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Study on the influence of seafloor soft soil layer on seismic ground motion

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Abstract. In the complex medium system of sea area, the overlying sea water and the surface soft soil have a significant impact on the seafloor ground motion, which brings great seismic risk to the safety of offshore engineering structures. In this paper, four sets of typical free field models are constructed and established, which are land model, land model with surface soft soil, sea model and sea model with surface soft soil. The dynamic finite difference method is used to carry out two-dimensional seismic response analysis of typical free field based on the input forms about P and SV wave. By comparing the seismic response analysis results of four groups of calculation models, the effects of overlying seawater and soft soil on peak acceleration and acceleration response spectrum are studied. The results show that when SV wave is input, the peak acceleration and response spectrum of the surface of soft soil on the surface and the seabed surface can be amplified, while the overlying sea water can significantly reduce the ground motion. When P wave is used, the effect of overlying seawater and soft soil on peak acceleration and response spectrum of surface and seabed can be ignored. The peak acceleration decreases first and then increases from the bottom to the surface, and the difference of peak acceleration calculated by four free field models is not obvious. The results show that the overlying sea water and the surface soft soil layer have little effect on the peak acceleration of ground motion below the surface.

1 Introduction

Both empirical and theoretical studies of earthquake damage show that the site conditions, especially the soft soil site conditions, are the important factors that affect the aggravation of surface earthquake damage and the significant amplification of theoretical ground motion (Celebi, 1991; Huang et al., 2009; Kubo et al., 2019; Wang et al., 2019). With the development of offshore engineering in recent years, some of them, such as offshore oil platform, cross sea bridge, subsea tunnel, etc., have been developed rapidly. Therefore, dynamic characteristics of subsea soft soil and its influence on the ground motion are paid more and more attention. The current research mainly focuses on the simulation of land-based ground motion. In the seismic response analysis of the actual sea area engineering site, the influence of the self weight stress of the overlying sea water and the action of the overlying saturated soft soil are ignored (Fan et al., 2018), and the one-dimensional frequency domain or time domain seismic response analysis method consistent with the land area engineering is still used (Idriss and Sun, 1992; Streeter et al., 1974; Bardet et al., 2000; Hashash and Park, 2001; Bardet and Tobita, 2001), which is inconsistent with the actual sea area saturated two-dimensional complex medium system. Contemporary studies have shown that the pore water saturation of underwater soil layer has a great influence on the amplitude of vertical in-plane motion (Yang and Sato, 2000; Yang, 2001; Wang and Hao, 2002; Zhang et al., 2012). However, none of these studies considered the effect of the sea water layer on the seismic ground motion in the offshore environment. Boore and Smith (1999) analyzed the seismic records obtained from the undersea seismic survey system deployed off the coast. The theoretical calculation shows that the influence of the sea water layer on the horizontal component of the ground motion can be ignored. Since there are few records of the sea floor movement, some methods have been proposed to simulate the spatial changes of the sea floor movement (Meng, 2007; He et al., 2015). Petukhin et al. (2010) analyzed two real seabed models with and without sea water layer, and concluded that when the thickness of sea water is within 5 km, the effect of sea water layer on Rayleigh wave is significant; when the thickness of sea water is greater than 10 km, the effect of sea water on ground motion can be ignored. Nakamura et al. (2014) used the strong earthquake data recorded on the surface of the Kii Peninsula and near the Nankai Trough to study the abnormal large earthquake amplification in the seabed area. Zhang et al. (2019) deduced the analytical expression of the wave of the seabed foundation site when the P wave or SV wave incident, and thought that the water depth had little influence on the peak value of the horizontal displacement, but the resonance frequency increased with the increase of the thickness of the water layer.

In view of this, in order to study the influence of the self weight stress of the overlying sea water, based on the second development of the finite difference software FLAC3D, this paper constructs four typical two-dimensional dynamic calculation models of the free field, carries out two-dimensional seismic response analysis of the free field, systematically studies the influence of the self weight stress of the overlying sea water and the soft soil layer on the peak value and acceleration response spectrum of the ground motion, through comparative analysis The difference of seismic response analysis results of land free field in sea area. The research results are helpful to reveal the influence mechanism of the saturated soil site on the ground motion, and further deepen and enrich the research progress and achievements in this field.In

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2 Brief introduction of seismic response method based on finite difference method

The quadrilateral element is utilized to divide the dynamic calculation area, the Mohr Coulomb criterion is used for the nonlinear constitutive model of soil, the free boundary is used for the artificial boundary, and the Rayleigh damping is selected for the damping. The dynamic equation (1), (2) are formed according to the node equilibrium condition. After the earthquake load is input, the fast Lagrangian finite difference method is used to solve the equation. The node velocity (3), (4) and node displacement (5), (6) are obtained, and then the next node is calculated. The above process is reiterated until the end of calculation.

$$M_i\ddot{u}_i^{\mathrm{t}}(t)+C_i\dot{u}_i^{\mathrm{t}}(t)+K_i\ddot{u}_i^{\mathrm{t}}(t)=F_{i\mathrm{x}}(t) \tag{1}$$

$$M_i\ddot{v}_i^{\mathrm{t}}(t)+C_i\dot{v}_i^{\mathrm{t}}(t)+K_i\ddot{v}_i^{\mathrm{t}}(t)=F_{i\mathrm{y}}(t) \tag{2}$$

Where: M is the mass matrix, C is the damping matrix, K is the stiffness matrix, u_i、v_i is the node displacement, $\dot{u}_i^{\mathrm{t}}$、$\dot{v}_i^{\mathrm{t}}$ is the node speed, $\ddot{u}_i^{\mathrm{t}}$、$\ddot{v}_i^{\mathrm{t}}$ is the node acceleration, $F_i(t)$ is the external force on the node.

$$\dot{u}_i^{\mathrm{t}}(t+\frac{\Delta\mathrm{t}}{2})=\dot{u}_i^{\mathrm{t}}(t-\frac{\Delta\mathrm{t}}{2})+\frac{\Delta\mathrm{t}}{M}F_{i\mathrm{x}} \tag{3}$$

$$\dot{v}_i^{t}(t+\frac{\Delta t}{2})=\dot{v}_i^{t}(t-\frac{\Delta t}{2})+\frac{\Delta t}{M}F_{i\mathrm{y}} \tag{4}$$

$$u_i(t+\Delta t)=u_i(t)+\Delta t\dot{u}_i(t+\frac{\Delta t}{2}) \tag{5}$$

$$v_i(t+\Delta t)=v_i(t)+\Delta t\dot{v}_i(t+\frac{\Delta t}{2}) \tag{6}$$

3 Dynamic calculation model

Four groups of free field calculation models are designed and constructed, including land layered site model, land layered site model with surface soft soil, sea layered site model and sea layered site model with surface soft soil. The layer thickness and sea water depth of each group of calculation models are presented in Figure 1. In order to effectively analyze the

influence of overlying sea water and soft soil layer on ground motion, the layered soil in the four calculation models in this paper refers to the calculation model of Chen (2016), and in order to simplify the calculation model and improve the simulation accuracy and efficiency, this paper regards sea water as ideal fluid and ignores its viscosity, and realizes the influence of overlying sea water self weight stress by setting dynamic water pressure, The horizontal layered free field of seawater saturated seabed basement is established. Layered soil in the four groups of calculation models uses the same physical and mechanical property parameters (Lan et al., 2012), and the calculation results are shown in Table 1 by using formulas (7) to (9).

$$G = V_S^{\,2}\rho \tag{7}$$

$$V_P = \sqrt{\frac{\lambda + 2G + \alpha^2 M}{\rho}} = \sqrt{\frac{G(2-2\mu')/(1-2\mu') + \alpha^2 M}{\rho}} \tag{8}$$

$$K = V_P^{\,2}\rho + \frac{4}{3}G \tag{9}$$

Where, G is the shear modulus, V_P is the compression wave velocity, K is the bulk modulus, μ' is the Poisson's ratio of soil skeleton, α is the compression parameter of soil, and M is the compression parameter of water.

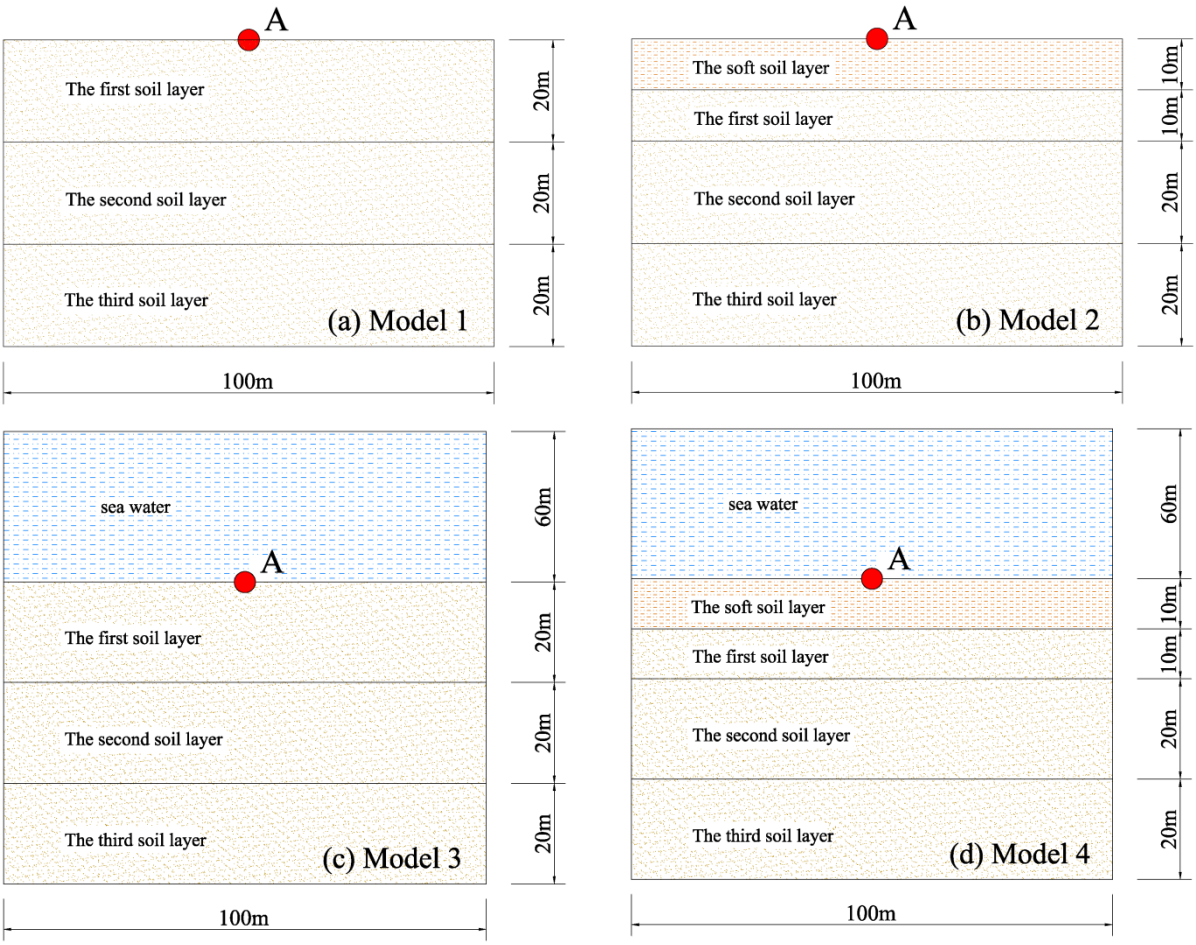


Figure 1. Four typical free field models

Table 1. Parameter of stratified layer model

Basic properties	Soft soil layer	First soil layer	Second soil layer	Third soil layer
ρ（kg/m^3）	1500	1700	2000	2250
G（MPa）	48.6	97	221	951
K（MPa）	354	478	6130	9130
v_s（m/s）	180	240	360	650
v_p（m/s）	1550	1700	1800	2170
C（kPa）	10	10	10	6500
φ(°)	18	30	30	45
μ’	0.5	0.5	0.5	0.5

Four groups of free field calculation models (Figure 1) are meshed by FLAC3D. According to the principle that the size of the grid element should not be greater than 1/10 of the minimum wavelength in the input seismic wave, the wave propagation in the soil layer can be more accurately simulated, i.e

$$\Delta l \leq (\frac{1}{10} \sim \frac{1}{8})\lambda \quad (10)$$

$$\lambda = \frac{V}{f} \quad (11)$$

Where,Δl is the maximum grid size, λ is the minimum input wavelength, f is the highest frequency of seismic wave, V is the wave velocity of seismic wave.

By substituting the soil parameters into the above formula, we can get the value of Δl =3m in the form of SV wave input and Δl =17m in the form of P wave input. In order to improve the simulation accuracy, the mesh size of SV wave input is 2m×2m, and that of P wave input is 5m×5m.

4 Analysis of numerical simulation results of earthquake response

4.1 Base input ground motion

Two representative natural ground motion time history, El Centro wave and Kobe wave, are selected for the input seismic wave of basement. In order to enhance the calculation efficiency, the time window of the input base time history is reduced, the first 20s of the time history curve is intercepted and retained, and the amplitude is scaled at the same time. The two peak values of seismic wave input are adjusted to 0.20g, which can simulate the seismic response under the action of a medium strong earthquake. The acceleration time history curve and the Fourier spectrum of El Centro wave and Kobe wave adjusted by the peak value and duration is given in Figure 2.

4.2 Effect of overlying seawater and soft soil on peak acceleration and amplification coefficien

Taking El Centro wave and Kobe wave as the basic input, SV wave and P wave are used respectively, and the finite difference method introduced in Section 1 is used to carry out the numerical simulation of two-dimensional free field seismic response analysis. The peak acceleration of ground motion at a point A of the surface and seabed surface of four groups of

free field models is calculated. At the same time, we define a peak amplification coefficient β, which is expressed as the ratio of the surface peak acceleration $PGA_{surface}$ to the base input peak acceleration of $PGA_{bedrock}$, i.e：

$$\beta = \frac{\text{PGAsurface}}{\text{PGAbedrock}} \quad (12)$$

Then, we get the peak acceleration and peak amplification coefficient of point a, as showed in Table 2 and Table 3.

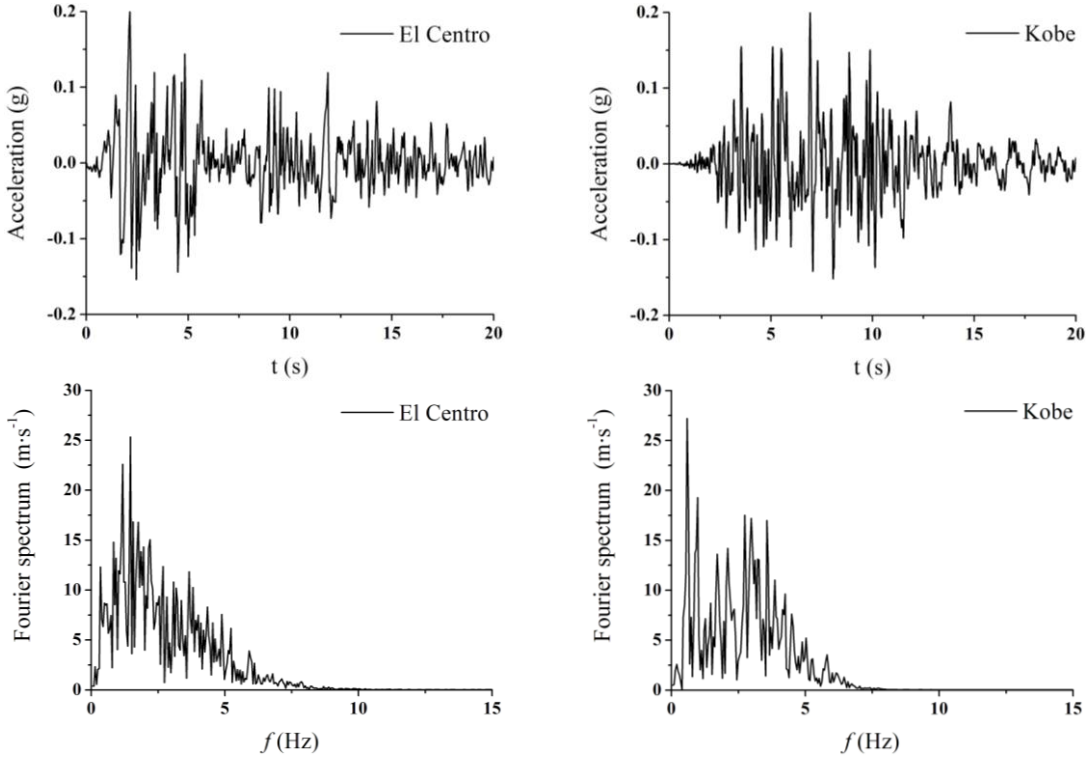


Figure 2. Acceleration time history curve of seismic waves

Table 2. Surface peak acceleration $PGA_{surface}$ of monitoring point A

Base input	Input form	Model 1	Model 2	Model 3	Model 4
El Centro	SV	0.659	0.774	0.651	0.705
	P	0.119	0.120	0.128	0.130
Kobe	SV	0.421	0.534	0.393	0.509
	P	0.119	0.120	0.123	0.123

Table.3 Peak amplification coefficient β of monitoring point A

Base input	Input form	Model 1	Model 2	Model 3	Model 4
El Centro	SV	3.29	3.87	3.26	3.57
	P	0.59	0.60	0.64	0.65
Kobe	SV	2.10	2.67	1.97	2.55
	P	0.59	0.60	0.61	0.62

It can be seen from the above results that when the seismic wave is input at the base in the form of SV wave, the peak acceleration and amplification coefficient β of point a of the four calculation models are obviously different. The results with the largest peak value and amplification coefficient are the land model with surface soft soil, then the sea model with surface soft soil, then the land model, and the sea model with the smallest result. Therefore, it

can be concluded that the surface soft soil can amplify the peak acceleration of the surface and the seabed surface, while the overlying sea water can significantly reduce the ground motion. It can also be seen from the results in Table 2 and table 3 that under the same set of calculation model conditions, the calculation results for El Centro wave as the basic input is higher than those with Kobe wave input

When the seismic wave is input as a base in the form of P-wave, the peak acceleration and amplification coefficient β of point a of the four calculation models are almost the same. The main reason for this phenomenon may be that the overlying sea water and the self weight of the soil layer restrain the seismic response and amplification effect of P wave as vertical input. At the same time, because of the property of P wave and the direction of vibration propagation, the vertical seismic action of P wave is small. However, the SV wave is horizontal input and perpendicular to the propagation direction, which can cause soil shear deformation. Furthermore, it can also be shown that in the seismic design and time history analysis of practical projects, the shear effect of horizontal ground motion is still the primary consideration and attention.

4.3 Effect of overlying seawater and soft soil on acceleration response spectrum

After calculation and analysis, the acceleration response spectra of four groups of free field models at point A of the surface and seabed surface under the input of El Centro wave and Kobe wave in the form of P and SV wave are given, as shown in Figure 3 and Figure 4.

It can be seen from Figure 3 that when El Centro wave is input in the form of SV wave, the acceleration response spectrum reaches the maximum value when the period is 0.6s, and the acceleration response spectrum results of the two groups of sea free field models are generally higher than those of the land model, and the response spectrum results of model 4 are slightly higher than those of model 3. When the Kobe wave is input in the form of SV wave, there are two obvious peaks in the acceleration response spectrum, and the long period components of the acceleration response spectrum of the two groups of sea free field models are generally higher than that of the land model.

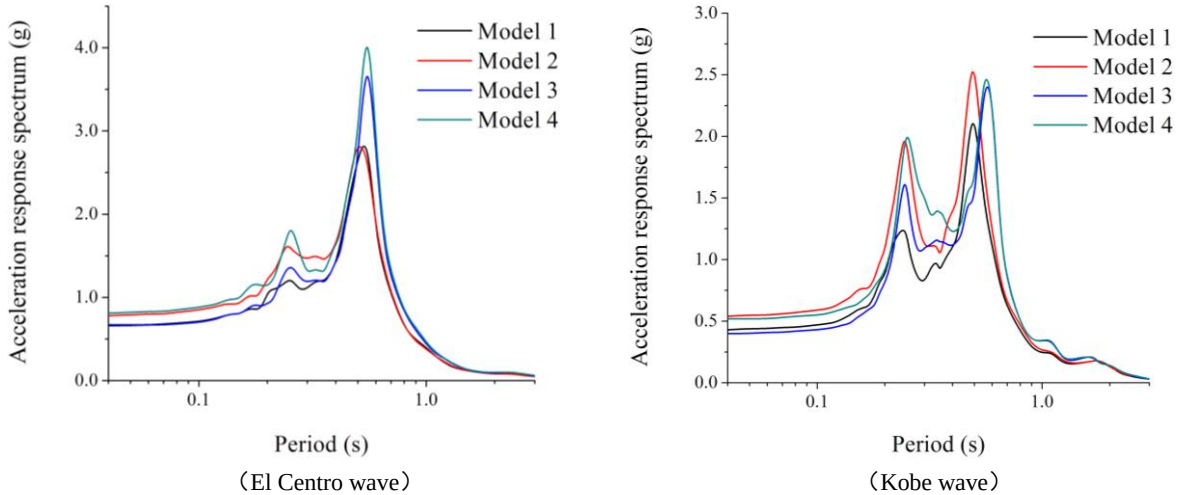
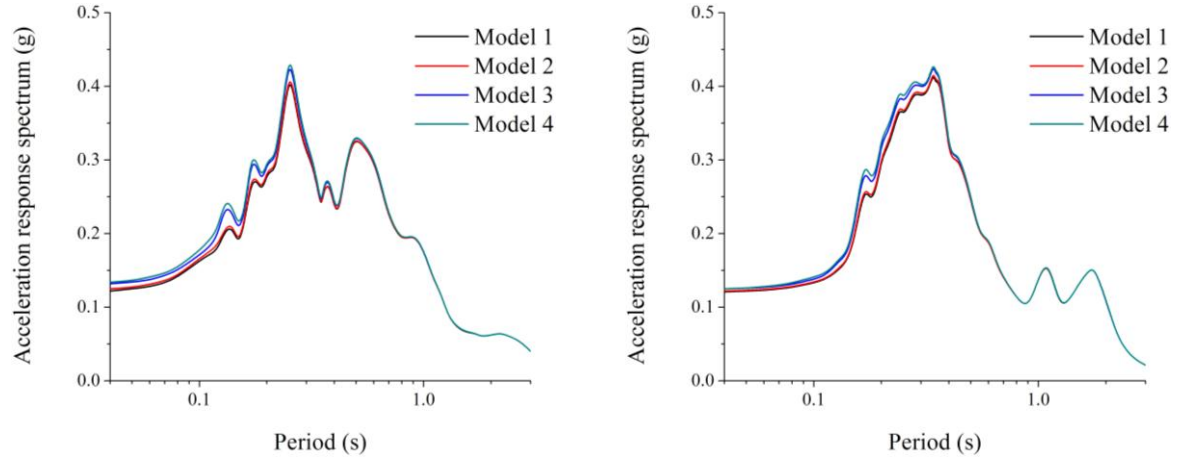


Figure 3. Acceleration response spectrum of point a of four free field models in the form of SV input

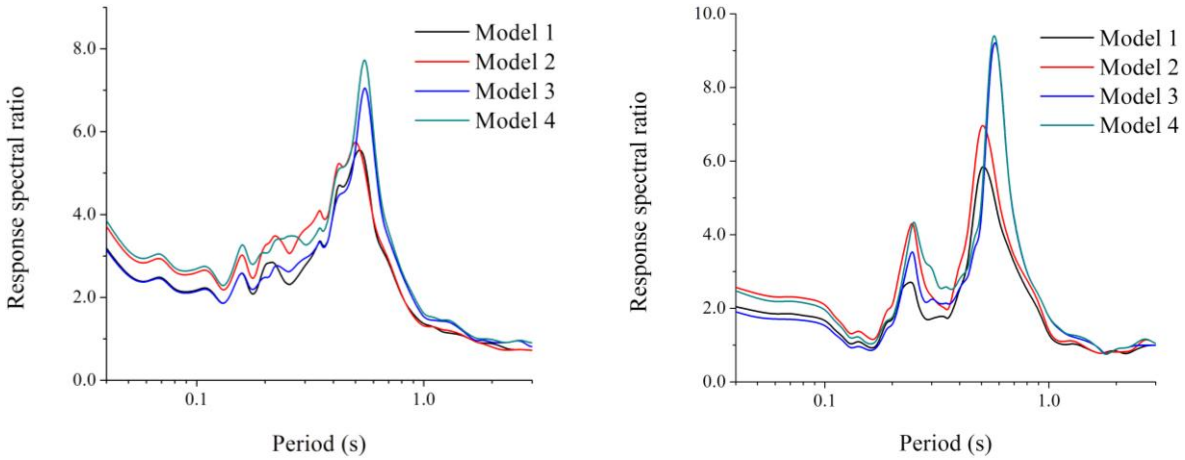


（El Centro wave） （Kobe wave）

Figure 4. Acceleration response spectrum of point a of four free field models in the form of P-wave input

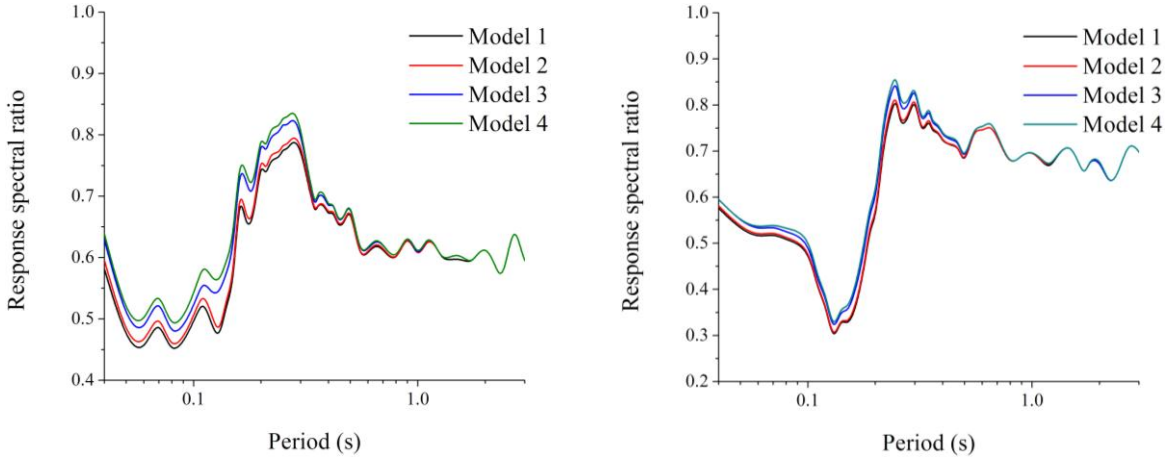
In order to investigate the amplification effect of the surface acceleration response spectrum in each period, the result of the acceleration response spectrum is divided by the base input response spectrum, and the result of the response spectral ratio is obtained, as shown in figures 5 and 6, in which the input form of ground motion in figure 5 is SV wave, and the input form of base ground motion in figure 6 is P wave.

According to figure 3 and figure 5, it can be found that the maximum value of reaction spectral ratio appears at the periodic point of the maximum value of response spectrum for the SV wave as input, and the amplification effect is very obvious, and the maximum amplification factor is about 8 to 10. As the result of the input form of P wave, we find that the period of the maximum acceleration response spectrum of figure 4 is inconsistent with that of the maximum response spectral ratio of figure 6, and the result of the response spectral ratio shows an undulating shape. Generally speaking, the surface response spectrum is not magnified compared with the base response spectrum, and shows a shrinking result in each period.



（El Centro wave） （Kobe wave）

Figure 5. Response spectral ratio between the surface and the base input of SV wave form



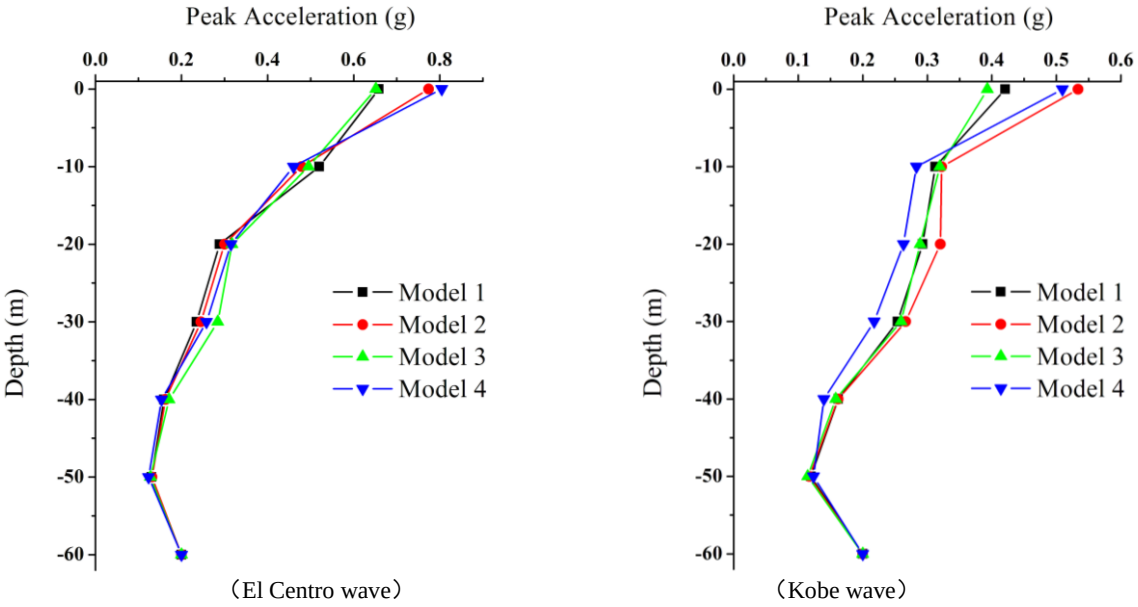
（El Centro wave） （Kobe wave）

Figure 6. Response spectral ratio between the surface and the base input of P wave form

4.4 Variation trend of amplification effect of ground motion along depth

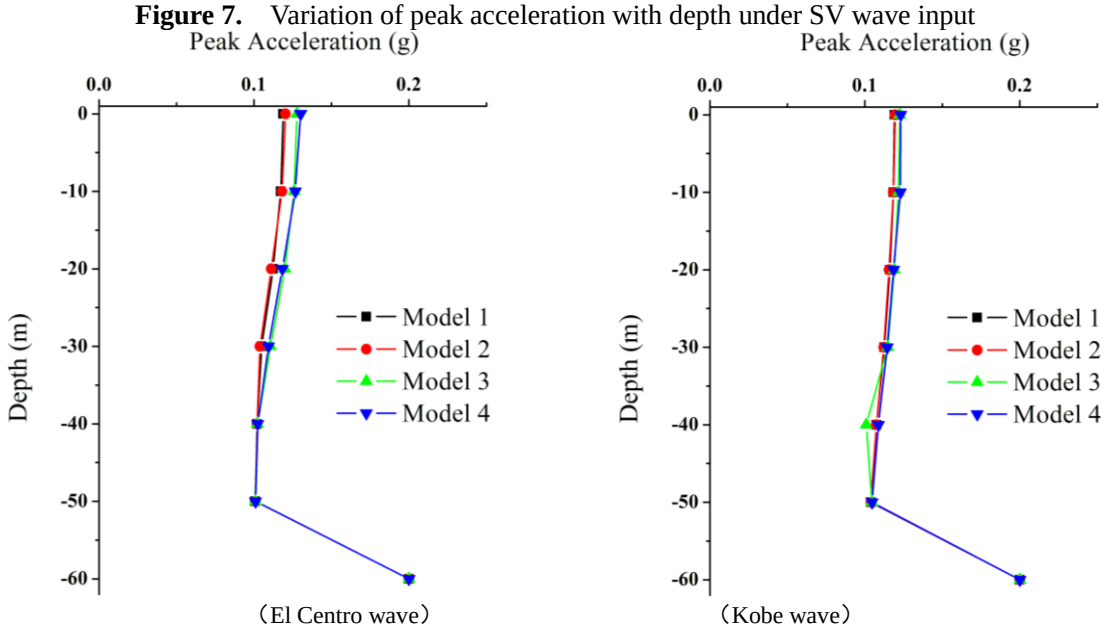
In order to analyze the propagation characteristics and attenuation law of seismic wave from the bottom of typical free field to the surface, in addition to monitoring point A of surface and seabed surface, monitoring calculation points are set every 10m for the above four groups of free field models, and the relationship curve of peak acceleration of four groups of free field models with the depth of soil layer is given. Figure 7 shows the results of SV wave input, and Figure 8 shows the results of P-wave input result. It can be seen from Figure 7 that the peak acceleration of the ground motion from the bottom to the surface decreases first and then increases, which shows that the ground motion changes at 50m underground and generally enlarges at the surface, as shown in Table 4. At the same time, Figure 7 also shows that the peak acceleration difference of four groups of free field models under the surface of 10 meters is small. Because there is no difference in the calculation parameters and physical and mechanical properties of the calculated model site soil, it shows that under the input condition of SV wave, the impact of overlying sea water and surface soft soil layer on the peak acceleration of ground motion under the surface is small.

For the case of P wave input, the difference of peak acceleration among the four groups of free field models is small, and the peak acceleration decreases first and then increases from the bottom to the surface, which shows that there is a change at 50m underground, and it shows a reduction effect on the surface as a whole. Similarly, under the condition of P-wave input, the effect of overlying sea water and soft soil layer on the peak acceleration of ground motion under the surface is unimportant.



（El Centro wave） （Kobe wave）

Figure 7. Variation of peak acceleration with depth under SV wave input



（El Centro wave） （Kobe wave）

Figure 8. Variation of peak acceleration with depth under P wave input

5 conclusion

In this paper, FLAC3D is used to construct four sets of typical free field calculation models. Natural seismic waves of SV and P waves are used as the base input, and the finite difference method is used to carry out two-dimensional seismic response analysis. Four sets of calculation results of peak acceleration and acceleration response spectrum of typical free field are obtained, and the following preliminary conclusions are summarized

(1) When the seismic wave is input in the form of SV wave, the surface soft soil can amplify the peak acceleration of the surface and seabed surface, while the overlying sea water can significantly reduce the ground motion. When the seismic wave is newly input as a base in the form of P wave, the effect of overlying sea water and soft soil on the peak acceleration of the surface and seabed surface is small and can be ignored.

(2) When El Centro wave is input as the base in the form of SV wave, the acceleration

response spectrum results of the two groups of sea free field models are generally higher than those of the land model, and the response spectrum results of model 4 are slightly higher than those of model 3. When the Kobe wave is input as the base in the form of SV wave, the long period component of acceleration response spectrum of the two groups of sea free field models is generally higher than that of the land model. Similar to the peak acceleration results, when the seismic wave is input in the form of P wave, the difference between the four groups of free field models is small.

(3) The peak acceleration decreases first and then increases from the bottom to the surface. In addition to the results of the peak acceleration of the surface, the peak acceleration difference between the layers of the underground obtained by each model is not obvious. For the input of SV wave, the overlying seawater and soft soil layer have little effect on the peak acceleration of ground motion below the surface, and show an amplification effect on the whole at the surface. For the P-wave input, the difference of peak acceleration between the underground layers is small, and the effect of reduction on the surface is overall.

In conclusion, through the comparative analysis of the two-dimensional seismic response analysis results of four typical free field models, it shows that the overlying sea water and the surface soft soil layer have certain influence on the ground motion, which is an important factor that cannot be ignored in the actual engineering seismic design analysis and checking calculation. Therefore, the conclusion of this paper is helpful to improve the understanding of the dynamic characteristics of saturated soft soil and the amplification effect of site ground motion, and has certain reference value for seismic design of sea area engineering.

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

Author contributions. All authors (JL^1, JL^2, XS) contributed to this paper. JL^1 and JL^2 discussed and wrote the original manuscript. JL^2 collected calculating data and established the different models. JL^1 and XS ran the simulations, formal analysis, and data curation. JL^1 made all the figures, and prepared the writing with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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