SEISMIC RESPONSE ANALYSIS OF THE LARGE BRIDGE PIER SUPPORTED BY GROUP PILE FOUNDATION CONSIDERING THE EFFECT OF WAVE AND CURRENT ACTION

BAI De-gui [1,2] , CHEN Guo-xing[1] and WANG Zhi-hua[1]

[1] *Institute of Geotechnical Engineering, Nanjing University of Technology , Nanjing. China*
[2] *Chongqing Survey Institute, Chongqing, China*

ABSTRACT :

On the basis of the ABAQUS software and parallel calculation technology, this paper presents a 3D finite element method to model the pier-piles -soil system. In the analysis model, the soil is represented as an assembly of 8 node solid elements and the viscous-plastic memorial nested the yield surface model of soil was used to describe its dynamic nonlinear. The piles are represented as an assembly of beam elements and the dynamic plastic-damage model was used to describe the concrete's dynamic character. And based on the Morison's hydrodynamic pressure formula and representing sea wave by Stokes fifth-order wave theory, the wave force was putted on the bridge pier and group piles as a distributed load. The pile's seismic response characteristics in lenitic condition and including the influence of the wave and current action were analyzed, and the influence of the wave height and current velocity on the pile's seismic response was discussed. The results show that the wave and current action increases the pile's peak response of relative displacement, shear force and moment obviously, but has slight influence on the pile's peak response of acceleration. The influence of the wave height on the pile's seismic response is related to the earthquake wave characteristics. The current velocity has an obvious influence on the pile's response of relative displacement. As the velocity increased, the relative displacement along the river direction increased, but the relative displacement against the river direction decreased. It shows that it is necessary to consider the effect of the wave and current action on the large bridge pier's seismic response.

KEYWORDS: Morison's formula,wave and current action,wave theory,group pile's pier,seismic response

1. INTRODUCTION

With the development of the social economy, many large span bridges across channels and rivers continuously appear so as to support the urban traffic demand. In general case, these piers of the bridge across channels and rivers are in deep water and theirs working environment is so bad that they must bear many complex environment loads. The finished projects has demonstrated that these deepwater pile foundations can well satisfy the using functions and safety requirements and some of them even can pass through the dynamic effect test of wind, damp, flow etc. Though, their seismic stability caused by strong earthquake, especially the combined effect of strong ground motion and wave action, has not been verified yet. Actually, the deepwater pile foundations are located in 10m below the water level, and they are subjected to both the excited vibration under ground motion and the hydrodynamic pressure caused by water wave and current. From the angle of mechanics, the hydrodynamic pressure caused by water wave and current composes the pile's additional moment directly, which has influence on the pile's internal force.
According to the dynamic response of water structure under combination of seismic ground motion and wave action, many scholars at home and abroad have studied it, and some beneficial results have been obtained. Yamada and Kawano analyzed the offshore structure's dynamic response by the way of random vibration, in which the wave was simulated by Bretschneider power spectrum and the strong ground motion was simulated by Kanai power spectrum; Karadeniz analyzed the 3D structure's dynamic response under the coupling effect of the seismic ground motion and deepwater wave using spectrum analysis method, in which the wave and seismic ground motion were regarded as stochastic processes; Fukusumi and Uchida simulated the wave as simple harmonic wave, and analyzed the dynamic response effects caused by structural stiffness, flow and fluid density, and the flexible structure's seismic response was obtained; Etemad and Gharabaghi used the Nogami model to consider the pile-soil interaction, and analyzed the pile foundation's seismic response under two situations: the directions of the wave and seismic ground motion are the same and opposite; Abbasi and Gharabaghi took the material nonlinearity into consideration and established a 3D jack-up offshore platform model to analyze the wave direction's influence on the seismic response; Li Furong and Chen Guoxing used the additional mass method to establish a pile-soil-pier-water model, and analyzed the effect of dynamic water pressure and water level change; He Xiaoyu and Li Hongnan analyzed the structure's seismic response under the coupling effect of seismic ground motion and wave action, based on the Morison's formula and theory of rule wave. However, there are two problems in these studies: one is that the structure is simplified too much to consider the interaction among the soil, pile foundation and the pier structure; and the other one is that the effect of fluid is not simulated exactly, or even ignored. Therefore, it is quite necessary to find a 3D finite element model to simulate the pier-piles-soil-water wave and current system accurately and analyze the seismic response of the large bridge piers.

2. WAVE AND OCEAN CURRENT ACTION

Presently, most research about the coupling effect of wave and deep-water structure under earthquake ground motion is based on the Morison formula. In the formula, the influence on wave motion caused by structure is ignored and the influence on the structure caused by wave motion is made up of the inertia force and the drag force along the wave motion direction. And then the inertia force and the drag force are caused by the undisturbed acceleration field and velocity field separately. The formula to calculate the wave force is as follows：

$$F_{\mathrm{w}} = C_M \rho V \ddot{u} - C_A \rho V(\ddot{x} + \ddot{x}_g) + \frac{1}{2} C_D \rho D \left[(\dot{u} - \dot{x} - \dot{x}_g) \left| (\dot{u} - \dot{x} - \dot{x}_g) \right| \right] \tag{2.1}$$

And
$$F_{\mathrm{I}} = C_M \rho V \ddot{u} - C_A \rho V(\ddot{x} + \ddot{x}_g), \quad F_{\mathrm{D}} = \frac{1}{2} C_D \rho D \left[(\dot{u} - \dot{x} - \dot{x}_g) \left| (\dot{u} - \dot{x} - \dot{x}_g) \right| \right]$$

Where, ρ is water density, V is the structure volume under water, D is the structure's diameter, $\ddot{u}$ and $\dot{u}$ are water's absolute acceleration and absolute velocity, $\ddot{x}$ and $\dot{x}$ are structure's absolute acceleration and

absolute velocity, $\ddot{x}_g$ is the earthquake ground motion acceleration, C_M is the hydrodynamic inertial force factor, C_D is the hydrodynamic viscosity damping coefficient, C_A is the additional mass factor, FI is the inertia force, FD is the drag force. And based on DNV Environment Conditions and Load Standard, $\ddot{u}$ and $\dot{u}$ can be obtained by Stokes' fifth order wave theory.
In Stokes fifth order wave theory, velocity potential:

$$\Phi = \frac{Lc}{2\pi}\sum_{n=1}^{5} D_n ch\frac{2\pi n}{L} z \sin 2\pi n(\frac{x}{L}-\frac{t}{T}) \tag{2.2}$$

The horizontal absolute velocity of the water particle:

$$\dot{u} = \frac{\partial \Phi}{\partial x} = ce_1 \tag{2.3}$$

The horizontal absolute acceleration of the water particle:

$$\ddot{u} = \frac{2\pi c}{T}[-(1+e_1)e_3 + e_2 e_4] \tag{2.4}$$

The factors Di（i=1-5）and ei（i=1-4）between equation（2.2）and（2.4）can be found in literatures, its value relates to wavelength L, wave velocity c, period T, action time t, water depth d and the horizontal distance x between structure and the coordinates origin.
In engineering, the ocean current is always considered as a steady flow, whose action to the pile is just only the drag force; and the velocity of the ocean current varies slowly along the water depth, and then the velocity can be thought equivalent along the same vertical line. However, the coupling effect between wave and flow is so complicated that their drag forces can not be linear superposition simply. In current project design, the drag force can be calculated according to the following formula:

$$\mathbf{F}_D = \frac{1}{2}C_D \rho D(\mathbf{V}+\mathbf{V}_c-\dot{\mathbf{X}}_s)\left|\mathbf{V}+\mathbf{V}_c-\dot{\mathbf{X}}_s\right| \tag{2.5}$$

In the formula, V is wave velocity vector, Vc is flow velocity vector and Xs is the structure's absolute displacement vector. Suppose that the directions of wave, flow and earthquake ground motion are the same, the drag force can be simplified as a horizontal force as follows:

$$F_D = \frac{1}{2}\rho C_D D(\dot{u}+v_c-\dot{x}-\dot{x}_g)\left|\dot{u}+v_c-\dot{x}-\dot{x}_g\right| \tag{2.6}$$

3. THE SOIL-PILE-PIER MODEL CONSIDERING THE EFFECT OF WATER WAVE AND CURRENT

Taking the soil-piles-pier structure of a large span bridge across a channel as its research background, the large bridge pier's seismic response under the combination of water wave and ocean-current and earthquake ground motion is simulated exactly, and the schematic diagram about the sections of ocean-current direction, seabed, field soil, piles-pier is as Fig.1. The size of the pier is 49.8m×27m×6m, whose concrete strength is C50, and the pile group under the pier are made up of 38 2.5m diameter, 112.5m length bored piles, with 85.5m in the soil and its concrete strength is C30. The longitudinal and horizontal spaces between piles are 6m and 5m respectively, and their arrangement mode is as Figure 2. The 100-year wave-current parameters of the field area are as Tab.1. According to Environment Conditions and Load Standard, it can be known that CD=1. 2, CM=2. 0，CA =1.0. On the basis of the ABAQUS software and parallel calculation technology, a soil-piles-pier model is established as Figure3, which uses the Zhuang Haiyang and Chen Guoxing's dynamic visco-plastic memorial nested the yield surface model to describe soil's dynamic characteristics. The parameter values in the model are as Tab.2 ,with the assumption that the soil is saturated and it is undrained during earthquake, and its passion ratio is 0.49. The whole region of the foundation soil is 400m×240m×90.4m, and the effect on the wave caused by region truncation is considered as a 3D time-domain visco-elastic artificial boundary, which is developed by Liu Jingbo and Wang Zhenyu et al, and there are 12810 spring, damping elements. The soil layer, whose shear wave velocity is more than 500m/s, is chosen as the bedrock surface. The piles are dispersed as the beam element, whose dynamic characteristics under cyclic loading are considered as Jeeho Lee's concrete dynamic plastic injury constitutive model(see Tab.3), and there are 2242 elements, 2280 nodes in all. The mass of superstructure is made up of the main tower and the half bridge deck of both sides, which is about 4.0×107kg.

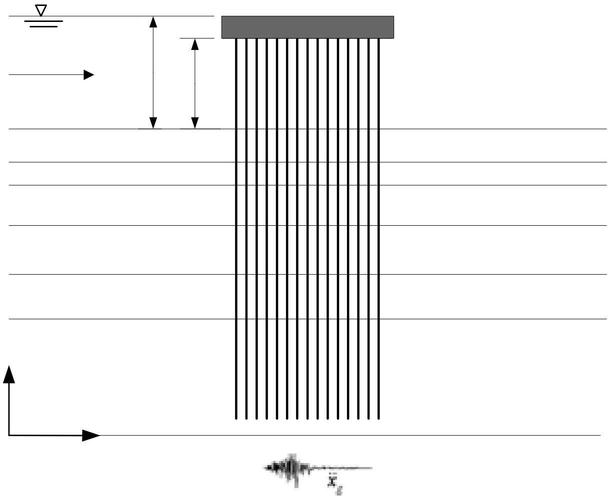


Figure 1 the schematic diagram about the sections of ocean-current direction, seabed, field soil, piles-pier

Table 1 wave-current parameters

Return period /year	Wave heigth/m			Wave period T/s	Wave length L/m	Wave velocity c/m·s^{-1}	Flow velocity m/s
	$H_{1\%}$	$H_{4\%}$	$H_{13\%}$				
100	6.62	5.75	4.81	8.23	84.60	10.30	2.19

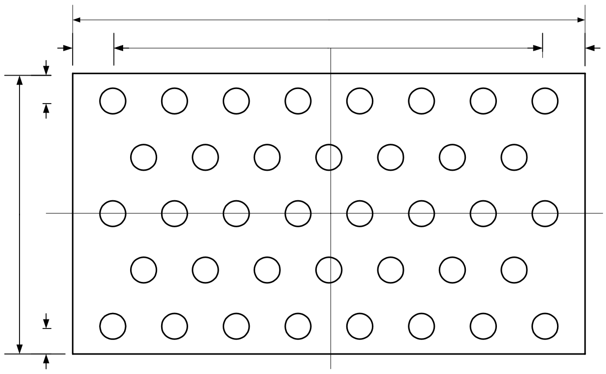


Fig. 2 The plane schematic diagram of the piles

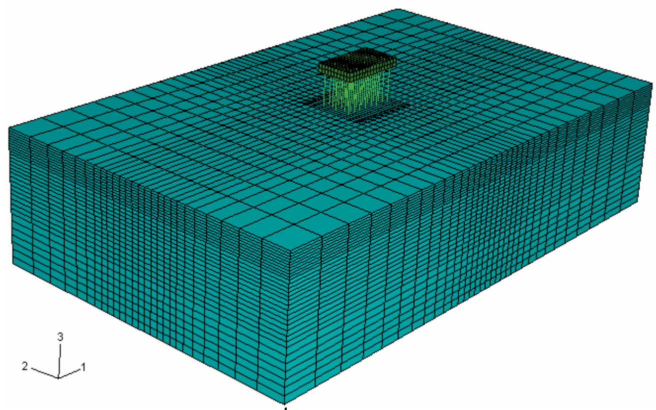


Fig. 3 The 3D bridge-piles finite element model

The Kobe wave, El centro wave and Loma Prieta wave are chosen as the input bedrock ground motion, and their acceleration time histories and fourier spectra are shown in Figure 4. In order to consider the effect of the ground motion intensity, there are two peak acceleration levels: 0.1g and 0.2g.

The dynamic equilibrium equation of the soil-piles-pier system considering the combination of earthquake ground motion and wave action is:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{I\}\ddot{x}_g+\{F_w\} \tag{3.1}$$

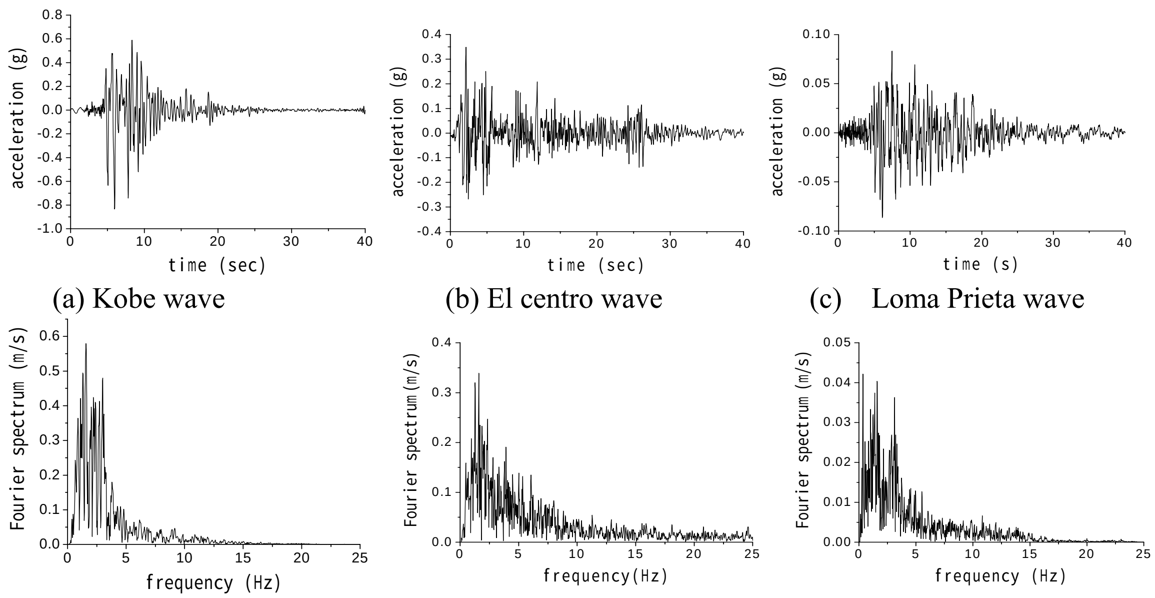
Where, [M], [C] and [K] are the mass matrix, the damp matrix and the stiffness matrix of the soil-piles-pier system respectively, $\{I\}$ is the indication vector of the inertia force.

Table 2 The soil parameters in the model

Soil types	thickness	density (kg/m3)	fhear wave velocity (m/s)	cohesion (kPa)	friction angle (°)
①muddy silty clay	9.8	1700	115	10	5
②muddy clay	6.8	1760	134	15	5
③clay	11.9	1890	186	35	7
④silty clay	14.4	1900	240	30	12
⑤sandy silt	13.2	1960	323	15	21
⑥silty fine sand	34.3	2000	415	5	30
⑦compacting	12.6	2030	507	32	15

Table 3 The concrete's dynamic parameters in the constitutive model

C30 concrete		C50 concrete	
Density ρ/kg.m-3	2500	Density ρ/kg.m-3	2550
Elastic modulus E/MPa	3.0×104	Elastic modulus E/MPa	3.45×104
passion ratio ν	0.15	passion ratio ν	0.18
Expansion angle ψ/0	36.31	Expansion angle ψ/0	36.31
Initial yield stress σc0/MPa	13.0	Initial yield stress σc0/MPa	14.5
Limit stress σcu/MPa	24.1	Limit stress σcu/MPa	35.5
Initial yield tensile stress σt0/MPa	2.9	Initial yield tensile stress σt0/MPa	2.64
Stiffness recovery factor wt	0	Stiffness recovery factor wt	0
Stiffness recovery factor wc	1	Stiffness recovery factor wc	1
Uniaxial compression injury variable dc	0	Uniaxial compression injury variable dc	0
ξ	0.1	ξ	0.1



(a) Kobe wave (b) El centro wave (c) Loma Prieta wave

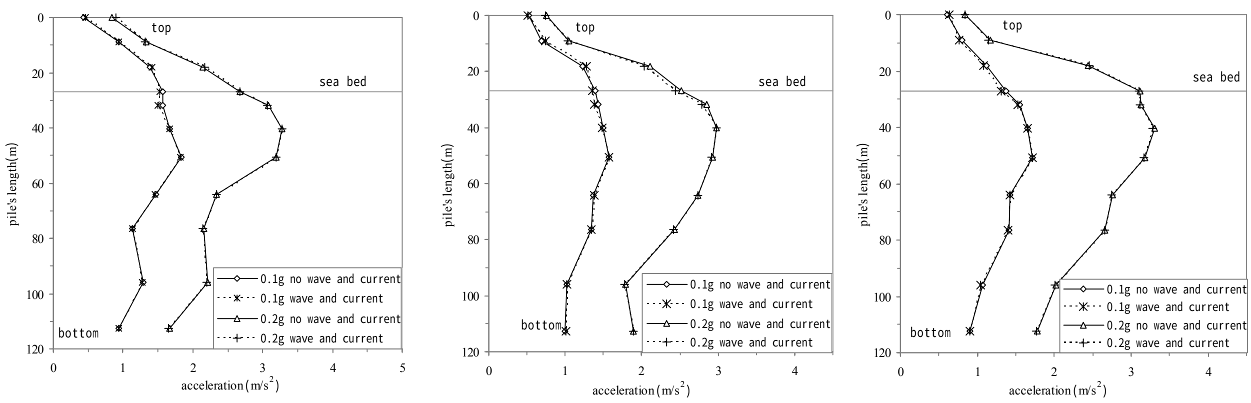
(d) Fourier spectrum of Kobe wave (e) Fourier spectrum of El centro wave (f) Fourier spectrum of Loma Prieta wave

Fig. 4 The acceleration time-histories and spectra of bedrock earthquake ground motion

4. NUMERICAL SIMULATION AND ANALYSIS

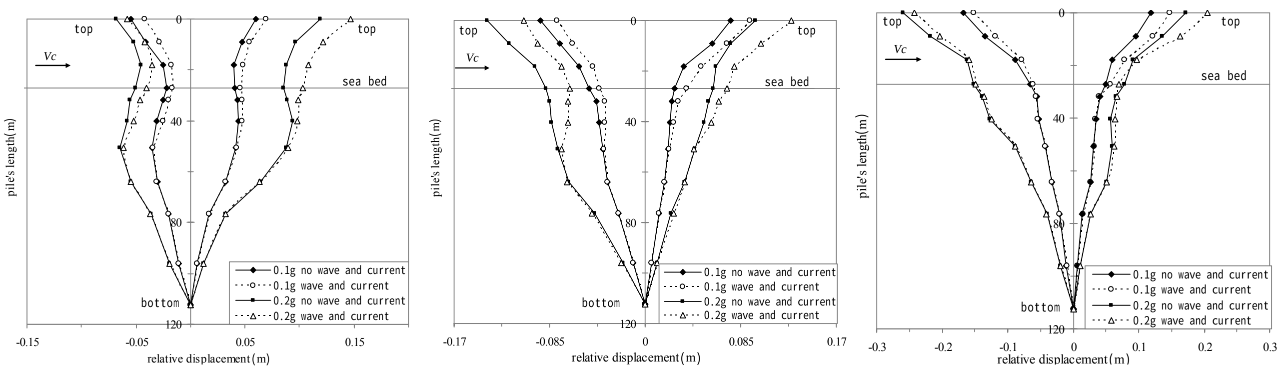
4.1. Analysis on The Eeffect of Wave-Current Effective

When the flow velocity is 2.19m/s, the wave height is H13%, the peak acceleration and the relative displacement response of the 1# pile body under different ground motion are shown in Fig.5 and Fig.6; the peak acceleration in the pile top of 1#, 4#, 12#, 15#, 16# and 19# is as Tab.4 under Kobe wave. The data above shows that: From the pile toe to the seabed surface, the peak acceleration of the pile body is gradually bigger, while the peak acceleration from the seabed surface to the pile top reduces obviously and it reaches the least in the pile top; conclusively, it can be known the effect on peak acceleration caused by flow-current is little. In addition, the peak displacement response of the pile body versus the pile toe increases gradually, when taking no account of the wave action, the pile's relative displacement peak along the water-current direction (positive) under the Kobe wave is greater than the one against the water-current direction (negative); though, the pile's relative displacement peak along the water–current direction is less than the one against the water-current direction evidently under the El centro wave and Loma Prieta wave. When the wave-current is considered, the pile body is impacted by the ocean-current, the relative displacement against the water-current direction of the pile body in water decreases, while the one along the water-curent direction increases obviously. Therefore, when the Kobe wave is inputted, the relative displacement peak is further increased by the wave-current, though when the El Centro wave and the Loma Prieta wave are inputted, the relative displacement peak is decreased.



(a) input Kobe wave (b) input El centro wave (c) input Loma Prieta wave

Fig.5 Peak acceleration response of the 1# pile



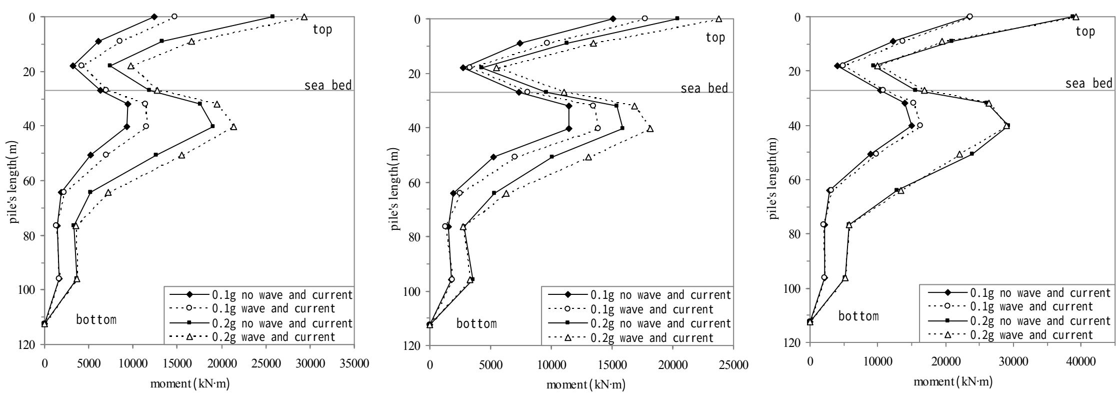
(a) input Kobe wave (b) input El centro wave (c) input Loma Prieta wave

Fig. 6 Relative displacement response of the 1# pile

The moment response peak of the 1# pile body is as Figure 7. It can be seen that: it increases and then decreases from the pile toe to the seabed surface, and it reaches the maximum in the interface between ②silt clay and ③clay; over the seabed surface, the moment continues to reduce, but it increases obviously over 9m from the seabed surface and the maximum value is on the pile top. When the Kobe wave and El centro wave are inputted, the wave-current effect makes the pile body increase evidently from the top to the 75.6 length, while the Loma Prieta wave is inputted, the wave-current effect on the pile body is little.

Table 4 Peak acceleration response of the pile top and its influence coefficient under Kobe wave

peak acceleration of input ground motion	condition	1#pile	4# pile	12# pile	15# pile	16# pile	19# pile
0.1g	Taking no account of the wave-current (m/s^2)	-0.435	-0.419	-0.436	-0.435	-0.434	-0.417
	Taking account of the wave-current (m/s^2)	-0.463	-0.448	-0.466	-0.462	-0.462	-0.447
	K_a (%)	6.44	6.92	6.88	6.20	6.20	7.19
0.2g	Taking no account of the wave-current (m/s^2)	-0.844	-0.837	-0.847	-0.873	-0.841	-0.828
	Taking account of the wave-current (m/s^2)	-0.901	-0.882	-0.883	-0.923	-0.891	-0.874
	K_a (%)	6.75	5.37	4.25	5.71	5.94	5.55



(a) input Kobe wave (b) input El Centro wave (c) input Loma Prieta wave
Fig. 7 the moment response of the 1# pile

In order to analyze the wave-current effect on the pile top's peak acceleration conveniently, the influence factor K is defined as follows:

$$K = \frac{\textit{the seismic response peak value taking account of the wave-current} - \textit{the seismic response peak value taking no account of the wave-current}}{\textit{the seismic response peak value taking no account of the wave-current}} \times 100\%$$

where, Ka, Kd and Km express the influence factor on the pile top acceleration peak, the pile top relative displacement peak and the moment peak.

The influence factors on the pile top acceleration peak are as Tab.4 under Kobe wave and Tab.5 contains the other influence factors. It is found that: the influence on the pile top acceleration is little, though the influence on the pile top relative displacement is great, and the value is less than 10% under the Loma Prieta wave, while it reaches 14.75% to 32.79% under the El centro wave and the Kobe wave. In addition, the effect on the pile top moment is little under the Loma Prieta wave, but it reaches 13.64% to 18.97% under the El centro wave and the Kobe wave. It shows that the wave-current's effect on the pile seismic response lies on the earthquake wave's characteristic.

4.2. The Effect Caused by Wave Height and Flow Velocity

The wave flow condition of bridge piers in sea area is complicated, as the wave height and ocean current velocity are continuously changing, the time of earthquake occurrence is unexpected, the wave-current effect on bridge piers aslo changes dynamically. So it is necessary to analyze the influence of wave height and flow velocity on the seismic response of bridge piers. When the peak ground motion acceleration is 0.1g, sea current velocity Vc =2.19m/s, the seismic response peak of the 1# pier top taking account of the influence of wave height is shown in Fig.8 . It shows that wave height has the greatest influence on the pile relative displacement, the moderate influence on pile moment, and the least influence on the pile acceleration response peak; at the same time, the effect of wave height on the seismic response of piles relates to the characteristics of earthquake ground motion. The acceleration of the pile top, the relative displacement response and the moment response along the water-current direction increase with the wave height increasing under El Centro wave and Loma Prieta wave; but the acceleration of the pile top, the relative displacement and moment response along the water-current direction increase with the wave height decreasing under Kobe wave; the effect law of the wave height to the pile top's relative displacement against the water-current direction is exactly contrary to the one along the water-current direction.

Table 5 Wave and current action influence coefficient

the peak acceleration of the input ground motion		K_a /%	K_d /%		K_m /%
			against the current direction	along The current direction	
Kobe wave	0.1g	6.44	-23.41	15.38	18.97
	0.2g	6.75	-14.75	23.74	13.64
El centro wave	0.1g	-2.67	-16.27	22.36	17.72
	0.2g	-1.33	-22.88	32.79	16.59
Loma Prieta wave	0.1g	-2.43	-9.37	23.40	0.51
	0.2g	-0.36	-6.46	19.14	1.08

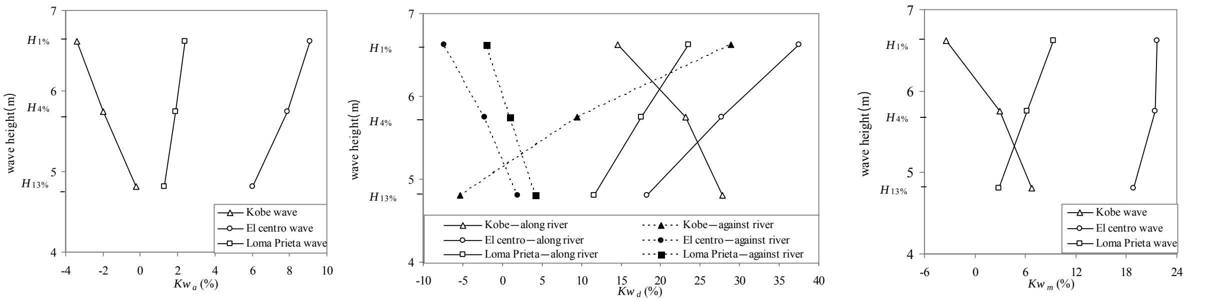


Fig. 8 Relationship between the peak seismic response influence coefficient of1# pile top and the wave height

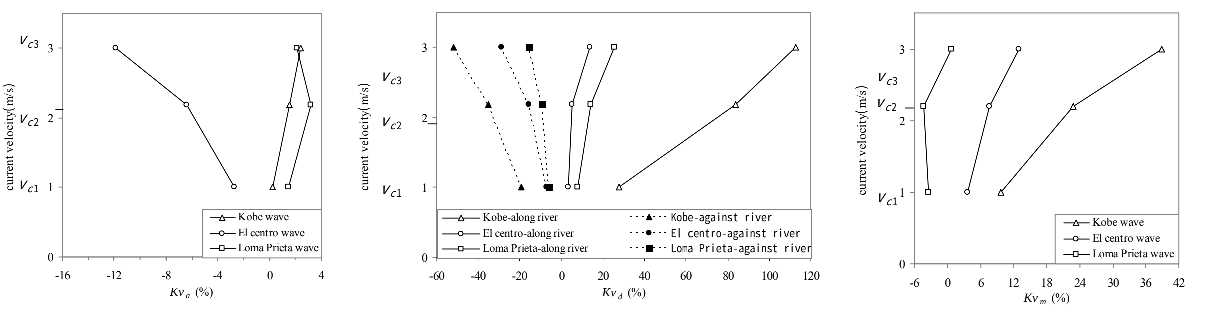


Fig.9 The relationship between the peak seismic response influence coefficient and the current velocity

When the acceleration peak of the ground motion is 0.1g, wave height H13%=4.81m; the effect on the peak seismic response of the 1# pier top taking account of the influence of ocean current is shown in Figure9. It can be seen that the flow velocity effect on the pile seismic response related to the earthquake wave's characteristics; the flow velocity's effect on the pier top acceleration decreases with the flow velocity increasing under El centro wave, but the flow velocity's effect on the acceleration increases a little with the flow velocity increasing under the Kobe wave and the Loma Prieta wave; the effect of flow velocity makes the relative displacement peak along the water-current direction increasing, while the one against the water-current direction decreases, and the influence degree increases with the flow velocity increasing, the degree is especially significant under the Kobe wave; at the same time, the effect of flow velocity makes the pier moment increasing, and the increasing extent increases with the flow velocity increasing.

5．CONCLUSION

According to Stokes' fifth order wave theory, the wave force calculated by the Morison formula is loaded on the bridge pier in the form of distributed force, the nonlinear seismic response characteristics of large pile group foundation pier structure in deep water is analyzed, the main findings are as follows:

1. The wave and ocean current has little effect on the acceleration response of the pile body.
2. The wave and ocean current has great effect on relative displacement of the pile body. The wave and ocean current make the relative displacement against the water-current direction decreasing, and make the one along the water-current direction increasing. And the influence extent increases with the flow velocity increasing, but the change law with wave height is closely related to the earthquake ground motion characteristics.
3. The effect of wave and ocean current makes the pile moment increasing, and the influence extent increases with the flow velocity increasing, but the change law with wave height is closely related to the earthquake ground motion characteristics .
4. In order to ensure safety and reliability of large span bridges across channels and rivers it is necessary to take account of the influence of wave and ocean current in seismic design of large pile group foundation pier structure in deep water.

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