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NONLINEAR SEISMIC RESPONSE ANALYSIS OF BRIDGE PIERS IN DEEP WATER DURING BIDIRECTIONAL EARTHQUAKES

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Abstract

Deep-water piers will be subjected to the hydrodynamic pressure induced by the interaction between bridge piers and surrounding water under earthquake excitations, which will affect the dynamic responses of the piers. In addition, actual earthquake excitations are usually multidirectional and normally the bidirectional horizontal excitations control the behavior of the piers. Hence, it is necessary to study the nonlinear seismic responses of bridge piers in deep water under bidirectional earthquake excitations. In this paper, a water-pier interaction model under bidirectional earthquake excitations considering the effects of hydrodynamic pressure, geometric nonlinearity, and material nonlinear, is proposed using the potential-based fluid element through finite element analysis software ADINA. In the analysis model, 3D solid elements and 3D potential-based fluid elements are used to model the bridge pier and the water, respectively. The data fitted concrete material model is used for the nonlinear constitutive relationship of concrete. Taking a typical solid pier of a large span bridge as the research object, the nonlinear seismic responses of the bridge pier in different water depths under unidirectional and bidirectional excitations are simulated. The effect of hydrodynamic pressure on the nonlinear seismic responses of the bridge pier is evaluated by analyzing the time histories of the relative displacement and the bending moment at the top and bottom of the pier, respectively. Numerical results show that the effect of hydrodynamic pressure on the nonlinear seismic responses under bidirectional earthquake excitations is more significant than the effect under unidirectional earthquake excitations. The effect under bidirectional earthquake excitations increases with the increase of water depth. In addition, the effect on the direction with wider upstream face is larger than the effect on the other direction under bidirectional earthquake excitations.

Keywords: deep-water piers; bidirectional earthquakes; hydrodynamic pressure; nonlinear seismic response analysis

1. Introduction

In order to meet the needs of transportation and economic development, several river-crossing and sea crossing bridges have been built or are under construction in China at present. These bridges are mostly located in deep water, and will be subjected to the hydrodynamic pressure induced by the interaction between bridge piers and surrounding water under earthquake excitations. Some research work [1-3] has showed that the hydrodynamic pressure not only changes the dynamic characteristics of the piers, but also affects the dynamic responses of the piers. Therefore, to guarantee the safety of bridge structures which are the important parts of lifeline engineering, it is necessary to study the hydrodynamic pressure on the piers under earthquake excitations. In recent years, many scholars have been devoted to study the simulation method of water-pier interaction and the effect of hydrodynamic pressure on the seismic responses of deep-water piers. Based on the Morison equation and radiation wave theory, Lai [4] developed an effective approach for calculating the hydrodynamic pressure on the pier, pile cap and pile groups, and applied it to study the seismic responses of deep-water piers and bridges. Zhu and Gao [5] adopted both the potential flow element and the added mass method based on the Morison equation to calculate the hydrodynamic pressure excited by earthquakes, and studied the influence of hydrodynamic pressure on the seismic responses of bridge piers in deep water. Huang and Li [6, 7] established an earthquake induced hydrodynamic pressure formulary of bridge piers in deep water by using radiation wave theory and variables separation method, which could consider the effects of free surface wave, water compressibility and bottom flexible reflection boundary. However, these studies mainly focused on the seismic responses of deep-water piers under unidirectional earthquake excitations. Actually, the piers are subjected to multidirectional earthquake excitations and normally the bidirectional horizontal excitations control the behavior of the piers. As the bidirectional earthquake excitations can produce significantly different seismic responses of the piers comparing with only considering unidirectional earthquake excitations [8], it is necessary to study the nonlinear seismic responses of bridge piers in deep water under bidirectional earthquake excitations.

For above reasons, a water-pier interaction model under bidirectional earthquake excitations considering the effects of hydrodynamic pressure, geometric nonlinearity, and material nonlinear, is proposed using the potential-based fluid element through finite element analysis software ADINA in this paper. Taking a typical solid pier of a large span bridge as the research object, the effect of hydrodynamic pressure on the nonlinear seismic responses of the bridge pier under bidirectional horizontal earthquake excitations is studied by analyzing the time histories of the relative displacement and the bending moment at the top and bottom of the pier, respectively.

2. Theory of potential-based fluid elements

Three methods are normally adopted to simulate the water-pier interaction, including analytical or semi-analytical method [4, 9], experimental method [10, 11] and numerical method [12, 13]. The analytical or semi-analytical method is the most effective one, but it needs to satisfy some assumptions and is only applicable to simple structures. The results obtained by the experimental method are close to the actual situation, but the experiment takes long time and the cost is high. The numerical method is widely accepted considering its relatively high accuracy and low cost, but normally it has a low computing efficiency. In this paper, a potential-based fluid element is used to simulate the interaction between the bridge piers and surrounding water under earthquake excitations, which is a more effective numerical method provided by ADINA.

The elements have the following assumptions. (1) The medium is inviscid and irrotational with no heat transfer. (2) The medium is almost incompressible. (3) The displacements of the fluid boundary are relatively small. (4) There is no actual fluid flow. In the fluid, the basic equations of continuity and energy/momentum are as follows [14]:

$$\dot{\rho}+\nabla\cdot\left(\rho\nabla\phi\right)=0 \quad (1)$$

and

$$h = \Omega(\mathbf{x}) - \dot{\phi} - \frac{1}{2}\nabla\phi \cdot \nabla\phi \tag{2}$$

where ρ is the fluid density; ϕ is the fluid velocity potential ($\mathbf{v} = \nabla\phi$ where $\mathbf{v}$ is the fluid velocity and ∇ is the nabla operator); h is the specific enthalpy (defined as $h = \int \frac{dp}{\rho}$); p is the pressure and $\Omega(\mathbf{x})$ is the potential of the (conservative) body force accelerations at position $\mathbf{x}$.

The pressure p is assumed to be a function of the density ρ, and the pressure-density relationship is described as

$$\frac{\rho}{\rho_0} = 1 + \frac{p}{\kappa} \tag{3}$$

where ρ_0 is the nominal density and κ is the bulk modulus.

The velocities and the density changes are assumed to be infinitesimally small, and Eqs. (1) and (2) become

$$\dot{\rho} + \nabla \cdot (\rho\nabla\phi) \approx \dot{\rho} + \rho_0\nabla^2\phi \approx \frac{\rho_0\dot{p}}{\kappa} + \rho_0\nabla^2\phi = 0 \tag{4}$$

and

$$h \approx \frac{p}{\rho} \approx \frac{p}{\rho_0} \approx \Omega(\mathbf{x}) - \dot{\phi} \tag{5}$$

Substituting Eq. (5) into Eq. (4) gives

$$-\rho_0\ddot{\phi} + \kappa\nabla^2\phi = -\rho_0\dot{\Omega} \tag{6}$$

The fluid pressure on the structure is

$$\delta F_u = \int_{S_1} p\mathbf{n} \cdot \delta\mathbf{u}\, dS_1 \approx \int_{S_1} \left(\rho_0\Omega + \rho_0\frac{\partial\Omega}{\partial\mathbf{x}} \cdot \mathbf{u} - \rho_0\dot{\phi} \right) \mathbf{n} \cdot \delta\mathbf{u}\, dS_1 \tag{7}$$

where S_1 is the part of the boundary adjacent to the structure; F_u is the additional force provided by the fluid pressure on the structure adjacent to S_1; $\mathbf{n}$ is the inwards normal on S_1; and $\mathbf{u}$ is the displacement of boundary S_1.

Then the basic equation of dynamics can be written as

$$\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & -\mathbf{M_{FF}} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{U}} \\ \ddot{\boldsymbol{\phi}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} & \mathbf{C_{FU}^T} \\ \mathbf{C_{FU}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{U}} \\ \dot{\boldsymbol{\phi}} \end{bmatrix} + \begin{bmatrix} (\mathbf{K_{UU}})_\mathbf{S} & \mathbf{0} \\ \mathbf{0} & -\mathbf{K_{FF}} \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \boldsymbol{\phi} \end{bmatrix} = \begin{bmatrix} (\mathbf{R_{UB}})_\mathbf{S} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ -\dot{\mathbf{R}}_\mathbf{FB} \end{bmatrix} \tag{8}$$

where $\mathbf{M_{FF}}$ is a matrix from the $\ddot{\phi}\delta\phi$ term; $\mathbf{U}$ is a vector containing unknown nodal displacements; $\boldsymbol{\phi}$ is a vector containing unknown nodal fluid potentials; $\mathbf{C_{FU}}$ is a matrix from the $\dot{\mathbf{u}} \cdot \mathbf{n}\delta\phi$ term; $(\mathbf{K_{UU}})_\mathbf{S}$ is a matrix from the $\left(\rho_0\frac{\partial\Omega}{\partial\mathbf{x}} \cdot \mathbf{u}\right)\mathbf{n} \cdot \delta\mathbf{u}$ term; $\mathbf{K_{FF}}$ is a matrix from the $\nabla\phi \cdot \delta\nabla\phi$ term; $(\mathbf{R_{UB}})_\mathbf{S}$ is a loads vector from the $(\rho_0\Omega)\mathbf{n} \cdot \delta\mathbf{u}$ term; and $\dot{\mathbf{R}}_\mathbf{FB}$ is a loads vector from the $\rho_0\dot{\Omega}\delta\phi$ term.

3. The water-pier interaction model during bidirectional earthquakes

In this paper, the nonlinear seismic responses of the bridge pier under bidirectional earthquake excitations are simulated by taking a typical solid pier of a large span bridge as the research object. The section of the pier is rectangular, whose size is 6 m×4 m and height is 40 m. The data fitted concrete material model in ADINA, which is based on the work described in [15] and [16], is used for the constitutive relationship of concrete. The density of concrete is 2350 kg/m^3, and the uniaxial cylinder compressive strength is 23 MPa. The bridge superstructure is simplified as a concentrated mass on the top of the pier, which is 1.0×10^6 kg. The bridge pier is modeled using three-dimensional solid elements, and the water is modeled using three-dimensional potential-based fluid elements, whose depth is 0 m, 10 m, 20 m and 30 m. The calculation range of water is 60 m×60 m, as the hydrodynamic pressure on the surrounding walls of water is small when the numerical model is calculated using this range of water. The density of water is 1000 kg/m^3, and the bulk modulus is 2.2×10^3 MPa. The finite element model of water-pier interaction is shown in Fig.1.

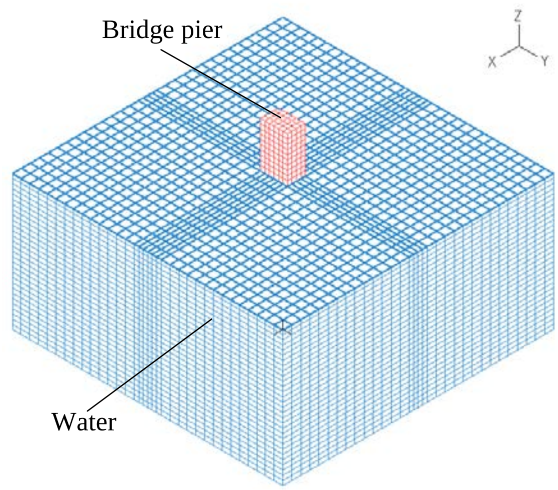


Fig. 1 – The finite element model of water-pier interaction

The acceleration time histories of El-Centro earthquake (1940, north-south and east-west directions) and Taft earthquake (1952, north-south and east-west directions) are chosen as the input bidirectional horizon earthquake excitations. The peak accelerations are scaled to 0.2 g, which is equivalent to the eighth-degree seismic fortification criterion according to Chinese Standards, and the duration time is 20 s. The earthquake excitations are applied from the bottom of the bridge pier. The characteristics of the input earthquake excitations are listed in Table 1, and the acceleration time histories are shown in Fig.2. The Rayleigh type damping ratio of 5% is adopted for the bridge pier. Before the earthquake load is applied, the pier model is preloaded by gravity and hydrostatic pressure, and the results are used as initial conditions for dynamic analysis.

Table 1 – The characteristics of the input earthquake excitations

Earthquake	Magnitude	Record	PGA/g	PGV/(cm/s)	PGD/cm	Direction
El-Centro 1940	7.0	I-ELC270	0.215	30.2	23.91	x-direction
		I-ELC180	0.313	29.8	13.32	y-direction
Taft 1952	7.4	TAF111	0.178	17.5	8.99	x-direction
		TAF021	0.156	15.3	9.25	y-direction

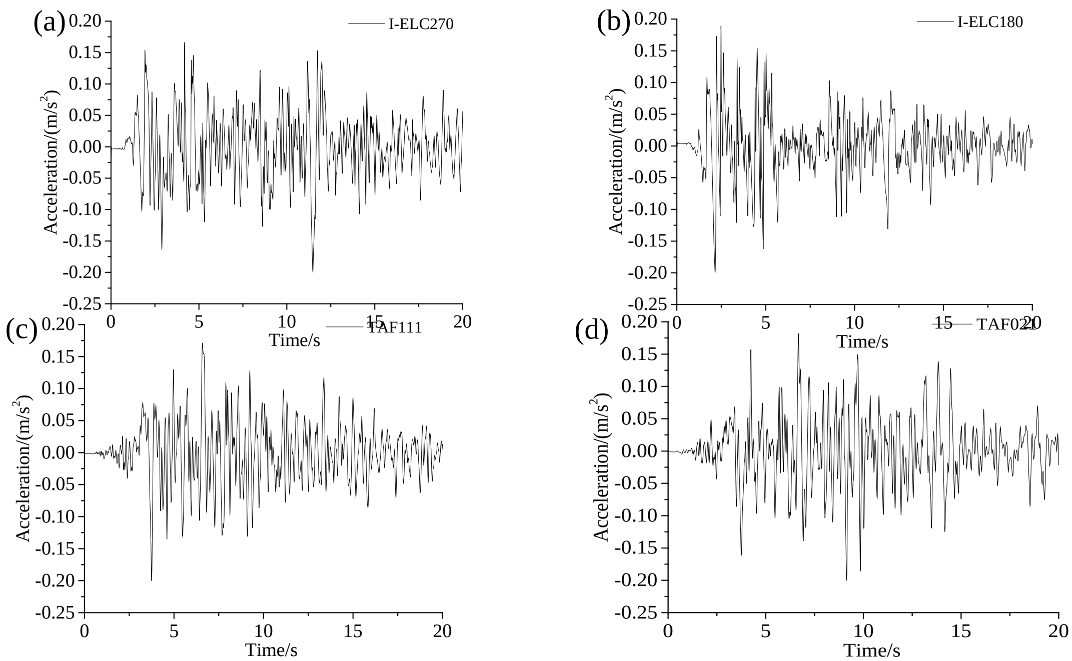


Fig. 2 – The acceleration time histories of the input earthquake excitations: (a) I-ELC270, (b) I-ELC180, (c) TAF111, (d) TAF021

4. Simulation results

Table 2 and Table 3 show respectively the peak nonlinear seismic responses of the bridge pier in different water depths under unidirectional and bidirectional excitations of El-Centro and Taft earthquakes. The seismic responses including the relative displacement and the bending moment at the top and bottom of the pier are focused. The seismic response time histories of the bridge pier in 30 m deep water are shown in Figs.3 and 4.

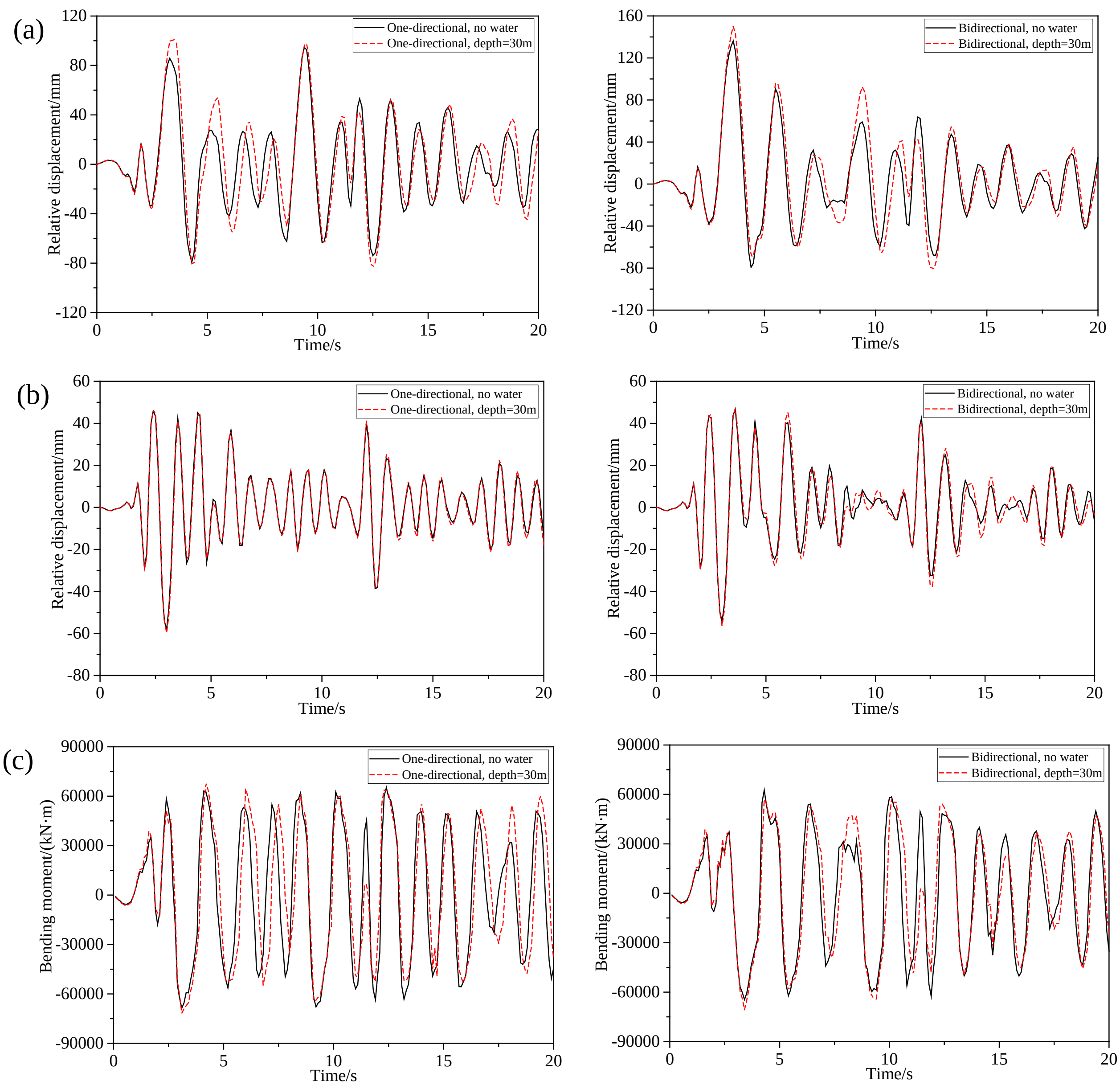
Table 2 – The peak nonlinear seismic responses of bridge pier under El-Centro earthquake

Depth /m	**X-component**				**Y-component**			
	Displacement/mm		**Moment/(kN·m)**		**Displacement/mm**		**Moment/(kN·m)**	
	Uni-directional	**Bi-directional**	**Uni-directional**	**Bi-directional**	**Uni-directional**	**Bi-directional**	**Uni-directional**	**Bi-directional**
0	94.55	136.23	68660.10	64572.60	57.90	54.37	98834.40	95226.00
10	94.65	137.93	68754.00	65941.20	57.63	53.84	98385.30	96775.30
20	95.62	139.86	71318.80	67980.80	58.64	55.60	98084.70	97403.40
30	100.95	149.98	71678.70	70730.10	59.70	56.40	100016.00	99717.50

Table 3 – The peak nonlinear seismic responses of bridge pier under Taft earthquake

Depth	**X-component**	**Y-component**

/m	**Displacement/mm**		**Moment/(kN·m)**		**Displacement/mm**		**Moment/(kN·m)**	
	Uni-directional	**Bi-directional**	**Uni-directional**	**Bi-directional**	**Uni-directional**	**Bi-directional**	**Uni-directional**	**Bi-directional**
0	55.76	65.23	64369.30	60506.70	48.51	55.05	94301.00	90487.70
10	55.33	64.50	64766.80	61670.00	48.32	55.16	94578.70	89447.70
20	59.67	66.38	65859.30	63276.50	48.08	55.72	94384.20	90689.20
30	61.03	79.56	65168.90	65062.30	46.69	58.42	97205.20	93774.20



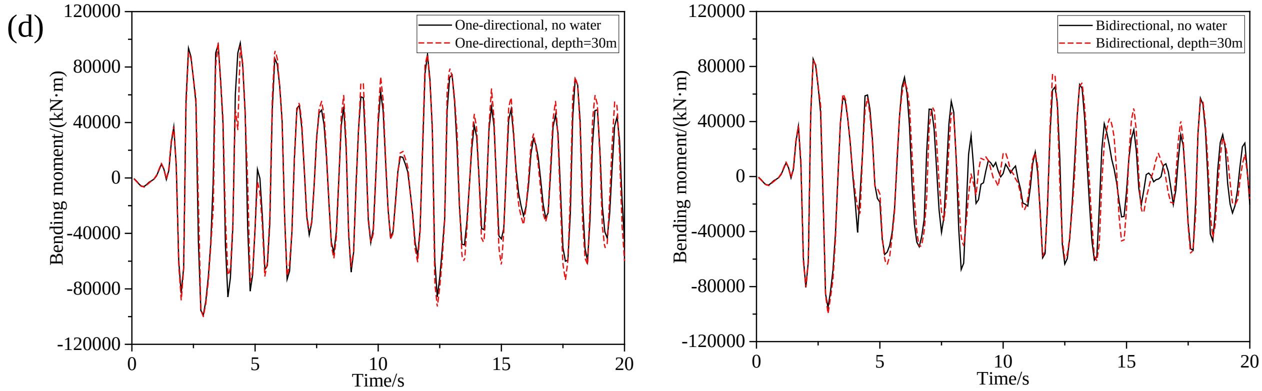
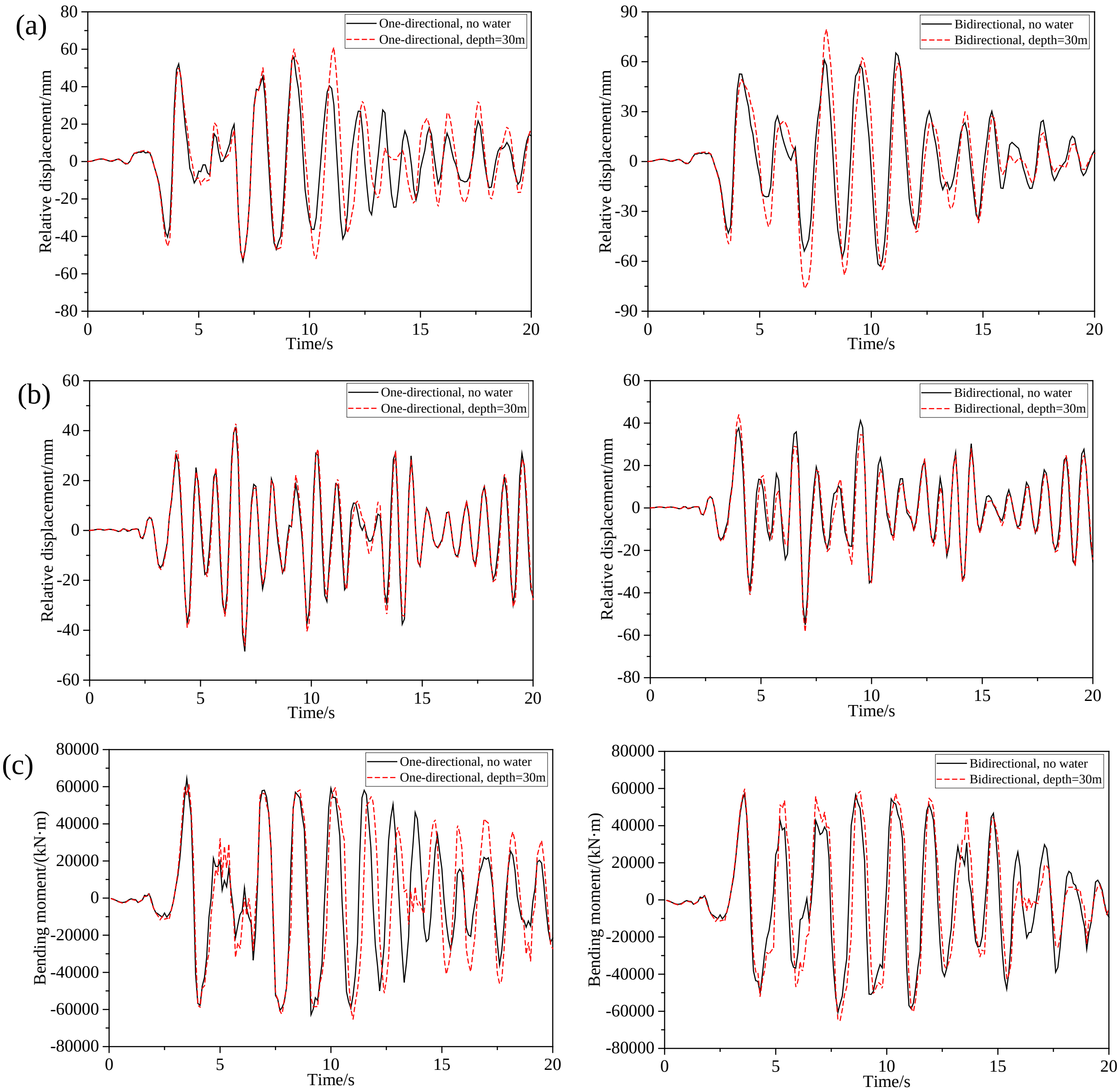


Fig. 3 – The seismic response time histories of bridge pier under El-Centro earthquake: (a) the x-component of relative displacement of pier top, (b) the y-component of relative displacement of pier top, (c) the x-component of bending moment of pier bottom, (d) the y-component of bending moment of pier bottom



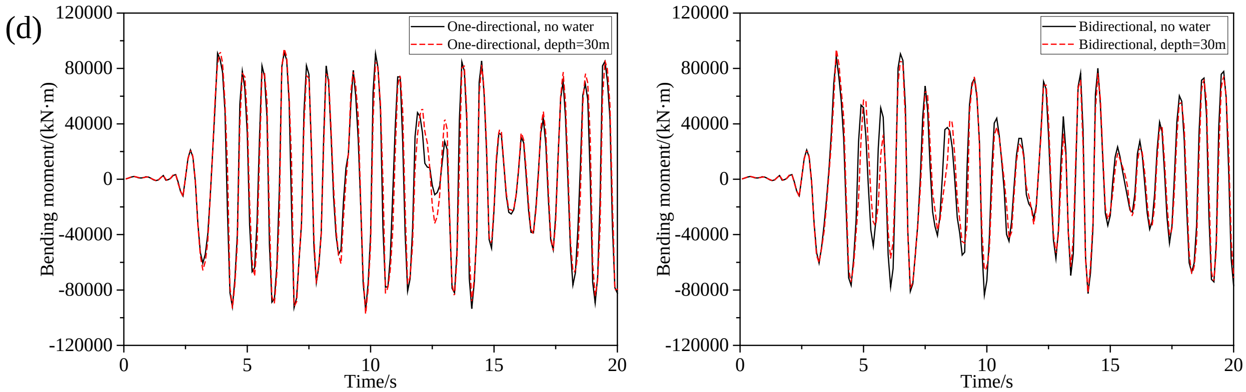


Fig. 4 – The seismic response time histories of bridge pier under Taft earthquake: (a) the x-component of relative displacement of pier top, (b) the y-component of relative displacement of pier top, (c) the x-component of bending moment of pier bottom, (d) the y-component of bending moment of pier bottom

In order to evaluate the effect of hydrodynamic pressure on the nonlinear seismic responses of the bridge pier, the influence coefficients R_d and R_m are defined as follows:

$$R_d = \frac{D_w - D_d}{D_d} \times 100\% \tag{9}$$

and

$$R_m = \frac{M_w - M_d}{M_d} \times 100\% \tag{10}$$

where R_d and R_m are the hydrodynamic pressure influence coefficients of the relative displacement and the bending moment at the top and bottom of the pier, respectively; D_w and D_d are the peak relative displacements at the top of the pier considering and without considering hydrodynamic pressure, respectively; M_w and M_d are the peak bending moments at the bottom of the pier considering and without considering hydrodynamic pressure, respectively. Table 4 and Table 5 show the hydrodynamic pressure influence coefficients under El-Centro and Taft earthquakes, respectively.

Table 4 – The hydrodynamic pressure influence coefficients under El-Centro earthquake

Depth /m	**X-component**				**Y-component**			
	R_d /%		**R_m /%**		**R_d /%**		**R_m /%**	
	Uni-directional	**Bi-directional**	**Uni-directional**	**Bi-directional**	**Uni-directional**	**Bi-directional**	**Uni-directional**	**Bi-directional**
10	0.10	1.25	0.14	2.12	-0.46	-0.97	-0.45	1.63
20	1.13	2.67	3.87	5.28	1.29	2.27	-0.76	2.29
30	6.77	10.10	4.40	9.54	3.11	3.73	1.20	4.72

Table 5 – The hydrodynamic pressure influence coefficients under Taft earthquake

Depth	**X-component**	**Y-component**

/m	R_d /%		R_m /%		R_d /%		R_m /%	
	Uni-directional	Bi-directional	Uni-directional	Bi-directional	Uni-directional	Bi-directional	Uni-directional	Bi-directional
10	-0.78	-1.12	0.62	1.92	-0.40	0.20	0.29	-1.15
20	7.01	1.75	2.31	4.58	-0.89	1.22	0.09	0.22
30	9.44	21.97	1.24	7.53	-3.76	6.12	3.08	3.63

It can be seen from Table 4 that the maximum influence coefficients of the x-component and y-component of relative displacement at the top of the bridge pier under bidirectional excitations of El-Centro earthquake are 10.10% and 3.73%, respectively; while the maximum influence coefficients under unidirectional excitations are only 6.77% and 3.11%, respectively. The maximum influence coefficients of the x-component and y-component of bending moment at the bottom of the bridge pier under bidirectional excitations of El-Centro earthquake are 9.54% and 4.72%, respectively; while the maximum influence coefficients under unidirectional excitations are only 4.40% and 1.20%, respectively. It shows that the effect of hydrodynamic pressure on the nonlinear seismic responses under bidirectional earthquake excitations is more significant than the effect under unidirectional earthquake excitations. This is because the biaxial stress state of concrete material is more adverse than the uniaxial stress state. The concrete piers under bidirectional earthquake excitations are easier to crack than the piers under unidirectional earthquake excitations, and the crack of concrete leads to the deterioration of strength and stiffness. Therefore, the bidirectional earthquake excitations reduce the stiffness of the piers, and increase the hydrodynamic pressure amplifications of seismic response of the piers.

It also can be seen from Table 4 that when the water depth is 10 m, the influence coefficients of the x-component and y-component of relative displacement at the top of the bridge pier under bidirectional excitations of El-Centro earthquake are only 1.25% and -0.97%, respectively; however, when the water depth is 30 m, the influence coefficients are 10.10% and 3.73%, respectively. When the water depth is 10 m, the influence coefficients of the x-component and y-component of bending moment at the bottom of the bridge pier under bidirectional excitations of El-Centro earthquake are only 2.12% and 1.63%, respectively; however, when the water depth is 30 m, the influence coefficients are 9.54% and 4.72%, respectively. It shows that the effect of hydrodynamic pressure on the nonlinear seismic responses under bidirectional earthquake excitations increases with the increase of water depth. This is because the deeper water results in larger total hydrodynamic force and higher position of force acting point.

By comparing the influence coefficients of the x-component of seismic response under bidirectional excitations of El-Centro earthquake with the influence coefficients of the y-component in Table 4, the conclusion can be drawn that the effect of hydrodynamic pressure on the direction with wider upstream face is larger than the effect on the other direction under bidirectional earthquake excitations. This is because wider upstream face will induce larger hydrodynamic total force, and the cross section flexural rigidity of the direction with wider upstream is smaller than the rigidity of the other direction. Likewise, similar conclusions can be drawn from the seismic responses under Taft earthquake in Table 5.

5. Conclusions

In this paper, the nonlinear seismic responses of a bridge pier in deep water during bidirectional earthquakes are examined. In order to evaluate the hydrodynamic pressure effect under bidirectional earthquake excitations, the time histories of the relative displacement and the bending moment at the top and bottom of the pier are analyzed. The results show that the effect of hydrodynamic pressure on the nonlinear seismic responses under bidirectional earthquake excitations is more significant than the effect under unidirectional earthquake excitations. The effect under bidirectional earthquake excitations increases with the increase of water depth. In addition, the effect on the direction with wider upstream face is larger than the effect on the other direction under bidirectional earthquake excitations.

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