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Damping coefficient calculation method for shore-side container cranes under the seismic conditions

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Abstract. Shore-side container cranes (SCC) are widely used in ship loading and unloading. However, the SCC is often damaged by the seismic wave shock. In seismic response analysis, the setting of damping coefficients has a large impact on the accuracy of the calculation results. In order to better design the SCC mechanical performance, the improved damping coefficient calculation method is proposed. The results of the simulation and the experiment are compared under the different seismic conditions. The results show that the influence of the damping coefficient calculation method on the SCC seismic response increases with strengthened seismic intensity. When the peak acceleration is small, the simulation results under different damping coefficients are almost the same and are close to the experiment values. When the peak acceleration is large, only the error between the simulation results obtained by the improved method and the experimental values is less than 5%. It is thus concluded that the improved damping coefficient calculation method is accurate and reliable.

Keywords: Shore-side container crane / seismic conditions / damping coefficient / experiment

1 Introduction

Shore-side container crane (SCC) is a piece of important loading and unloading equipment at ports, and the damage to SCC caused by the earthquake has drawn high attention from many scholars. The designer must master the dynamic performance of the structure under different working conditions, predict the dangerous parts of the structure under different earthquake conditions, and make reasonable improvements to the structure to avoid major accidents when the earthquake comes. However, only similar model tests can be carried out since on-site tests are not available for such large structures. Before the model test, seismic dynamic simulation analysis should be conducted for them, where damping coefficient has always been a difficulty in the research because reasonable setting of damping coefficient may make the simulation results more accurate and reliable.

Although many research achievements have been achieved in seismic tests for large engineering structures, they are targeted at high buildings [1–3], gravity dams [4–6] and bridges [7–9]. In order to obtain the SCC mechanical performance, Jacobs et al. [10] built a 1:20 scale model of SCC to carry out a series of finite element simulation analyses, and they achieved satisfactory results. Kanayama and Kashiwazaki [11] designed a 1:8 test model to research the multi-rigid-body dynamic behavior of SCC and the damage forms. Japanese researchers [12,13] built a 1:15 test model of pier foundation and the SCC, they carried out a series of seismic tests for the interaction between pier foundation and SCC. Lou et al. [14] discussed the influence of mass proportional damping matrix on the calculation results, and then the determination method of mass proportional damping coefficient was proposed. At present, the research of proportional damping hypothesis has been relatively mature, and there are many cases in the field of large structure as civil engineering and machinery. However, there is no explanation on how to determine the damping coefficient in the numerical calculation of finite elements, and the Rayleigh damping models are often considered as a basis for damping matrix construction commonly utilized in the seismic time history analysis of large structures [15].

Existing studies do not set the corresponding effective damping coefficient for the SCC. In this paper, the improved damping coefficient calculation method is proposed based on the most common four Rayleigh damping coefficient calculation methods, where a simulation analysis model is built for dynamic time history

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analysis with the SCC model as the experimental subject. In the time history analysis, five groups of damping coefficients obtained by the above methods are used to compare the seismic response of SCC with different damping coefficients. Finally, the shaking table tests are conducted for the model, and the results show that the improved method is more available.

2 Main components of SCC

The research object of this article is the J248 SCC structure, which is mainly welded and assembled by Q345 high-strength steel. The yield limit of the material is 345 MPa, and the elastic modulus is $E = 2.06\times10^{11}\,\mathrm{N/m^2}$, the Poisson's ratio is 0.3, the density is $7850\,\mathrm{kg/m^3}$. The SCC mainly consists of the crane span traveling mechanism, gantry structure (mainly includes landside and seaside pillars, landside and seaside beams, horizontal beams, drawbars, and other components), front and rear girders, drawbar system, machine room, traveling trolley, and slings, etc., as shown in Figure 1.

During operation, the SCC travels along the track that is parallel to the coastal line, while the traveling trolley transfers containers along the track on the beam for loading and unloading operations.

3 Calculation method for damping coefficient

The existence of damping makes the amplitude of the system in the resonance cannot be infinitely amplified, and it can consume the energy of earthquakes. Unlike the physical quantities such as mass and stiffness, the damping cannot be measured directly on the structure or expressed clearly by mathematical methods. Therefore, the damping matrix $[C]$ is written as the sum of the linear proportions of the mass matrix $[M]$ and the stiffness matrix $[K]$ [16]:

$$[C] = \alpha[M] + \beta[K], \tag{1}$$

where α and β are damping coefficients.

The setting of damping parameters includes damping coefficient α and β and damping ratio ξ, which needs to be set artificially in the simulation software. The value of α and β can be calculated in the following formula:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \frac{2\omega_m\omega_n}{\omega_n^2-\omega_m^2}\cdot\begin{pmatrix}\omega_n & -\omega_m\\ -\dfrac{1}{\omega_n} & \dfrac{1}{\omega_m}\end{pmatrix}\cdot\begin{bmatrix}\xi_m\\ \xi_n\end{bmatrix}, \tag{2}$$

where ξ_m and ω_m are the damping ratio of the number m order vibration mode and its corresponding fixed frequency; ξ_n and ω_n are the damping ratio of the number n order vibration mode and its corresponding fixed frequency. Upon calculation of α and β, the damping ratio of other order vibration mode may be solved through the following formula:

$$\xi_n = \frac{\alpha}{2\omega_n} + \frac{\beta\omega_n}{2}. \tag{3}$$

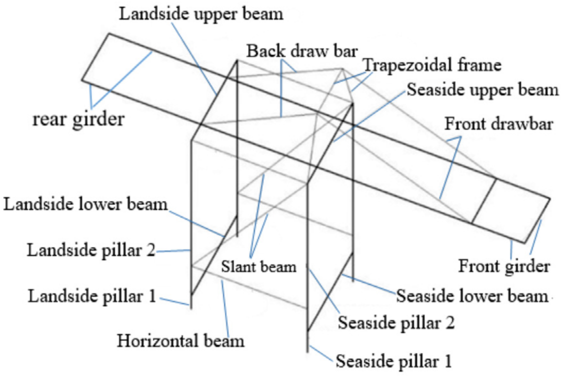


Fig. 1. Main components of SCC structure.

It can be seen from equation (3) that the damping ratio in time domain calculation is frequency dependent [17]. The selection of appropriate frequency can help obtain the most reasonable α and β. Namely, the data which are closest to the actual situations are obtained through finite element simulation experiments, providing accurate and reliable data reference for the model tests.

At present, in the calculation of the dynamic response of the structure in engineering, the coefficient α and β are usually calculated using the following methods:

Method 1: Assuming that the contributions of mass matrix and stiffness matrix in Rayleigh damping is the same. Then the damping coefficient α and β can be expressed as:

$$\begin{cases}\alpha = \xi\omega_1\\ \beta = \dfrac{\xi}{\omega_1}\end{cases}. \tag{4}$$

The drawback of this method is that all damping within the frequency range is overestimated, resulting in relatively low dynamic response of structure under the same external dynamic load incentive.

Method 2: The sensitive frequency ranges of the selected object structure is ω_a and ω_b. The damping ratio at the boundary of frequency may be expressed with the following formula:

$$\begin{cases}\xi_a = \dfrac{1}{2}\left(\dfrac{\alpha}{\omega_a} + \beta\omega_a\right)\\ \xi_b = \dfrac{1}{2}\left(\dfrac{\alpha}{\omega_b} + \beta\omega_b\right)\end{cases}. \tag{5}$$

This method underestimates the damping between ω_a and ω_b, it also overestimates the damping beyond the frequency range. Therefore, the structural dynamic response calculated by this method is too high.

Method 3: Based on method 2, relevant scholars improved the calculation method [18], let

$$\frac{d\xi}{d\omega} = -\frac{\alpha}{2\omega^2} + \frac{\beta}{2}, \tag{6}$$

where $\omega = (\alpha/\beta)^{1/2}$, by substituting it into equation (3), the minimum damping ratio $\xi_{\min} = (\alpha\beta)^{1/2}$ can be obtained. The damping ratio at ω_a and ω_b may be expressed as:

$$\begin{cases} \xi_{\max} = \dfrac{1}{2}\left(\dfrac{\alpha}{\omega_a} + \beta\omega_a\right) \\ \xi_{\max} = \dfrac{1}{2}\left(\dfrac{\alpha}{\omega_b} + \beta\omega_b\right) \end{cases}, \tag{7}$$

$\xi_0 = (\xi_{\max} + \xi_{\min})/2$ is defined, where $\xi_{\max}$ and $\xi_{\min}$ are the maximum and minimum damping ratios, respectively. If the calculated damping ratio $\xi < \xi_0$, then $\xi = \xi_0$. According to equation (7), α and β may be calculated. Then the underestimated damping ratio between ω_a and ω_b may be partially made up.

Method 4: Based on method 1, the two frequencies of ω_1 and ω_2 are used for calculating α and β. ω_1 is the fundamental frequency of the structure; $\omega_2 = n\omega_1$, where n is an odd number which is greater than ω_e/ω_1, and where ω_e is the main frequency of the seismic wave. The frequency characteristics of structure and the characteristics of seismic frequency are considered, but the structure damping within the ranges of ω_1 and ω_2 is underestimated. α and β can be expressed as [19]:

$$\begin{cases} \alpha = 2\xi\dfrac{\omega_1\omega_2}{\omega_1 + \omega_2} \\ \beta = 2\xi\dfrac{1}{\omega_1 + \omega_2} \end{cases}. \tag{8}$$

Improved method in this paper: The essential difference of the calculation method of damping coefficient mainly lies in the way of frequency selection. Hence, considering the advantages and disadvantages of the above methods, the improved Rayleigh damping coefficient calculation method is proposed. In this method, the ω_1 as the fundamental frequency of structure in method 4 is changed to the minimum inherent frequency. Here, ω_1 is the first order inherent frequency of structure vibration under the ground motion excitation. $\omega_2 = n\omega_1$, n is an odd number which is greater than ω_e/ω_1, where, ω_e is the main frequency of seismic wave. After two main frequencies are determined, the method 3 is used to calculate damping coefficient α and β. The frequency characteristics of structure and spectrum characteristics of seismic waves are considered, without underestimating or overestimating the damping of structure within the ranges of ω_1 and ω_2.

4 Simulation and experiment

4.1 Model parameters and conditions

3D simulation model of the SCC is established by the software ABAQUS, as shown in Figure 2a. To compare the seismic response of the SCC structure with different damping coefficients and prove the correctness of the improved calculation method, an SCC model is adopted for simulation, the key measurement points of the model are shown in Figure 2b. Among them, the connection between the model leg and the vibrating table is to simulate the real situation, that is, the real contact between the walking wheel at the bottom of the quay crane and the track.

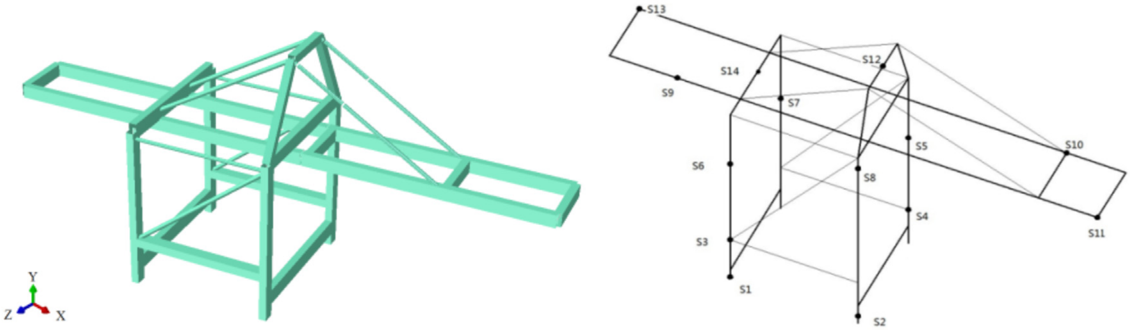
Meanwhile, according to the real wheel-rail contact model, the real wheel-rail contact model of the experimental model is established, which is a reduced scale (1:15) representation of the J248 SCC structure, as shown in Figure 2c. Similarity relation of the scale model of SCC structure can be seen in Table 1. The main parameters of the shaking table are as follows: The table top of the shaking table is 1500 mm long and 1500 mm wide. The maximum acceleration in the horizontal direction is $\pm 50\,\mathrm{m/S^2}$, the maximum acceleration in the vertical direction is $\pm 30\,\mathrm{m/S^2}$, the maximum displacement in the horizontal direction is ±200 mm, the maximum displacement in the vertical direction is ±100 mm, the maximum speed in the horizontal direction is 0.8 m/s, the maximum speed in the vertical direction is 0.8 m/s, and the maximum bearing capacity is 2 t, The frequency range is 0.1–100 Hz. Furthermore, the dynamic response data of each key point of the experiment model under seismic excitation is extracted and analyzed, and then it is compared with the simulation results.

In order to calculate damping coefficient, the frequency of finite element model is first extracted in software ABAQUS. Through hammering modal test, the first 8 order frequencies of SCC are measured, as shown in Table 2.

The scale model of SCC is placed on the shaking table for frequency sweep, thus obtaining the self-vibration frequency of SCC. In the loading setting of shaking table, the range of frequency sweep is set to 10–50 Hz. The acceleration sensors are arranged according to the layout of measuring points. Data recorded by the acceleration sensor are read after the sweep test. The frequency corresponding to the peak value is the self-vibration frequency of SCC structure. Through frequency sweep test, the vibration of the model is the most intense when the excitation frequency is close to 45.97 Hz. Therefore, 45.97 Hz can be determined as the self-vibration frequency (natural frequency) of the model. The frequency of the fourth mode in the finite element modal analysis of the model is 46.60 Hz, which is consistent with the experimental results. The simulation modal analysis results are in good agreement with the swept frequency test results, indicating that the simulation results are comparable with the test values.

4.2 Simulation results

The recorded acceleration of the EL-Centro (The name of ground motion) wave and Taft wave (The first seismic wave in the world that successfully records the whole process data) is set as input seismic excitation, and the peak acceleration is adjusted to 0.22 g, 0.4 g and 0.62 g, respectively. Where EL-Centro and Taft are two different types of seismic waves. Their dominant frequencies are 27.27 Hz and 34.1 Hz respectively. In the simulation and shaking table experiment, the EL-Centro wave and Taft wave in different peak acceleration is input directly. The scope of this study is within the linear range, so the nonlinear factors appearing in the test are constrained.



(a) 3D simulation model

(b) Diagram of key measurement points

(c) Shaking table experiment set-up

Fig. 2. 3D simulation model and experiment model.

Table 1. Similarity relation of the scale model.

Similarity parameter	Similarity ratio	Similarity parameter	Similarity ratio
Geometric dimension	15	Frequency	1/15
Density	1	Time	15
Mass	15^3	Elastic modulus	1
Displacement	15	Section inertia radius	15

Four damping coefficient calculation methods commonly used in engineering and improved coefficient calculation methods are adopted. The frequency is selected according to the above damping coefficient calculation method, and 5 groups of different damping coefficients are obtained by solving the equations, as shown in Table 3. When method 4 is adopted for calculation, $n = 1$, namely, $\omega_2 = n\omega_1$. At this time, the calculated damping coefficient is the same with that calculated with method 1. Therefore, the finite element simulation results of T1 and T4 are the consistent, they can be merged. In the time history calculation, the measurement points of S3, S6, S11, S12 on the model are monitored.

As shown in Figure 3, it is clear that the trend of the acceleration time domain curve of the measurement point is similar under the different damping parameter settings, and the main difference is the magnitude of the peak acceleration. The maximum peak acceleration is 2721.4 mm/s^2 under T1 and T4, which is the minimum peak acceleration among several groups of parameters, it is consistent with the calculation characteristics of Method 1. The maximum peak acceleration is 3348.4mm/s^2 under T2, which is the maximum peak acceleration among several groups of parameters, it is consistent with the calculation characteristics of Method 2. The maximum peak accelerations under T3 and T5 are respectively 3099.8 mm/s^2 and 2967.8 mm/s^2, which is between Method 1 and Method 2.

To clearly show the dynamic effects of damping coefficients on different test points on the model, the acceleration amplification coefficient envelopes of the model on measurement points S3, S6, S11, and S12 are plotted in Figure 4.

Table 2. Self-vibration frequency of SCC structure.

Order	1	2	3	4	5	6	7	8
Frequency/Hz	20.79	29.86	36.93	46.60	48.51	50.59	80.21	92.94

Table 3. Damping coefficient of the model.

Method	T1	T2	T3	T4	T5
α	1.039	1.698	1.189	1.039	2.173
β	24.1e-4	8.79e-4	6.15e-4	24.1e-4	5.01e-4

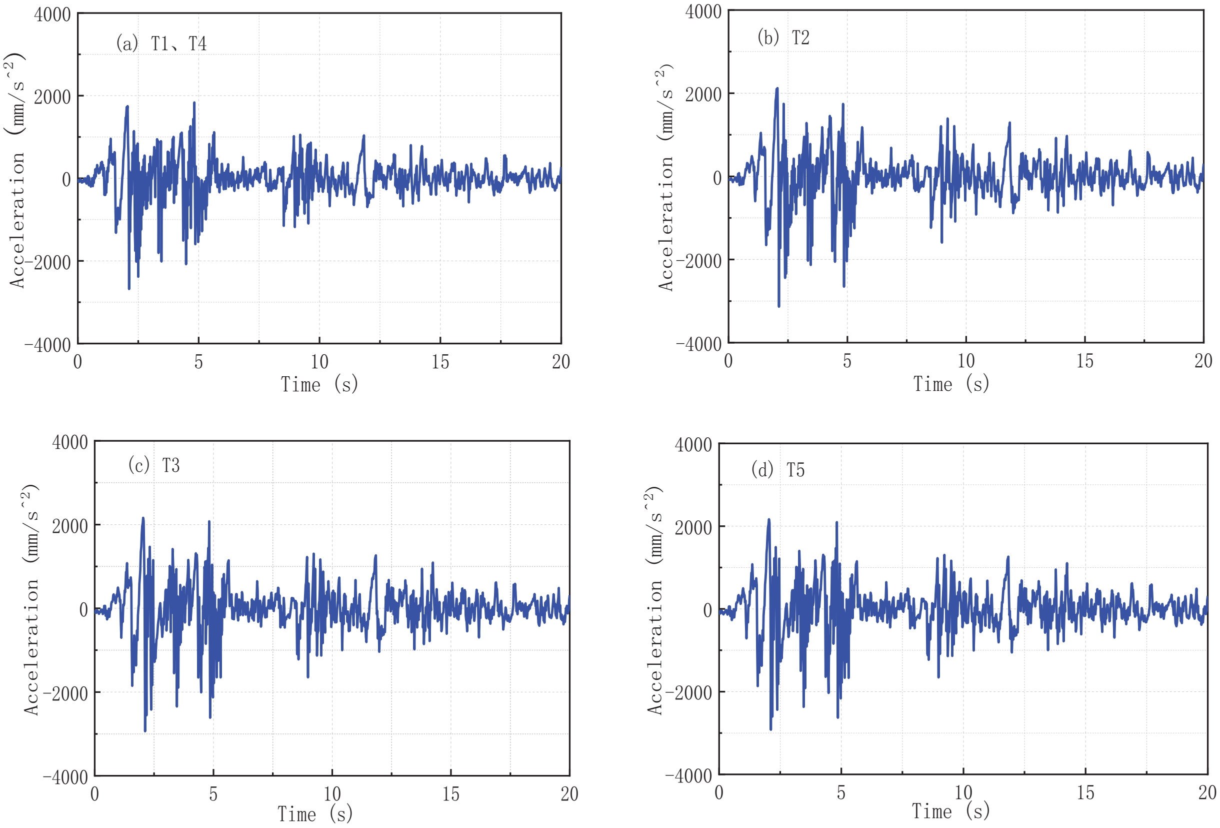


Fig. 3. The time domain characteristic of S3 point under the condition of EL Centro wave 0.22g (a) T1 and T4; (b) T2; (c) T3; (d) T5.

From Figure 4, under El-Centro and Taft seismic wave excitation with peak acceleration adjusted to 0.22 g, 0.4 g and 0.62 g, the peak acceleration of measuring points is different under different damping coefficient settings (T1-T5), which can be reflected in the acceleration amplification factor. According to the acceleration amplification factor at the measurement points, the deviation between the simulation value of different models and the T5 can be calculated. The deviation is more obvious under the action of El-Centro seismic wave with strength of 0.22 g. The deviation between T2 and T5 at measuring point S3 is 7.81%. Under Taft seismic wave, the deviation is smaller, and the maximum value is 2.29% between T1, T4 and T5. It shows that the damping coefficient has little effect on the SCC when the peak acceleration is adjusted to 0.22 g, and the El-Centro seismic wave model is more sensitive to the damping coefficient than Taft seismic wave. Compared with 0.22 g earthquake excitation, the deviation of acceleration amplification coefficient envelope under 0.4 g earthquake is enlarged. Similarly, the deviation is obvious under El-Centro seismic wave, in which the deviation between T2 and T5 at measuring point S3 reaches 12.9%, and the deviation is smaller under Taft seismic wave, with the maximum value of 2.73% between T1, T4 and T5. When the peak acceleration is adjusted to 0.62 g, the deviation is obvious under El-Centro seismic wave, where the deviation between T2 and T5 reached 17.9% at the measuring point S3. The deviation is small under Taft seismic wave, and the maximum value is 3.76% between T1, T4 and T5.

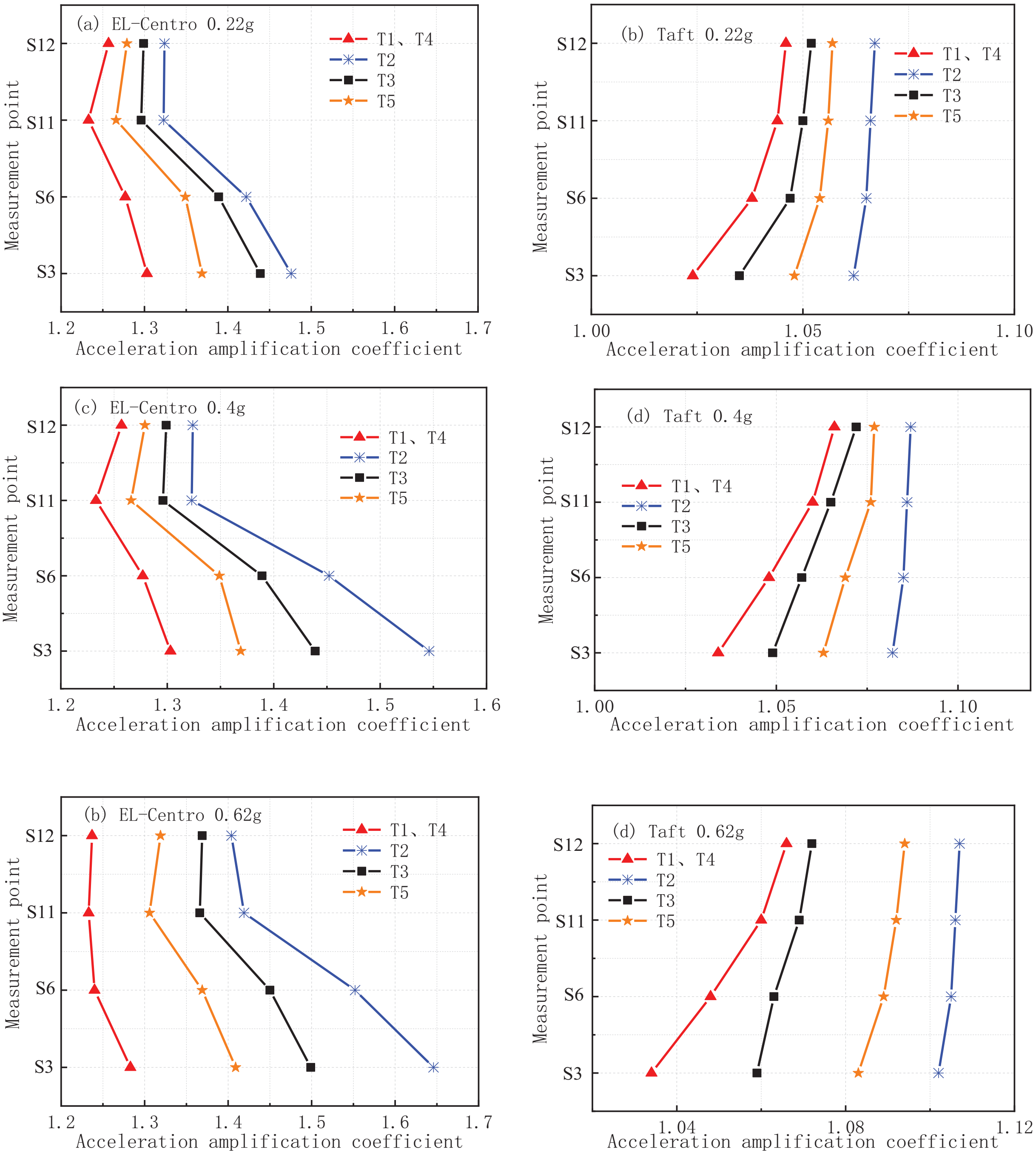


Fig. 4. Envelope curve of acceleration amplification coefficient with the seismic wave (0.22 g; 0.4 g; 0.62 g).

4.3 Experiment results

Whether the calculation method of damping coefficient of SCC is reliable can be verified by shaking table experiment. The dynamic response data of key points under earthquake excitation are extracted and compared with the previous simulation analysis results. If the experiment values are in great agreement with the simulation values obtained by using the improved damping coefficient calculation method, it shows that the improved method is accurate and reliable.

Bolts are used to form a fixed connection with the shaking table at the support of the model legs, which is similar to the boundary conditions in civil engineering. In practice, the boundary condition between the SCC and the port's ground is the contact between the supporting wheel of crane and the port's track. The edited seismic wave is input into the shaking table control system. El-Centro and Taft seismic wave is set to 0.22 g, 0.4 g and 0.62 g.

Figure 5 shows the time domain value of acceleration measured at the points of S3 and S6 of the SCC model under the excitation of 0.22 g EL-Centro wave.

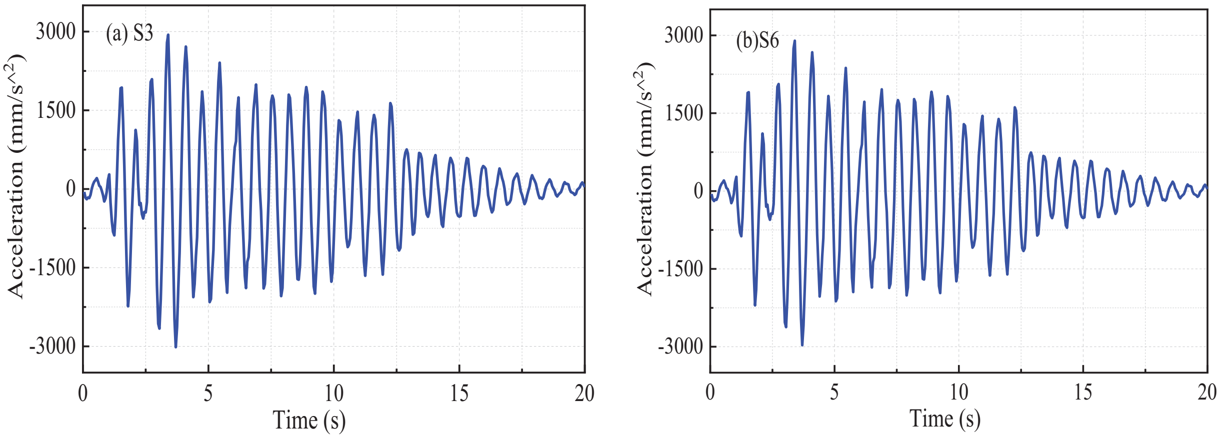


Fig. 5. Acceleration test value of measurement point under 0.22 g EL-Centro wave (a) S3; (b) S6.

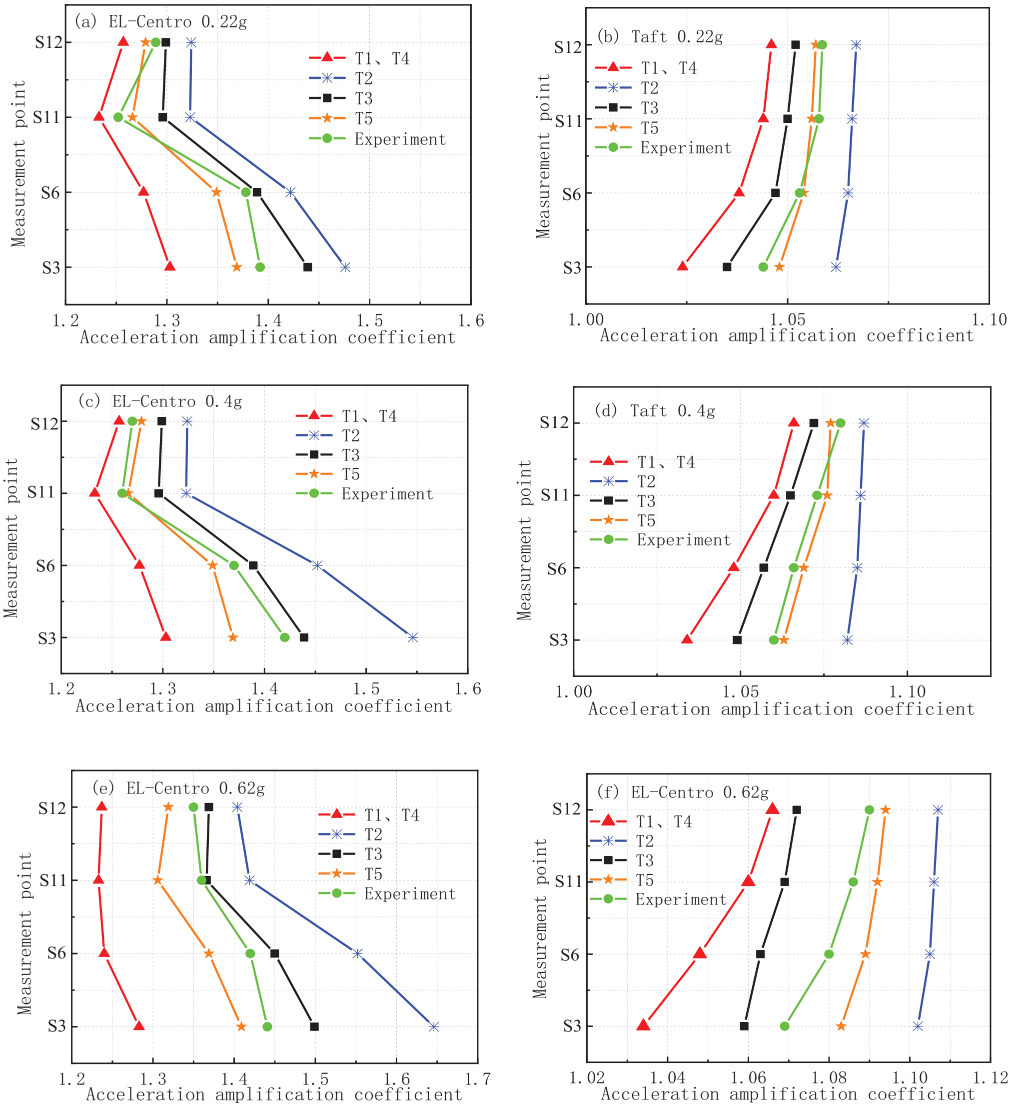


Fig. 6. Envelope curve of acceleration amplification coefficient with the seismic wave (0.22 g; 0.4 g; 0.62 g).

The extreme value of acceleration at each point in the test is extracted to calculate the amplification coefficient of its acceleration. Figure 6 is the envelope curve of acceleration amplification coefficient between T1-T5 and experiment points.

Under El and Taft waves, the simulation calculation results are compared with the experimental values. In general, the closest finite element calculation result to the test value is the damping parameter obtained with T5 method. That is, the new calculation method proposed in this article. When the peak acceleration is 0.22 g, the deviation between the simulation value (T1–T5) and experimental value is relatively minor, and it is indicated that the five methods are applicable to seismic simulation calculation of the SCC model. However, with the peak acceleration increases, the deviation between simulation value and the experimental value is gradually enlarged. When the peak acceleration is adjusted to 0.62 g, there are measurement point models with deviation exceeds 10% with the calculation method T1-T4, while the deviation between the simulation results and experimental value are within 5% with the new calculation method T5. It is clear that the closest simulation results to experimental value are the damping parameters obtained with the T5, or namely, the new calculation method proposed herein. Therefore, the improved damping coefficient calculation method is accurate and reliable.

5 Conclusions

Through the improved damping coefficient calculation method, the simulation results and experimental results of SCC seismic response under different seismic conditions are compared. The main conclusions are summarized as follows:

- Four calculation methods of damping coefficient α and β in the dynamic response calculation of engineering structures are summarized. Considering the advantages and disadvantages of the above methods, an improved Rayleigh damping coefficient calculation method is proposed. The calculation method of damping coefficient has a great influence on the SCC mechanical performance analysis with different seismic wave excitation parameters, the deviation of the acceleration amplification coefficient simulation results among the method is up to 17.9%.
- The reliability of the calculation method of SCC damping coefficient is verified by shaking table experiment. The dynamic response data of key points with earthquake excitation are extracted and compared with the simulation results. The improved calculation method of damping coefficient is verified, which can be used to predict SCC mechanical performance, as the deviation between the simulation results and experimental value are within 5%.

From the above findings and analysis, the application of the improved damping coefficient calculation method provide an effective way for the study of SCC performance under seismic conditions.

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Conflict of interest

The authors declare that no conflicts of interest exist in this manuscript.

References

[1] J.P. Moehle, Seismic analysis, design, and review for tall buildings, Struct. Des. Tall Spe Build. **15**, 495–513 (2006)
[2] D.W. Ko, H.S. Lee, Shaking table tests on a high-rise RC building model having torsional eccentricity in soft lower storeys, Earthq. Eng. Struct. Dyn. **35**, 1425–1451 (2006)
[3] H.S. Lee, D.W. Ko, Seismic response characteristics of high-rise RC wall buildings having different irregularities in lower stories, Eng. Struct. **29**, 3149–3167 (2007)
[4] A.M. Riyaz, C.A. Taylor, An experimental investigation into earthquake-induced failure of medium to low height concrete gravity dams, Earthq. Eng. Struct. Dyn. **24**, 373–393 (1995)
[5] R. Tinawi, P. Leger, M. Leclerc, G. Cipolla, Seismic safety of gravity dams: from shake table experiments to numerical analysis, J. Struct. Eng. **126**, 518–529 (2000)
[6] D.G. Zou, B. Xu, X.J. Kong, Study of influence of different methods for calculating Rayleigh damping coefficient on high earth-rock dam seismic response, Rock Soil Mech. **32**, 797–803 (2011)
[7] M.A. Hosam-Eddin, A.M. Abdel-Ghaffar, Seismic energy dissipation for cable-stayed bridges using passive devices, Earthq. Eng. Struct. Dyn. **23**, 877–893 (1994)
[8] K.R. Karim, F. Yamazaki, Effect of earthquake ground motions on fragility curves of highway bridge piers based on numerical simulation, Earthq. Eng. Struct. Dyn. **30**, 1839–1856 (2001)
[9] B.B. Chen, Z.R. Feng, H.M. You, Seismic response analysis of long-span cable-stayed bridge with nonlinear viscous dampers under different periodic seismic waves, Civ. Eng. J. **27**, 114–131 (2018)
[10] L.D. Jacobs, D.R. Reginald, T.L. Roberto, Seismic behavior of a Jumbo container crane including uplift, Earthq. Spectra **27**, 745–773 (2011)
[11] T. Kanayama, A. Kashiwazaki, Study on the dynamic behavior of container cranes under strong earthquakes. ASME PVP, Seismic Eng. **364**, 276–284 (1998)
[12] S. Yamamoto, T. Sugano, T. Tanabe, The shaking table test of the interaction between the pier type wharf and the container crane during earthquakes. Trans. Jpn. Soc. Mech. Eng. **68**, 3209–3216 (2002)
[13] T. Eto, Model experiment on dynamic interaction of a container crane and a pier in a large-scale earthquake, Kuren. **37**, 20660–20665 (1999)
[14] M.L. Lou, X.G. Shao, Coefficient selection of damping matrix in explicit calculation of soil layer seismic response, J. Tongji. Univ. **41**, 1126–1132 (2013)
[15] Z.Q. Song, C.H. Su, Computation of rayleigh damping coefficients for the seismic analysis of a hydro-powerhouse, Shock Vib. 2046345 (2017)

[16] A.K. Chopra, R.K. Goel, A modal pushover analysis procedure for estimating seismic demands for buildings, Earthq. Eng. Struct. Dyn. **31**, 561–582 (2002)

[17] Z.G. Xu, X.L. Du, C.S. Xu, C.Y. Zang, J.W. Jiang, Comparison of determination methods of site Rayleigh damping coefficients in seismic responses analysis of underground structures, Rock Soil Mech. **40**, 4838–4847 (2019)

[18] N. Yoshida, S. Kobayashi, I. Suetomi, Equivalent linear method considering frequency dependent characteristics of stiffness and damping, Soil Dyn. Earthq Eng. **22**, 205–222 (2002)

[19] Z. Li, C. Xu, S.Y. Wu, Calculating the Rayleigh damping coefficient under seismic dynamic simulation of a quayside container crane, Aust. J. Mech. Eng. 1–10 (2019)

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