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Dynamic Interaction Behavior between Jumbo Container Crane and Pile-Supported Wharf under Near-Field and Far-Field Ground Motions

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Abstract

Playing an important role in local and national seaport activities, container wharves are susceptible to structural failure and damage during earthquake events. Therefore, factors that affect the seismic response of crane–wharf structures under different types of earthquake ground motions should be elucidated. In this paper, 3D finite element models were established to investigate the differences of natural vibration characteristics between the wharf and crane–wharf structures. The dynamic response of a typical pile-supported wharf structure and the interaction behavior of a crane and wharf structural system under seismic actions of near-field and far-field ground motions were studied by performing numerical simulation and time-history response analysis. Axial force–moment relation curves were adopted to analyze the elastic–plastic limit state of the wharf structure under different ground motions. Results showed that the consideration of the container crane increased the natural vibration period of the pile-supported wharf structure and affected the dynamic characteristics of the structure. Compared with the far-field earthquake ground motion, the near-field earthquake exerted a more significant impact on the structural dynamic response that controlled the elastic–plastic limit state. With the presence of a crane, the moment and shear force of the pile-top decreased and the location of the extreme value moved down obviously. The findings demonstrated that considering the crane changed the failure mechanism of the wharf structure, and the eccentric effect of the crane may amplify the dynamic response as the peak ground acceleration increases. The results provide reference for the seismic design and the evaluation of the seismic response of container wharves.

Keywords: Container Crane, Pile-Supported Wharf, Near-Field and Far-Field Ground Motions, Seismic Response, Dynamic Interaction

1. Introduction

After the 1995 Southern Hyogo Prefecture Earthquake, many harbor facilities, building structures, and cranes at the container terminal of Kobe Port were severely damaged, and the service functions of several terminals became completely lost. The economic and social activities were seriously affected not only in the Kobe area but also abroad, including Japan [1].

In that earthquake, given that land transportation had been almost completely paralyzed, the emergency relief for delivering supplies to disaster areas was performed by utilizing seismic strengthening wharves (including the wharves put into service after emergency reinforcement), which played an important role in the entire relief process [1][2]. In addition, while the restoration and reconstruction of the disaster areas are still in progress, the harbor green space can be used as temporary residential districts and storage sites for emergency supplies, further demonstrating the importance of functional wharves [3]. With the developments of national trade and container throughput, large-scale and specialized functional terminals have been successfully implemented and used. In view of the experiences and lessons learned from the Great Hanshin earthquake and the important roles that harbor facilities played after the disaster, as well as in consideration of the sociality and the economy, important facilities should be considered as seismic strengthening ones for seismic performance design to resist exceptionally strong earthquakes. In the Technical Standards and Commentaries for Port and Harbor Facilities (2007, Japan), the performance design of harbor facilities was stipulated in terms of safety, repairability, and usability [4]. Usability indicates that for a type of harbor facility, the transportation function of emergency supplies after rare earthquakes should be ensured. Moreover, the allowable damage limit suffered by facilities from unexpected and rare disasters is defined in a relatively small range to ensure the usability of harbor facilities. For these purposes, the factors that affect the seismic performance of harbor structures under different earthquake ground motions should be understood.

2. Literature Review

Many experts have analyzed the seismic performance of large-scale wharf and upper equipment, such as jumbo container cranes. Jacobs et al. [5] conducted shake table experiments on a 1:10 scale model of a typical container

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crane and investigated the various failure modes of derailment, local buckling of the legs, and collapse. Jaradat et al. [6] conducted nonlinear time history response analysis to analyze the interaction between the crane and the wharf. Basing on the Port of Long Beach Wharf Design Criteria and the different seismic performance design levels, they amended the structural design of cranes. Consequently, the lateral displacement of the wharf structure was decreased, thereby reducing the requirement of the rail shear capacity. In addition, Jacobs et al. [7] presented the results of the scale testing and analysis of a typical jumbo container crane subjected to earthquake loading and found that the portal frame response dominated elastic behavior and was closely coupled with an uplift and derailment rocking-type response at higher excitation levels. Shafieezadeh et al. [8] used numerical simulation to explore a number of typical pile-supported wharf and container crane structures. Dynamic response analysis of the foundation–wharf–crane structural system showed that the deformation demand of the wharf will be significantly increased with the presence of a crane. Zheng Pei [9] and Yang An [10] et al. conducted a hammering modal test and a series of seismic shaking table tests to obtain the dynamic characteristics and seismic responses of a scale model with and without an anti-seismic isolator. Azeloglu et al. [11] established physical and mathematical models to study the behavior of container cranes under seismic loadings, and the mathematical modeling of the container crane structure revealed reasonable results under dynamic loadings. Arena et al. [12] presented a 3D modeling of container cranes subjected to wind loads; the model was analyzed with full-scale experimental tests, system identification, and model validation. Time integration was performed to validate the mechanical model by comparing its predictions with the experimental results. Kohama [13] and Miyata [14] et al. analyzed the dynamic response characteristics of a crane structure under the action of a rare earthquake by performing model experiments and numerical simulation. Azeloglu et al. [15] verified the mathematical modeling of container cranes under earthquake loadings with shake table test results; the developed mathematical model reasonably represented the dynamic behavior of the crane structure both in time and frequency domains. Inadomi et al. [16] carried out a series of the vibration tests of a prototype wharf and calculation simulation of the wharf and the crane to study the vibration characteristics of the structures; they observed that the crane exerted an insignificant effect on the vibration of the wharf when the acceleration was small (not exceeding 20 gal). Sugano et al. [17] assessed the effectiveness of a seismic isolation system by using a scale model test, such as the reduction of crane acceleration response and the prevention of wheel derailment; their findings indicated that nonlinear seismic response analysis effectively simulated the dynamic behavior of the crane with and without an isolation system. Kohama et al. [18] arranged the strong-motion earthquake records observed at a container crane and pile-supported wharves in 2011 off the Pacific coast of the Tohoku Earthquake and clarified the seismic properties of low-lying container cranes and wharf structures.

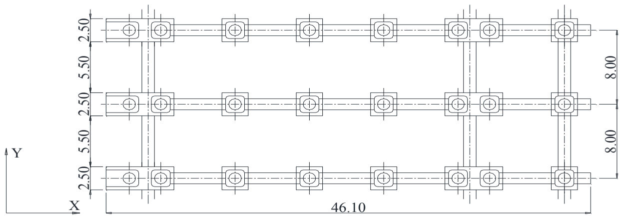
Recent studies on the seismic design and analysis of container cranes have not sufficiently investigated the effect of the presence of cranes on the dynamic response of wharf structures as well as the seismic damage mechanism when the crane and the wharf are considered as one integral structure. As the lifeline engineering facilities for emergency relief after disasters, the safety service and usability of functional wharves, cranes, and other equipment should be ensured after rare earthquakes. An upper crane is a type of irregular and high-rise structure that is not completely fixed with the wharf structure. Under the action of an earthquake, the specific failure phenomena and seismic response characteristics, such as derailment and the uplift of legs, would occur, causing the seismic dynamic response of the crane–wharf structure to become more complex and affecting the seismic response characteristics and damage mechanism of the lower wharf structure. Therefore, in the present paper, on the basis of the 3D finite element model of the crane–wharf structure and numerical simulation, as well as in consideration of the dynamic effect of the crane, the seismic response and damage mechanism of the pile-supported wharf were analyzed and compared with the finite element numerical simulation results of the wharf structure without a crane. The results of this study will provide reference and basis for the seismic design of container terminals.

The remainder of this paper is organized as follows. Section 3 describes the research background. Section 4 presents the 3D finite element model and describes the natural vibration characteristics of the pile-supported wharf and crane–wharf structures. Section 5 explores the effects of different ground motions on the dynamic response of the structures. Section 6 provides the drawn conclusions.

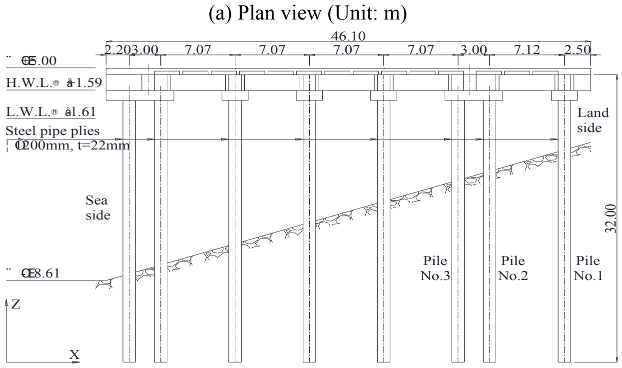
3. Methodology

3.1 Research subject

A typical pile-supported wharf with a jumbo container crane on top is selected in this study. The configuration of the pile-supported wharf is shown in Fig. 1. The width of the wharf structure is 46.1 m, the spacing of the bent frame is 8.0 m, and each bent frame includes eight piles. The length of the pile is 32.0 m, the diameter is 1200 mm, and the thickness is 22 mm. The steel pile is made of grouted reinforced concrete. The steel grade is 420 and concrete strength is C35. Two rail beams of 1.5 m width and 2.47 m height as well as one longitudinal beam of 1.2 m width and 2.47 m height are placed on top of the wharf structure. The width of the cross beam is 1.2 m and the height is 2.47 m.



(a) Plan view (Unit: m)



(b) Transverse section view (Unit: m)

Fig.1. Configuration of the pile-supported whar

The weight of the crane is 1600 t and the lifting capacity is 65 t. The outreach is 64 m and the rail gauge is 30.48 m. The main dimensions of the crane structure are shown in Fig. 2.

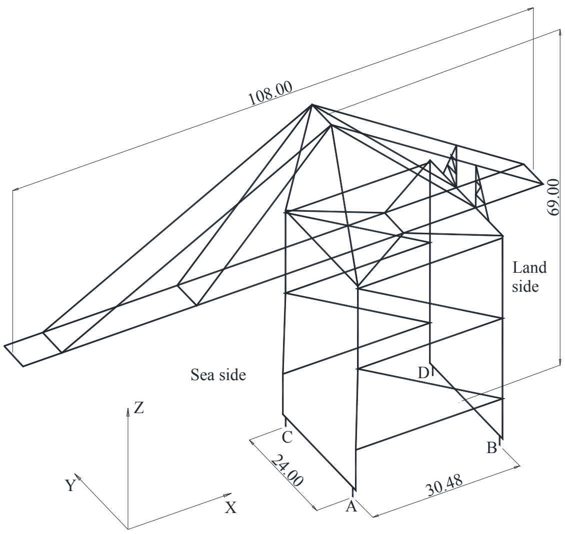


Fig.2. Main dimensions of crane (Unit: m)

The soil is mainly composed of silt and sand. The soil layer properties are shown in Table 1.

Table 1. Soil layer properties

No.	Soil layer	Thickness of soil layer /m	Dry density /t/m^3	Specific weight of soil particle	Void ratio
1	Silt	7	1.60	2.72	0.70
2	Layered silt	13	1.51	2.70	0.80
3	Fine silty sand	6	1.54	2.69	0.75

3.2 3D finite element modeling

To analyze the natural vibration characteristics and perform numerical simulation, 3D finite element models are established by SAP2000. The beam element is used to simulate the rail beam, the longitudinal beam, and the pile. The plate element is used to simulate the deck. P-y curve method is adopted to simulate the interaction between piles and the soil. For the finite element modeling, the moving direction along the rail of the crane is defined as the Y direction and the perpendicular direction to the rail is defined as the X direction. The 3D models of the wharf structure and the crane–wharf structure are respectively shown in Figs. 3 and 4.

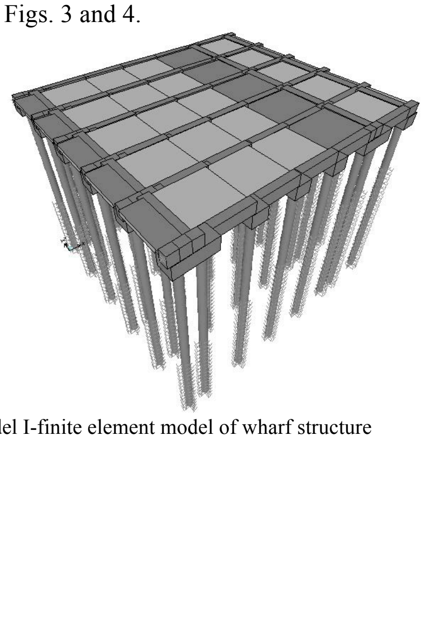


Fig.3. Model I-finite element model of wharf structure

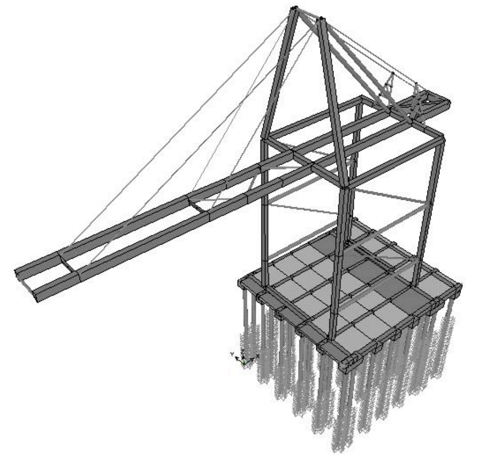


Fig.4. Model II-finite element model of crane-wharf structure

The constraints of the joint between the beam elements of the crane legs and the lower wharf structure are identified according to the practical working situation of the crane. The crane moves on the rails with the four sets of wheels, and the positions of the wheels are points A, B, C, and D, as shown in Fig. 5. Given that the crane moves along the rail direction with wheels, elastic deformation of the wheels is allowed in the Y direction. In view of the limitation of wheel flange on the rail, the wheels are constrained in the X direction. At the same time, the rotation of the wheel sets around the X and Z directions are also constrained. The treatment method of constraints for finite element modeling is that for points A and B, the rotations around the Y direction are released, and the degrees of freedom in the other directions are constrained. For points C and D, the displacement and rotation around the Y direction are released and the others are constrained.

The counterweight and other lifting operation equipment are loaded on the model structures as concentrated masses.

3.3 Selection of seismic ground motions

The typical seismic ground motions applied to site class III of the Nihonkai-Chubu earthquake (far-field) and the Hyogo-ken Nanbu earthquake (near-field) are selected as the input ground motions [19]. The peak ground accelerations of the seismic ground motions are adjusted to different levels for the time-history response analysis to analyze the seismic response characteristics of the structures. The seismic ground motion characteristics are shown in Table 2, and the accelerogram of the seismic ground motions are shown in Fig. 5.

4. Results analysis

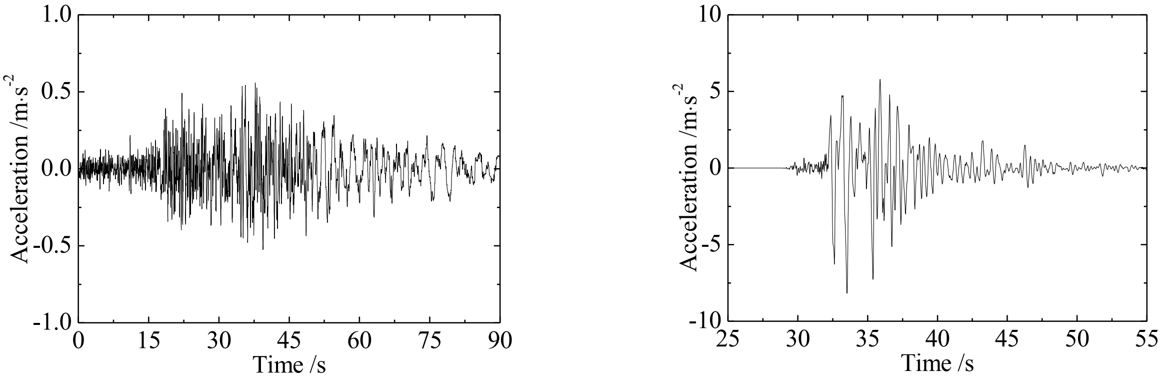
4.1 Comparison of natural vibration characteristics

The main modes of the two model structures are compared and analyzed to identify the effect of the upper crane structure on the natural vibration characteristics of the lower pier structure. The calculation results of the vibration characteristics are shown in Tables 3 to 5.

The main mode of model I (wharf structure) is mode 1 and the period is 0.73 s. According to the modal analysis and participation ratio of model II (crane-wharf structure), modes 1 to 5 show the vibration of the upper crane along the moving direction and perpendicular to the moving direction. The main mode is mode 6 and the period is 0.79 s which is 8.2% longer than that of model I.

Table 2. Characteristics of seismic ground motions

Seismic ground motion records	Epicentral distance /km	Peak ground acceleration /m·s^{-2}	Duration /s
1983 Nihonkai-Chubu Earthquake	210.0	0.586	90.0
1995 Hyogo-ken Nanbu Earthquake	16.5	8.180	30.0



(a) Nihonkai-Chubu earthquake

(b) Hyogo-ken Nanbu earthquake

Fig.5. Accelerogram of the seismic ground motions

Table 3. Natural vibration characteristics

Model structures	Natural vibration frequency and period	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7
Model I Wharf structure	Period /s	0.73	0.57	0.53	0.52	0.51	0.50	0.37
	Mass participation ratio	0.74	1.5e-6	1.9e-6	9.9e-9	--	--	--
Model II Crane-wharf structure	Period /s	4.78	2.22	1.17	1.14	0.93	0.79	0.65
	Mass participation ratio	4.0e-11	3.0e-8	0.24	1.7e-3	0.11	0.41	2.7e-6

Table 4. Main Mode of model I (wharf structure)

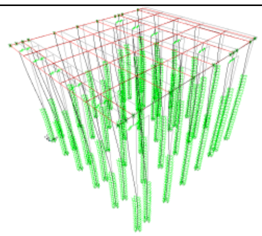
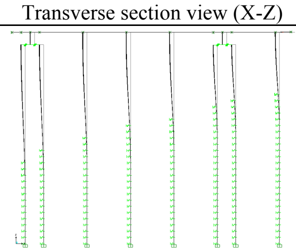
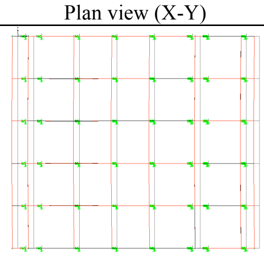
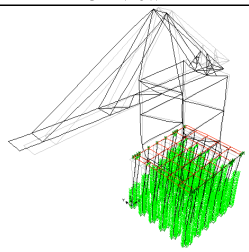
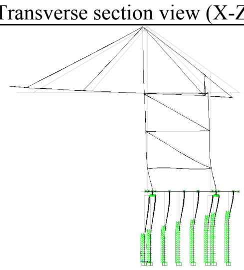
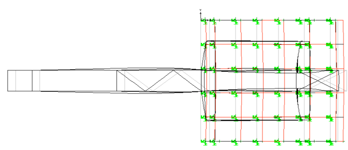
Mode	3D view	Transverse section view (X-Z)	Plan view (X-Y)
Mode 1	 Period: 0.73s Wharf: horizontal movement to sea side (-X direction)		

Table 5. Main Mode of model II (crane-wharf structure)

Mode	3D view	Transverse section view (X-Z)	Plan view (X-Y)
Mode 6	 Period: 0.79s Wharf: horizontal movement to land side (X direction)		

The calculation results of the natural vibration characteristics reveal that compared with model I, the natural vibration frequency of each mode in model II decreases and the periods become longer. Therefore, the presence of the crane affects the dynamic characteristics and dynamic response mechanism of the wharf structure under an earthquake action.

The main modes of the two structures are analyzed to further clarify the effects of the crane on the dynamic response mechanism of the wharf structure. The main mode (mode 1) of model I primarily shows the horizontal movement to the sea side (-X direction). The main mode (mode 6) of model II primarily shows the horizontal movement to the land side (X direction) opposite to model I. The main reason for the difference is the eccentric effect of the crane, and the overturning to the sea side can be observed from the modes. Under the action of dynamic response of the effect, the wharf structure shows the displacement to the land side opposite to the crane structure.

4.2 Effect of different ground motions on dynamic response of structures

The ground motions of the Nihonkai-Chubu earthquake and the Hyogo-ken Nanbu earthquake with the peak ground acceleration of 220 gal are adopted to analyze the effect of near-field and far-field ground motions on the dynamic response characteristics of model II of the crane-wharf structure. As shown by the envelope curve of the shear force and the moment of pile No.1 (Figs. 6 and 7), under the actions of ground motions, the response values of the shear force and the moment are different, but the variation tendency is similar.

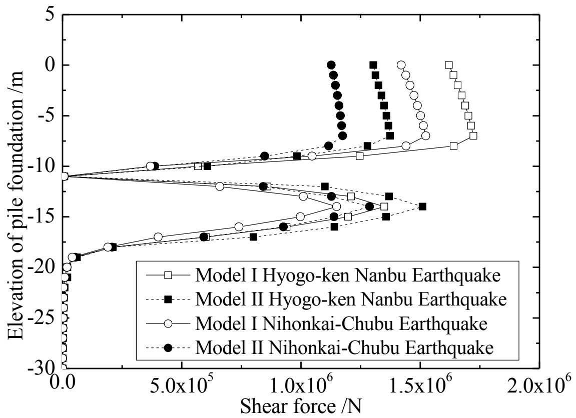


Fig.6. Shear force envelope curve under different seismic ground motions

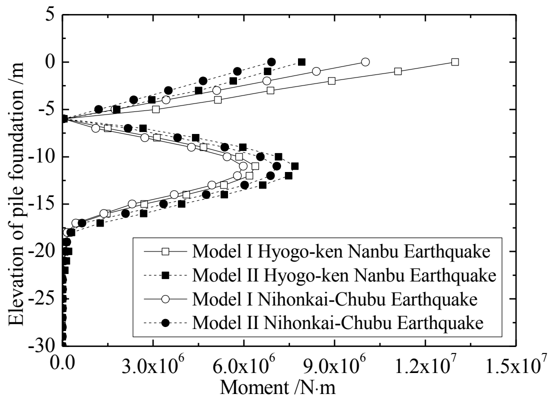


Fig.7. Moment envelope curve under different seismic ground motions

In model II, under the action of the Nihonkai-Chubu earthquake ground motion, the maximum value of the shear fore is 1.24×10^6 N and the maximum value of the moment is 7.1×10^6 N·m. Under the action of the Hyogo-ken Nanbu earthquake ground motion, the maximum value of the shear fore is 1.75×10^6 N and the maximum value of the moment is 1.02×10^7 N·m. Under the action of near-field ground motion (Hyogo-ken Nanbu earthquake), the maximum value of the shear fore and the moment of the structure are 1.41 times and 1.44 times of the values under the action of far-field ground motion (Nihonkai-Chubu earthquake), respectively. Therefore, near-field ground motion exerts the most significant effect on the dynamic characteristics of the structure and would therefore be the main controlling factor of the elastic–plastic limit state, and would play the dominant role in the dynamic response analysis, seismic design, and seismic performance evaluation of the crane–wharf structure.

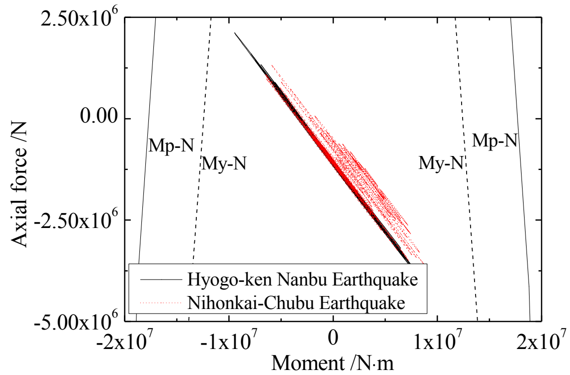


Fig.8. Axial force-moment curve of pile No.2 under different seismic ground motions

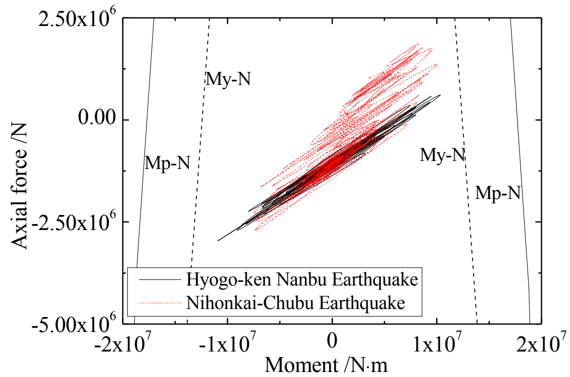


Fig.9. Axial force–moment curve of pile No.3 under different seismic ground motions

Axial force–moment curves of pile No.2 and pile No.3 in model II are shown in Figs. 8 and 9. Under the actions of the two different types of seismic ground motions with peak ground acceleration of 220 gal, all of the piles are in elastic state. Compared with the result of far-field ground motion (Nihonkai-Chubu earthquake), under the action of near-field ground motion (Hyogo-ken Nanbu earthquake), the axial force–moment curve shows that the effect of seismic action increases more substantially and is closer to the critical value curve of elastic area. When the acceleration peak value increases continuously, the difference of the types of the near-field and far-field ground motions affects the elastic–plastic state of piles. The response curves may exceed the elastic area and then enter the plastic state.

4.3 Effect of ground motions with different peak ground accelerations on dynamic response of structures

The peak ground acceleration of the Hyogo-ken Nanbu ground motion record is adjusted to 35, 70, 140, and 220 gal. The response peak values of acceleration, displacement, moment, and shear force of pile No.1 (first pile from land side) are shown in Figs. 10 and 11.

As shown in Fig. 10, as the acceleration increases, the displacement response value linearly increases. When the acceleration is 35 gal, the envelope of acceleration and displacement almost coincide, indicating that when the acceleration is smaller, the crane almost has no effect on the crane–wharf structure. This finding is consistent with the analysis results of experimental research and numerical simulation from reference [16].

With an increase in peak ground acceleration, the displacement response values of model I is greater than that of model II, and the difference increases gradually. When the peak ground acceleration is 220 gal, the maximum displacement of model I is 7.3 cm and is 1.52 times of the maximum 4.8 cm for model II. The presence of a crane reduces the acceleration and displacement responses of the lower wharf structure under seismic actions, and the dynamic response of the integral structure decreases within a certain range.

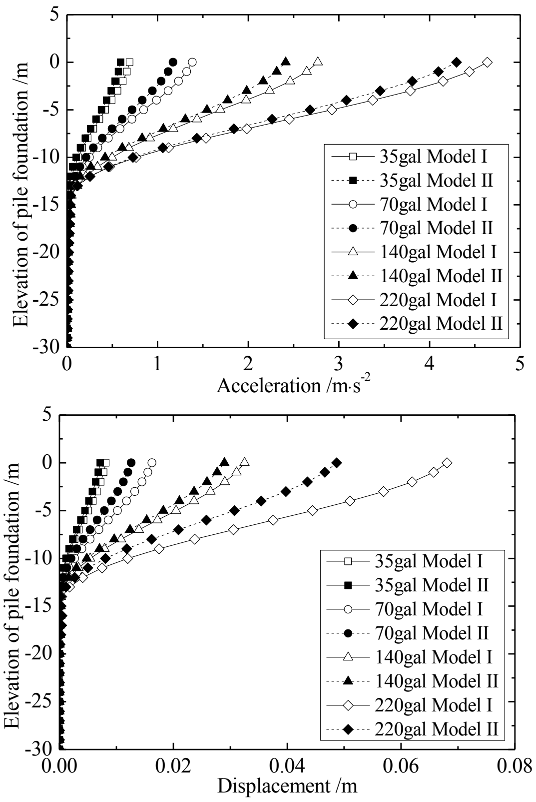


Fig.10. Envelope curve of acceleration and displacement

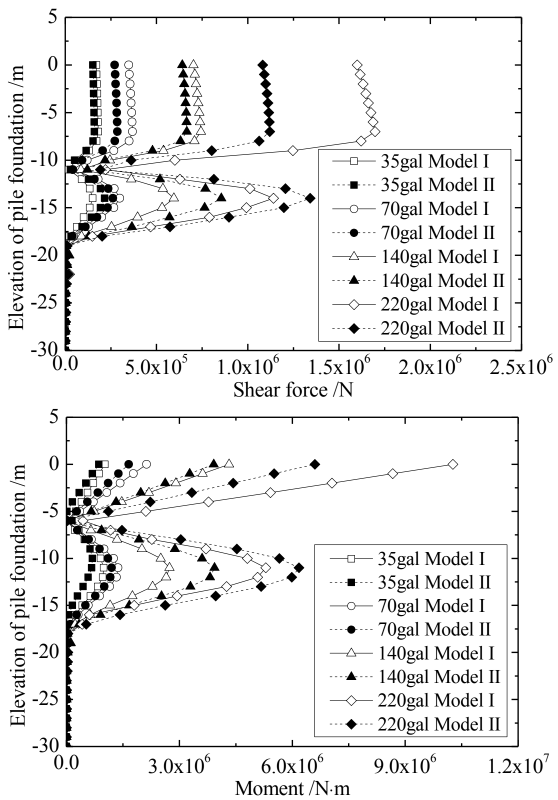


Fig.11. Envelope curve of shear force and moment

Fig. 11 shows that because of the effect of the crane, the shear force and moment in piles of the lower wharf structure decrease. When the peak ground acceleration is smaller, the difference is not obvious. When the peak ground acceleration increases to 220 gal, the significant difference of the shear force and the moment in piles occurred between model I and model II. The moment in top of pile No.1 in model II decreases to 64% of the moment response value in model I. In addition, the maximum value of the shear force in model I occurred at the elevation of -7.50 m. For model II, the shear force appears near the elevation of -14.00 m. The comparison of the two models shows that the existence of a crane affects the value and distribution of internal forces in piles for the lower wharf structure, and with the increase in peak ground acceleration of seismic ground motion, the response becomes more remarkable. In addition, under the action of rare earthquakes, the presence of a crane will cause the plastic areas to develop more rapidly when the plastic state occurs in piles.

5. Conclusions

The dynamic response characteristics of the crane–wharf structure under the actions of different peak ground acceleration and near-field and far-field ground motions were studied by establishing a 3D finite element model and performing numerical simulation. The effects of the dynamic response of the container crane on the dynamic characteristics of the lower wharf structure were analyzed by comparing the calculation results of the integral model and the wharf model. On the basis of all the obtained results, the following conclusions are drawn:

(1) The crane causes the natural vibration frequency of the crane–wharf structure to decrease and the period to increase. This result suggests that the effect of crane on the natural vibration characteristics of wharf structure and the crane–wharf interaction cannot be ignored.

(2) When the peak ground acceleration is smaller, the difference of the shear force and the moment response values in piles for the integral model and the wharf model is not obvious. With an increase in acceleration, the difference of the shear force and the moment response values between the two structures starts to be increase. Compared with the wharf model, the presence of the crane causes the position to moved down significant where the shear force extremum occurs, thereby affecting the plasticity development of the piles and the damage mechanism of the crane–wharf structure.

(3) Time-history response analysis of the crane–wharf structure shows that near-field ground motion exerts the most significant effect on the dynamic characteristics of the structure, making it the main factor of the elastic–plastic limit state. This finding confirmed why so many harbor facilities in Kobe Port were damaged seriously after the Hyogo-ken Nanbu earthquake.

(4) With an increase in peak ground acceleration, the eccentric effect of the crane on the lower wharf structure increases. When the action of seismic excitation is larger than a certain level, the legs of the crane on land side uplift and the structure system is only supported by the legs of the sea side. Then, the eccentric effect will further increase. The damages and failures of overturning and instability for the crane are not considered in this paper and need to be studied in further research.

Acknowledgments

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