EXPERIMENTAL AND NUMERICAL STUDY ON FREE SPANNING PIPELINES SUBJECTED TO EARTHQUAKES

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ABSTRACT :

A series of model experiments of free spanning submarine pipeline are carried out on an underwater shaking table in the Sate Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The factors to affect the dynamic response of pipeline, including seismic wave types and input directions are studied in the dynamic experiments. A hydrodynamic force model on the base of Wake force model is presented to analyze dynamic response of free spanning submarine pipeline under earthquakes. Using finite element method, discrete equations of motion are derived from the hydrodynamic force model. Three dimensional FE model is established to simulate the experimental conditions. The numerical results considering sine wave inputs and simulated El centro earthquake inputs are obtained. The comparison of numerical results with experimental results shows that the improved Wake force model could satisfactorily predict dynamic response on the free spanning submarine pipelines subjected to earthquakes.

KEYWORDS: Free spanning submarine pipelines, dynamic model tests, hydrodynamic force model, finite element analysis, earthquake

1. INTRODUCTION

Submarine pipelines transporting oil and gas are buried in the seabed, or unburied in the trench, or installed on the seabed directly. Free span will be present due to uneven seabed for the pipelines resting on the seabed or seabed scouring effects for the buried and trenched pipelines. The maximum horizontal acceleration reaches to 0.25 g at Bohai Bay, China. The combined earthquake and operating loads become the critical condition in design. However, a literature search has revealed a scarcity of published literature dealing with the seismic analysis and design of offshore pipeline. Added masses introduced to simulate interaction between pipeline and surrounded fluid on the base of Morison equation and the assumption neglecting wave and current are used to establish equations of motion of free spanning submarine pipelines subjected to earthquakes (Datta, 1990, Kalliontzis, 1998, Zhou, 2005). The characteristics of earthquake compared with wave and current are short duration, ample frequency content and high magnitude. Thereby, it is of significance to study on the hydrodynamic force model to simulate and simplify interacting model between pipeline and water subject to earthquakes.

Model tests are carried out to analyze dynamic characteristics of free spanning submarine pipelines. Based on the experimental results, a more accurate hydrodynamic model derived from Wake force model is introduced to analyze seismic response of submarine pipelines. The equations of motion are derived from the above model. Finite element model is established to simulate the experimental conditions. The numerical results obtained from improved Wake force model are compared with experimental results.

2. DYNAMIC MODEL TESTS

2.1 Model design

Organic glass was selected as model pipe material. The outer diameter of the model pipe displayed in Fig. 1 is D_o =150 mm, wall thickness t_p =5 mm, dynamic elastic module E_m =3450 MPa, mass density ρ =1.2×10^3 kg/m^3, Possion ratio μ=0.34.

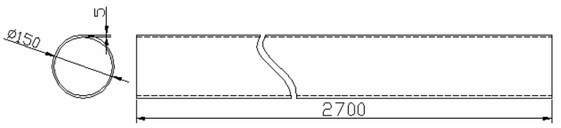


Figure 1 Sizes of model pipe (unit: mm)

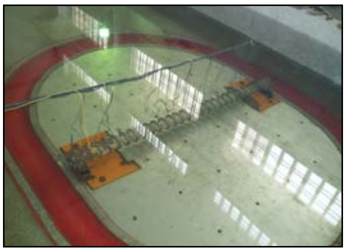


Figure 2 Test rig setup

The model tests of free spanning submarine pipelines were performed on an underwater shaking table in the State Key Laboratory of Coastal and Offshore Engineering (SLCOE), Dalian University of Technology, China. It can simulate the ground motion in both horizontal and vertical direction. Figure 2 shows the test rig of model pipe during experiment.

2.2 Experimental cases

Table 1 lists the scenarios were investigated in the experiment. The sine wave with 5 Hz equal to the natural frequency of model submarine pipe is selected as on type of seismic input shown in Fig. 3. El Centro earthquake, May 18, 1940 (NS component) which is adjusted in amplitude and duration in order to satisfy similitude relationship between model and prototype is chosen as the other type of seismic input shown in Fig. 4..

Table 1 Factors and cases in model experiments

No.	Factor	Experimental case
1	Exciting wave	Sine wave, El Centro simulation wave
2	Exciting direction	Horizontal direction, vertical direction
3	Pipe type	Submarine pipe, onshore pipe
4	Spanning length (m)	2.7
5	Support	Simple support

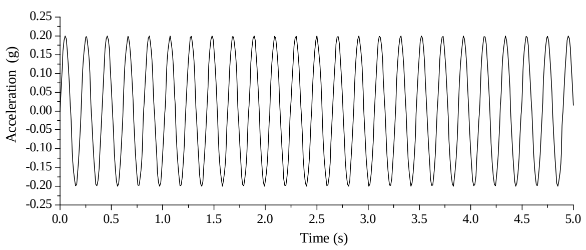


Figure 3 Acceleration time history of 5 Hz sine wave

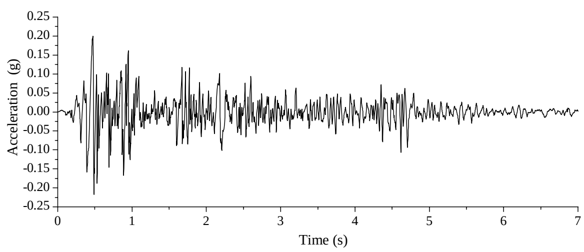


Figure 4 Acceleration time history of El Centro wave

2.3 Experimental results

Water in the flume looks like still and only emerges tiny ripple on the surface under horizontal excitation as shown in Fig. 5(a); much larger waves appear on the surface of water under vertical excitation as shown in Fig. 5(b). The phenomena are similar for both sine and El Centro simulated wave inputs.

(a) Horizontal input (b) Vertical input

Figure 5 Phenomena at the surface of water under sine wave excitation

3. WAKE FORCE MODEL SUITABLE FOR EARTHQUAKES

3.1 Wake force model

Basic findings from Exxon's Pipeline Field Measurement Program (PFMP) show that conventional force model such as Morison equation can not satisfactorily predict hydrodynamic forces imposed on submarine pipelines under waves and currents. Wake force model presented by Lambrakos et al. (1987) on the base of the measurement obtained from PFMP uses the same basic relationships between the force components and the flow kinematics as described earlier for Morison equation. The difference is that the velocity in Wake force model is modified to include the pipe's encounter with the wake flow. Effective velocity defined as the superposition of wake velocity and ambient fluid velocity relative to pipe is introduced to substitute for water particle velocity in Morison equation. Coefficient for the drag forces in the model is time-dependent, which is referred to as a "start-up" effect.

Provided that cylinder is rigid, the Wake force model expressions for intertial force, f_i, and drag force, f_d, are:

$$f_i = C_M \frac{\pi}{4}\rho D^2 \dot{U} - C_{AW}\frac{\pi}{4}\rho D^2 \dot{U}_w \tag{3.1}$$

$$f_d = C_D(t)\frac{1}{2}\rho D U_e |U_e| \tag{3.2}$$

in which ρ is the density of water; D is the outside diameter of the pipe; U is the velocity of the water particles; C_M is the inertial coefficient; C_{AW} is the added mass coefficient associated with the wake flow passing the pipe; U_W is wake velocity; $C_D(t)$ is time-dependent drag coefficient; U_e is the effective velocity.

Wake and its velocity distribution are shown in Fig. 6 for a pipe moving in still water. The wake velocity (u_w) for a cylinder in steady motion through water and remote from a boundary is:

$$u_w = \dot{v}\sqrt{\frac{C_{DS}D}{x}}\left[1-\left(\frac{y}{b}\right)^{1.5}\right]^2 \tag{3.3}$$

in which v is the cylinder displacement; x is the distance from the cylinder along the motion direction; y is the distance from the point x in a direction transverse to the motion; b is the width of the wake; C_{DS} is the the steady flow drag coefficient for the cylinder.

A simple expression for wake velocity is needed in engineering practice. Thus, the average far-wake velocity over the pipe diameter is selected and taken as:

$$U_W = k\dot{v} \quad x \le \frac{C_{DS}D}{k^2} \tag{3.4}$$

$$U_W = \dot{v}\sqrt{\frac{C_{DS}D}{x}} \quad x > \frac{C_{DS}D}{k^2} \tag{3.5}$$

where U_W is the wake velocity along horizontal axis of the cylinder; k is a constant less than or equal to unity. The above equations display the wake velocity variation behind the pipe up to a limiting value near the pipe. After reaching a limiting value, the wake velocity is assumed to be constant in a region near the pipe.

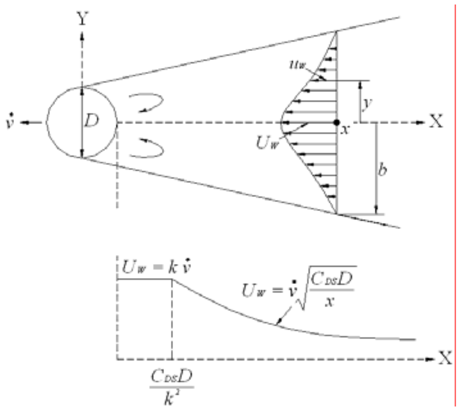


Figure 6 Wake flow for a pipe moving with constant speed in still water

3.2 Wake force model under three dimensional earthquake input

Considering seismic input directions the hydrodynamic force model of flexible submarine pipeline is proposed from Wake force model. Based on the experimental results and FE analysis with the interaction between fluid and structure (Li, 2008), the following assumptions are made in the formulation of the problem:
(a) No interaction occurs between the transverse and vertical response of the pipe;
(b) seismic loading is exclusively considered, no current exists on the bottom at the time of earthquake and the pipeline is so deep that wave action does not affect it, thus the influences of current and wave are ignored;
(c) he velocity of water particle equals to zero under horizontal seismic input;
(d) the velocity of water particle is the same as the ground velocity under vertical seismic input;
(e) start-up effect is not taken into account;
(f) wakes flow adjacent to the pipe all the time since the pipe moves in small vibration.

When earthquake parallel to pipeline moves along horizontal direction, no hydrodynamic force imposes on the submarine pipeline along earthquake movement direction, namely

$$f_{longitudinal} = 0 \tag{3.6}$$

While earthquake perpendicular to pipeline moves along horizontal direction, since the pipe is flexible, inertial force imposed on free spanning submarine pipeline is given as:

$$f_i = C_M \frac{\pi}{4}\rho D^2 \dot{U} - C_A \frac{\pi}{4}\rho D^2 \ddot{v} - C_{AW}\frac{\pi}{4}\rho D^2 \dot{U}_w \tag{3.7}$$

Drag force imposed on free spanning submarine pipeline is taken as:

$$f_d = C_D \frac{1}{2}\rho D(U - \dot{v} + U_W)\left|U - \dot{v} + U_W\right| \quad (3.8)$$

Following the assumption that water particle kinematics are zero, U=0, the total hydrodynamic force due to transverse earthquake is expressed as

$$f_{transvers} = f_i + f_d = -C_A \frac{\pi}{4}\rho D^2 \ddot{v} - C_{AW}\frac{\pi}{4}\rho D^2 \dot{U}_w + C_D \frac{1}{2}\rho D(-\dot{v} + U_W)\left|-\dot{v} + U_W\right| \quad (3.9)$$

Submarine pipeline subjected to earthquake moves reciprocally in higher frequencies compared with wave. This is a simplifying assumption that wakes move around the pipe all the while. Then, the wake velocity is

$$U_W = k(\dot{v} - U) = k\dot{v} \quad (3.10)$$

Substituting Eq. (3.10) into Eq. (3.9) yields the following form of hydrodynamic force subjected to transverse earthquake excitation:

$$f_{transvers} = -(C_A + kC_{AW})\frac{\pi}{4}\rho D^2 \ddot{v} - C_D \frac{1}{2}\rho D(1-k)\dot{v}\left|\dot{v}\right| \quad (3.11)$$

While earthquake perpendicular to pipeline moves along vertical direction, based on the assumption that $U = \dot{u}_g$, the total hydrodynamic force due to vertical earthquake is

$$f_{vertical} = f_i + f_d = C_M \frac{\pi}{4}\rho D^2 \ddot{u}_g - C_A \frac{\pi}{4}\rho D^2 \ddot{v} - C_{AW}\frac{\pi}{4}\rho D^2 \dot{U}_w + C_D \frac{1}{2}\rho D(\dot{u}_g - \dot{v} + U_W)\left|\dot{u}_g - \dot{v} + U_W\right| \quad (3.12)$$

Assumed that wakes move nearby the pipe, wake velocity can be given as:

$$U_W = k(\dot{v} - U) = k(\dot{v} - \dot{u}_g) \quad (3.13)$$

Inserting Eq. (3.13) in Eq. (3.12) deduces the following form of hydrodynamic force subjected to vertical earthquake excitation:

$$f_{vertical} = (C_M + kC_{AW})\frac{\pi}{4}\rho D^2 \ddot{u}_g - (C_A + kC_{AW})\frac{\pi}{4}\rho D^2 \ddot{v} - C_D \frac{1}{2}\rho D(1-k)(\dot{v} - \dot{u}_g)\left|\dot{v} - \dot{u}_g\right| \quad (3.14)$$

4. NUMERICAL PROCEDURES

4.1 Equations of Motion

Using Eq. (3.6), (3.11) and (3.14), and ignoring the effects of wave and current, hydrodynamic force per unit length of submarine pipeline subjected to earthquake may be given as:

$$f_{sW} = -m_{AW}\ddot{v} - d_{AW}(\dot{v} - \dot{w})\left|\dot{v} - \dot{w}\right| + f_{AW}\ddot{u}_g \quad (3.15)$$

in which the parameters are listed in Table2.

Table 2 Parameter Definition

Input direction	m_{AW}	d_{AW}	f_{AW}	w
Longitudinal	0	0	0	0
Transverse	$(C_A + kC_{AW})\frac{\pi}{4}\rho D^2$	$C_D \frac{1}{2}\rho D(1-k)$	0	0
Vertical	$(C_A + kC_{AW})\frac{\pi}{4}\rho D^2$	$C_D \frac{1}{2}\rho D(1-k)$	$(C_M + kC_{AW})\frac{\pi}{4}\rho D^2$	u_g

4.2 Discretized equation of motion for a submarine pipeline under multi-support seismic excitation

Introducing hydrodynamic force, the equation of motion for *n*-degree-freedom pipeline model under ground motions input at *m* supports can be written in the matrix form

$$\begin{bmatrix} \mathbf{M} & \mathbf{M}_c \\ \mathbf{M}_c^T & \mathbf{M}_g \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{V}} \\ \ddot{\mathbf{U}}_g \end{Bmatrix} + \begin{bmatrix} \mathbf{C} & \mathbf{C}_c \\ \mathbf{C}_c^T & \mathbf{C}_g \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{V}} \\ \dot{\mathbf{U}}_g \end{Bmatrix} + \begin{bmatrix} \mathbf{K} & \mathbf{K}_c \\ \mathbf{K}_c^T & \mathbf{K}_g \end{bmatrix} \begin{Bmatrix} \mathbf{V} \\ \mathbf{U}_g \end{Bmatrix} = \begin{Bmatrix} \mathbf{F}_s \\ \mathbf{F} \end{Bmatrix} \tag{3.16}$$

where **V** is the *n*-vector of displacements at unconstrained degrees of freedom; $\mathbf{U_g}$ is the *m*-vector of prescribed support displacements; **M**, **C** and **K** are the $n \times n$ mass, damping and stiffness matrices associated with the unconstrained degrees of freedom, respectively; $\mathbf{M_g}$, $\mathbf{C_g}$ and $\mathbf{K_g}$ are the $m \times m$ matrices associated with the support degrees of freedom; $\mathbf{M_c}$, $\mathbf{C_c}$ and $\mathbf{K_c}$ are the $n \times m$ coupling matrices associated with both sets of degree of freedom; and **F** is the *m*-vector of the reacting forces at the support degrees of freedom; $\mathbf{F_s}$ is the *n*-vector of the hydrodynamic forces. **V** may contain translational as well as rotational components while $\mathbf{U_g}$ may only include translational components.

From the first equation of Eqs. (3.16),

$$\mathbf{M}\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = \mathbf{F}_s - \mathbf{M}_c\ddot{\mathbf{U}}_g - \mathbf{C}_c\dot{\mathbf{U}}_g - \mathbf{K}_c\mathbf{U}_g \tag{3.17}$$

supposing the lumped mass matrix, then $\mathbf{M_c}$=0. In general, the damping matrix $\mathbf{C_c}$ can hardly be evaluated and the damping force in the right side can be neglected (Wilson, 2002). Eq. (3.17) can be approximately rewritten as

$$\mathbf{M}\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = \mathbf{F}_s - \mathbf{K}_c\mathbf{U}_g \tag{3.18}$$

4.3 Discretized equation of motion based on Wake force model

Based on Eq. (3.15), hydrodynamic force vector $\mathbf{F_s}$ can be given as

$$\mathbf{F}_s = -\mathbf{M}_{AW}\ddot{\mathbf{V}} - \mathbf{D}_{AW}(\dot{\mathbf{V}} - \dot{\mathbf{W}})|\dot{\mathbf{V}} - \dot{\mathbf{W}}| + \mathbf{F}_{AW}\ddot{\mathbf{U}}_g \tag{3.19}$$

where $\mathbf{M_{AM}}$ is the added mass matrix; $\mathbf{D_{AM}}$ is the added dampness matrix; $\dot{\mathbf{W}}$ is the water velocity matrix; $\mathbf{F_{AW}}$ is the inertial coefficient matrix due to ground motion. Substitution of Eq. (3.19) into Eq. (3.18) yields equation of motion for a submarine pipeline subjected to multi-support seismic excitation on the base of Wake force model.

$$(\mathbf{M} + \mathbf{M}_{AW})\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{D}_{AW}(\dot{\mathbf{V}} - \dot{\mathbf{W}})|\dot{\mathbf{V}} - \dot{\mathbf{W}}| + \mathbf{K}\mathbf{V} = -\mathbf{K}_c\mathbf{U}_g + \mathbf{F}_{AW}\ddot{\mathbf{U}}_g \tag{3.20}$$

5. COMPARISONS BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

FE models are established to simulate the experimental conditions. Numerical analyses are performed to study dynamic response of free spanning submarine pipeline under multi-dimensional earthquakes on the base of Wake force model respectively. The inertial coefficient, C_M, is taken as 2.0 according to Code for Submarine Pipeline Systems (SY/T 4804-92), China (1992). The parameters, C_D, C_{AW}, and k derived from the PFMP rough pipe data are taken as 1.1, 0.25 and 0.5 respectively. The parameters, C_M, C_D, C_{AW} and k are assumed constant for all flow conditions. Both simple supports of model pipe were fixed on the shaking table during tests, thereby, seismic inputs from both supports are identical. Using Eq. (3.20), the equations of motion of multi-support input can be simplified as that of identical input.

A comparison of peak acceleration and strain between experimental and numerical results is listed in Table 3. The relative errors based on Wake force model are less than 10%. The hydrodynamic force model derived from Wake force model is in agreement with experimental results in engineering precision under earthquakes.

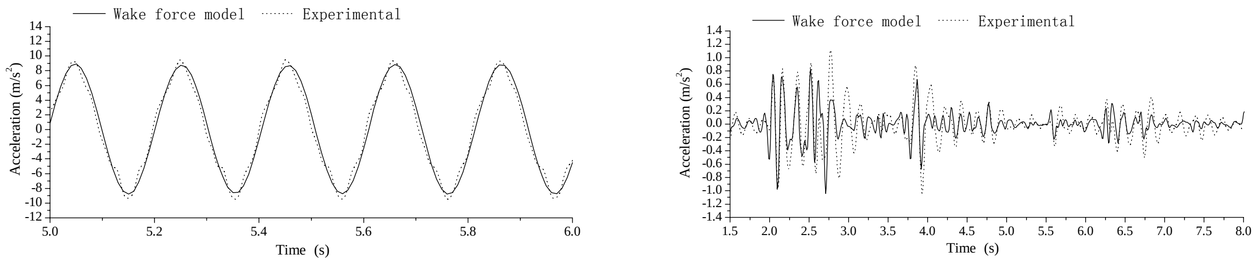
Although neglecting the interaction between the vertical and horizontal response of the pipe does not accord with practice, the error of numerical and experimental results are within the acceptable range.

Table 3 Comparison of peak values of numerical and experimental results

Type	Seismic wave	Excited direction	Experimental result	Numerical result	Relative error
Acceleration (m/s^2)	Sine	Horizontal	9.58	8.92	6.89%
		Vertical	2.87	2.64	8.01%
	Simulated El Centro	Horizontal	1.09	1.04	4.59%
		Vertical	0.73	0.69	5.48%
Strain (10^{-6})	Sine	Horizontal	969	1032	6.50%
		Vertical	271	290	7.01%
	Simulated El Centro	Horizontal	120	108	10.00%
		Vertical	41	38	7.32%

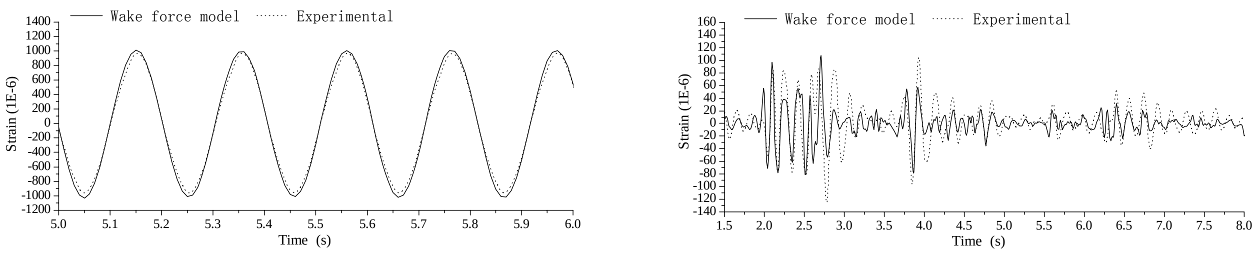
Note: relative error is defined as the ratio of absolute value of numerical result minus experimental result to experimental result.

Acceleration and strain time histories at the center of pipe span under horizontal excitations are shown in Fig. 7 and Fig. 8 respectively. The numerical results from Wake force model compared with experimental results predict satisfactorily the general shape, phase and magnitude under horizontal sine wave input as well as horizontal simulated El Centro wave input.



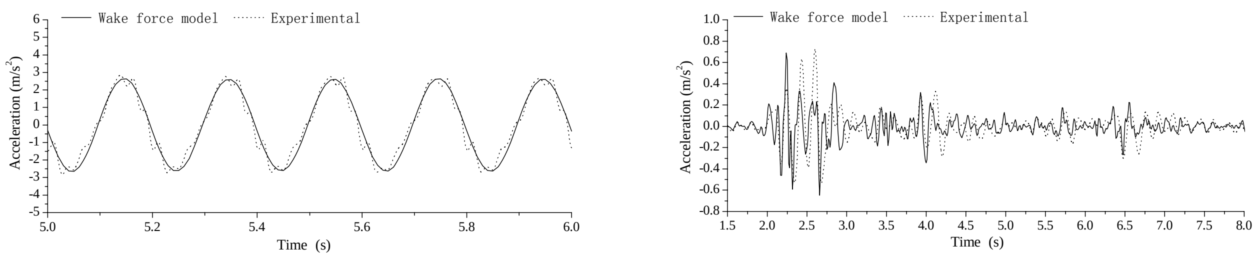
(a) Sine wave (b) El Centro simulated wave

Figure 7 Acceleration time histories at the center of pipe span under horizontal excitations



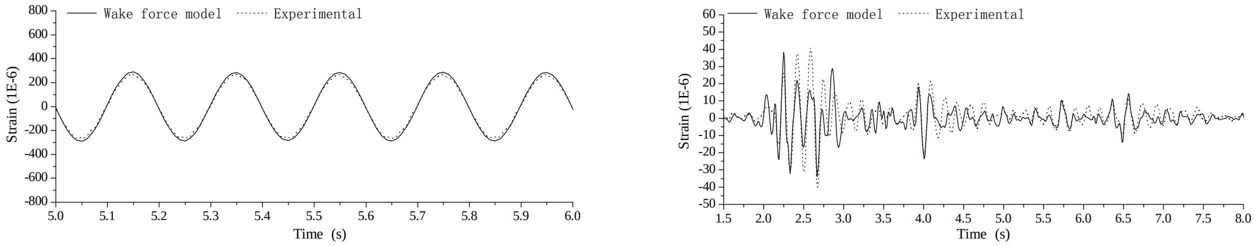
(a) Sine wave (b) El Centro simulated wave

Figure 8 Strain time histories at the center of pipe span under horizontal excitations



(a) Sine wave (b) El Centro simulated wave

Figure 9 Acceleration time histories at the center of pipe span under vertical excitations



(a) Sine wave (b) El Centro simulated wave

Figure 10 Strain time histories at the center of pipe span under vertical excitations

Figure 9 and Fig. 10 display acceleration and strain time histories at the center of pipe span under vertical excitations respectively. From the figures shape, phase and magnitude of acceleration and strain based on numerical analysis from Wake force model accord very well with experimental results.

6. CONCLUSIONS

Hydrodynamic force model based on Wake force model is developed for evaluation of dynamic response of free spanning submarine pipelines due to three dimensional earthquakes. The numerical results of finite element analysis are compared with experimental results. The following conclusions can be drawn:

(1) Hydrodynamic force models derived on the base of the assumptions that the water velocity equals to zero under horizontal seismic input and the water velocity is the same as the ground velocity under vertical seismic input, are suitable for analyzing dynamic response of free spanning submarine pipelines subjected to earthquakes.

(2) The comparisons between numerical results from Wake force model and experimental results show that hydrodynamic force models can predict satisfactorily dynamic response of free spanning submarine pipeline under earthquakes.

(3) Hydrodynamic force models derived on the base of some assumptions are suitable for analyzing dynamic response of free spanning submarine pipelines subjected to earthquakes. However, further study has to be done such as the fluid field measurement surrounded pipe and interaction model of hydrodynamic force considering different seismic input directions.

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