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Research Article

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Influence of thick soft superficial layers of seabed on ground motion and its treatment suggestions for site response analysis

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Abstract: The thick soft superficial layers of the seabed greatly influence ground motion generally. It is worth studying how to find out the influence of these soft layers on ground motion parameters and determine reasonable seismic fortification parameters for ocean engineering. Numerical experiments of site response analysis are designed using two offshore engineering sites in this study. First, the borehole profiles are selected and stripped layer by layer to generate new profiles. Second, 108 acceleration time histories are synthesized which basically represent the diversity of input motions' amplitude and frequency. Third, a method that can automatically calculate characteristic periods and normalize response spectra is created to improve calculation efficiency. Fourth, peak accelerations, response spectra, and characteristic periods at different depths of the profiles with different stripping depths are calculated. The results show that the thick soft superficial layers can significantly decrease peak ground accelerations and increase characteristic periods, resulting in serious "low-fat" response spectra. The situation can be greatly improved by stripping off the soft superficial layers. After stripping off the thick soft superficial silt layers, if stripping is continued further, the variation in the superficial amplification ratios of peak accelerations and superficial characteristic periods will no longer be drastic, and the superficial amplification ratios and characteristic periods both tend to be mostly the same. The relative deviation of the amplification ratio of peak ground acceleration between a profile stripped and that without stripping can be 143%, and it can be 83% for characteristic period. It is advisable to strip off thick soft superficial layers to perform site response analysis, and the shear force at the bottom of the silt should be considered in engineering based on local seismic activity level, and the silt's and the structure's physical parameters.

Keywords: offshore site, thick soft superficial layer, site response analysis, peak ground acceleration, characteristic period, response spectrum

1 Introduction

Marine projects, such as offshore platforms, cross-sea bridges, wind farms, and undersea tunnels, have laid an important foundation for the rational exploitation and utilization of the seas. With the continuous development of ocean engineering, the problem of seismic fortification has been paid more attention by engineering experts. The engineers usually calculate ground motion parameters with different exceeding probabilities through seismic risk assessment and site response analysis, for use in engineering's an anti-seismic design. Site response analysis is an extremely important work, because site soils have a great influence on ground motion parameters, and in some cases it even exceeds the influence of the earthquake wave's transmission path [1,2]. Compared to land, the sea site response analysis has its own peculiarity and has been studied a lot.

One of the research focuses is the influence of seawater on site response analysis. Compared to land, seawater covers soil layers of the seabed, which has different degrees of influence on the ground motion of soil layers. At present, the general understanding is that for a flat seabed, the seawater layer's influence on horizontal ground motion is negligible [3–6]. For most projects, the influence of the horizontal ground motion on the structure is crucial. Therefore, this study focuses on the study of

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horizontal ground motion, and as a simplified treatment method, the effect of seawater will be ignored in site response analysis. Many other studies focused on how to consider the effect of seawater on saturated soft soil [7]. Although this problem can be solved theoretically by the principle of effective stress [8,9], it is often difficult to obtain relevant parameters in practice [10]. At present, it is generally handled by approximate calculation.

In addition, marine soil layers usually have strong nonlinearity [11–13]. At present, the equivalent linear and the nonlinear methods are mainly used for site response analysis. SHAKE2000 [14] and DEEPSOIL [15,16] are typical calculation programs of the two methods, respectively. In terms of dealing with nonlinear problems, the nonlinear method has advantages. When the input motion is strong or the soil is very soft, the nonlinear method is more accurate than the equivalent linear method, especially for periods between 0.1 and 0.6 s [17–19]. However, according to practical experience and research comparison, the equivalent linear method can also achieve good results in most cases. Furthermore, in engineering practice, response spectra are usually normalized to calculate peak accelerations and characteristic periods. This process can reduce the influence of differences between the equivalent linear and the nonlinear methods. The advantages of the nonlinear method over the equivalent linear method are not obvious [20,21]. This means that the equivalent linear method can also be used to study the nonlinear change of soil layers.

At the bottom of seawater, the seabed is usually covered with thick soft silt. There is no doubt that soft surface soils have a great influence on the calculated results of site response analysis [22–25]. Therefore, how to quantitatively evaluate the influence of the thick soft superficial soil and determine reasonable seismic fortification parameters for ocean engineering are worth studying. In this study, offshore borehole profiles are selected, site response analysis experiments are designed and carried out to study the influence of the thick soft superficial soil of the seabed on ground motion parameters, and suggestions on the treatment of the thick soft superficial layers are put forward from a safe and conservative perspective, so as to provide a reference for site response analysis work in the sea area. Due to its simplicity and high efficiency, the equivalent linear method has been widely used in site response analysis. In China, the commonly used computer program based on the equivalent linear method is LSSRLI, whose principle and precision are not significantly different from that of SHAKE2000 [26]. In order to give suggestions for practical work, this study mainly used LSSRLI for site response calculations, and used the DEEPSOIL program as a comparative reference to gain a more comprehensive understanding of the impact of thick soft superficial layers in the sea area. Unlike previous studies, in this study a huge amount of calculations which contain input motions of various intensities were performed to analyze the variations of peak ground acceleration and characteristic period. It is shown that stripping off the thick soft superficial silt to perform site response analysis is a more advisable way to obtain ground motion parameters for anti-seismic design. After stripping off the thick soft superficial silt, if stripping is continued, the variation in the superficial amplification ratios of peak accelerations and superficial characteristic periods will no longer be drastic, and the superficial amplification ratios and characteristic periods both tend to be mostly the same. Great shear force will appear at the bottom of the silt, and it is suggested that the shear force should be considered in engineering based on local seismic activity level, and the silt's and the structure's physical parameters.

2 Equivalent linear method

Equivalent linear method is a method which uses the equivalence principle to deal with nonlinear problems of the soil profile [27]. When the soil is subjected to an earthquake, its stress–strain relationship presents a complex loop image, and the size, shape, and orientation of each loop will change. The equivalent linear method approximately replaces all loops with an equivalent steady-state loop in the average sense. The strain amplitude of this loop is called equivalent strain amplitude. In another sense, the basic idea of the equivalent linear method is to use an equivalent shear modulus and equivalent damping ratio to replace the shear moduli and damping ratios [28,29] at different strain amplitudes. Since the shear modulus and damping ratio are considered to be independent of strain amplitudes, the nonlinear problem is reduced to a linear problem. Therefore, the equivalent linear method includes two main aspects: one is the equivalent linearization of nonlinear problems; the other is the solution of wave equation in the frequency domain for linear problems. Generally, the equivalent shear moduli and equivalent damping ratios are calculated by the iterative method, and the equivalent shear strain amplitude is taken as 0.65 times of the maximum value of the shear strains at the midpoint of each layer (equation (1)). The iteration will go on until the difference between the equivalent shear moduli and the equivalent damping ratios in the two iterations falls below an allowable value.

$$\Gamma = 0.65\gamma_{n,\max}, \quad (1)$$

where Γ is the equivalent shear strain amplitude, and $\gamma_{n,\max}$ is the maximum shear strain at the midpoint of nth layer.

The program LSSRLI is an equivalent linear frequency domain analysis method. On account of its convenience, reliability, and high efficiency, this program is widely used for site response analysis in China. Figure 1 shows the programming flowchart of LSSRLI [28]. $\bar{G}_{n0}$ is the nth layer's initial equivalent shear modulus, $\bar{\zeta}_{n0}$ is the nth layer's initial equivalent damping ratio, $\bar{G}_n$ is the nth layer's calculated equivalent shear modulus, $\bar{\zeta}_n$ is the nth layer's calculated equivalent damping ratio, and ε is the allowed error.

3 Soil profiles

In this study, two engineering survey borehole profiles, located in the Pearl River Estuary of the South China Sea and the Dalian Bay of the Yellow Sea are used, which are referred to as the Pearl River Estuary profile and the Dalian Bay profile, respectively (as shown in Figure 2). The two boreholes are very far apart, and the straight-line distance between them is more than 2,000 km, and the two borehole sites have different geological evolution histories. So the two profiles have representativeness of offshore borehole profiles to some extent. There are some similarities and differences between the two boreholes. The similarities are: their surfaces are covered by silt, and the thicknesses of the silt are more than 10 m; shear wave velocities of the silt are less than 150 m·s^{-1}; underwater terrains around the boreholes are flat, and are suitable to perform one-dimensional site response analyses; and the soils are mostly soft or medium soft. These characteristics are ubiquitous for offshore borehole profiles. The

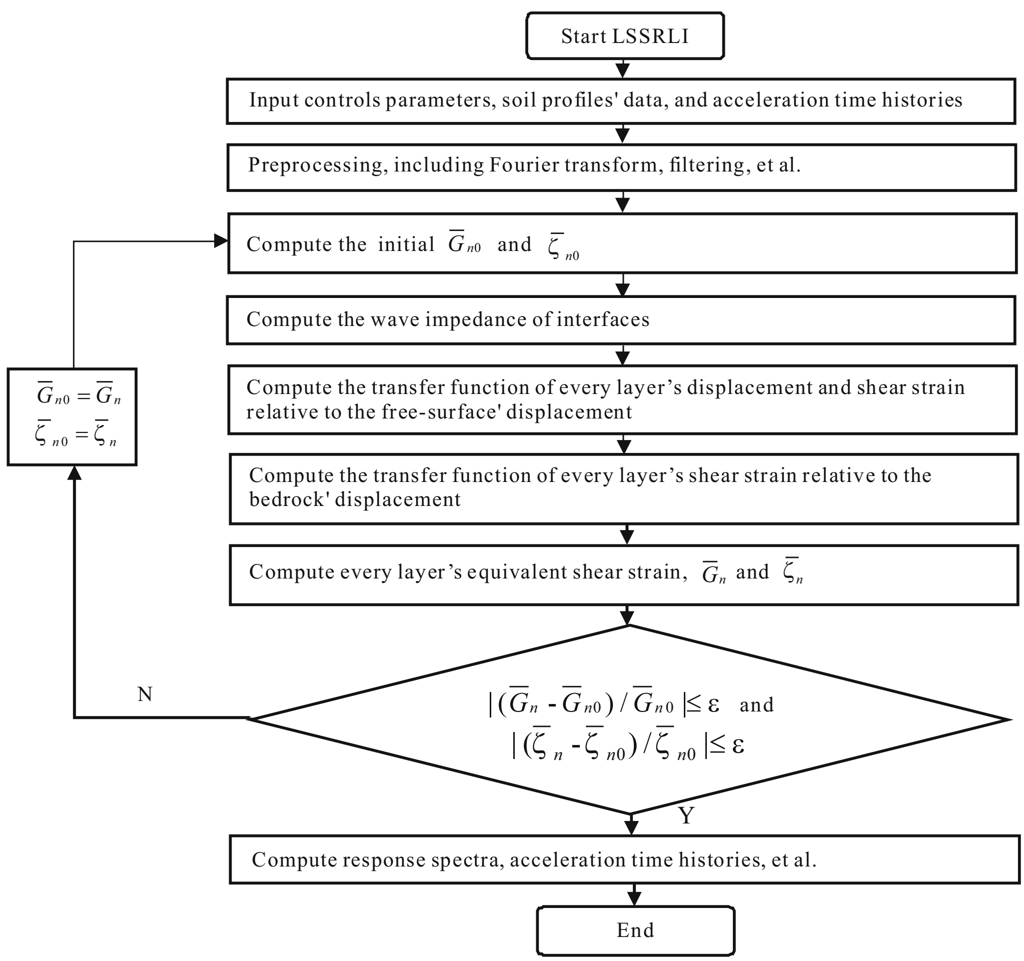

Figure 1: The programming flowchart of LSSRLI.

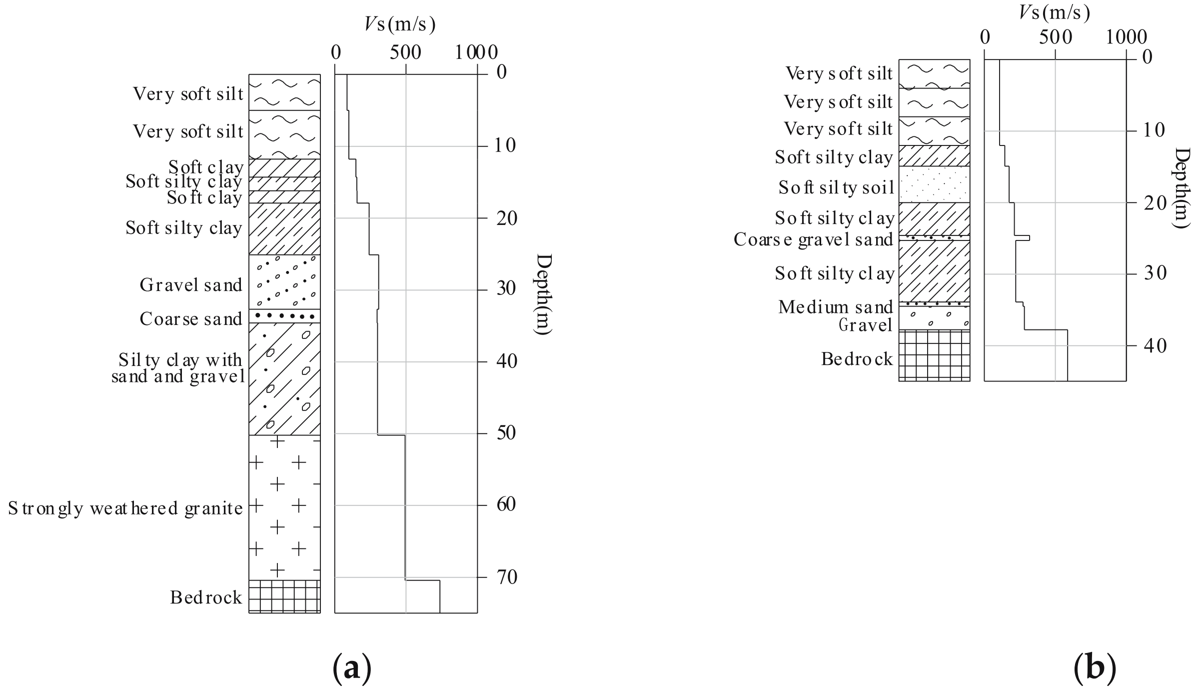

Figure 2: Borehole profiles: (a) Pearl River Estuary profile and (b) Dalian Bay profile.

differences are mainly reflected in geological stratification, buried depth of bedrock, and shear wave velocities. The main sediments of the Pearl River Estuary profile from top to bottom are Holocene marine sedimentary (Q_4^m) silt, Late Pleistocene terrestrial sedimentary (Q_3^{al+pl}) silt or clay, Late Pleistocene marine alluvium (Q_3^{m+pl}), and early Late Pleistocene River alluvium (Q_3^{pl}). The main sediments of the Dalian Bay profile from top to bottom are Holocene marine sedimentary (Q_4^m) silt, Holocene marine sedimentary (Q_4^m) silty clay, Holocene marine sedimentary (Q_4^m) silty soil, Late Pleistocene terrestrial sedimentary silty clay (Q_3^{al+pl}), Late Pleistocene terrestrial sedimentary medium-coarse sand (Q_3^{al}), and Late Pleistocene terrestrial sedimentary gravels (Q_3^{al}). The bedrock depth of the Pearl River Estuary profile and the Dalian Bay profile are 70.4 and 37.8 m, respectively; V_{S30} of the Pearl River Estuary profile and the Dalian Bay profile are about 142 and 146 m·s^{-1}, respectively. The basic condition of the two boreholes is shown in Table 1. In Table 1, V_{S30} is the time-averaged shear wave velocity at top 30 m, Z_{Bedrock} is the depth of the bedrock, $V_{S\text{Bedrock}}$ is the shear wave velocity of the bedrock, $V_{S\text{Topsoil}}$ is the time-averaged shear wave velocity of the soil on top of the bedrock, f_e is the equivalent fundamental frequency of the profile, and the value of f_e equals $V_{S\text{Topsoil}}$ divided by four times of Z_{Bedrock}.

In order to analyze the variation trends of peak ground accelerations and response spectra with depth, this study further divided the soil layers of the two profiles into sub-layers, whose thickness is much smaller, and calculated the peak ground accelerations and response spectra of each sub-layer. Finally, the Pearl River Estuary profile's 11 layers are divided into 101 sub-layers, and the Dalian Bay profile's 11 layers are divided into 91 sub-layers. The two profiles' detailed parameters, modulus

Table 1: Basic condition of the two boreholes

No.	Borehole name	V_{S30} (m·s^{-1})	Z_{Bedrock} (m)	$V_{S\text{Bedrock}}$ (m·s^{-1})	$V_{S\text{Topsoil}}$ (m·s^{-1})	f_e (Hz)
1	Pearl River Estuary borehole	142.3	70.4	737.0	220.7	0.78
2	Dalian Bay borehole	146.0	37.8	587.0	159.6	1.06

where $f_e = V_{S\text{Topsoil}}/(4Z_{\text{Bedrock}})$.

reductions, and damping ratios of the soils are available in Appendix A (Tables A1 and A2; Figure A1).

4 The input motions

The input motions are generated by artificial synthesis using a program named SAW which is widely used in engineering practice in China. This program uses bedrock acceleration response spectra which can be set artificially to generate acceleration time histories. In this program, parameters such as peak acceleration, spectra accelerations, periods, and random phase are required as inputs. In the Code for Seismic Design of Buildings (GB50011-2010) [29], the normalized response spectrum is given as a piecewise function (equation (2)), and its form is shown in Figure 3. In this study, we refer to the form of the normalized spectrum to generate spectra accelerations as input. The peak accelerations are taken as 50, 100, 150, 200, 300, and 400 cm·s^{-2} in turn, and these six levels are named as A, B, C, D, E, and F in the same sequence. According to the Code for Seismic Design of Buildings, the first inflection periods T_0 of response spectra are taken as 0.10 s. The characteristic periods T_g of the response spectra are taken as 0.30, 0.35, 0.40, 0.45, 0.55, and 0.65 s in turn, where these six levels are named as 1, 2, 3, 4, 5, and 6 in the same sequence. The damping ratios of the response spectra are taken as 0.05. Based on 6 levels' peak accelerations and 6 levels' characteristic periods, a total of 36 different bedrock response spectra are combined (as shown in Figure 4), named as A1, A2... F5, F6. These names have specific meanings. For example, A1 means the input peak acceleration belongs to level A and the characteristic period belongs to level 1, and so on.

$$\alpha = \begin{cases} 0.45\alpha_{\max}, & T = 0\text{ s} \\ \dfrac{\eta_2\alpha_{\max} - 0.45\alpha_{\max}}{0.1}T + 0.45\alpha_{\max}, & 0\text{ s} < T < 0.1\text{ s} \\ \eta_2\alpha_{\max}, & 0.1\text{ s} \le T \le T_g \\ \left(\dfrac{T_g}{T}\right)^{\gamma}\eta_2\alpha_{\max}, & T_g < T < 5T_g \\ [\eta_2 0.2^{\gamma} - \eta_1(T - 5T_g)]\alpha_{\max}, & 5T_g \le T < 6\text{ s}, \end{cases} \quad (2)$$

$\alpha_{\max}$ is platform value of the normalized response spectrum. When the damping ratio of the building structure is 0.05, $\gamma = 0.9$, $\eta_1 = 0.02$, $\eta_2 = 1$.

Considering the influence of the random phases, three random phases are taken corresponding to each bedrock response spectrum (as shown in Figure 5). Finally,

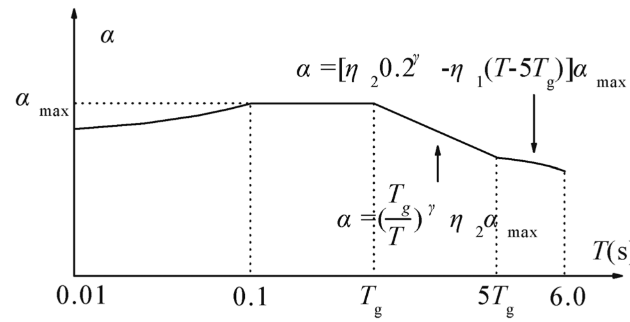

Figure 3: The normalized response spectrum's form in log–log coordinate frame.

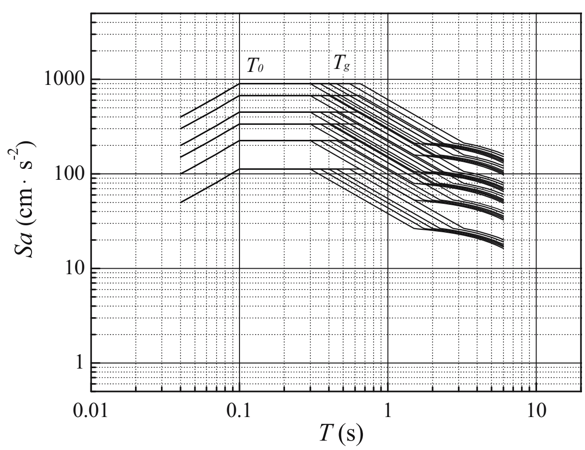

Figure 4: Thirty-six bedrock response spectra corresponding to six levels' peak accelerations and six levels' characteristic periods.

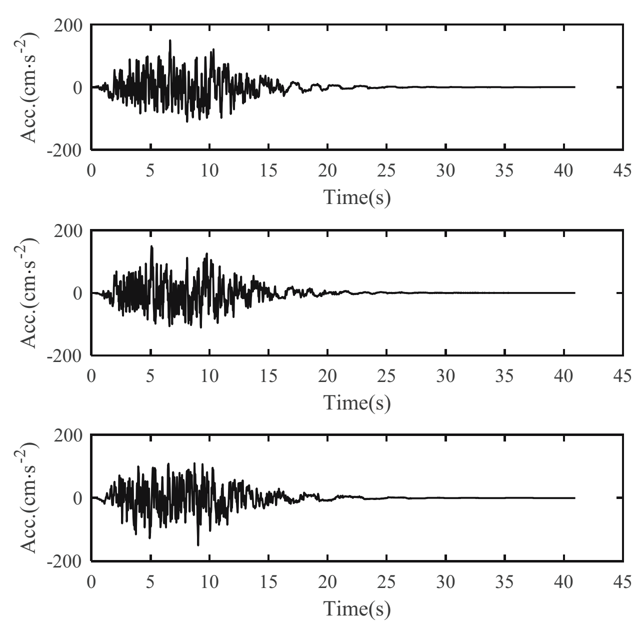

Figure 5: The synthesized C5 level's acceleration time histories of the three random phases.

108 acceleration time histories in total are synthesized, which basically represent the diversity of the input motions' amplitude and frequency.

5 Data processing of site response analysis

To comprehensively analyze the influence of offshore soft superficial soil on peak ground accelerations and response spectra, both borehole profiles are stripped layer by layer from top to bottom to form a series of new borehole profiles (as shown in Figure 6), and site response analyses are performed on these profiles using 108 acceleration time histories as input motions. The Pearl River Estuary profile is stripped of nine layers to form nine new profiles, and the stripping depths are marked as −5, −11.8, −14.3, −16.2, −17.9, −25.1, −32.7, −34.6, and −50.2 m; the Dalian Bay profile is stripped of eight layers to form eight new profiles, and the stripping depths are marked as −4, −8, −12, −14.9, −20, −24.6, −25.3, and −33.9 m.

Through site response analyses, the peak accelerations and the characteristic periods and response spectra of each sub-layer are calculated. Since over 124,000 sub-layer response spectra are obtained from this calculation, calculating the characteristic periods of all response spectra remains a heavy task. The author has created a method that can automatically calculate characteristic periods and normalize response spectra by referring to the provisions of the Code for Seismic Design of Buildings (GB50011-2010) to improve calculation efficiency. The idea of this method is to obtain the characteristic period by iteration. After the platform value of the normalized response spectrum is obtained according to the maximum spectral acceleration, if we assume an initial value of the characteristic period, the descending branch of the normalized response spectrum can be calculated based on equation (2). Then we compare it with the target response spectra. If the descending branch of the normalized response spectrum can envelop the target response spectra, iteration ends; if it cannot envelop, the characteristic period will be increased by an increment, and the next round of iteration will go on. One of the automatically normalized response spectra and its target response spectra are shown in Figure 7.

The amplification ratios between each sub-layer's peak accelerations and input accelerations are calculated. The amplification ratio profiles of different stripping depths and the characteristic period profiles of different stripping depths are plotted for analysis. All amplification ratio profiles and characteristic period profiles are available in Appendix B.

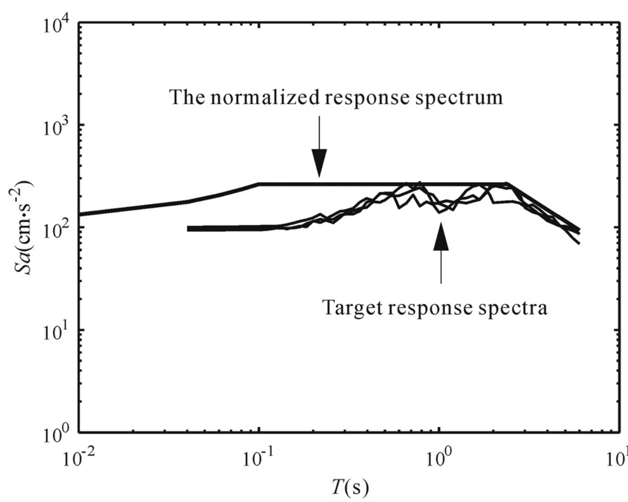

Figure 7: The automatically normalized response spectrum and its target response spectra.

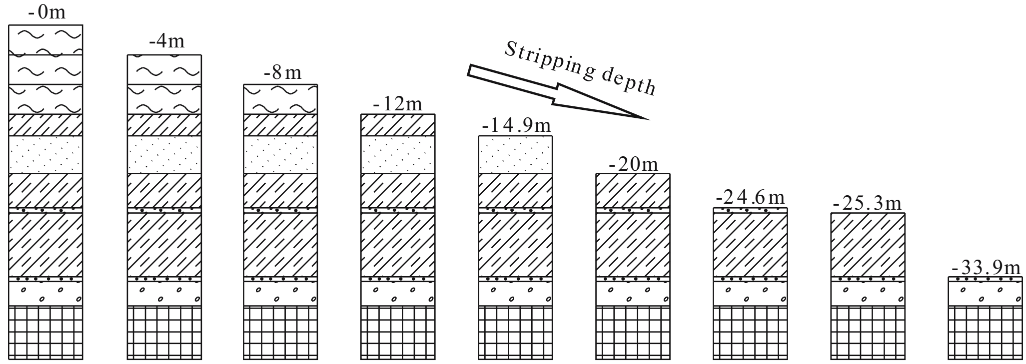

Figure 6: A diagram of the stripping method.

6 Analysis of calculation results

6.1 Analysis of the variation of the amplification ratios of peak accelerations

The analyses in this section are based on the results of the amplification ratio profiles of different stripping depths for the Pearl River Estuary profile and the Dalian Bay profile (as shown in Figure 8; Figures B1 and B2 in Appendix B). In this study, the amplification ratio means the ratio of the peak acceleration of the surface to the bedrock.

When the characteristic periods of the input motion's response spectra are the same, with the increase of the peak acceleration of input motion, the superficial amplification ratios mostly tend to decrease first and then stabilize. This indicates that when the input motions' intensity is weak, such as the input motion of level A, the attenuation effect of the soil to ground motion is not obvious. However, with the increase of the intensity of the input motion, the attenuation effect of the soil to ground motion may become stronger.

When the peak accelerations of the input motions are the same, the superficial amplification ratios tend to increase with the increase in the characteristic periods of the input motions' response spectra. The trend is more obvious, especially in the case of not stripping silt layers. After the silt layers are stripped off, the trend becomes not obvious. It indicates that the increase of the characteristic periods, that is, the increase of the low-frequency components of the input motions will, to some extent, weaken the attenuation effect of the silt to ground motions and makes the peak accelerations of ground motions increase.

When the profiles are not stripped, the superficial amplification ratios are mostly less than 1.0, except in the case of the input motions of level A or B, where the intensity of the input motions is weak. After the silt layers are stripped off, the superficial amplification ratios become more than 1.0. This indicates that the superficial thick soft silt has a strong attenuation effect on ground motions, making the intensity of the superficial ground motions smaller than the intensity of the input motions. After the silt layers are stripped off, the superficial amplification ratios will increase significantly, which are greater than the amplification ratios of the superficial layers of the profiles without stripping, and most of them are also greater than the amplification ratios of the profiles without stripping at the same depth. After stripping off the silt layers, if we go on stripping, the change of the superficial amplification ratios will no longer be drastic and tend to be basically the same.

After two layers of soft soil are stripped off from the Pearl River Estuary profile and the Dalian Bay profile, the amplification ratios mostly reach the maximum, and they are basically greater than the amplification ratios of the profiles without stripping at the same depth. From the safe and conservative point of view, the peak accelerations used for engineering seismic fortification should adopt the maximum values. According to equation (3), the maximum

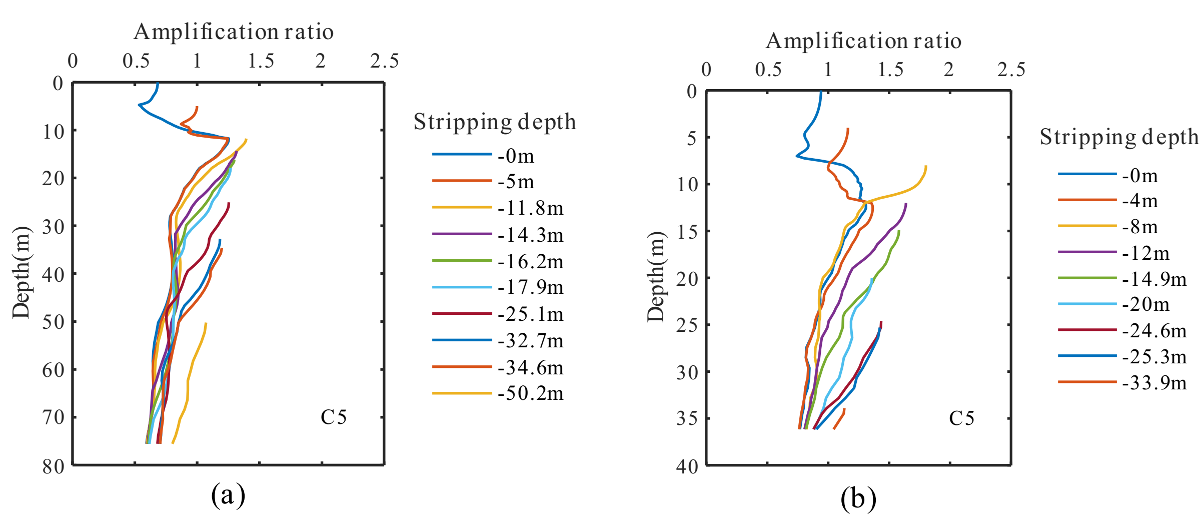

Figure 8: The amplification ratio profiles of different stripping depths under the input motion of level C5: (a) Pearl River Estuary and (b) Dalian Bay.

relative deviation between the superficial amplification ratios of the Pearl River Estuary profile with two layers stripped off and that of the Pearl River Estuary profile without stripping is up to 143%, and the average relative deviation for 36 levels' input motions reaches 80%. The maximum relative deviation between the superficial amplification ratios of the Dalian Bay profile with two layers stripped off and that of the Dalian Bay profile without stripping is up to 120%, and the average relative deviation for 36 levels' input motions reaches 71%. The high values of the relative deviations mainly appear in the case of medium or strong input motions. This indicates that the thick soft superficial layer with shear wave velocity around $100\,\mathrm{m\cdot s^{-1}}$ has a great influence on peak ground accelerations, and that the profiles should be stripped layer by layer to do site response analysis and their results should be compared.

Relative deviation between A and B is defined as follows:

$$\mathrm{RD}_{AB} = \frac{|A - B|}{B}. \tag{3}$$

6.2 Analysis of the variation of the characteristic periods of response spectra

The analyses in this section are based on the results of the characteristic period profiles of different stripping depths for the Pearl River Estuary profile and the Dalian Bay profile (as shown in Figure 9; Figures B3 and B4 in Appendix B).

When the characteristic periods of the input motions' response spectra are the same, with the increase in the peak accelerations of input motions, the superficial characteristic periods mostly tend to increase. This phenomenon is obvious when the silt layers are not stripped off, which indicates that the superficial silt has strong nonlinearity, and the low-frequency components will increase significantly when the input motion becomes more intense.

After the silt layers are stripped off, the superficial characteristic periods will be significantly reduced, which are also smaller than that of the profiles without stripping at the same depth, indicating that the superficial silt can significantly increase superficial characteristic periods. The superficial silt is not taken as bearing layer in engineering practice generally. If we simply take the superficial characteristic periods of the profiles without stripping as seismic fortification parameters, the characteristic periods for seismic fortification will be seriously overestimated. After stripping off silt layers, if we keep stripping, the change of superficial characteristic periods mostly will no longer be drastic and the superficial characteristic periods tend to be mostly the same.

According to equation (3), the maximum relative deviation between the superficial characteristic periods of the Pearl River Estuary profile with two layers stripped and that of the Pearl River Estuary profile without stripping can be 83%, and the average relative deviation for 36 levels' input motions reaches 65%. The maximum relative deviation between the superficial characteristic

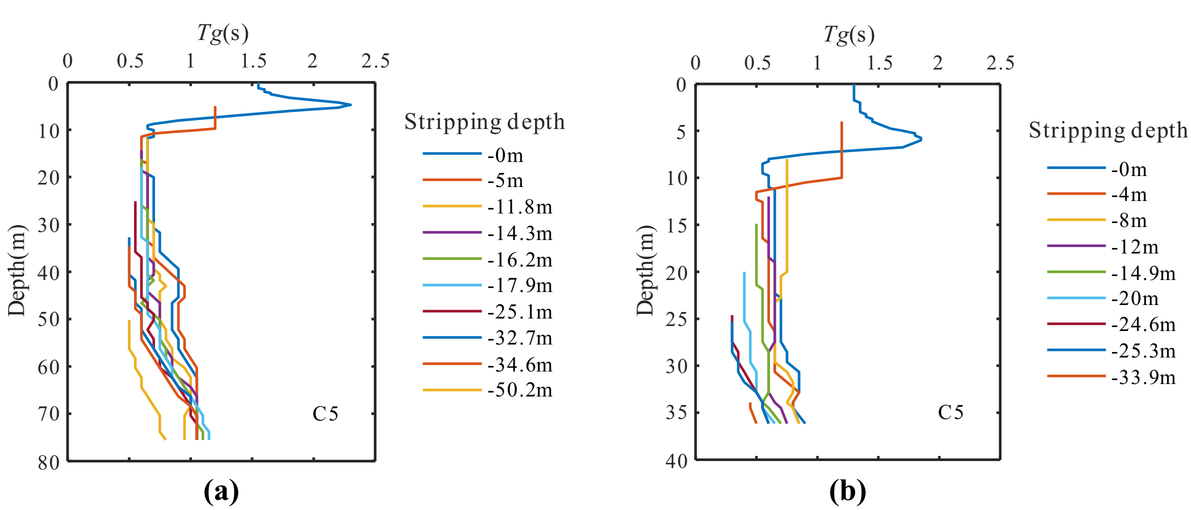

Figure 9: Characteristic period profiles of different stripping depths under the input motion of level C5: (a) Pearl River Estuary and (b) Dalian Bay.

periods of the Dalian Bay profile with two layers stripped and that of the Dalian Bay profile without stripping can be 69%, and the average relative deviation for 36 levels' input motions reaches 48%. The high relative deviation values mainly appear in the case of medium or strong input motions with small characteristic periods.

6.3 Analysis of the variation of response spectra

The spectrum accelerations' amplification ratios between the superficial response spectra and the input are calculated, and the variations of these amplification ratios with stripping depths are plotted.

According to the calculation results of the response spectra, when the input peak accelerations are the same, with the increase of the characteristic periods of the input motions, the long period part of the superficial response spectra will increase basically. When the superficial soft soil of the seabed is not stripped off, the response spectra are "low-fat" [30]. As this phenomenon is mainly affected by superficial silt, it is unreasonable to apply these ground motion parameters to the seismic fortification of construction projects. However, after the superficial soft silt is stripped off, the medium-long period part of the response spectra will decrease, the medium-short period part of the response spectra will increase (as shown in Figure 10), and the phenomenon of "low-fat" response spectra will be greatly improved, indicating the importance of the stripping off of the thick soft superficial soil. With the increase of the stripping depth, the superficial response spectra with the same input motion tend to be basically consistent, and the nonlinear change of soil basically tends to be stable.

7 Comparison with results calculated by DEEPSOIL

In order to better understand the nonlinear performance of offshore soil, and verify the rationality of the calculation results of the equivalent linear program LSSRLI, this study performed site response analysis using the DEEPSOIL nonlinear method on the profiles without stripping and the profiles stripped off of two soft superficial layers with the same input motions. The pressure-dependent hyperbolic model (MKZ) was selected as the default soil model in DEEPSOIL. As an example, the amplification ratio profiles and characteristic period profiles of the Pearl River Estuary profile without stripping and the profile stripped off of two soft superficial layers with C5 level's input motions are shown in Figure 11. The results show that there is a certain degree of difference between the nonlinear method and the equivalent linear method, but the variation rules are basically the same. The nonlinearity of the soil is generally more obvious in the calculation results of the nonlinear method. For the calculation results of the nonlinear method, when the profiles are not stripped, peak ground accelerations are seriously small, characteristic periods are seriously large, and the response spectra are "low-fat." When the soft superficial soil is stripped off, the difference between the calculation results of the equivalent linear method and those of the nonlinear method becomes much smaller. As an example, the superficial response spectra of the Pearl River Estuary

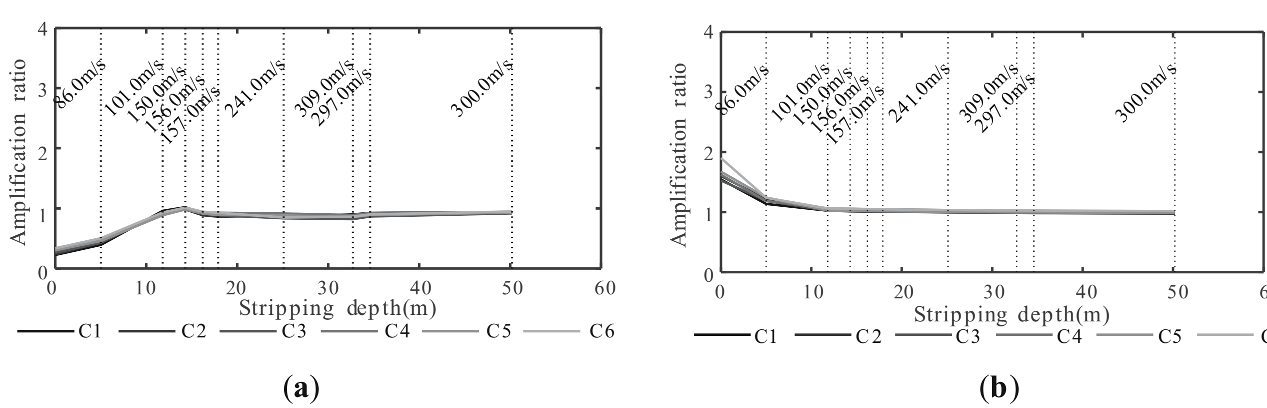

Figure 10: The variation of the spectrum accelerations' amplification ratios with stripping depths for the Pearl River Estuary profile: (a) when the period is 0.1 s and (b) when the period is 3.0 s.

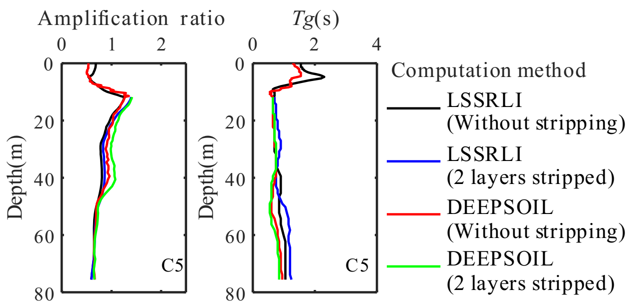

Figure 11: The amplification ratio profiles and the characteristic period profiles of the Pearl River Estuary profile using different computation methods with the input motions of C5 level.

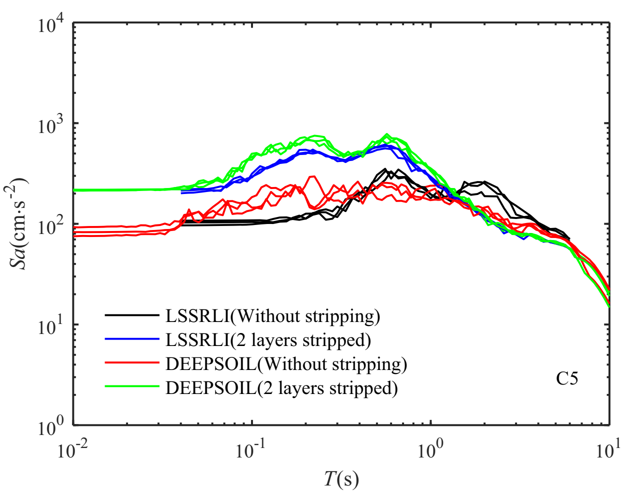

Figure 12: The superficial response spectra of the Pearl River Estuary profile using different computation methods with the input motions of C5 level.

profile using different computation methods with the input motions of C5 level are shown in Figure 12.

8 Shear force at the interface beneath superficial soft silt

Based on the site response analysis results, due to the huge difference in ground motions between soft silt and soils beneath the soft silt, great shear force will appear at the interface which is dangerous for structures like the casing string of oil wells, wind turbines, and so forth. It is not hard to understand this matter. Soft silt usually has low shear strength, and the interface between it and soils beneath has low shear strength too. So soft silt's shearing motion cannot keep pace with the soils beneath. Then the structure has to suffer from the shear force caused by the soils' inconsistent motions. If we calculate this shear force, we have to consider the soil–structure interaction, and consider the size of the different structures, material, depth, and so forth. But it is worth noting that the maximum shear strain near the bottom of the silt can reflect this inconsistent motion, and it can reflect the shear force's intensity. So we carried out a numerical experiment where superficial silt was stripped meter by meter to see how the silt's thickness and input motions' intensity affect the maximum shear strain. In the experiment, site response analysis was performed using DEEPSOIL nonlinear method.

The result shows that when the input motions are the same, with the increase of the thickness of the soft silt, the maximum shear strain near the bottom of the silt increases generally (as shown in Figure 13). And when the thickness of the silt is the same, with the increase of the input motion's intensity, the maximum shear strain near the bottom of the silt increases generally, even when the silt is thin (as shown in Figure 14). This means that both the silt's thickness and the input motion's intensity can increase the shear force, and the shear force should be considered in engineering based on local seismic activity level, the silt's and the structure's physical parameters.

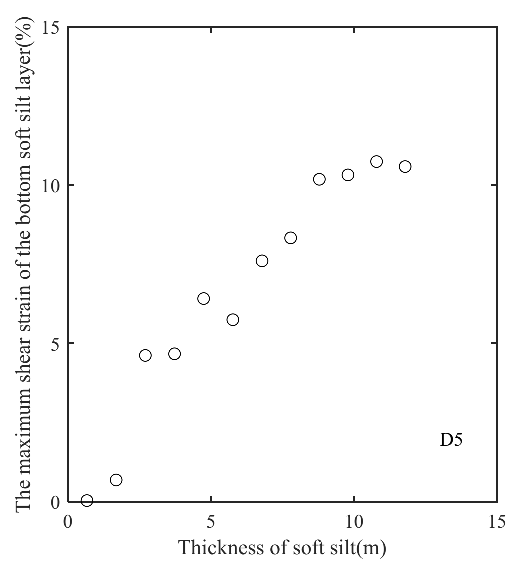

Figure 13: The variation of the maximum shear strain of the bottom soft silt layer with the thickness of the soft silt for the Pearl River Estuary profile with the input motion of D5 level.

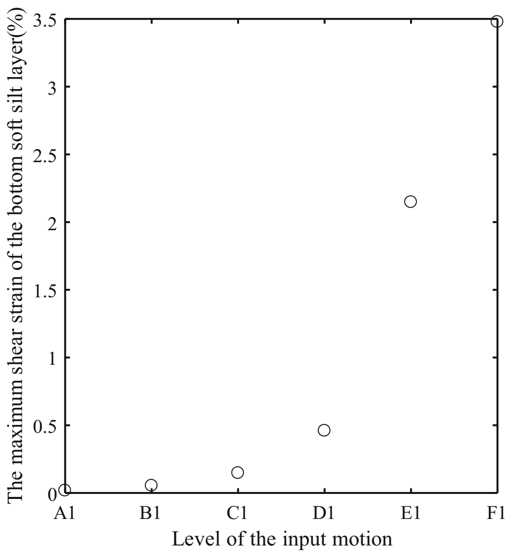

Figure 14: The variation of the maximum shear strain of the bottom soft silt layer with the intensity of the input motion for the Pearl River Estuary profile when the silt's thickness is 1.7 m.

9 Conclusion

The nonlinearity of the offshore soft soil is obvious, especially for the soft superficial silt. The thick soft superficial soil of the seabed has a significant influence on the calculation results of site response analysis. It may lead to seriously small peak ground accelerations and large characteristic periods, and result in serious "low-fat" response spectra.

When the soft superficial silt layers are stripped off, the superficial amplification ratios of peak accelerations will increase significantly, which are greater than the superficial amplification ratios of the profiles without stripping, and most of them are also greater than the amplification ratios of the profiles without stripping at the same depth. In engineering practice, from the perspective of safety, it is advisable to strip off the thick soft superficial silt layers and perform site response analyses, and adopt the maximum calculation results compared with the site response analysis results of the profiles without stripping. When the soft superficial silt layers are stripped off, the characteristic periods of the superficial response spectra will decrease, and the "low-fat" form of the superficial response spectra will be greatly improved.

After stripping off the thick soft superficial silt layers, if we go on stripping, the variation of the superficial amplification ratios of peak accelerations and the superficial characteristic periods will no longer be drastic and the superficial amplification ratios and the characteristic periods both tend to be mostly the same. The relative deviations between the superficial amplification ratios of the profile with soft superficial layers stripped off and that of the profile without stripping can be up to 143%. The high values of the relative deviations of peak accelerations mainly appear in the case of medium or strong input motions. The relative deviations between the superficial characteristic periods of the profile with soft superficial layers stripped off and that of the profile without stripping can be up to 83%. The high relative deviation values of the characteristic periods mainly appear in the case of medium or strong input motions with small characteristic periods. Due to the huge difference of ground motions between the soft silt and the soils beneath, great shear forces will appear at the bottom of the silt. This may cause great damage to offshore projects, especially to the casing string of oil wells or wind turbines. And it is suggested that the shear force should be considered in engineering based on the local seismic activity level, the silt's and the structure's physical parameters.

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Appendix A

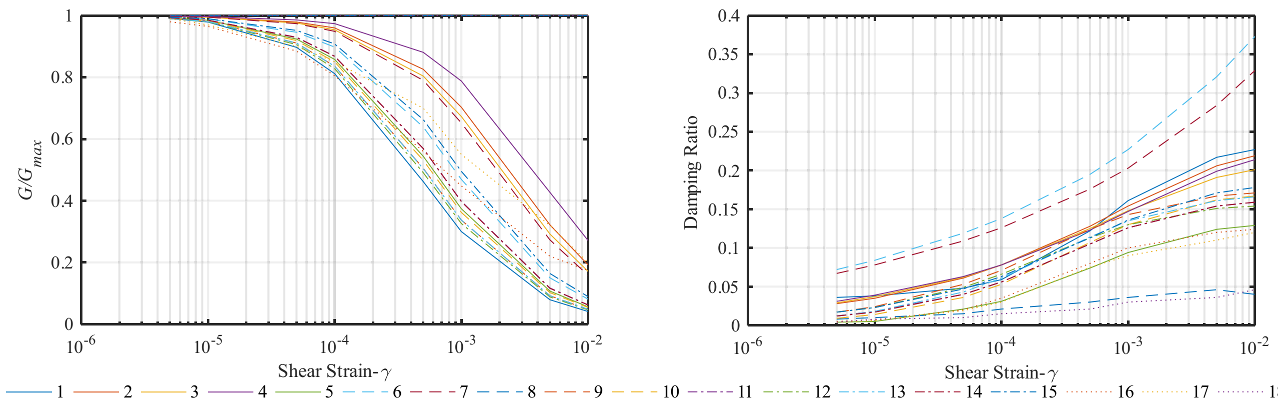

Figure A1: Modulus reductions and damping ratios of soils with different soil class ID.

Table A1: Parameters of the Pearl River Estuary borehole profile

No.	Soil property description	Soil class ID	Layer's top depth (m)	Layer's thickness (m)	Sub-layer's thickness (m)	v_s (m·s^{-1})	Density (t·m^{-3})
1	Very soft silt	1	0	5.0	0.250	86.0	1.61
2	Very soft silt	1	5.0	6.8	0.340	101.0	1.61
3	Soft clay	4	11.8	2.5	0.500	150.0	1.91
4	Soft silty clay	2	14.3	1.9	0.475	156.0	1.87
5	Soft clay	4	16.2	1.7	0.425	157.0	1.91
6	Soft silty clay	2	17.9	7.2	0.720	241.0	1.87
7	Gravel sand	5	25.1	7.6	0.950	309.0	2.15
8	Coarse sand	6	32.7	1.9	0.950	297.0	2.15
9	Silty clay with sand and gravel	3	34.6	15.6	1.200	300.0	1.83
10	Strongly weathered granite	7	50.2	20.2	2.020	493.0	1.97
11	Bedrock	8	70.4			737.0	2.10

Table A2: Parameters of the Dalian Bay borehole profile

No.	Soil property description	Soil class ID	Layer's top depth (m)	Layer's thickness (m)	Sub-layer's thickness (m)	v_s (m·s^{-1})	Density (t·m^{-3})
1	Very soft silt	9	0	4.0	0.250	108.0	1.58
2	Very soft silt	12	4.0	4.0	0.250	108.0	1.65
3	Very soft silt	10	8.0	4.0	0.250	108.0	1.66
4	Soft silty clay	13	12.0	2.9	0.290	144.0	1.72
5	Soft silty soil	14	14.9	5.1	0.510	175.0	1.92
6	Soft silty clay	11	20.0	4.6	0.460	212.0	1.87
7	Coarse gravel sand	16	24.6	0.7	0.700	320.0	2.10
8	Soft silty clay	15	25.3	8.6	1.075	222.0	1.98
9	Medium sand	16	33.9	0.6	0.600	272.0	2.05
10	Gravel	17	34.5	3.3	1.650	283.0	2.20
11	Bedrock	18	37.8			587.0	2.65

Appendix B

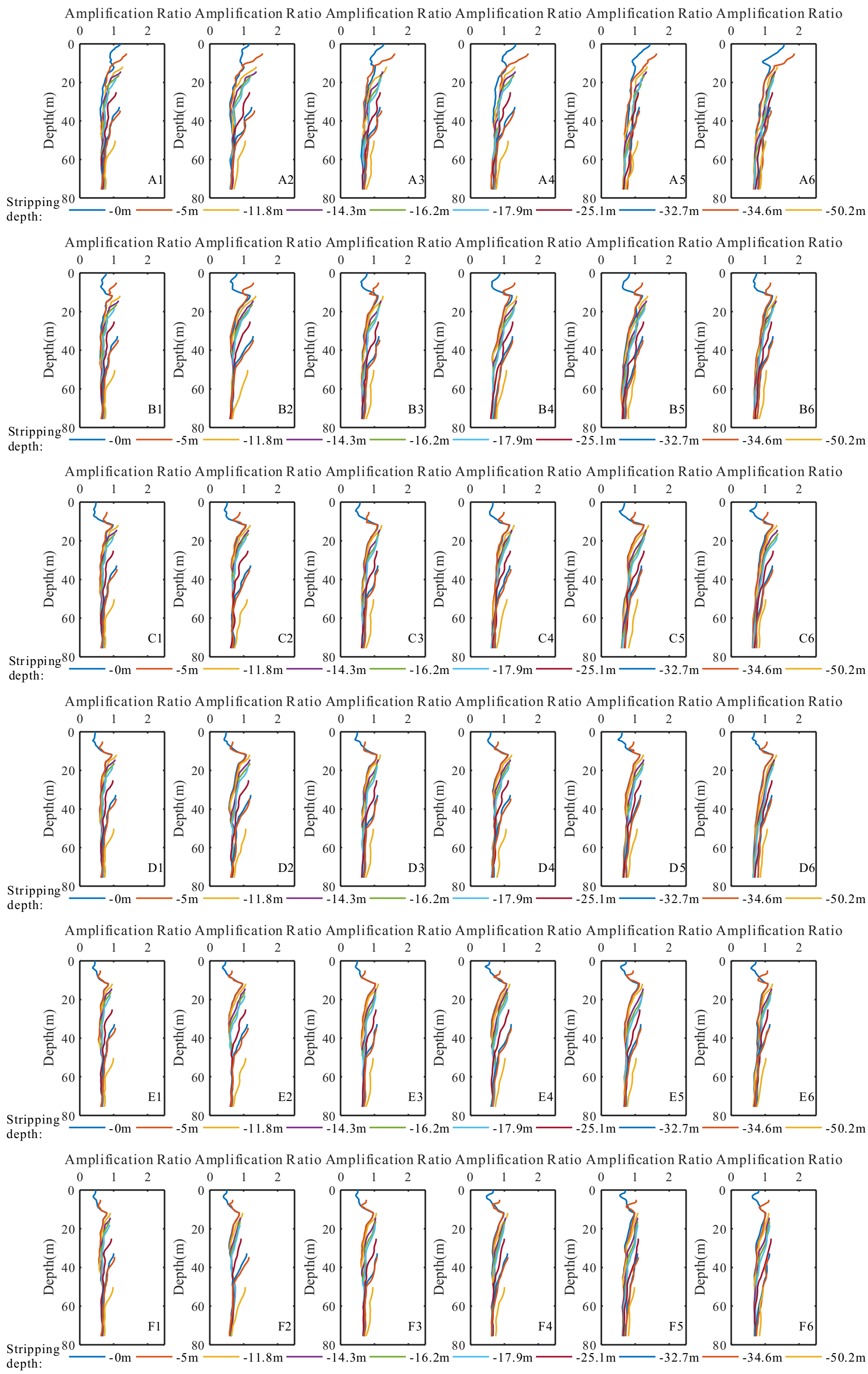

Figure B1: Amplification ratio profiles of different stripping depths for Pearl River Estuary.

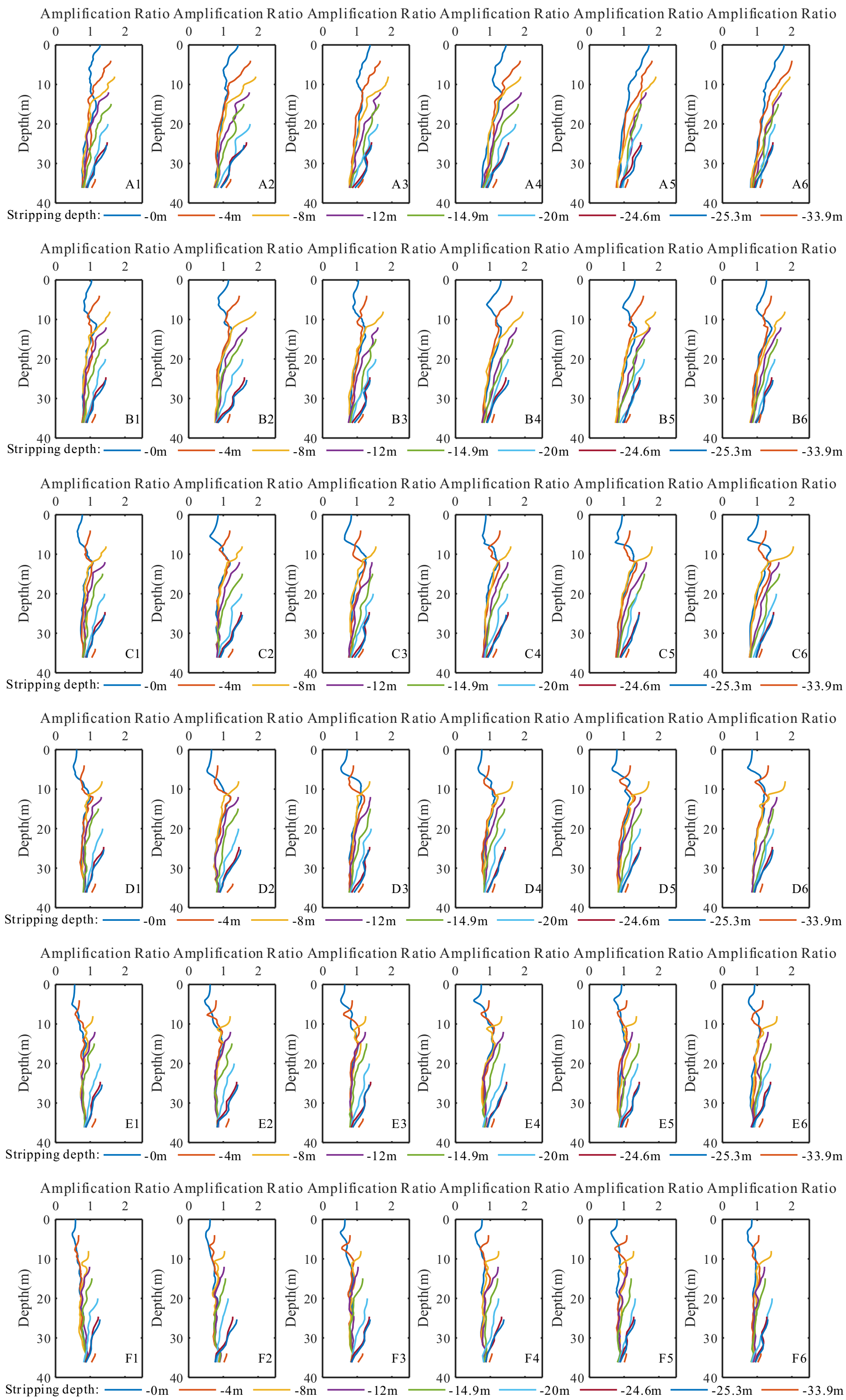

Figure B2: Amplification ratio profiles of different stripping depths for Dalian Bay.

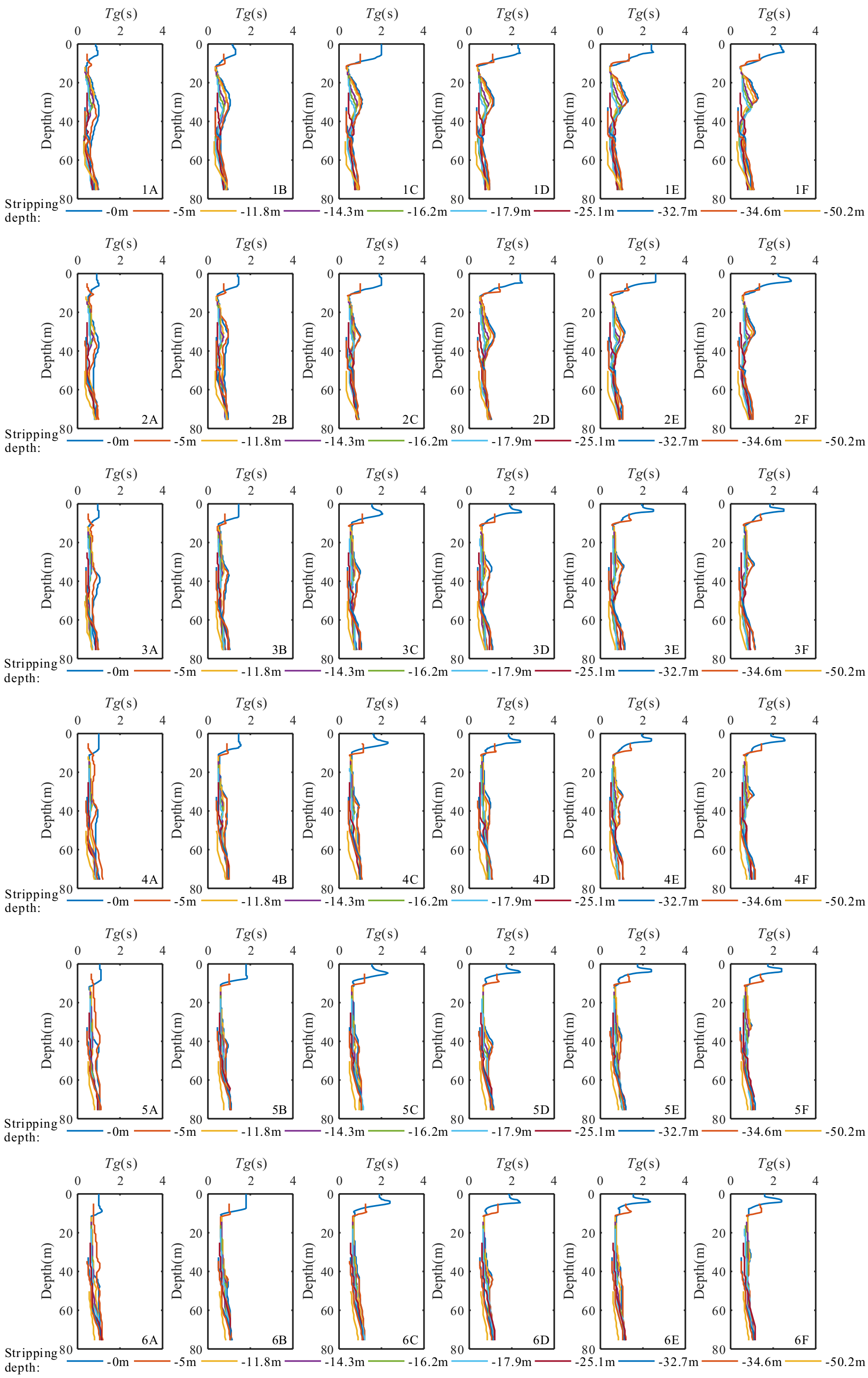

Figure B3: Characteristic period profiles of different stripping depths for Pearl River Estuary.

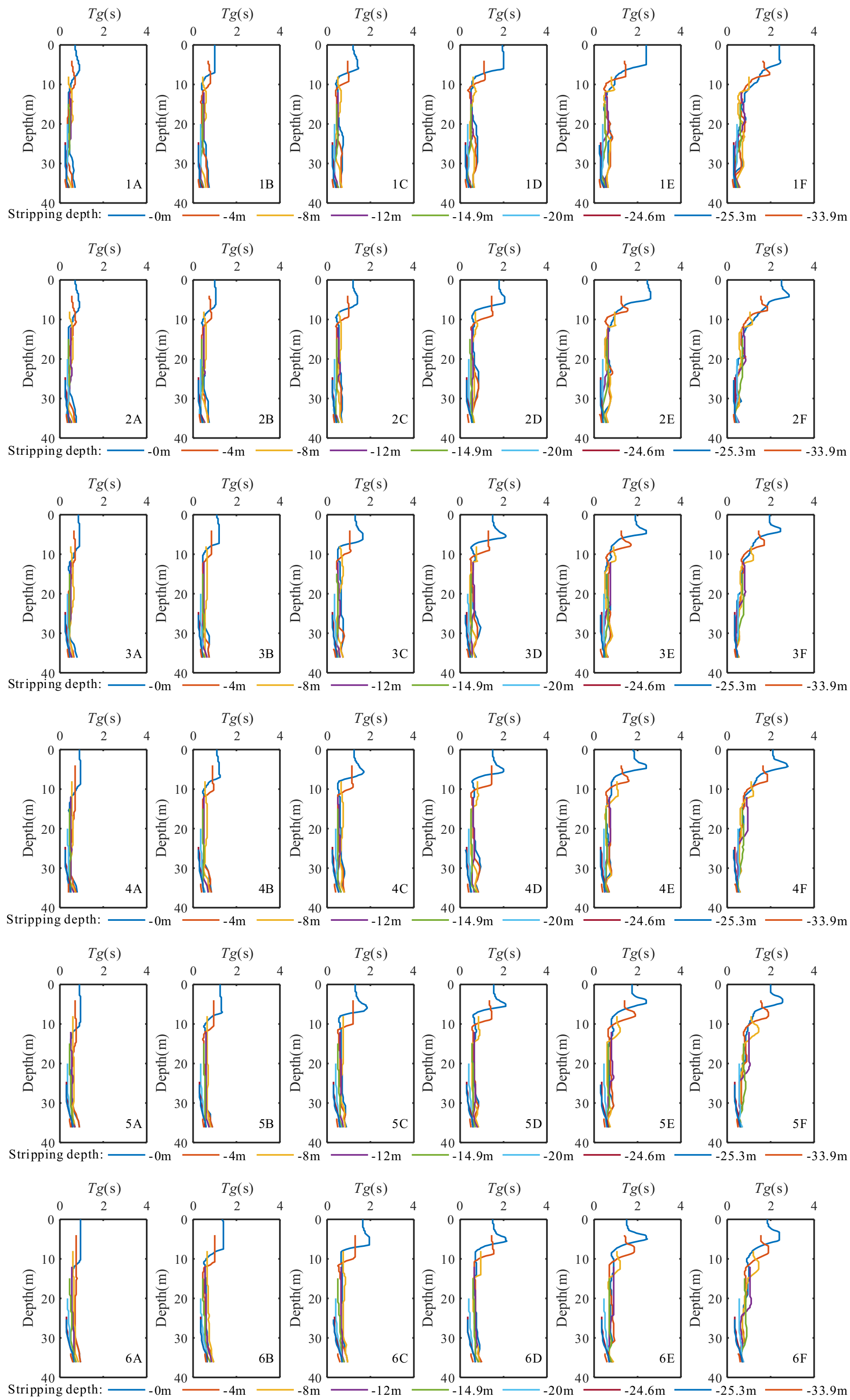

Figure B4: Characteristic period profiles of different stripping depths for Dalian Bay.