Dynamic Interaction of Soil-Isolated Structure: A Systematic Review

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Abstract: Isolation technique of ground structure is a hot topic in the field of earthquake engineering and structure dynamics. Since soil-isolated structure dynamic interaction study is of great significance to enhance seismic performance of isolated structures and revision of relevant isolation specifications, research on dynamic interaction of soil-isolated structure has attracted more and more attention. Based on the basic theory of soil-structure dynamic interaction, we summarize and analyze the research status quo of soil-isolated structure dynamic interaction by means of theoretical analysis, numerical simulation, model test, prototype observation and seismic performance. After reviewing the results of previous research, we reveal that some key issues, which can be used to uncover dynamic interaction mechanism and seismic response characteristics of soil-isolated structures interaction system, should not be neglected. Based on the concept of seismic performance design and the latest research of soil-isolated structure dynamic interaction, we predict the future development of soil-isolated structure dynamic interaction by elastoplastic time history analysis method, seismic performance level and practical analysis method based on energy.

Key words: isolated structure; earthquake resistance; soil-structure interaction

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0 Introduction

The isolation technique, as an advanced technology, has an important impact on earthquake engineering in the future. It has been a hot issue over years in the field of structural earthquake resistance. Most of the existing theories about active and passive control of structures are based on the assumption of rigid ground. The ground and foundation of the structure are regarded as rigid bodies, regardless of the influence of the foundation soil on the dynamic response characteristics of the structure[1-3]. For structures built on bedrock or on hard ground, seismic waves can act on the basement of structure without change. However, for the structure built on soft soil ground, the soil will affect the dynamic response of the structure from the input ground motion, the wave energy radiation propagating outward from the structure, and the rocking motion of the structure. In extreme cases, it may become a control factor that affects the design. In view of this, Japan's current "Design Specifications for Isolated Structures" states that when the isolated structure is built on a relatively hard ground, the influence of the interaction between the building and foundation is small, while in the case of soft soil ground, the ground motion will show the characteristic of long period. Moreover, soil-structure interaction may have a considerable impact on the characteristics of input seismic waves[4-6]. China's latest seismic design code (GB50011—2010) provisions 12.1.3 also provides that site category suitable for isolated buildings should be I, II, III, and designer should choose the foundation with better stability.

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However, the relevant regulations and calculation methods for the isolated structure built on soft soil ground are not given. To sum up, it is necessary to consider the interaction of soil-isolated structures for the isolated structures built on soft soil ground.

1 Basic Concepts of Soil - Structure Dynamic Interaction

The dynamic interaction of soil and structure refers to the facts that the inertial force generated by the structure will be transmitted back to the foundation soil when the ground motion is transmitted from the source to the surrounding structure in the form of waves, due to the non-negligible mass of the structure, which makes the structure, foundation and ground form a whole system with united work because of the repeated propagation and exchange of inertial forces. Fig.1 shows the mechanism of soil-structure dynamic interaction. Fig.1(a) assumes that the foundation is rigid, the vibration performance of the structure depends on the superstructure, in this case, there is no interaction. Fig.1 (b) indicates that the structure is built on soil foundation. When the ground motion $\ddot{x}_{g1}$ is input into the bedrock and transmitted to the bottom of the foundation through soil, the peak and spectrum of the ground motion have changed and the ground motion then becomes $\ddot{x}_{g2}$. Futhermore, the dynamic characteristics of structure also changed because of soil-structure interaction (SSI) effect. To compared with SSI, the study of soil-structure dynamic interaction needs to solve the following problems: the solution of motion problems, the boundary effect of soil, nonlinear dynamic contact, material nonlinearity and input ground motion characteristics. The combination of many factors complicates the solution of soil-structure dynamic interaction problems.

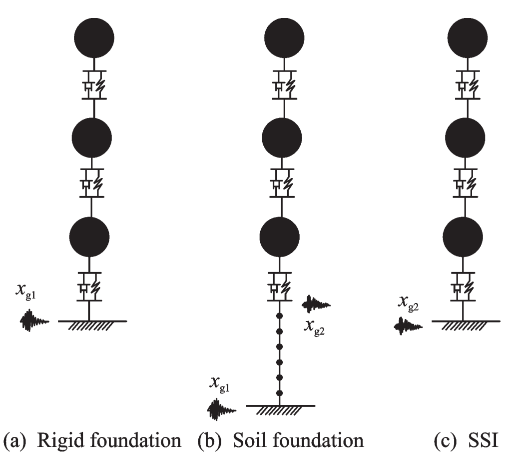


Fig.1 Schematic plan of dynamic soil-structure interaction

2 Research on Soil - Isolated Structure Dynamic Interaction

SSI effect are basically ignored in the design of isolated structure, especially in theoretical analysis. However, previous studies have shown that the SSI effect has a great influence on the dynamic characteristics of the isolated structure and the input ground motion, which in turn affects the control effect of the isolated structure. Therefore, many domestic and foreign scholars have paid close attention to this scientific issue and conducted related research. The main research methods for this scientific problem can be divided into theoretical analysis, model test and numerical model simulation.

2.1 Theoretical analysis on soil - isolated structure interaction system

In terms of theoretical analysis, Constantinou et al.[7], Novak et al.[8] and Pender et al.[9] used a simplified analysis model earlier to study the influence of SSI effect on the dynamic characteristics of isolated structures, and verified the importance of the consideration of SSI in isolated structure system. Perez et al.[10], Luco et al.[11], and Spyrakos et al.[12] also used springs and dampers to simulate the interaction between soil and structure, established related theoretical analysis models, and gave a specific simplified calculation method, which provided a more reliable method for the theoretical analysis of the scientific problem. Novak[13] used fixed dynamic stiffness to study the influence of the rotation of the isolation layer on the modal characteristics of isolated structure. Chinese scholar Li et al.[14] extended the simplified analysis method of conventional non-isolated structures to the interaction analysis of isolated structures based on the lumped parameter model, and established the simplified analysis model of the isolated structure with SSI considered , as shown in Fig.2 , which is suitable for isolated struc-

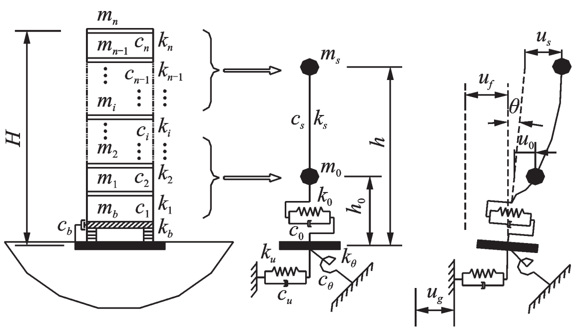


Fig.2 Simplified calculation mode of soil-base-isolated-structure system

tures with large aspect ratio in consideration of SSI effect. Vibration period and damping ratio of interaction system are shown as

$$T_{1,2}=\frac{\lambda\sqrt{2a/(1+\mu)}}{\sqrt{b\mp\sqrt{b^2-4a\lambda^2/(1+\mu)}}}T_0 \tag{1}$$

$$C_i^*=\boldsymbol{\phi}_i^{\mathrm{T}}C\boldsymbol{\phi}_i=\varphi_i^2c_0+(1-\varphi_i)^2c_s+(\lambda_1\varphi_i)^2c_u+\left[\beta\varphi_i+\frac{\mu(1-\beta)(1-\varphi_i)}{\lambda^2(1+\mu)}\right]^2\frac{\lambda_2^2c_\theta}{h^2} \tag{2}$$

$$T_0=2\pi\sqrt{(m_0+m_s)/k_0}$$

where parameters in Eqs.(1)—(3) can be found in Ref.[14].

To date, great progress and plentiful achievements have been made in theory and application in the study of dynamic interaction of soil-structures at home and abroad. Prediction methods considering SSI effect for engineering applications have also been incorporated into ATC and BSSC specifications[15], However, for the dynamic interaction system of soil-isolated structure, research on simplified prediction methods for engineering application is still rare. Veletsos et al. have deeply research on the interaction of soil-foundation, the vibration impedance of foundation has been extensively studied, and its research results[16-17] have laid a foundation for simplified design method of soil-isolated structure interaction system. Song et al.[18]. took LRB (Lead rubber Bearing) base isolated structure on soft soil site as the research object. A simplified model of soil-base isolated structure system was proposed, which considersed the frequency dependence of the dynamic response of the foundation and the nonlinearity of the isolation layer. The influence law of relevant parameters on seismic reduction factor of system were revealed by using the method of response spectrum analysis. The relevant parameters include the ratio of buckling weight, the ratio of structural rigidity to foundation rigidity, the ratio of height to width and the period of upper structure. Yu and Zhuang et al.[19-20] also studied the theoretical analysis method of the dynamic characteristics of the isolated structural system considering the SSI effect in recent years, which provided reasonable advices and guidance for the design of the isolated structure and its simplified calculation with the SSI effect considered, the simplified analysis model is shown in Fig.3, which is suitable for isolated structures with small aspect ratio in consideration of SSI effect.

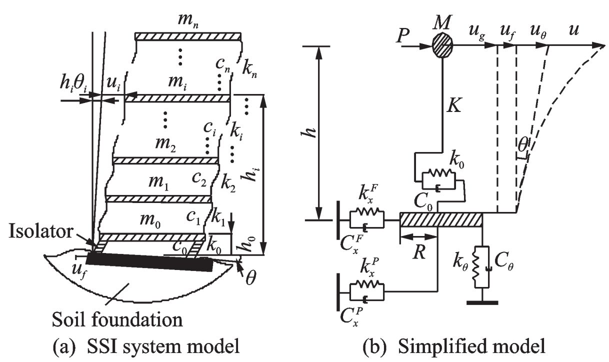


Fig.3 Simplified model for soil-isolated structure dynamic interaction

By the simplified model shown in Fig. 3, the dynamic properties of the soil-isolated structure interaction system ($\widetilde{T}_{\text{iso}}$ and $\widetilde{\xi}_{\text{iso}}$) can be corrected by the dynamic properties of fixed-base structure (T_{iso} and ξ_{iso}).

$$\widetilde{T}_{\text{iso}}=T_{\text{iso}}\sqrt{1+\frac{K_0'}{K_x}\left(1+\frac{K_xh^2}{K_\theta}\right)} \tag{3}$$

$$\widetilde{\xi}_{\text{iso}}=\left(\frac{\widetilde{\omega}_{\text{iso}}}{\omega_{\text{iso}}}\right)^2\xi_{\text{iso}}+\left[1-\left(\frac{\widetilde{\omega}_{\text{iso}}}{\omega_{\text{iso}}}\right)^2\right]\xi_s+\left(\frac{\widetilde{\omega}_{\text{iso}}}{\omega_x}\right)^2\xi_x+\left(\frac{\widetilde{\omega}_{\text{iso}}}{\omega_\theta}\right)^2\xi_\theta \tag{4}$$

where $\widetilde{T}_{\text{iso}}$ and $\widetilde{\xi}_{\text{iso}}$ are the fundamental vibration period and damping ratio of soil-isolated structure interaction system, respectively; T_{iso} and ξ_{iso} are the fundamental vibration period and damping ratio of the fix-base isolated structure, respectively.

$$\omega_{\text{iso}}=\sqrt{K_0'/M}=\sqrt{K_0'/\sum m_i},\ \omega_x=\sqrt{K_x/M} \quad (5)$$

$$\omega_\theta=\sqrt{K_\theta/Mh^2} \quad (6)$$

$$T_{\text{iso}}=2\pi\sqrt{M/K_0'}=2\pi\sqrt{\sum m_i/K_0'} \quad (7)$$

$$\xi_{\text{iso}}=\frac{C_0}{2\sqrt{K_0'M}},\xi_x=\frac{C_x}{2\sqrt{K_xM}} \quad (8)$$

$$\xi_\theta=\frac{C_\theta}{2\sqrt{K_\theta Mh^2}} \quad (9)$$

The stiffness of foundation with the piles is corrected by an approximate method.

$$K_x=\sqrt{(K_x^F)^2+(K_x^P)^2},K_\theta=K_\theta^F+K_\theta^P \quad (10)$$

where K_x^F and K_θ^F are the horizontal and rotational stiffnesses of soil foundation without piles, respectively; and K_x^P and K_θ^P are those of the pile foundation, respectively.

The wave parameter $(1/\sigma)$ has a great effect on the dynamic characteristics of the soil-structure system, especially on those of the non-isolated structure[20], as shown in Fig.4, the wave parameter $(1/\sigma)$ is

$$\frac{1}{\sigma}=\frac{h\sqrt{K/M}}{2\pi v_s} \quad (11)$$

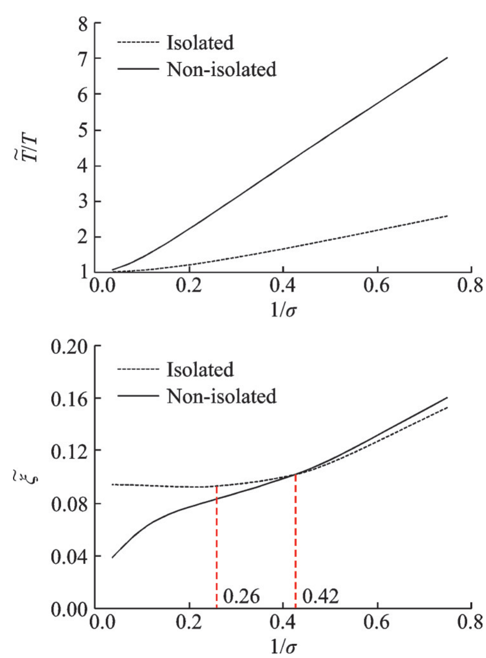


Fig.4 Natural period and damping of the SSI system as a function of wave parameter $(1/\sigma)$

where parameters in Eq. (11) are detailed in Ref.[20].

Based on fundamental vibration period and damping ratio of interaction system, the simplified prediction methods for seismic reduction factor β and displacement $\Delta_{\max}$ of isolation layer on soft soil foundation are established by considering the SSI effect[21], which can be given by

$$\beta=\begin{cases}\eta_{2\text{iso}}\left(\dfrac{T_g}{\tilde{T}_{\text{iso}}}\right)^{r_{\text{iso}}} & 0.1s\leqslant\tilde{T}\leqslant T_g\\ \dfrac{\eta_{2\text{iso}}}{\eta_2}\left(\dfrac{T_g}{\tilde{T}_{\text{iso}}}\right)^{\gamma_{\text{iso}}}\left(\dfrac{\tilde{T}}{T_g}\right)^{\gamma} & T_g\leqslant\tilde{T}\leqslant 5T_g\end{cases} \quad (12)$$

$$\Delta_{\max}=\eta_{2\text{iso}}\left(\frac{T_g}{\tilde{T}_{\text{iso}}}\right)^{\gamma_{\text{iso}}}\alpha_{\max}\frac{T_{\text{iso}}^2 g}{4\pi^2}=248.5\left(\frac{T_g}{\tilde{T}_{\text{iso}}}\right)^{\gamma_{\text{iso}}}\eta_{2\text{iso}}\alpha_{\max}T_{\text{iso}}^2 \quad (13)$$

where parameters in Eqs.(12)—(13) are detailed in Ref.[21].

2.2 Numerical simulation on soil-isolated structure interaction system

The rapid development of the integral numerical calculation method of soil-structure dynamic interaction can make up for the shortcomings of simplified calculation methods, and the effect of complex geological conditions on dynamic response of upper isolation structure can be fully considered. The complex geological conditions involves multi-layer, non-linear and anisotropy of foundation soil. For example, Sayed et al.[22] used numerical calculations to demonstrade that foundation stiffness has a significant effect on the upper isolated structure. Kyung et al.[23] used the coupling of finite element and boundary element to verify the feasibility of the time domain numerical calculation method, which was used to analyze dynamic response of soil-isolated structure interaction system. According to the model test, Hokmabadi et al.[24] established the three-dimensional finite element model of soil-pile-structure interaction system by FLAC3D (Fig.5), and SSI effect on dynamic torsion and swing of structure was studied. Zou et al.[25] established the calculation model of isolated structure in consideration of pile-soil interaction (Fig.6), derived the vibration equation, and analyzed the effect of interaction of pile-soil on isolation structure. Li et al.[26] studied the effect of the soil-structure interaction on the dynamic behavior of a base-isolated system by the substructure approach (Fig.7).

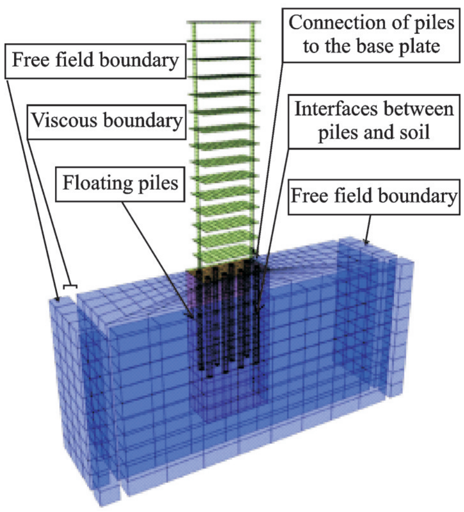


Fig.5 Numerical grid and model components in FLAC3D

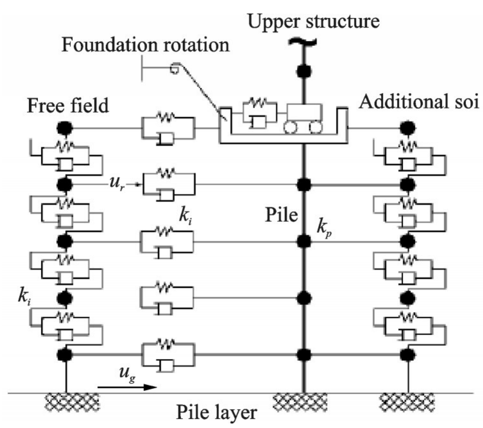


Fig.6 Calculating model of pile-soil-isloated structure

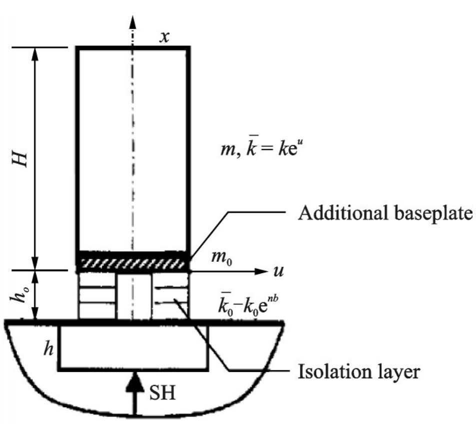


Fig.7 Calculation model of substructure method

Wang et al.[27], Li et al.[28], Zhang et al.[29], Xiang et al.[30], and Liu et al.[31] used finite element analysis method to comprehensively explore the law of soil-structure interaction effect on isolation effect of base-isolated structure. Li et al.[32] used the substructure method to analyze the influence of SSI on the fundamental frequency and the seismic response of base isolated structure, and believed that the influence of SSI should be considered in the design of the isolated structure. Zhang et al.[33] also used substructure method to analyze the influence of soil-structure interaction on the fundamental frequency and seismic response of the linear base isolation system. Zou et al.[34] analyzed the seismic response of based isolated structures built on pile foundation, and pointed out that pile-soil interaction has an effect on the seismic response of isolated structures, but the effect is much smaller than that of non-isolated structures, so the influence of SSI effect should not be considered in the general design of isolated structures. Tsai et al.[35] believed that the seismic response of the isolated structural system might increase significantly with SSI effect by finite element analysis of the soil-FPS isolated structure interaction system.

Yu et al.[36] used the finite element method to analyze the seismic response of pile-soil-10-storey steel frame isolated structure system, and concluded that the design of isolated structure based on the assumption of rigid foundation is not always safe, and the influence of soil-structure interaction effect should not be ignored in engineering design. In addition, based on the shaking table test for base isolated structure built on soft interlayer ground and rigid foundation, Yu and Zhuang et al.[37] established a 3-D finite element model (Fig.8) to simulate the dynamic soil-structure interaction, which has the same size with the test system. Then, the natural frequency of the isolated structure and the acceleration responses of the soil-structure interaction system are compared and analyzed.

2.3 Model test on soil-isolated structure interaction system

Model test on soil-isolated structures interaction system can effectively verify the correctness of

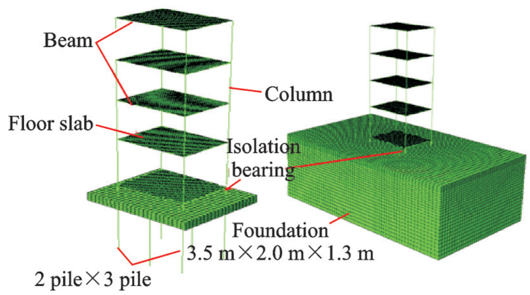
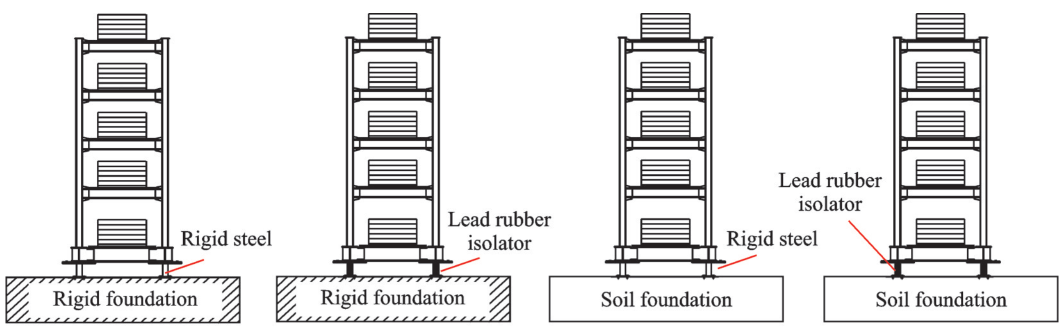


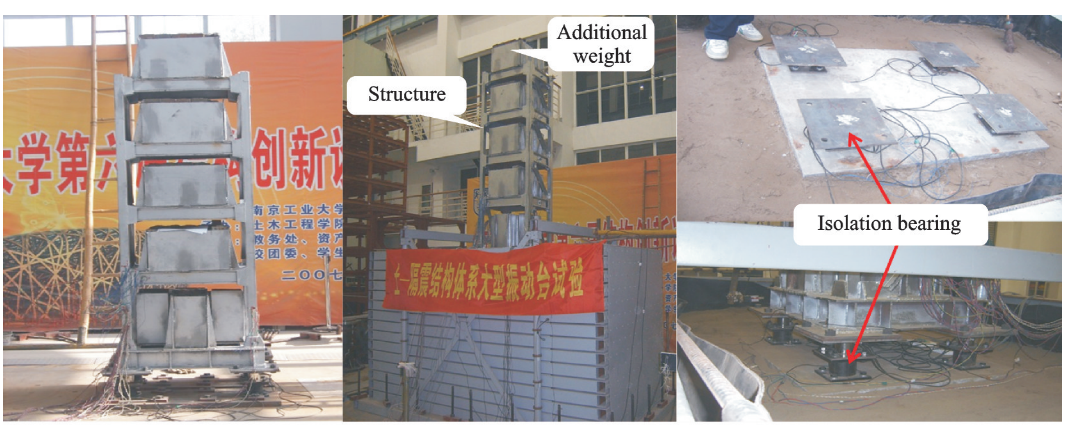
Fig.8 3D finite element model of soil-isolated structure system

relevant numerical calculation models and theoretical analysis methods. In recent years, relevant scholars have also carried out model test research on dynamic response of isolated structures on different sites. Yu and Zhuang et al.[37-40] carried out a series of model tests on the seismic response of isolated structures on rigid ground and soil ground. The tests are explained in Fig.9, and some photos in the test are shown in Fig.10. The basic principles of similitude ratios in these experiments were provided. The influence laws of SSI effect on the dynamic responses of isolated structure were verified and some new findings were provided. By tests, the damping ratio of interaction system with SSI effect is bigger than that of isolated structure on rigid foundation. The typical table is shown in Table 1. Others are detailed in Ref.[38]. The acceleration magnification factor (AMF) at each floor of isolated structure is larger than that of structure without SSI effect, with large PGA of input motion, AMFs increase monotonously along the height of isolated structure with SSI effect. The typical one is shown in Fig.11, and others are detailed in Refs.[38-40]. The more important findings in the test are that the rotation response of foundation can be amplified by the isolation layer, which further reduces the isolation efficiency of isolation layer obviously, in general; and that with the PGA of input motion larger, the isolation efficiency of base-isolated structure becomes lower obviously with SSI effect. The typical figure is shown in Fig.12, and the typical force-displacement hysteretic curves for the model lead-rubber bearings during tests are shown in Fig.13. Others are detailed in Refs.[37-38].



(a) Test Ⅰ (b) Test Ⅱ (c) Test Ⅲ (d) Test Ⅳ

Fig.9 Shaking table tests designed to model four different conditions



(a) Fixed on rigid foundation (b) Fixed on soil foundation (c) Lead rubber isolator

Fig.10 Tests of isolated structures on different foundations

Table 1 First-order vibration frequency and damping ratio of base-isolated structure

Load No.	Type of foundation							
	Rigid foundation				Soil foundation			
	Frequency / Hz		Damping ratio / %		Frequency / Hz		Damping ratio / %	
	Test Ⅰ	Test Ⅱ	Test Ⅰ	Test Ⅱ	Test Ⅲ	Test Ⅳ	Test Ⅲ	Test Ⅳ
STWN1/WN1	6.72	2.65	3.00	8.30	4.36	2.38	9.7	15.4
STWN2/WN2	6.72	2.65	3.00	8.70	4.36	2.37	10.9	16.2
STWN3/WN3	6.33	2.65	4.47	14.6	4.34	2.29	11.7	21.6
STWN4/WN4	6.12	2.62	4.90	15.2	4.20	2.29	12.2	22.1

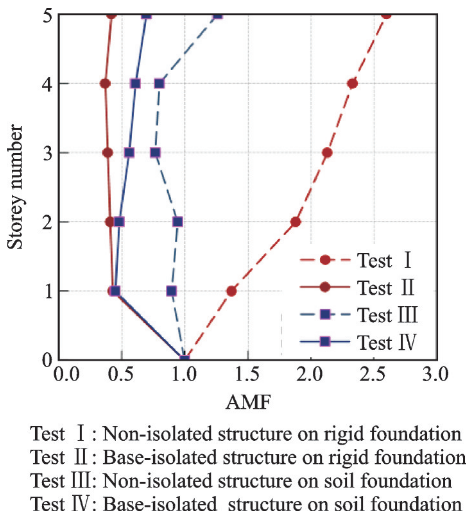


Fig.11 AMFs of the soil-isolated structure interaction system

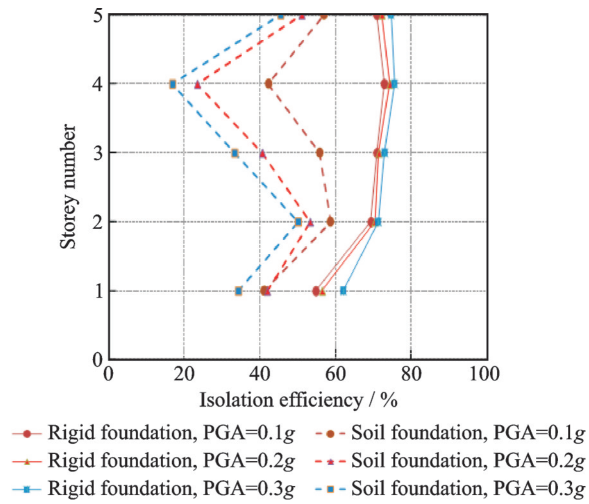


Fig.12 Isolation efficiency at each storey of base-isolated structure

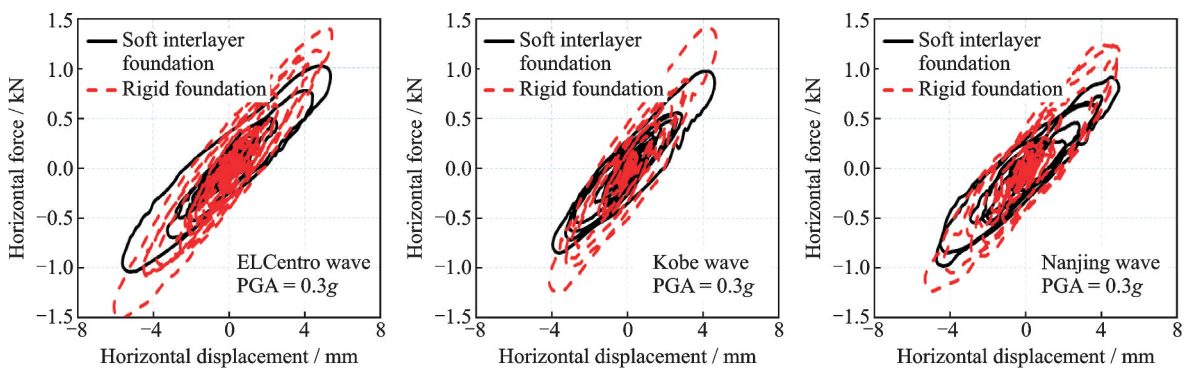


Fig.13 Force-displacement hysteretic curves of the model lead-rubber bearings during different tests

Li et al.[41] conducted a comparative shaking table test on the high-rise isolated structural model on rigid foundation and soft soil foundation (Fig.14). The seismic response characteristics and isolation effects of high-rise isolated structures on soft soil ground were studied, which provided experimental basis for subsequent theoretical analysis.

2.4 Prototype observation on soil-isolated structure interaction system

Prototype observations are one of the most reliable means to analyze the dynamic interaction of soil-isolated structures, but few prototype observations have been recorded. According to prototype observation records of East Japan earthquake in 2011, Saito[42] analyzed a 52-storey high-rise isolation building in Osaka. The seismic observation records and seismic response show that isolation effect of the structure is almost as expected, however, the displacement response of the top storey of the high-rise isolation building reaches 3 m.

It is found that the long period ground motion is dangerous to the isolated buildings. According to prototype observation records of Earthquake in

Fig.14 Test of high-rise isolated structure model on soil foundation

southern Hyogo County, Japan in 1995, Architectural Institute of Japan analyzed a 6-storey isolated structure in Hyogo County[4], and found that the acceleration reaction of the top storey of isolated structure is only 1/4 of the base acceleration reaction, and the maximum displacement response of top storey is 12 cm. The isolated structure has a good isolation effect. Although the prototype observation is reliable, the boundary conditions and geological environment of the site are very complex. Therefore, it is difficult to consider the influence of various factors[43-44]. Because of the suddenness and uncertainty of earthquakes, it is rarely used in current research.

2.5 Seismic analysis method of structure based on energy

The performance-based seismic design of structures mainly uses force displacement or energy as a quantitative index. The displacement response of the structure under the earthquake excitation can describe the damage degree of the structure. Therefore, the seismic design method using displacement becomes the main approach to realize the performance-based seismic design, which is the most extensive and mature performance-based design method. Housner[45] first proposed the seismic design idea based on energy. The cumulative hysteretic energy dissipation index of structures during seismic time-holding process reflects the cumulative damage effect of structures caused by earthquake. Therefore, the idea of seismic design based on energy can comprehensively reflect the seismic nature of structure. Bertero et al.[46] believed that it is effective to compare and judge the damage intensity of ground motion to structures by using the total input energy of structures. Fajfar et al.[47] used the instantaneous stiffness proportional damping model to study the relationship between the failure energy consumption ratio of the structure and structural parameters and ground motion with hysteretic models of various restoring forces considered. The analytical result showed that the upper limit of hysteretic energy consumption in total energy consumption is 80% and 90%. Qu et al.[48] proposed a seismic damage model with tow-parameter linear combination as follows

$$DM = (1-\beta_1)\frac{\mu_m}{\mu_u} + \beta\gamma_h^2\frac{\mu_m^2}{\mu_u} = (1-\beta_1 + \beta\gamma_h^2\mu_m)\frac{\mu_m}{\mu_u} \tag{14}$$

where parameters in Eq. (14) are detailed in Ref. [48]. On this basis, Qu presented seismic damage performance evaluation method based on energy analysis, which can accurately analyze the seismic damage performance of structures under the action of large earthquakes.

Zhou et al.[49] summarized the energy analysis method of earthquake resistant structure and shock absorbing structures, and proposed several problems that should be paid attention to in the application of energy analysis method. Ye et al.[50] pointed out that structural damage energy consumption mechanism is the key to determine the cumulative energy dissipation distribution of structures and realized seismic design based on energy. An implementation framework based on energy seismic design method is established (Fig.15). Benavent-Climent et al.[51] studied the main factors affecting the seismic performance of structures by analyzing the proportional relationship between the input seismic energy of the structure and the dissipative energy of structural members. Zhai et al.[52] analyzed the input energy spectrum characteristics of the single-degree-of-freedom system, and proved the necessity of considering aftershocks in energy-based seismic design.

Yu et al.[53] established energy response equations for a soil-isolated structure interaction system by energy method, the energy response equations for a soil-isolated structure interaction system can be expressed as

$$E_i^{sso}=E_k^{sso}+E_c^{sso}+E_s^{sso}+E_d^{sso} \tag{15}$$

where E_i^{sso} is the total input energy, E_k^{sso} the kinetic energy of interaction system, E_c^{sso} the damping energy of interaction system, and E_d^{sso} the hysteresis deformation energy of isolation layer, which can be obtained by

$$E_i^{sso}=-\sum_{j=0}^{N}\int_0^t m_j\ddot{u}_g\dot{x}_j\,dt \tag{16}$$

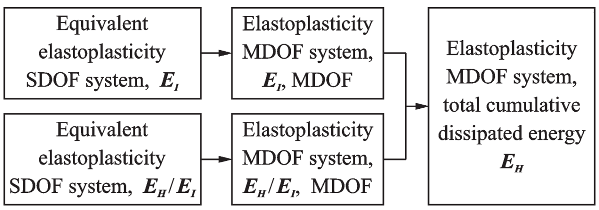


Fig.15 Procedure for calculating structural member total cumulative dissipated energy

$$E_k^{sso}=\sum_{j=0}^{N}\int_0^t m_j(\ddot{u}_j+\ddot{u}_0+h_j\ddot{\theta}+\dot{u}_f)\dot{x}_j\,dt=\sum_{j=0}^{N}\int_0^t m_j\ddot{x}_j\dot{x}_j\,dt \tag{17}$$

$$E_c^{sso}=\sum_{j=1}^{N}\int_0^t c_j(\dot{u}_j+\dot{u}_0)\dot{x}_j\,dt+\int_0^t c_0\dot{u}_0\dot{x}_0\,dt \tag{18}$$

$$E_d^{sso}=\int_0^t f_d\dot{x}_0\,dt \tag{19}$$

where parameters in Eqs.(16)—(19) are detailed in Ref.[54].

By comparative analysis on the energy dissipation of isolated structures set on different foundations in shaking table tests, the characteristics of energy dissipation of isolated structures set on soft interlayer soil foundation and rigid foundation were studied. The typical figures are shown in Fig. 16, where R_k is the ratio of E_k^{sso} to E_i^{sso}, R_h the ratio of E_s^{sso} to E_i^{sso}, R_c the ratio of E_c^{sso} to E_i^{sso}, R_d the ratio of E_d^{sso} to E_i^{sso}, and others are detailed in Ref.[54].

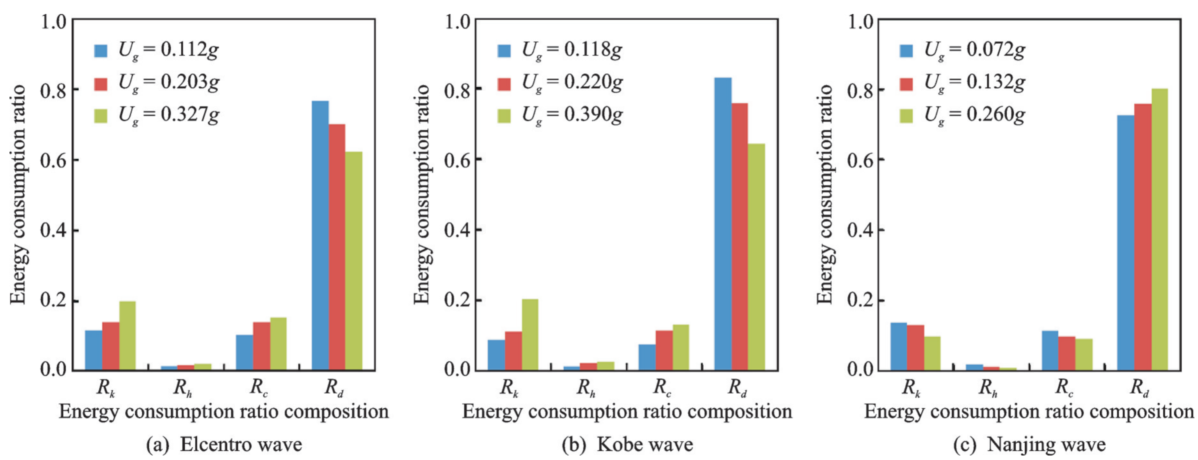


Fig.16 Ratio of energy dissipation of parts of isolated structure on softer interlayer soil foundation

2.6 Seismic performance on soil-isolated structure interaction system

Relatively speaking, the research on the seismic performance of the base isolated structure and its seismic design method is obviously lacking. Ma et al.[54-55] gave seismic performance levels and performance objectives (as shown in Table 2) in consideration with the characteristics of isolated structure, the suggested intensity values and horizontal shock-resistant coefficients corresponding with seismic measures and horizontal ground motion for upper-structure were given, performance control index of base-isolated building were presented (Table 3). Zhang et al.[56] proposed a seismic vulnerability analysis method for interlayer seismic isolation structures, and the method was based on performance. Sun et al.[57] analyzed stationary random seismic response and dynamic reliability of isolated structure with different period ratio, yield-to-weight ratio and damping ratio, which have guiding significance for the rational design and behavior control of the isolated structure; Fu et al.[58] proposed a seismic analysis method based on performance design according to the characteristics of magnetorheological intelligent seismic isolated structure.

According to the present situation of seismic fortification standard of offshore isolated bridges in China, Zou et al.[59] established the seismic fortification standard of offshore isolated bridges by introducing the seismic design idea based on performance. Mehrparvar et al. [60] developed a performance-based semi-active control algorithm for isolated structure according to the Skyhook control algorithm, and systematically studied the seismic performance level of base isolated structure which site is near to fault zone. Jensen et al. [61] also studied the seismic performance of the base-isolated structure under the action of near-fault earthquake waves, and gave the seismic performance evaluation and design method for the isolated structure based on the deformation of the isolation layer, interlayer displacement angle and the absolute acceleration response of upper structure. It has to be mentioned that Japan's 2 000 architecture design specification introduced a performance-based seismic design philosophy, which had involved the evaluation of seismic performance and calculation methods for isolated structures[62].

Table 2 The lowest seismic performance requirements of base-isolated structures under the various seismic level

Ground motion level	Target level of defensive behavior	Class III	Class II	Class I
Frequent earthquakes (TMJ year transcendental probability is 63%)	Ordinary fortification	Level 1	Level 1	Level 1
	Special fortification	Level 1	Level 1	Level 1
	Key fortification	Level 1	Level 1	Level 1
Defense earthquakes (TMJ year transcendental probability is 10%)	Ordinary fortification	Level 1	Level 1	Level 1 or 2
	Special fortification	Level 1	Level 1	Level 1
	Key fortification	Level 1	Level 1	Level 1
Rare earthquake (TMJ year transcendental probability is 2%—3%)	Ordinary fortification	Level 1	Level 1 or 2	Level 2 or 3
	Special fortification	Level 1	Level 1	Level 1 or 2
	Key fortification	Level 1	Level 1	Level 1

Table 3 Performance control index of base-isolated building

Damage index	Good condition	Minor damage	Moderate damage	Serious damage	Collapse
Interlayer displacement angle	⩽1/550	1/550—1/300	1/300—1/150	1/150—1/50	⩾1/50
Ductility coefficient	⩽1.0	1.0—3.0	3.0—6.0	6 0—10.0	>10.0
Acceleration /($cm \cdot s^{-2}$)	⩽10	10—200	200—1 000	1 000—50 000	>5 000

3 Problems and Prospects

Due to the short research time of the dynamic interaction of soil-isolated structures, there are many problems to be further studied:

(1) For theoretical research, due to the lack of deep research and understanding on the dynamic interaction mechanism of soil-isolated structures on soft soil ground, the existing theoretical analysis models and simplified calculation methods cannot meet the requirements of seismic design of isolated structures on soft soil ground.

(2) For numerical simulation, most of the existing numerical analysis methods consider the nonlinearity of soil materials by the equivalent linear model, which cannot consider damping characteristics of real soil and its nonlinear stiffness attenuation. Meanwhile, most of the existing numerical models have been over-hypothesized and simplified due to the limitation of calculation conditions, which leads to a big gap between the actual engineering and theoretical calculation. Furthermore, most of the laws and conclusions obtained by numerical calculation have not been verified by model test.

(3) In the model test research, the current soil-structure dynamic interaction model test has a single foundation soil, and lacks of systematic consider-

ations for evolution process of stiffness of soft soil ground. It is extremely important that the relevant model test results can only qualitatively analyze the effect of SSI on the seismic response of isolated structures, and cannot quantitatively verify the accuracy of relevant theoretical analysis and numerical results for the limitations of experimental techniques.

(4) In the study of seismic performance, due to lack of research on the seismic performance level of isolated structures (especially on soft soil ground), the corresponding national specifications and standards are still imperfect, and there are no clear classification standards and requirements for the seismic performance level and seismic design objective of isolated structure on soft soil ground. There are no corresponding quantitative parameters and evaluation criteria for describing the seismic performance of isolated structures on soft soil ground. Therefore, the seismic design method of the isolated structure on soft soil ground is still in the preliminary research stage. It is urgent to find out the dynamic characteristics of the isolated structure on soft soil ground, propose the classification method of seismic performance level and quantitative indicators, and establish performance-based seismic design method.

(5) In the field of earthquake damage investigation and observation, the earthquake disaster provides a large number of real and effective data, but there are few seismic observations on the dynamic interaction of soil-isolated structures. Therefore, it is necessary to increase the research in this field.

In view of the problems existing in the aforementioned soil-isolated structure dynamic interaction, future research mainly focuses on the following aspects:

(1) Basic theory of dynamic interaction of soil-pile-isolated structure and its elastoplastic time history analysis method. The nonlinear dynamic interaction mechanism of soil-pile-isolated structure and its elastoplastic time history analysis method will be studied.

(2) Research on the dynamic characteristics and seismic performance level of the base-isolated structure on soft soil ground with variable stiffness. The qualitative and quantitative evaluation methods for the seismic performance level of isolated structures on soft soil ground are to be studied.

(3) Research on practical seismic analysis method for isolated structures on soft soil ground based on energy dissipation. The theoretical analysis model of the dynamic interaction system of soil-pile-isolated structure is to be studied, and the energy-based seismic analysis method of isolated structure built on soft soil ground with SSI effect considered in this paper should be established.

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土-隔震结构动力相互作用的系统综述

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摘要:隔震技术研究已成为结构抗震领域的一个热点,而土-隔震结构动力相互研究更是该研究领域的前沿问题,土-隔震结构动力相互研究对提高隔震结构的抗震性能以及相关隔震规范的修订具有重要意义。本文从土-结构动力相互作用的基本原理出发,对土-隔震结构动力相互作用的理论分析、数值模拟、模型实验、原型观测和抗震性态的研究现状进行了总结和分析。以往土-隔震结构动力相互研究主要以理论分析和数值模拟为主,而模型实验研究相对较少,本文对已有的研究成果进行了综述,指出了其不足之处。同时揭示了已有研究中被忽视的一些关键问题,这些问题有助于探明土-隔震结构动力相互作用机理及其地震反应特征。从结构性能化抗震设计理念出发,延续已开展的研究,从弹塑性时程分析方法、抗震性态水平和基于能量的实用抗震分析方法等方面指出了土-隔震结构动力相互作用未来的发展方向。

关键词:隔震结构;抗震;土-结构动力相互作用