laminar boundary in x direction and set free in z direction. It means that there is no reflection of seismic wave on the lateral sides of the seabed foundation. On the surface of the seabed foundation, only the hydrostatic water pressure is applied (ocean wave loading is not considered in this study). Meanwhile, the effective stresses remain at zero at all times on the surface of seabed floor due to the fact that the seabed foundation is porous (have no relationship with water depth). In order to simulate the working status of the pipeline, a pressure with a value of 200 kPa driving the crude oil flowing in the pipeline is applied to the crude oil.

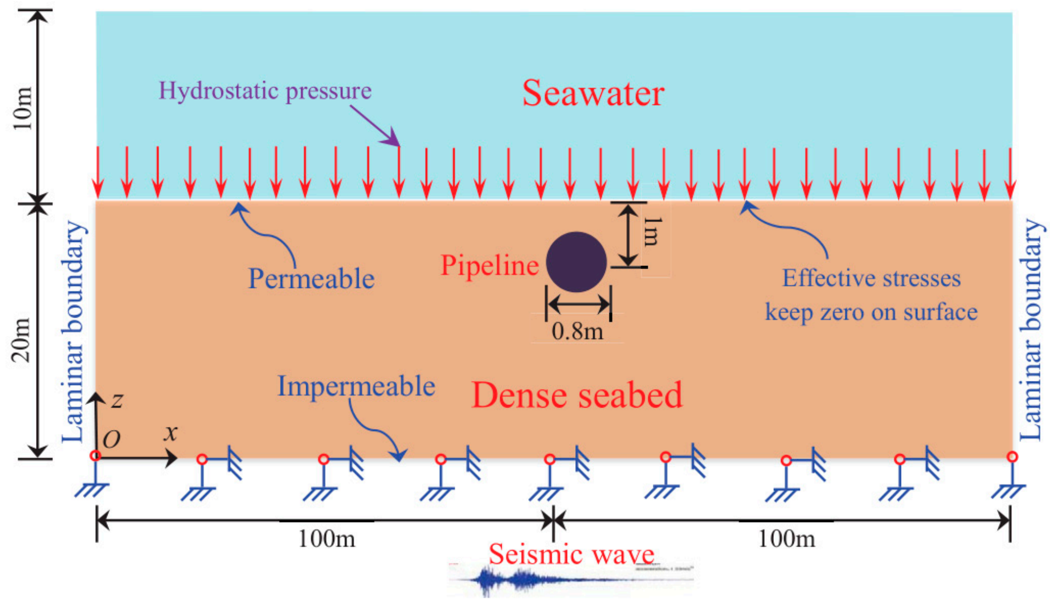


Figure 1. Sketch map of the pipeline-seabed system adopted in computation. A submarine pipeline is buried in the dense seabed foundation. Only the hydrostatic water pressure is applied on the surface of seabed, and the laminar boundary condition is applied on the two lateral sides.

The FE mesh system of the pipeline-seabed used in computation is illustrated in Figure 2. In total, 23,316 four-node elements are used. In the zone around the pipeline, the size of elements (0.02–0.2 m) are much smaller than that in the other zone (0.5–2.0 m). In the mesh system, the pipeline treated as impermeable and rigid steel circle (thickness = 2 cm), and the crude oil in it is also meshed. Two typical point A and B are labelled in Figure 2 to demonstrate the characteristics of seismic dynamics of seabed soil near to the pipeline thereafter.

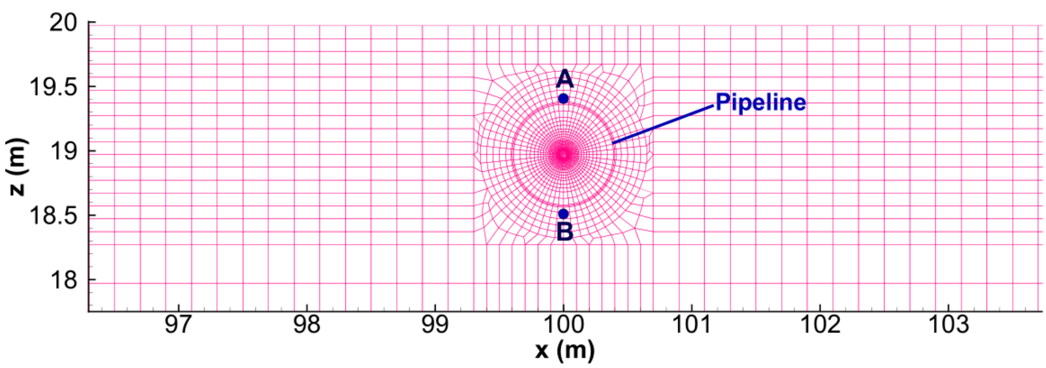
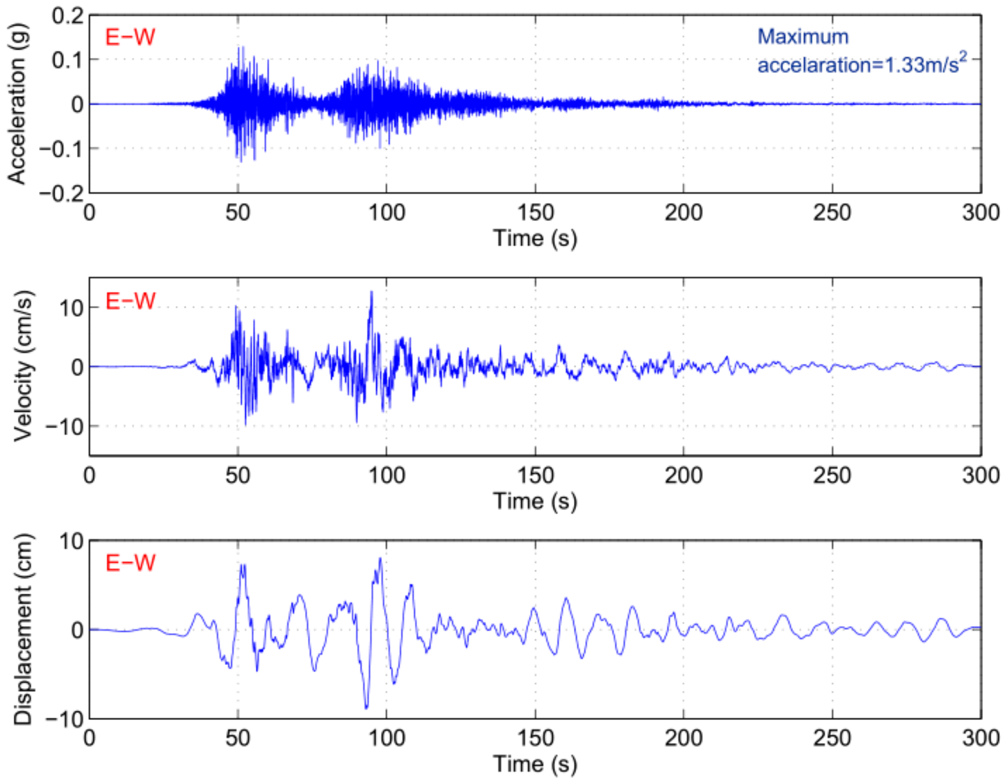
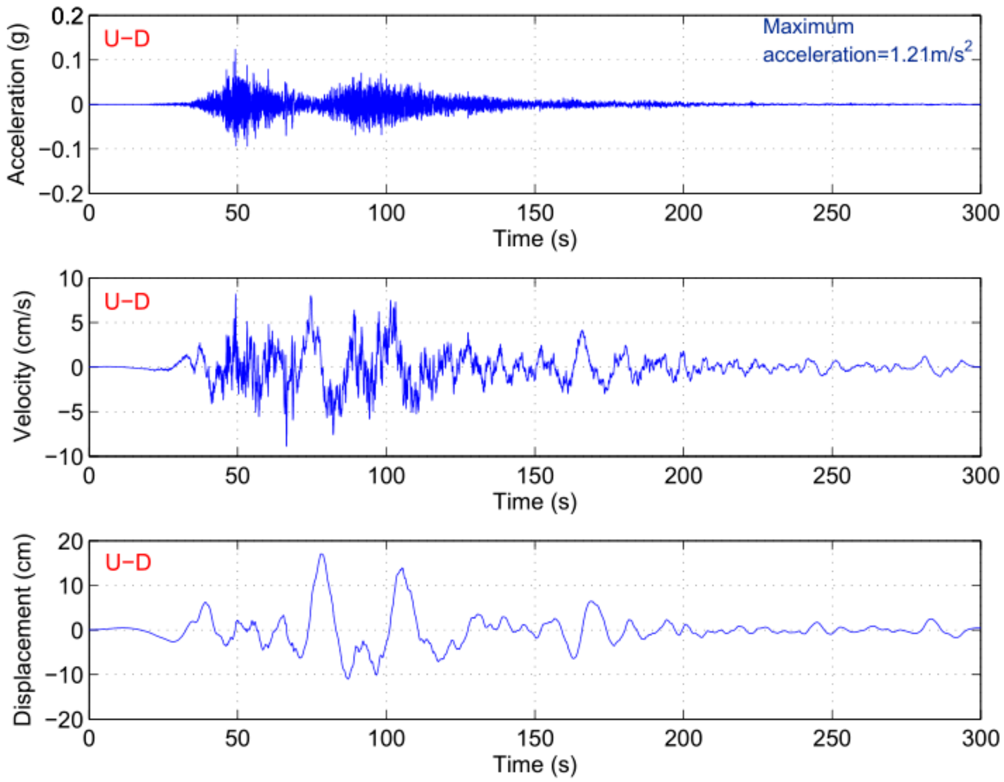


Figure 2. Mesh system of the pipeline-seabed in computation (Noted: The crude oil in the pipeline is also considered, and only the mesh around the pipeline is shown).

In seismic analysis, the seismic wave truly recorded in offshore area would be the best choice to be the input seismic excitation (definitely better than a synthetic seismic wave based on an acceleration response spectrum). Here, the recorded seismic wave at the observation station MYGH03 (141.6412E, 38.9178N, buried depth = 120 m, at Karakuwa, Japan), which is near to the Pacific coastal line in Japan, 311 off-Pacific coast of Tohoku earthquake (M_L = 9.0), is adopted as the input seismic wave (Figure 3). The input horizontal (E-W) and vertical (U-D) seismic acceleration wave are applied on the bottom of the seabed foundation simultaneously.



(a) Horizontal direction



(b) Vertical direction

Figure 3. Input seismic wave after wave filtering adopting the recorded seismic wave at the station MYGH03 (141.6412E, 38.9178N, buried depth = 120 m) at Karakuwa, Japan during 311 off-Pacific earthquake event. Noted: Noncausal butterworth filter is used; filtering range: f ≤ 0.03 Hz and f ≥ 30 Hz.

In offshore area, there is not only loosely deposited seabed soil, but also relative dense seabed soil. For example, the hard layer sand widely distributes in the seabed floor at the Yellow River Estuary, Bohai, China (Zhang et al. (2009) [45]). Dense seabed soil generally is formed due to the multi-process of sand liquefaction-post densification under ocean wave or seismic wave. Previous investigations indicated that poro-elastic model was applicable to describe the behavior of dense seabed soil, so long as the magnitude of external loading is not too great. In this study, poro-elastic model is used for the dense seabed foundation (property parameters are listed in Table 1). Generally, marine pipeline is made of steel (density = 7.85 g/cm^3). Therefore, it can be modelled by elastic model. Here, the pipeline is considered as a kind of impermeable medium without porosity. The crude oil transported by the pipeline is considered as a kind of incompressible and fluidized elastic medium with a small value of Young's elastic modulus. It means v = 0.5 and porosity n = 1.0. The density of crude oil is set as 0.85 g/cm^3, which is significantly less than that of water. In computation, a great value of permeability 1.0×10^{-1} m/s is given to the crude oil due to the fact that there is no a solid medium to block the flowing of crude oil in pipeline. In this study, the flowing process of crude oil in pipeline cannot be modelled in 2D condition. Consideration of the crude oil helps determine the effect of the crude oil mass on the seismic dynamics of pipeline-seabed system. In previous literature, such as Ling et al. [29], Luan et al. [30], and Zhang and Han [31], the pipeline is set as empty without any mass, resulting in that the effect of the mass of crude oil on the seismic dynamics of pipeline-seabed system is ignored. In this study, the consideration of crude oil in pipeline actually is an innovative point relative to previous studies.

Table 1. Model parameters of seabed foundation, pipeline and crude oil.

Parameter	Seabed	Pipeline	Crude Oil
Elastic modulus E (MPa)	20	200×10^3	1×10^{-1}
Poisson's ratio v	0.33	0.25	0.5
Porosity n	0.4	0	1.0
Permeability k (m/s)	1.0×10^{-5}	0	1.0×10^{-1}
Saturation Sr (%)	98	0	100
Density ρ (g/cm^3)	2.65	7.85	0.85

In computation, the density of pure pore water in seabed soil is 1.0 g/cm^3, and the bulk modulus is 2.24×10^9 Pa. The saturation S_r is set as 98% due to the fact that there are more or less NH3/CH4 or air bubbles in real seabed soil. It has been widely recognized and accepted that Biot's equation can accurately describe the mechanical behavior of seabed soil when its saturation is greater than 95% by introducing a parameter, bulk of compressibility $\beta = \frac{1}{K_f} + \frac{1-S_r}{p_{w0}}$, where $K_f = 2.24 \times 10^9$ Pa is the bulk modulus of pure water, S_r is the saturation of soil, and p_{w0} is the absolute water pressure. Furthermore, the effect of temperature on properties of soil and pore water is not considered. Elastic modulus, permeability, and saturation of seabed soil are constant in computation, not depending on the confining pressure.

For loosely deposited seabed foundation, the poro-elastic model is not applicable to describe its complicated behavior. In this circumstance, an elasto-plastic model must be used. The seismic dynamics of marine pipeline buried in loosely deposited seabed soil is an interesting topic. It would be further studied by FSSI-CAS 2D in the future adopting advanced elasto-plastic models.

4. Results

4.1. Initial Status

Before arrival of the seismic wave, there is an initial status for the pipeline-seabed foundation system. This initial status should be taken as the initial condition for the seismic dynamics analysis thereafter. The distributions of displacement and effective stresses of the pipeline-seabed foundation in the initial status are shown in the Figures 4 and 5. It is clearly observed that the existence of pipeline has significant effect on the distributions of displacement and effective stresses in the seabed foundation around the pipeline. In Figure 4, it can be seen that the vertical displacement of pipeline and crude oil is basically the same, and slightly greater than that of surrounding seabed. It is shown that the pipeline-crude oil system slightly subsides relative to its surrounding seabed soil.

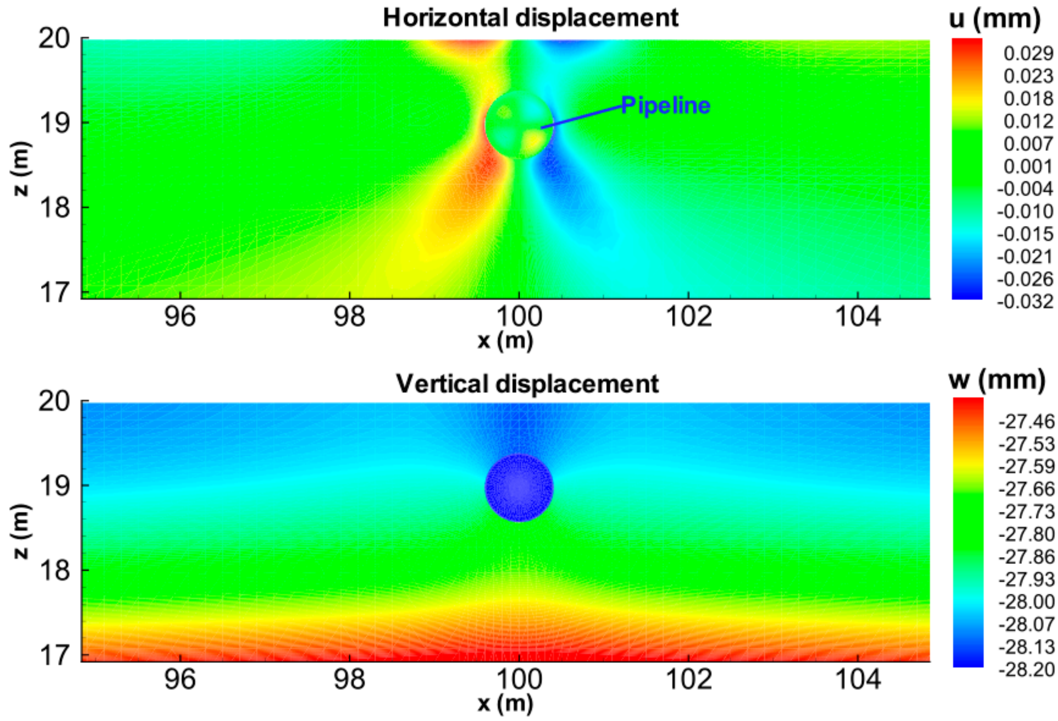


Figure 4. Displacement distribution of the pipeline-seabed in consolidated status. The effect of the pipeline on horizontal displacement is obvious, and the pipeline slightly subsides relative to its surrounding seabed soil.

In Figure 5, it is found that the pore pressure is layered in the seabed foundation due to the fact that the pipeline is made of impermeable steel. The driven pressure of crude oil (200 kPa) in the pipeline is isolated with the pore pressure in the seabed outside of the pipeline. There is no excess pore pressure in the initial status before seismic wave arriving. Due to the effect of the pipeline, the distribution of vertical effective stress σ_z' is not layered. However, the zone where the effective stress is affected by the pipeline is limited in the range x = 98 m to 102 m, and z = 16 m to 20 m. In the other zone, the distribution of effective stress is basically layered. Additionally, it is interesting to find that there is a small zone (labelled by red color) in the seabed beneath the pipeline where the effective stress is very small, comparing with that in the zone near to it. The physical mechanism is that some volume of pore water is expelled by the pipeline, resulting in an upward buoyancy applied on the pipeline. As a result, the effective stress in the seabed soil beneath the pipeline of course decreases. In the surrounding seabed soil of pipeline, the magnitude of shear stress is significant (greater than 5 kPa), and the distribution has symmetrical characteristics. Furthermore, there is also shear stress in the pipeline itself. However, there is no shear stress in the crude oil due to the fact that fluid cannot resist shear stress.

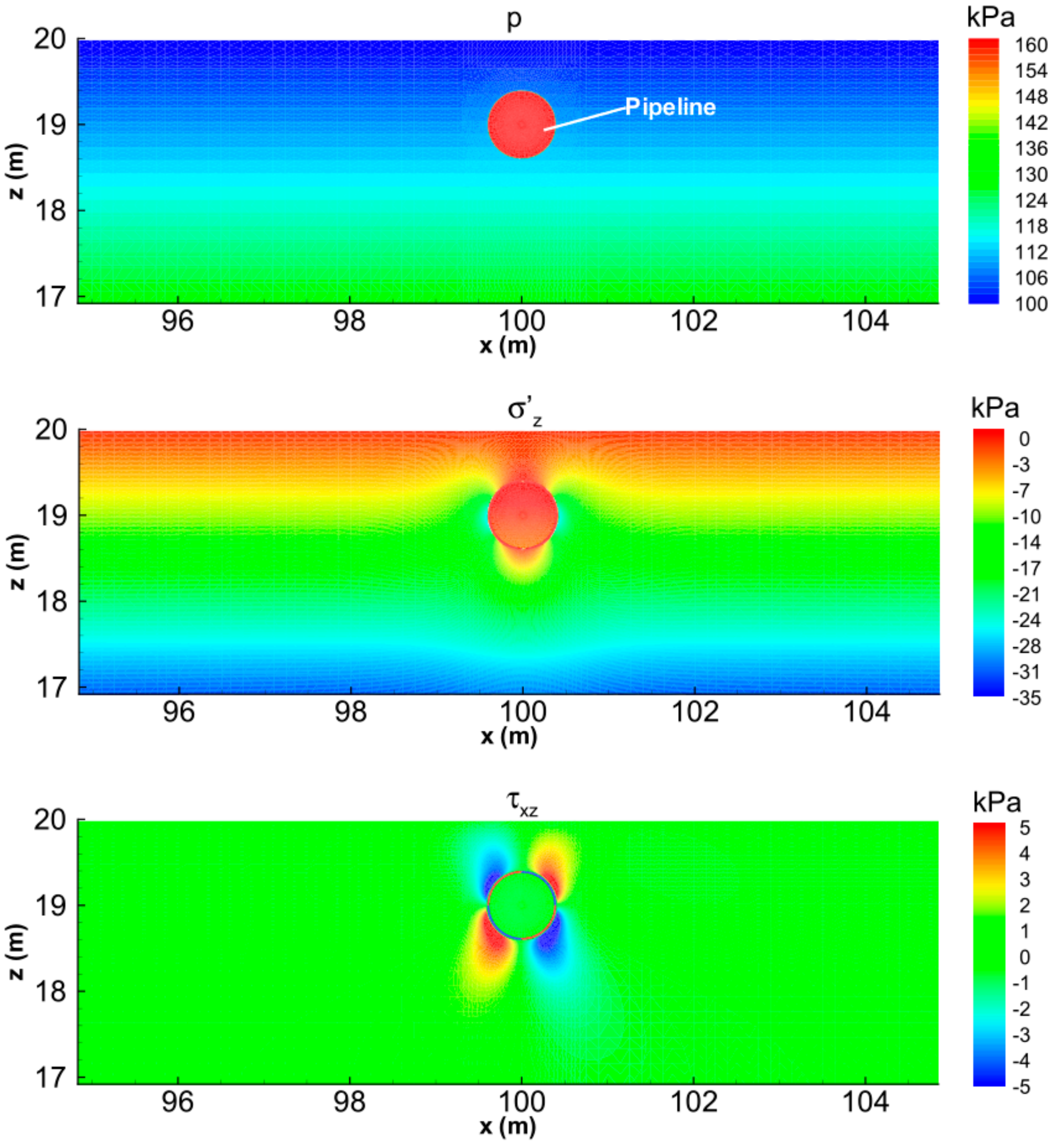


Figure 5. Effective stress and pore pressure distribution of the pipeline-seabed in consolidated status. The distribution of the vertical effective stress σ_z' indicates that an upward buoyancy is applied on the pipeline.

4.2. Seismic Dynamics of Pipeline

Taking the initial status as the initial condition, the seismic dynamics of the pipeline is modelled adopting the coupled numerical model FSSI-CAS 2D. The time history of seismic acceleration of the pipeline is illustrated in Figure 6. It is observed that the peak acceleration of the pipeline is 0.242 g and 0.345 g, respectively, in E-W and U-D direction. Compared with the input seismic wave on the bottom of seabed foundation, the amplification factor of peak acceleration reaches up to 1.78 and 2.79, respectively, in E-W and U-D direction. It is indicated that the acceleration amplification of pipeline buried in dense seabed foundation in vertical direction is stronger than that in horizontal direction. Another interesting phenomenon observed in Figure 6 is that there is significant resonance in the horizontal acceleration response of the pipeline. However, there is no resonance in vertical direction due to the suppression effect of gravity. In horizontal direction, this resonance is very significant after t = 170 s. Even at the end of computation, the vibration of horizontal acceleration of the pipeline does not vanish.

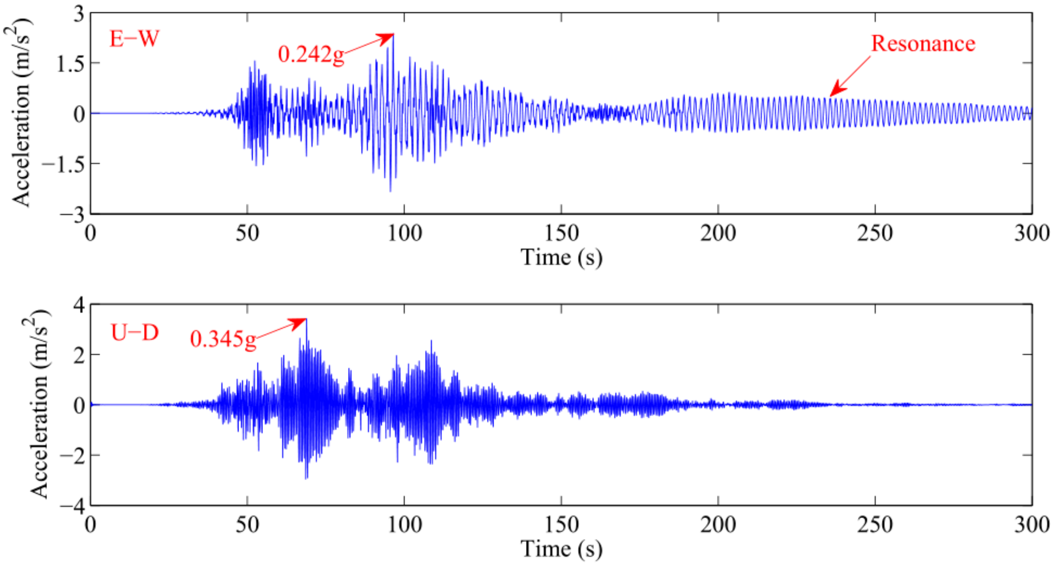


Figure 6. Time history of acceleration of the pipeline responding to input seismic wave. It is shown that there is a significant resonance in horizontal direction.

The time history of displacement of the pipeline responding to the input seismic wave is shown in Figure 7. It is found that the maximum amplitude of horizontal displacement of the pipeline responding to the input seismic wave reaches up to 139.6 mm. Meanwhile, the maximum amplitude of vertical displacement of the pipeline is only 24.6 mm. It is indicated that the displacement response of the pipeline buried in dense seabed foundation is much stronger in horizontal direction than that in vertical direction. Furthermore, the resonance of the horizontal dynamics of the pipeline can also be observed in Figure 7. As demonstrated in Figure 3, the input seismic wave on bottom of the seabed foundation basically vanishes after t = 170 s. However, the horizontal displacement of the pipeline continuously vibrates in a regular way in time domain.

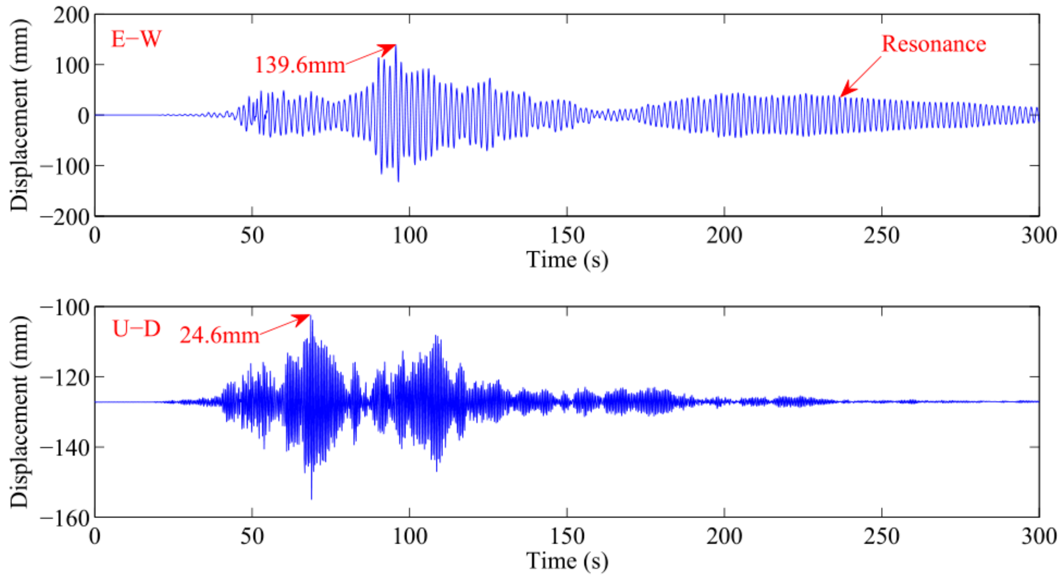


Figure 7. Time history of displacement of the pipeline responding to input seismic wave. It is shown that there is a significant resonance in horizontal direction.

In this study, the computation is actually a 2D case, without the ability to evaluate the risk of pipeline rupture due to excessive stress. The strength and elastic modulus of the steel pipeline is at least greater than 235 MPa, 210 GPa. Comparing with the surrounding seabed soil, the steel pipeline can be treated as a rigid body in computation. In the geometrical model, the thickness of the pipeline is only 2 cm, only two layers mesh are used to discretize the steel wall of the pipeline, as shown in Figure 2. As a result, the stress state in the steel wall of the pipeline would not have enough computational accuracy. If the risk of pipeline rupture is the focus in the future, then the computation must be three-dimensional, and more meshes are necessary to discretize the thin wall of pipeline.

It is necessary to explore the seismic dynamics characteristics of the dense seabed soil near to the impermeable and rigid steel pipeline. In Figure 8, the time history of pore pressure and mean effective stress I_1 on the two typical positions, A and B, labelled in Figure 2, are demonstrated. It is found that the wave form of the time histories on the two typical positions are basically the same, regardless of the pore pressure or the mean effective stress. They are all similar to the wave form of the input seismic wave on the bottom of seabed foundation. Due to the fact that the seabed soil is dense, poro-elastic model is used to describe the behavior of dense seabed soil in computation. There is only oscillatory pore pressure in seabed soil without the build-up of residual pore pressure. These characteristics are completely different compared to that in loosely deposited seabed soil [46,47].

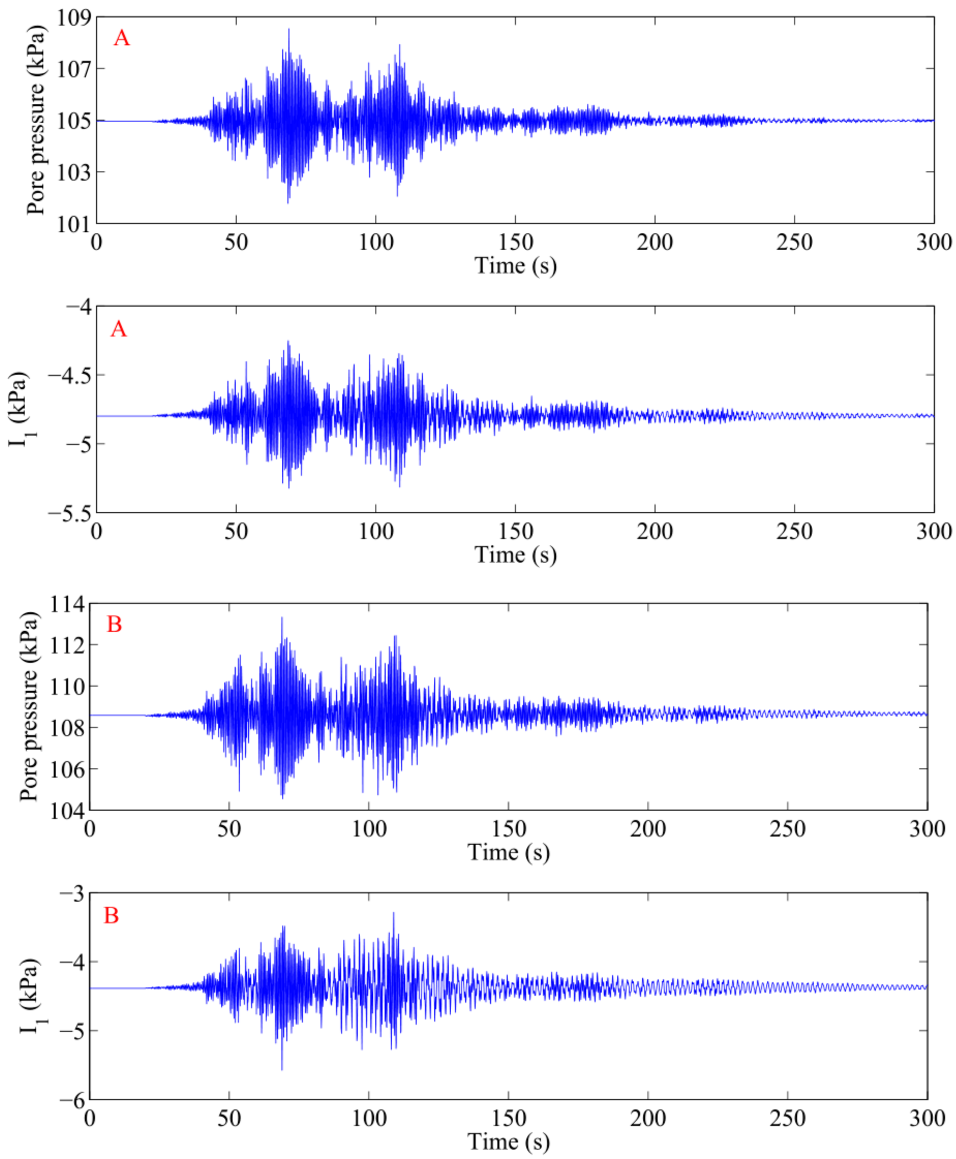


Figure 8. Time history of pore pressure and effective stress I_1 at the two typical position **A** and **B** in the seabed foundation labelled in Figure 2. There is no residual pore pressure built up in dense seabed soil.

Except for the time history of dynamics of the pipeline in time domain, the spectrum characteristics in frequency domain is also necessary to be analyzed. The acceleration spectrum of the pipeline responding to the input seismic wave is illustrated in Figure 9. It is observed that there are two peak values in the spectrum of horizontal acceleration of the pipeline. The corresponding periods for the peak values are 0.6 s and 1.85 s, respectively. Meanwhile, there is only one peak value in the spectrum of vertical acceleration of the pipeline. The corresponding period is also 0.6 s. As observed in Figure 9, it is known that there are two resonance periods for the pipeline-crude oil-seabed foundation system.

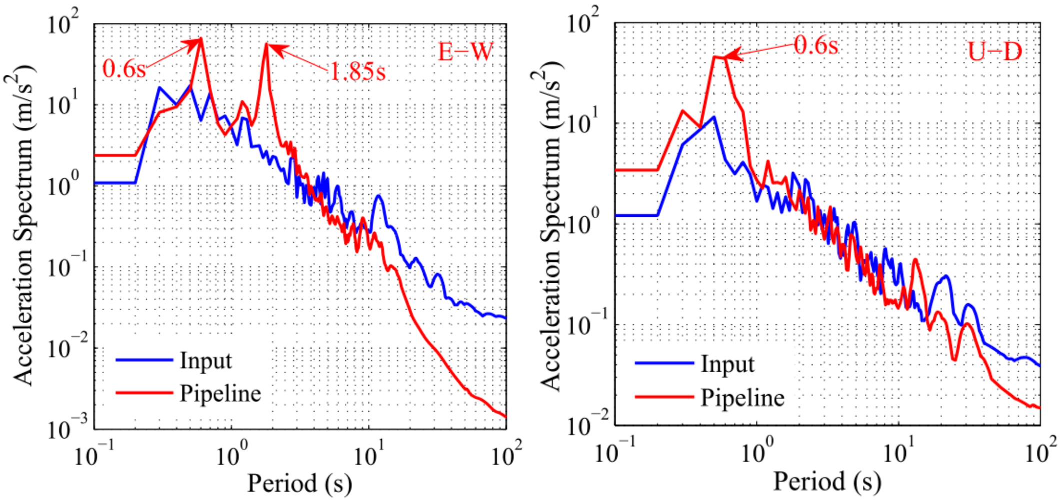


Figure 9. Acceleration spectrum of the pipeline responding to input seismic wave. It is observed that there are two resonance periods (0.6 s and 1.85 s) for the pipeline-crude oil-seabed foundation system.

4.3. Effect of Lateral Boundary Condition

In this study, the laminar boundary condition is applied on the two lateral sides of the seabed foundation. This kind of boundary condition can guarantee that there is no seismic wave reflection on the lateral sides. Laminar boundary without wave reflection on lateral sides is much more approaching the real situation because the seabed is infinite in horizontal in offshore environment. However, it is also interesting to investigate the effect of fixed lateral boundary condition on the seismic dynamics of the pipeline.

As demonstrated in Figure 10, the effect of fixed lateral sides on the horizontal seismic dynamics of the pipeline is significant. However, this effect on the vertical seismic dynamics of the pipeline is negligible. If the fixed lateral boundary condition is applied, the acceleration and displacement of the pipeline in horizontal direction responding to the input seismic wave are both significantly greater than that in which the laminar lateral boundary condition is applied before t = 150 s. Furthermore, the resonance of the pipeline in horizontal is very significant after t = 170 s in the case laminar lateral boundary condition is applied, as illustrated in Figures 6 and 7. It is found in Figure 10 that there is also resonance phenomenon if the lateral sides of seabed foundation are fixed. However, the amplitude of acceleration and displacement of the pipeline are generally less than that if the laminar lateral boundary condition is applied. Therefore, it is concluded that the peak horizontal acceleration and displacement of marine pipeline will be overestimated. Meanwhile, the seismic wave-induced resonance of marine pipeline will be underestimated if fixed lateral boundary condition is applied to seabed foundation. The lateral boundary condition without seismic wave reflection, such as laminar boundary condition or absorbing boundary condition, should be used in computation.

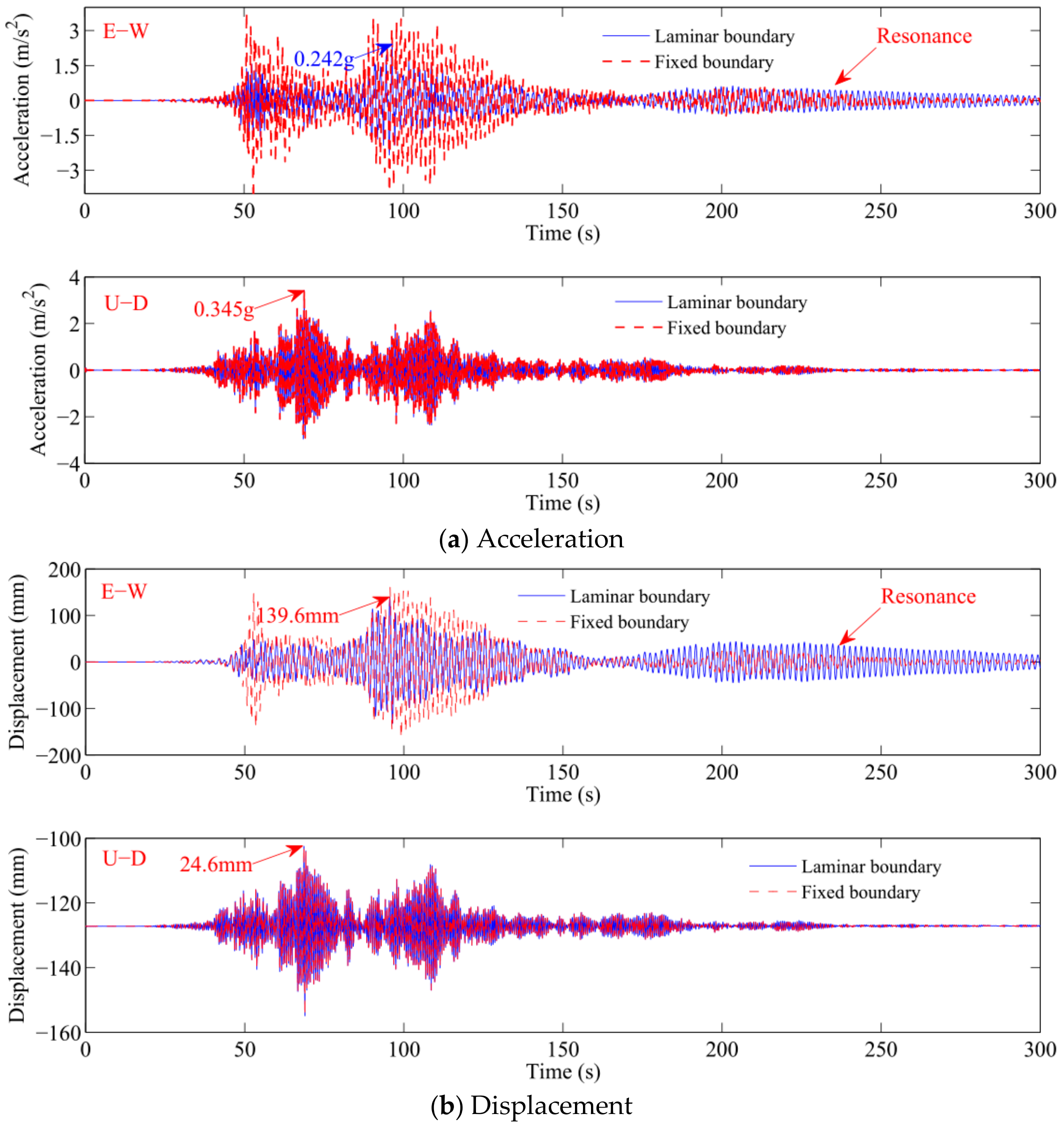


Figure 10. Effect of the fixed lateral side boundary on the dynamics of pipeline. It is shown that there is a significant adverse effect of the fixed lateral boundary condition on the horizontal dynamics.

4.4. Comparison with Pipeline-Gas System

In the practice of engineering, marine pipeline is not only used to transport crude oil, but also natural gas (density is 0.7174 kg/m^3). In this study, the seismic dynamics of pipeline-gas system buried in dense seabed foundation is also investigated under the same excitation of the input seismic wave. The time history of acceleration of the pipeline-gas system is demonstrated in Figure 11. Compared with the result of the pipeline-oil system shown in Figure 6, it is found that the difference of acceleration response between the two cases is not significant. The peak horizontal acceleration (0.242 g) of the pipeline-gas system is only slightly greater than that (0.225 g) of the pipeline-oil system. The peak vertical acceleration of the two systems are basically the same.

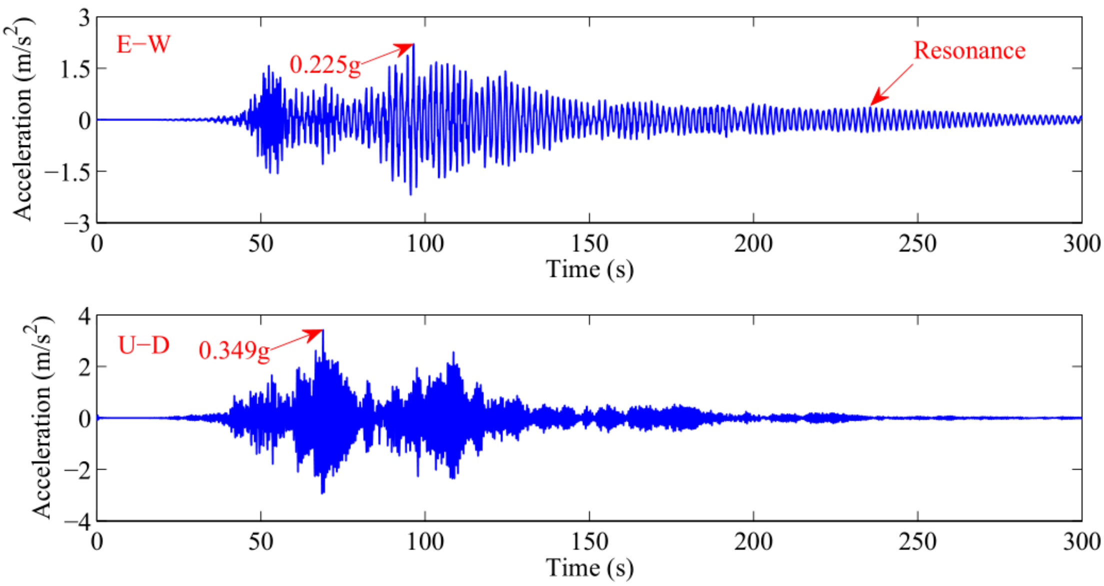


Figure 11. Time history of acceleration of pipeline-gas system responding to input seismic wave. There is also a significant resonance if natural gas is transported by the pipeline.

The comparison of the seismic dynamics between the pipeline-gas system and the pipeline-oil system in frequency domain is further illustrated in Figure 12. Figure 12 further proves that the difference of seismic dynamics is minor between the pipeline-gas system and the pipeline-oil system excited by the same seismic wave if buried in dense seabed.

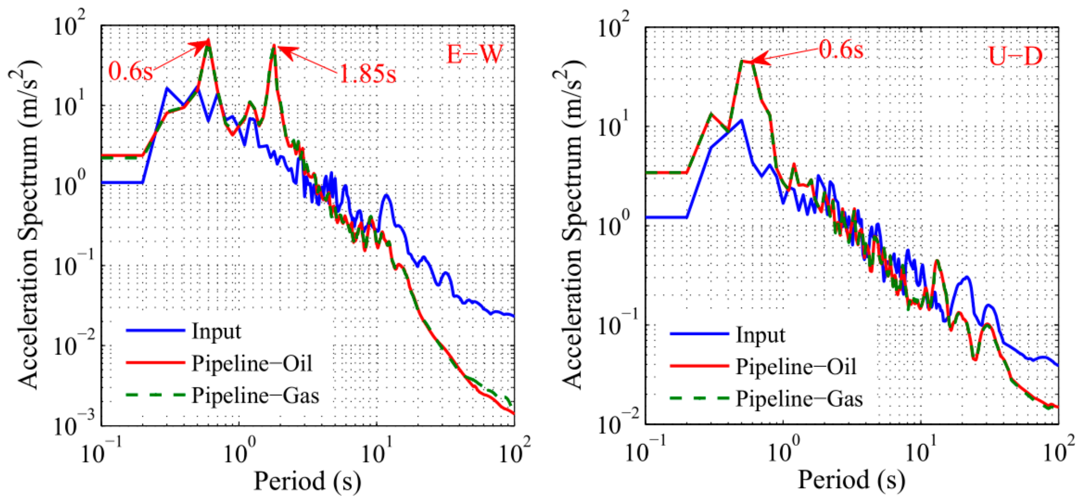


Figure 12. Acceleration spectrum of pipeline-gas system responding to input seismic wave. It is shown that the difference of seismic dynamics of the pipeline-oil system and the pipeline-gas system is minor.

Previous studies have indicated that seabed soil could significantly amplify the peak acceleration from its bottom to its surface. Figure 13 also confirms this amplification effect of the seabed foundation. It is observed that the peak acceleration in horizontal and vertical direction generally increases with the distance to the bottom of seabed foundation. It is also found that the amplification effect of the seabed foundation basically is the same, regardless of pipeline-oil system or pipeline-gas system. Adopting a perspective considering time history, spectrum of acceleration of the pipeline, as well as the amplification effect of seabed foundation, it is found that the difference of seismic dynamics of pipeline-oil system and pipeline-gas system is minor.

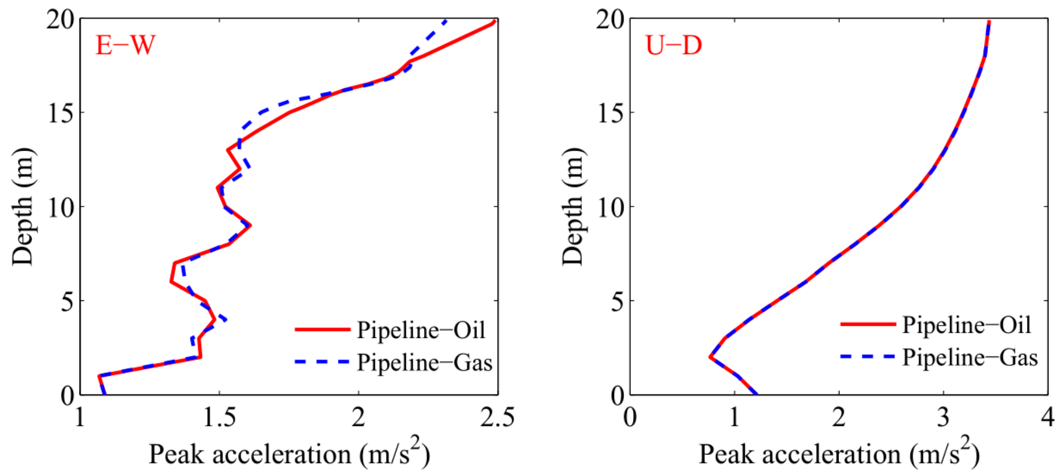


Figure 13. Amplification effect of the seabed soil along depth. It is confirmed that the seabed foundation has significant amplification effect to the input seismic wave in both horizontal and vertical direction.

5. Conclusions

In this study, taking the coupled numerical model FSSI-CAS 2D as a tool, the seismic dynamics of a marine steel pipeline transporting crude oil or natural gas buried in dense seabed soil is investigated. The computational results indicate that the marine steel pipeline buried in dense seabed soil strongly responds to seismic waves. The response peak acceleration of the pipeline could be twice of the peak acceleration of the input seismic wave. There is only oscillatory pore pressure in the dense seabed soil surrounding the pipeline without the build-up of residual pore pressure under the excitation of seismic wave. The resonance phenomenon is very significant in the horizontal dynamics of the pipeline. However, there is no resonance for the vertical dynamics of the pipeline. Fixed lateral boundary condition on seabed foundation has ill-natured effect on the computational results. Any type of lateral boundary condition which could avoid the wave reflection, such as laminar boundary and absorbing boundary, should be used in computation. It is also found from the computation results that the difference on the seismic dynamics of marine pipeline between pipeline-oil system and pipeline-gas system is minor. Finally, it is proven that the coupled numerical model is applicable to study the seismic dynamics of marine pipeline.

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