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Seismic Response of Adjacent Structure to Inter-Story Isolated Structure

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Abstract

Currently, land resources are becoming more and more constrained and structures are getting closer to each other. To investigate the seismic response of inter-story isolated structure to adjacent structure, models considering no soil-structure interaction (SSI), considering soil-structure interaction (SSI), and considering structure-soil-structure interaction (SSSI) were established. Nonlinear seismic response comparative analysis was conducted by varying the spacing between adjacent structure and inter-story isolated structure, as well as the weight of adjacent structure, under different earthquake inputs, in order to obtain the structural response characteristics. The results indicate that the inter-story drift and inter-story shear of the inter-story isolated structure without considering SSI are smaller than those considering SSI and SSSI. The inter-story drift and inter-story shear of the inter-story isolated structure considering SSSI are further affected compared to that of the inter-story isolated structure considering only SSI. As the spacing between adjacent structure and inter-story isolated structure increases, the influence of adjacent structure on inter-story isolated structure decreases. The variation in the spacing between the two structures has a negligible effect on the isolation layer of the inter-story isolated structure. With the increase in the weight of adjacent structure, the influence of adjacent structure on inter-story isolated structure becomes more significant. The increasing weight of adjacent structure has an increasing effect on the Isolation layer of the inter-story isolated structure.

Keywords

Soil-Structure Interaction (SSI), Structure-Soil-Structure Interaction (SSSI), Inter-Story Isolation, Adjacent Structure

1. Introduction

Inter-story isolated structure is a new type of seismic isolation structure developed from the foundation seismic isolation structure. Structure-soil-structure interaction (SSSI) is also proposed in recent decades. Structure-soil-structure interaction (SSSI) refers to the problem of interaction through soil dynamics in a multi-structural system.

The study of structure-soil-structure interaction started with Warburton *et al.* [1]. They discussed the interaction effects at different Poisson's ratios of semi-infinite space media and at different spacings of two mass blocks, and confirmed the significant influence of adjacent dynamic interaction effects. Luco *et al.* [2], Murakami *et al.* [3], and Wong *et al.* [4] investigated the structure-soil-structure interaction under the action of inclined and vertically incident SH waves by simulating an infinite-length 3D system with a simplified 2D plane strain model. The results show that the structure-soil-structure interaction is significant for low-level structure in the vicinity of high-level structure in the low-frequency case, but the effect of adjacent structure is negligible in the high-frequency case. Roy *et al.* [5] investigated the dynamic response of surface structure adjacent to different soil conditions, foundation embedment depths and structure spacing. It was shown that the response of the whole interaction system decreases with decreasing soil stiffness, increasing structure spacing and decreasing foundation embedment depth. Alielahi *et al.* [6] used a robust numerical algorithm based on the boundary element method for numerical time domain analysis of unlined tunnels to investigate the effect of tunnel size, depth of burial and shape on the soil response of the site, and found that the subsurface structure has an amplifying effect on the surface motion for incident waves with a short dominant frequency. Aldaikh *et al.* [7] conducted shaking table tests and established a two-dimensional numerical model for structure-soil-structure interaction of three neighboring structures. A shaking table test and a two-dimensional numerical model were developed to investigate the effect of structure-soil-structure interaction on the three structures under seismic excitation. The effect of structure-soil-structure interaction on the three structures under seismic excitation was investigated. HF Wang *et al.* [8] reviewed studies about interaction of ground structure and underground structure. ANSYS has been further developed and enhanced for damping of hysteretic type. We discussed the influence of subway station on the neighboring ground structure. We examined the influence parameter of the dynamic interaction.

In recent years, due to the constraints on land resources, buildings have become taller and closer to each other, but the study of the seismic response of the adjacent structure to the inter-story isolated structure considering SSSI has not yet been addressed by scholars. Based on this, the seismic response models of the layer interval seismic structure without considering SSSI, considering SSSI and considering SSSI are established. Under different seismic wave inputs, the nonlinear seismic response is comparatively analyzed by changing the spacing between the adjacent structure and the inter-story isolated structure and by changing the weight of the adjacent structure, so as to obtain the structural response law.

2. Finite Element Model

2.1. Project Overview

A 9-story frame structure adopts a story seismic isolation system, with a protection intensity of 8 degrees, site category III, seismic design group II, and seismic isolation located at the top of the 2nd floor. Its structure is a three-span frame with plan dimensions of 18 m × 18 m, each span of 6 m and story height of 3 m. The size of frame column is 700 mm × 700 mm, the size of frame beam is 700 mm × 350 mm, and the size of secondary beam is 600 mm × 300 mm; the strength grade of concrete of frame column is C40, the strength grade of concrete of frame beam is C30, and the strength grade of concrete of secondary beam is C30; the model of longitudinal reinforcement of frame column and the model of hoop reinforcement is HRB400; the model of longitudinal reinforcement of frame beam and secondary beam is HRB335; the thickness of protective layer of concrete of frame column is 40 mm, and the thickness of protective layer of concrete of frame beam and secondary beam is 60 mm. The model is HRB335; the thickness of protective layer of concrete for frame column is 40 mm, the thickness of protective layer of concrete for frame beam and secondary beam is 60 mm; the thickness of floor slab is 120 mm, the double-layer arrangement of reinforcing steel and the model of reinforcing steel is HPB300, and the thickness of protective layer of concrete is 30 mm; the uniform constant load of floor slab is 3 kN/m^2, the uniform live load is 2 kN/m^2, and the equivalent constant load of infill wall is 6 kN/m. The homogeneous foundation is a raft slab foundation with a raft slab thickness of 1.5 m. The damping ratio is 0.05 for the superstructure and 0.05 for the foundation soil, and Rayleigh damping is used for the superstructure and foundation soil. The parameters of the adjacent structure are exactly the same as those of the inter-story isolated structure, except that there is no seismic isolation layer.

2.2. Create a Finite Element Model of a Structure without Considering the Effect of Soil-Structure Interaction (SSI), with the Effect of Soil-Structure Interaction (SSI), and with the Effect of Structure-Soil-Structure Interaction (SSSI)

The finite element model of the inter-story isolated structure considering no SSI, considering SSI and considering SSSI was established by using SAP2000 (**Figures 1-3**). The beams and columns are simulated by frame units, the floor slabs are simulated by thin-shell units, the raft slabs are simulated by thick-shell units, the foundation soil is simulated by solid units, the contact section between the raft foundation and the soil is connected by nodal constrained coupling, and the bedrock layer under the soil is simulated by fixed supports. 10 times transverse boundary plus viscoelastic boundary artificial boundary for calculation, basically can eliminate the influence of the transverse boundary on the interaction system. In this paper, the structure to consider the influence of SSI effect and SSSI effect, then take 13 times the size of the structure as the side length of the foundation,

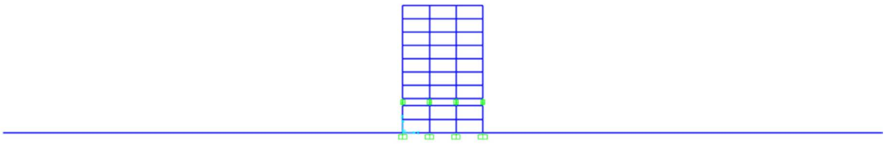


Figure 1. Section drawing of isolated structure considering no SSI.

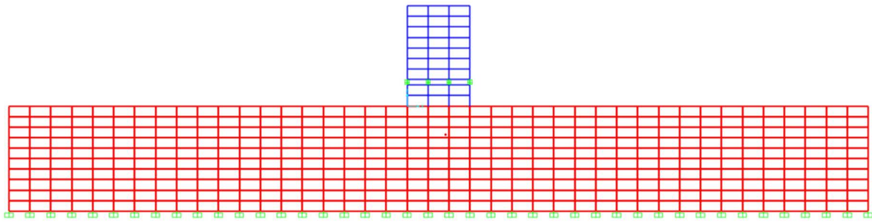


Figure 2. Section drawing of isolated structure considering SSI.

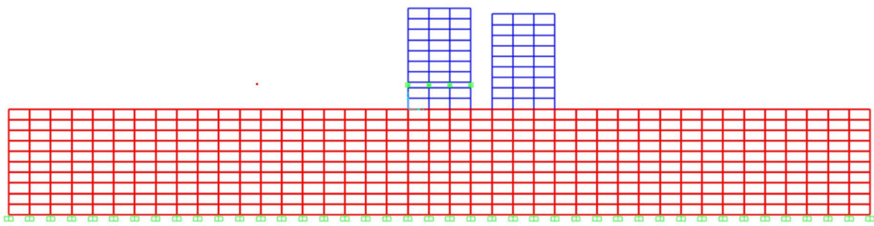


Figure 3. Section drawing of isolated structure considering SSSI.

the plane size of 234 m × 234 m. The use of layered foundation model that is more in line with the characteristics of the foundation soil, the soil mesh division unit 6 m × 6 m × 3 m, basically meet the accuracy of the operation, the parameters of the foundation soil are shown in **Table 1**, and set up visco-elastic artificial boundaries around the boundaries of the foundation soil. The nonlinear connection unit Damper-Exponential is selected to simulate the artificial boundary constraints around the foundation soil, and the relevant parameters of the artificial boundary are shown in **Table 2**. The seismic isolation bearing adopts the LRB900 type, and the parameters of the bearing are shown in **Table 3**.

2.3. Seismic Wave Selection

In this paper, three natural waves and one artificial wave applicable to three types of sites are selected for nonlinear time-range analysis: Hector Mine waveform with duration of 60 s, effective holding time of 50.4 s and sampling time interval of 0.02 s; Loma Prieta waveform with duration of 29.67 s, effective holding time of 26.64 s and sampling time interval of 0.01 s; and artificial waveform with duration of 30.02 s and effective holding time of 27.22 s. The duration of the waveform is 30.02 s, the effective holding time is 27.22 s, and the sampling time interval is 0.02 s. The peak acceleration of the three seismic waves is adjusted to 400 cm/s^2, which is equivalent to the peak acceleration corresponding to the rare earthquakes at 8 degrees. The acceleration response spectra of the seismic waves after peak adjustment are shown in **Figure 4**.

Table 1. Using different foundation soil parameters.

Number	Thickness (m)	Shear wave velocity (m/s)	Density (kg/m³)	Elastic modulus (MPa)	Poisson's ratio	Internal friction angle (˚)	Cohesive force (Pa)
1	3	100	2000	48	0.2	15	25000
2	3	120	2100	72.58	0.2	20	40000
3	24	140	2200	103.49	0.2	25	50000

Table 2. Parameters of artificial boundary.

Soil layer	Tangential spring stiffness coefficient	Normal spring stiffness coefficient	Tangential damping coefficient	Normal damping coefficient
1	81,301	162,602	200,000	326,598
2	122,887	245,774	252,000	411,514
3	175,071	350,142	308,000	502,962

Table 3. Parameters of isolation bearing.

Model Number	Effective diameter/ mm	Total thickness of rubber/mm	Stiffness before yield/(kN·m⁻¹)	Equivalent stiffness/(kN·m⁻¹)	Vertical stiffness/(kN·mm⁻¹)	Yielding force/kN
LRB900	900	162	17046	2213	5233	212

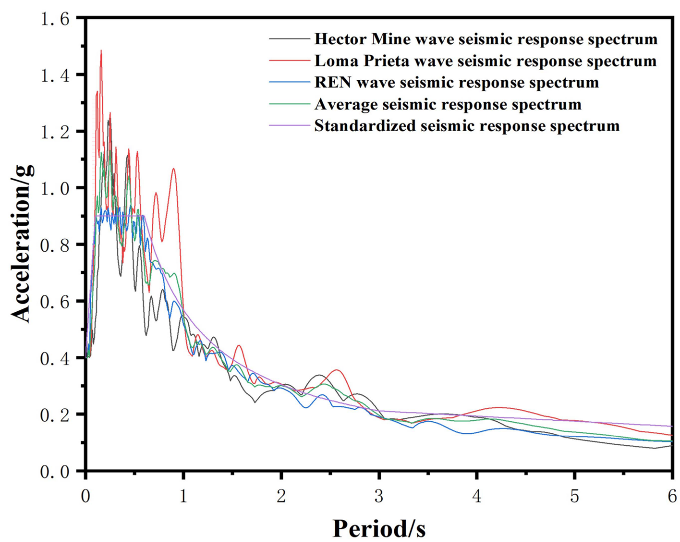


Figure 4. Seismic wave response spectrum.

3. Consider the Seismic Response of Inter-Story Isolated Structure with Adjacent Structure

3.1. Study the Effect of Different Spacing between Two Structures on the Inter-Story Isolated Structure

- The inter-story isolated structure is 9 stories, the adjacent structure is 9 stories, and the spacing between the two structures is 6 m, 12 m, 18 m, 24 m, 30 m, 36 m, 42 m, and 48 m.

- The structure-soil-structure interaction is realized through the foundation soil, and the vibration of the structure under seismic action forces the soil around the foundation to vibrate accordingly, which leads to the vibration of the adjacent structure, which feeds back the vibration to the surrounding structure. Therefore, the seismic response of a structure is not only influenced by the foundation soil, but also by the influence of adjacent structure through the foundation soil. This effect fades away as the spacing between the inter-story isolated structure and the adjacent structure becomes larger.
- The first three order periods of structural modal(s) analysis with different spacing between adjacent structure and inter-story isolated structure is shown in **Table 4**. From **Table 4**, it can be seen that the first three order periods of structural modal(s) analysis without considering SSI is lower than that of the structure considering both SSI and SSSI, and the first three order periods of structural modal(s) analysis considering SSSI are all smaller than that of the structure considering only SSI. As the spacing between the adjacent structure and the inter-story isolated structure keeps expanding, the first three order periods of structural modal(s) analysis also keep expanding.

From **Figures 5-7**, it can be seen that under the three selected seismic wave inputs, the inter-story drift and inter-story shear of the inter-story isolated structure without considering SSI are smaller than those of the inter-story isolated structure with considering SSI and SSSI. The inter-story drift and inter-story shear of the inter-story isolated structure considering SSSI is further affected compared to the inter-story isolated structure considering only SSI. As the spacing between the adjacent structure and the inter-story isolated structure becomes larger, the influence of the adjacent structure on the inter-story isolated structure becomes smaller and smaller, and the influence basically disappears when the spacing is 48 m.

From **Figure 8**, it can be seen that the change in the spacing of the two structures for the three selected seismic wave inputs has very little effect on the isolation layer of the inter-story isolated structure.

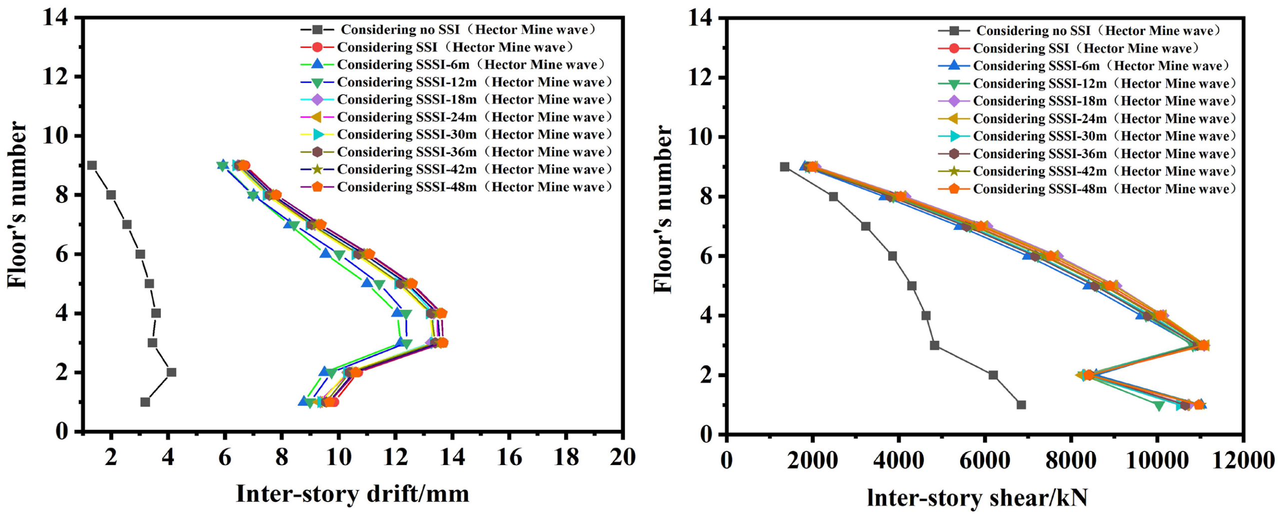
3.2. Study the Effect of Adjacent Structure with Different Weights on Inter-Story Isolated Structure

The inter-story isolated structure is 9-story, the spacing between the two structures is 6 m, and the number of story of the adjacent structures are 1, 5, 9, 13, 17, 21 and 25.

The structure-soil-structure interaction is realized through the foundation soil, and the vibration of the structure under seismic action forces the soil around the foundation to vibrate accordingly, which leads to the vibration of the adjacent structure, which feeds back the vibration to the surrounding structure. Therefore, the seismic response of a structure is not only influenced by the foundation soil, but also by the influence of adjacent structure through the foundation soil. This effect gradually increases as the weight of adjacent structure increases.

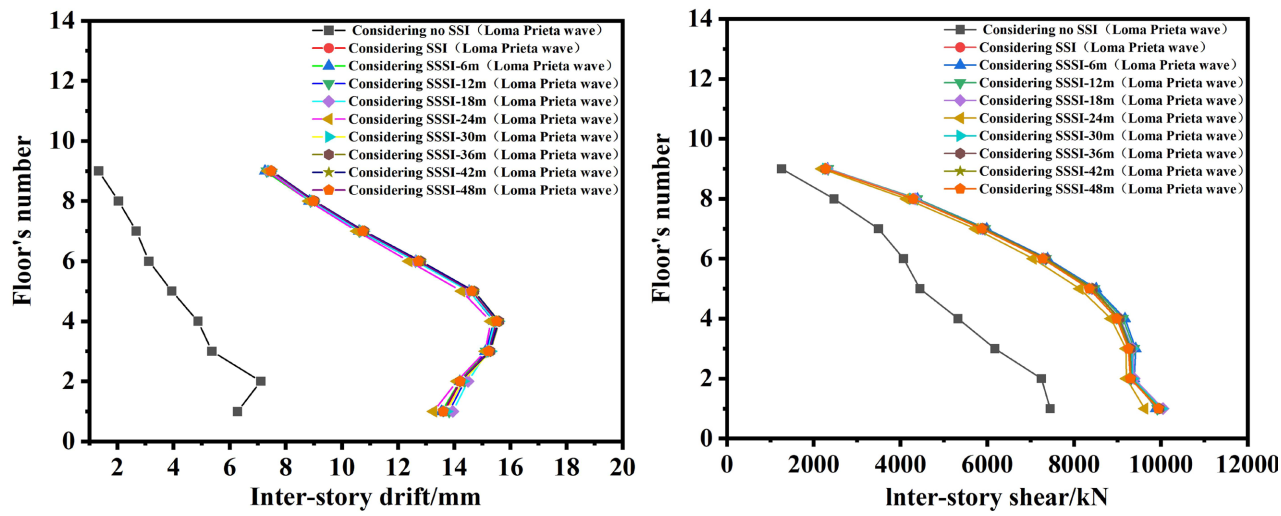
Table 4. The first three order periods of structural modal (s) analysis with different spacing between adjacent structure and inter-story isolated structure.

Order	No-SSI	SSI	SSSI-6	SSSI-12	SSSI-18	SSSI-24	SSSI-30	SSSI-36	SSSI-42	SSSI-48
1	2.2026	2.3055	2.3051	2.3054	2.3055	2.3055	2.3055	2.3055	2.3055	2.3055
2	2.1382	2.2432	2.2431	2.2431	2.2432	2.2432	2.2432	2.2432	2.2432	2.2432
3	1.8915	1.9058	1.9057	1.9058	1.9058	1.9058	1.9058	1.9058	1.9058	1.9058



(a) (b)

Figure 5. (a) The inter-story drift Hector Mine wave; (b) Inter-story shear of Hector Mine wave.



(a) (b)

Figure 6. (a) The inter-story drift of Loma Prieta wave; (b) The inter-story shear of Loma Prieta wave.

The first three order periods of structural modal(s) analysis with adjacent structure under different heights is shown in Table 5. From Table 5, it can be seen that The first three order periods of structural modal(s) analysis without considering SSI is lower than that of the structure considering either SSI or SSSI,

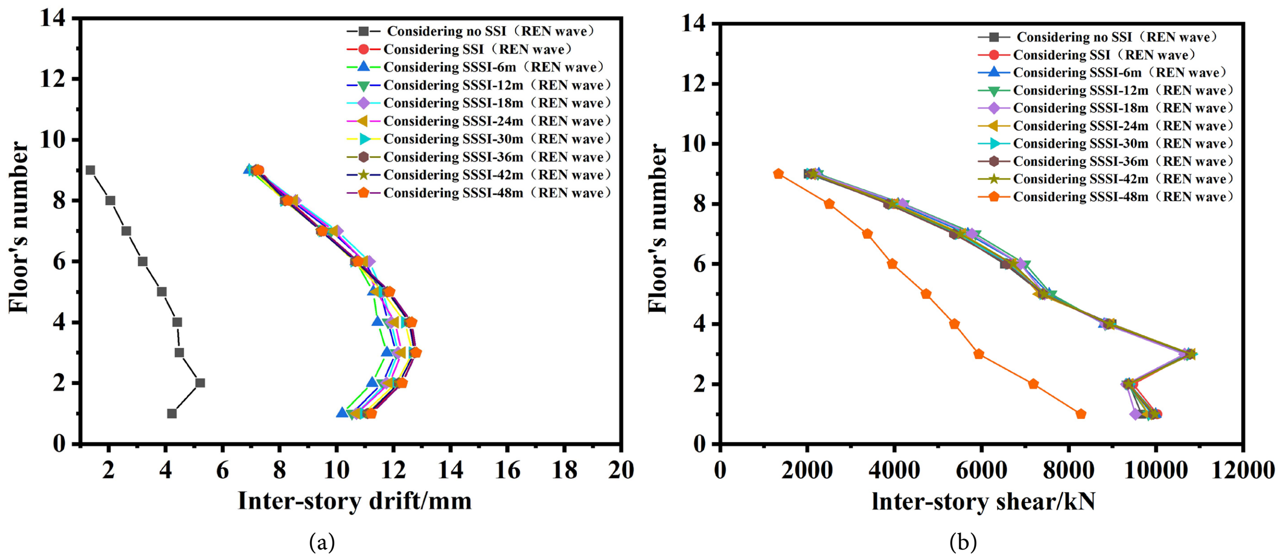


Figure 7. (a) The inter-story drift of REN wave; (b) The inter-story shear of REN wave.

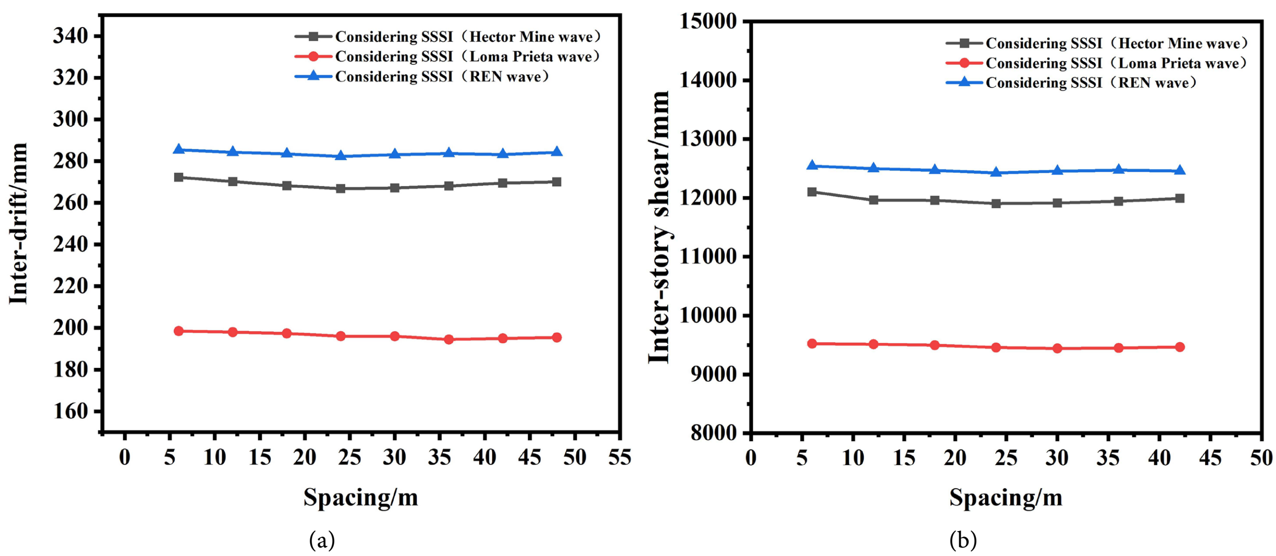
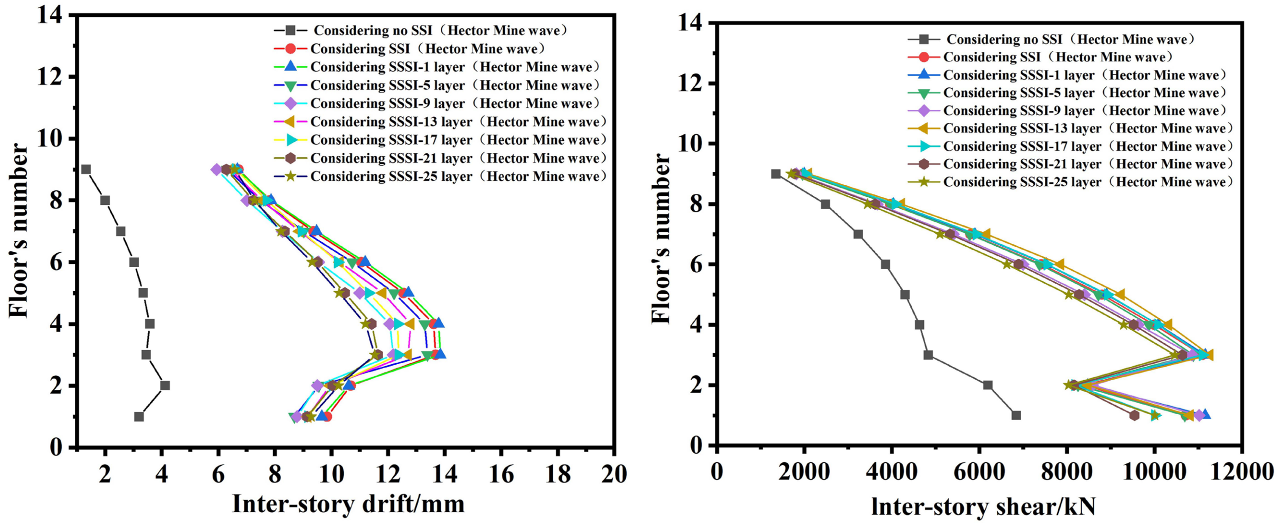


Figure 8. (a) The inter-story drift of three wave; (b) The inter-story shear of three wave.

Table 5. The first three order periods of structural modal(s) analysis with adjacent structure under different heights.

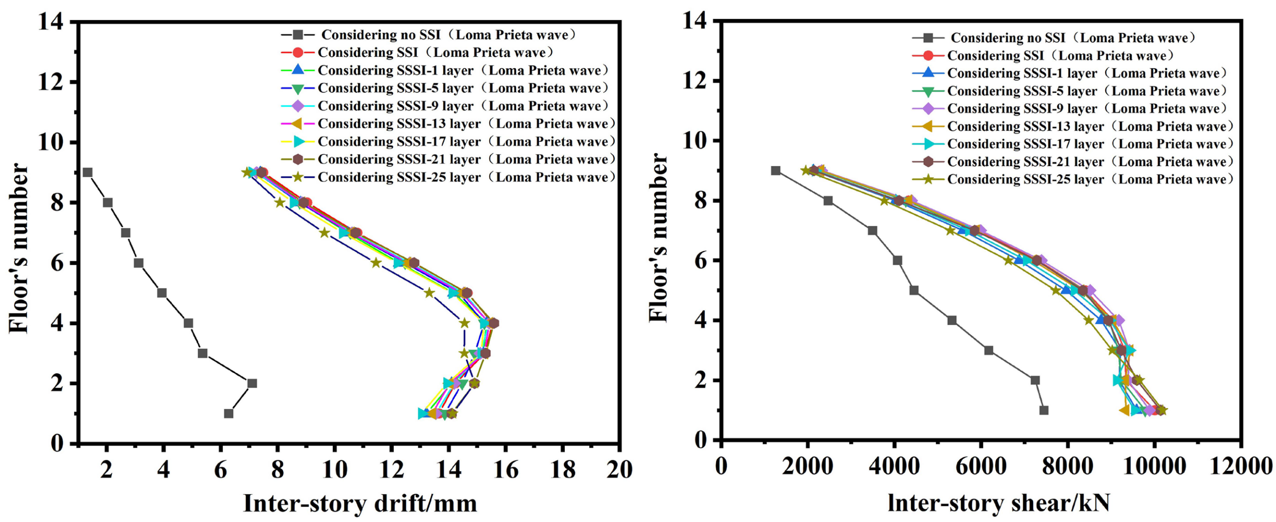
Order	No-SSI	SSI	SSSI-1	SSSI-5	SSSI-9	SSSI-13	SSSI-17	SSSI-21	SSSI-25
1	2.2026	2.3055	2.3051	2.3051	2.3051	2.3051	2.3077	2.9562	3.6942
2	2.1382	2.2432	2.2431	2.2431	2.2431	2.2432	2.2742	2.6923	3.3924
3	1.8915	1.9058	1.9057	1.9057	1.9057	1.9057	2.2438	2.3049	2.3050

and when the number of floors of the adjacent structure reaches 17 floors or more, the first three order periods of structural modal(s) analysis considering SSSI is higher than that of the structure considering only SSI. The first three order periods of structural modal(s) analysis expand as the weight of the adjacent structure increases.



(a) (b)

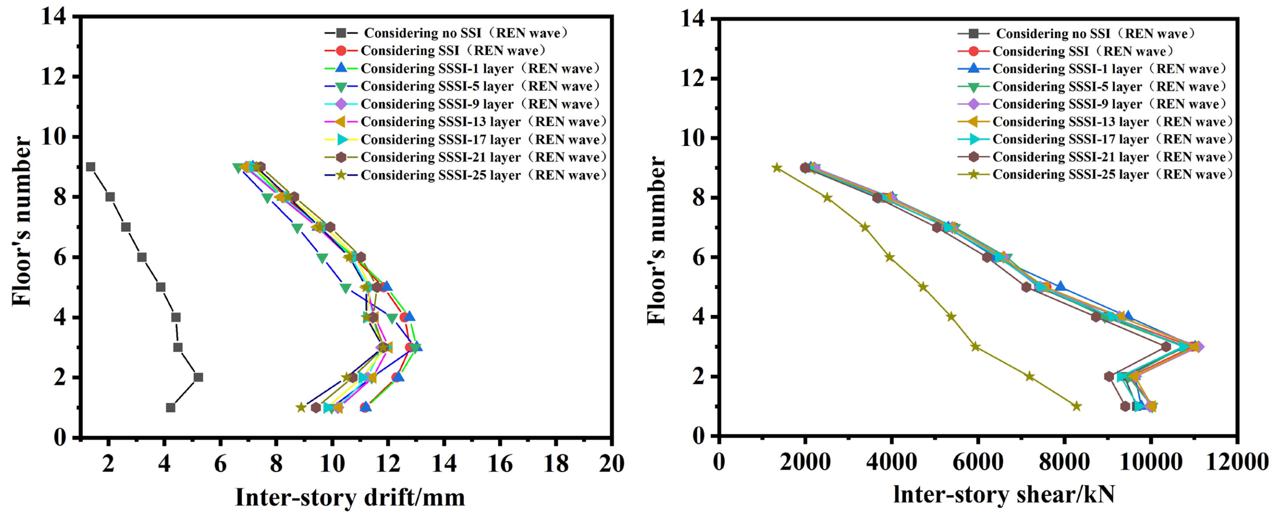
Figure 9. (a) The inter-story drift Hector Mine wave; (b) inter-story shear of Hector Mine wave.



(a) (b)

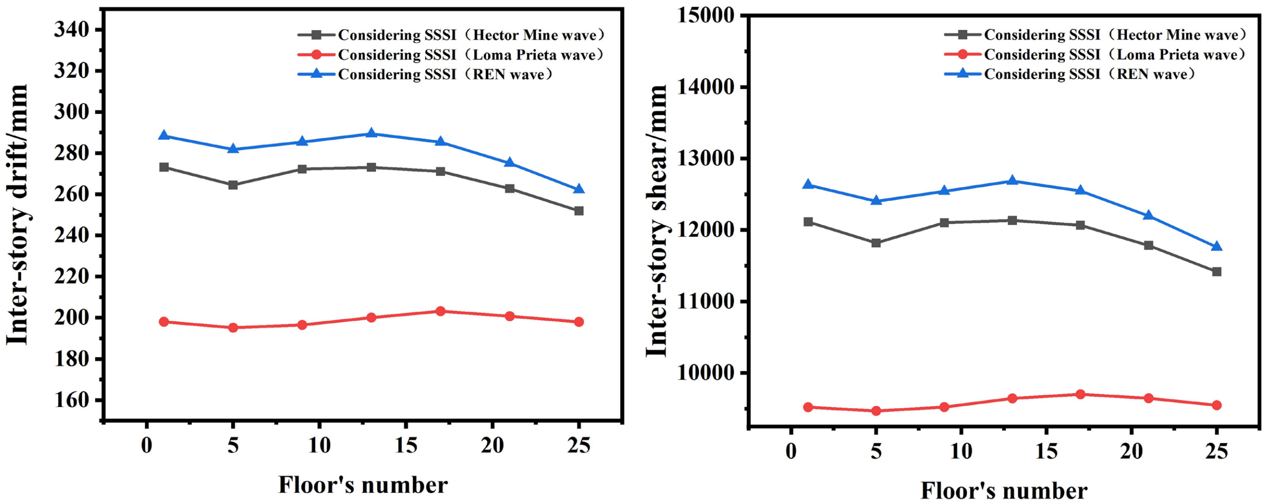
Figure 10. (a) The inter-story drift of Loma Prieta wave; (b) The inter-story shear of Loma Prieta wave.

From **Figures 9-11**, it can be seen that under the three selected seismic wave inputs, the inter-story drift and inter-story shear of the inter-story isolated structure without considering SSI are smaller than those of the inter-story isolated structure with considering SSI and SSSI. The inter-story drift and inter-story shear of the inter-story isolated structure considering SSSI is further affected compared to that of the inter-story isolated structure considering only SSI. As the weight of the adjacent structure continues to increase, the adjacent structure affects the inter-story isolated structure more and more. When the weight of the adjacent structure is greater than the weight of the inter-story isolated structure, the influence of the adjacent structure on the inter-story isolated structure increases significantly.



(a) (b)

Figure 11. (a) The inter-story drift of REN wave; (b) The inter-story shear of REN wave.



(a) (b)

Figure 12. (a) The inter-story drift of three wave; (b) The inter-story shear of three wave.

As can be seen in **Figure 12**: with three selected seismic wave inputs, the influence of the adjacent structure on the Isolation layer of the inter-story isolated structure increases as the weight of the adjacent structure continues to increase.

4. Conclusions

1) Under different seismic wave inputs, the inter-story drift and inter-story shear of the inter-story isolated structure without considering SSI are smaller than those considering SSI and SSSI. The inter-story drift and inter-story shear of the inter-story isolated structure considering SSSI are further affected compared to that of the inter-story isolated structure considering only SSI.

2) As the spacing between adjacent structure and inter-story isolated structure

increases, the influence of adjacent structure on inter-story isolated structure decreases. The variation in the spacing between the two structures has a negligible effect on the isolation layer of the inter-story isolated structure.

3) With the increase in the weight of adjacent structure, the influence of adjacent structure on inter-story isolated structure becomes more significant. When the weight of the adjacent structure is greater than the weight of the inter-story isolated structure, the influence of the adjacent structure on the inter-story isolated structure increases significantly. The increasing weight of adjacent structure has an increasing effect on the Isolation layer of the inter-story isolated structure.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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