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Dynamic analysis of immersion concrete pipes in water subjected to earthquake load using mathematical methods

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Abstract. In this paper, dynamic analysis of concrete pipe submerged in the fluid and conveying fluid is studied subjected to earthquake load. The structure is modeled by classical shell theory and the force induced by internal fluid is obtained by Navier-Stokes equation. Applying energy method and Hamilton's principle, the motion equations are derived. Based on Navier and Newmark methods, the dynamic deflection of the structure is calculated. The effects of different parameters such as mode number, thickness to radius ratios, length to radius ratios, internal and external fluid are discussed on the seismic response of the structure. The results show that considering internal and external fluid, the dynamic deflection increases.

Keywords: dynamic response; concrete pipe; fluid; numerical method; mathematical model

1. Introduction

A submarine pipeline (also known as marine, subsea or offshore pipeline) is a pipeline that is laid on the seabed or below it inside a trench. In some cases, the pipeline is mostly on-land but in places it crosses water expanses, such as small seas, straits and rivers. Submarine pipelines are used primarily to carry oil or gas, but transportation of water is also important. A distinction is sometimes made between a flow line and a pipeline.

Gong *et al*. (2000) applied a computational method for safety evaluation of submerged pipelines, subjected to underwater shock. Lee and Oh (2003) developed a spectral element model for the pipe conveying fluid to study the flow induced vibrations of the system by the exact constitutive dynamic stiffness matrix. Lam *et al*. (2003) examined the dynamic response of a simply supported laminated underwater pipeline exposed to underwater explosion shock. Yoon and Son (2007) studied the dynamic behavior of simply supported fluid-conveying pipe in due to the effect of the open crack and the moving mass. Lin and Qiao (2008) explored vibration and instability of an axially moving beam immersed in fluid with simply supported conditions along with torsional springs. Huang *et al*. (2010) used Galerkin's method to obtain eigen frequencies of tubes conveying fluid having different boundary conditions. Zhai *et al*. (2011) used the Timoshenko beam model for obtaining the dynamic response of a fluid-conveying pipe under random excitation. Liu *et al*. (2012) analyzed fluid-solid interaction problem for an elastic cylinder by numerical simulations and acquired the vibration of cylinder for both laminar and turbulent flows. Seismic response of natural gas and water pipelines in the Ji-Ji earthquake was considered by Chen *et al*. (2002). Abdoun*et al*. (2009) studied influencing factors on the behavior of buried pipelines subjected to earthquake faulting.

In none of mentioned investigations, the structure is not composite. Mechanical analysis of nanostructures has been reported by many researchers (Zemri 2015, Larbi Chaht 2015, Belkorissat 2015, Ahouel 2016, Bounouara 2016, Bouafia 2017, Besseghier 2017, Bellifa 2017, Mouffoki 2017, Khetir 2017). Rationally modeling collapse due to bending and external pressure in pipelines was presented by Nogueira (2012). Effect of using fiber-reinforced polymer composites for underwater steel pipeline repairs was studied by Shamsuddoha *et al*. (2013). Ray and Reddy (2013) made a study on the active damping of piezoelectric composite cylindrical shells conveying fluid. Alijani and Amabili (2014) used energy method with the Amabili-Reddy nonlinear higher-order shear deformation theory for determining the nonlinear vibrations and multiple resonances of fluid filled arbitrary laminated cylindrical shells. Seismic reliability analysis of a jacket-type support structure for an offshore wind turbine was performed by Kim *et al*. (2015). An investigation on the nonlinear dynamic response and vibration of the imperfect laminated three-phase polymer nanocomposite panel resting on elastic foundations was presented by Duc *et al*. (2015). Van Thu and Duc (2016) presented an analytical approach to investigate the non-linear dynamic response and vibration of an imperfect three-phase laminated nanocomposite cylindrical panel resting on elastic foundations in thermal environments. Thinh and Nguyen (2016) investigated the free vibration of composite circular shells containing fluid. They used the Dynamic Stiffness Method (DSM) based on the Reissner-Mindlin theory and non-viscous incompressible fluid equations for modelling of structure. Dynamic characteristic of steady fluid conveying in the periodical partially viscoelastic composite pipeline was studied by Zhou *et al*. (2017). Duc *et al*. (2017a, b, c)

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studied thermal and mechanical stability of a functionally graded composite truncated conical shell, plates and double curved shallow shells reinforced by carbon nanotube fibers. Based on Reddy's third-order shear deformation plate theory, the nonlinear dynamic response and vibration of imperfect functionally graded carbon nanotube-reinforced composite plates was analyzed by Thanh *et al*. (2017). Duc *et al*. (2018) presented the first analytical approach to investigate the nonlinear dynamic response and vibration of imperfect rectangular nanocompsite multilayer organic solar cell subjected to mechanical loads using the classical plate theory.

Non-linear vibration of laminated composite circular cylindrical shells using Donnell's shell theory and Incremental Harmonic Balance (IHB) method was analyzed by Dey and Ramachandram (2017). The influences of nanoparticles on dynamic strength of ultra-high performance concrete were tested by Su *et al*. (2016). Jafarian Arani and Kolahchi (2016) studied buckling analysis of concrete columns reinforced with carbon nanotubes by using Euler-Bernoulli and Timoshenko beam models. Buckling of concrete columns retrofitted with Nano-Fiber Reinforced Polymer was investigated by Safari Bilouei *et al*. (2016). Inozemtcev *et al*. (2017) improved the properties of lightweight concrete with hollow microspheres with the nanoscale modifier. Mathematical modeling of concrete pipes reinforced with CNTs conveying fluid for vibration and stability analysis was done by Zamani Nouri (2017). Vibration of Silica nanoparticles-reinforced concrete beams considering agglomeration effects was considered by Shokravi (2017). Also, Rabani Bidgoli and Saeidifar (2017) studied time-dependent buckling of SiO2 nanoparticles reinforced concrete columns exposed to fire. A hybrid pipe-shell element based numerical model programmed by INP code supported by ABAQUS solver was proposed by Liu *et al*. (2017) to explore the strain performance of buried X80 steel pipeline under reverse fault displacement. Recently, Seismic response of SiO2 nanoparticles-reinforced concrete surface pipes was investigated by Motezaker and Kolahchi (2017). Dynamic response of the horizontal concrete beam subjected to seismic ground excitation was investigated by Mohammadian *et al*. (2017). Sharifi *et al*. (2018) studied the dynamic analysis of a concrete column reinforced with titanium dioxide (TiO_2) nanoparticles under earthquake load.

In this paper, dynamic response of submerged concrete pipe conveying fluid subjected to earthquake load is studied. The structure is simulated by classical shell model. The effects of internal and external fluid are considered. Based on Navier and Newmark methods, the dynamic deflection of the structure is calculated. The effects of different parameters such as mode number, thickness to radius ratios, length to radius ratios, internal and external fluid are discussed on the seismic response of the structure.

2. Formulation

In Fig. 1, a concrete pipe with length L, radius R and thickness of h is shown. The pipe is subjected to forces of internal fluid, external fluid and earthquake loads.

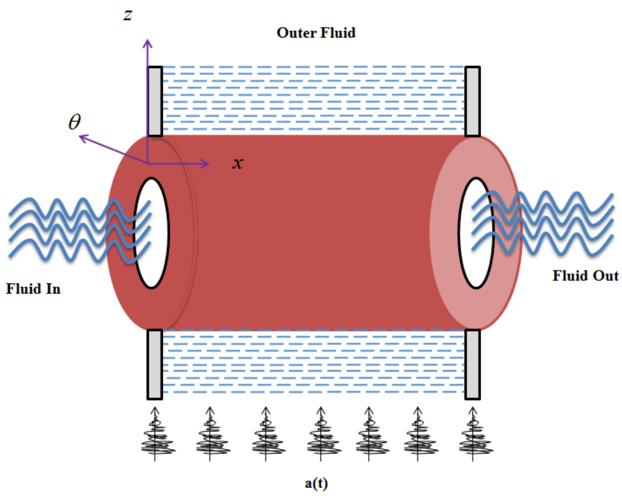

Fig. 1 Schematic of underwater concrete pipe conveying fluid

There are many new theories for modeling of different structures. Some of the new theories have been used by Tounsi and co-authors (Bessaim 2013, Bouderba 2013, Belabed 2014, Ait Amar Meziane 2014, Zidi 2014, Hamidi 2015, Bourada 2015, Bousahla *et al* 2016a, b, Beldjelili 2016, Boukhari 2016, Draiche 2016, Bellifa 2015, Attia 2015, Mahi 2015, Ait Yahia 2015, Bennoun 2016, El-Haina 2017, Menasria 2017, Chikh 2017). Based on classical shell mode, we have (Brush and Almroth 1975)

$$u_1(x,\theta,z,t) = u(x,\theta,t) - z\frac{\partial w(x,\theta,t)}{\partial x}, \tag{1}$$

$$u_2(x,\theta,z,t) = v(x,\theta,t) - \frac{z}{R}\frac{\partial w(x,\theta,t)}{\partial \theta}, \tag{2}$$

$$u_3(x,\theta,z,t) = w(x,\theta,t), \tag{3}$$

where (u_1, u_2, u_3) denotes the displacement components at an arbitrary point (x,θ,z) in the shell, and (u,v,w) are the displacement components of the middle surface of the shell in the axial, circumferential and radial directions, respectively. The strain relations can be written as

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w}{\partial x^2}, \tag{4}$$

$$\varepsilon_{\theta\theta} = \frac{\partial v}{R\partial\theta} + \frac{w}{R} - \frac{z}{R^2}\frac{\partial^2 w}{\partial\theta^2}, \tag{5}$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u}{R\partial\theta} + \frac{\partial v}{\partial x}\right) - z\frac{\partial^2 w}{R\partial x\partial\theta}, \tag{6}$$

The stress-strain relations of the structure are

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{\theta\theta}\\ \tau_{x\theta}\end{bmatrix} = \begin{bmatrix}C_{11} & C_{12} & 0\\ C_{21} & C_{22} & 0\\ 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{\theta\theta}\\ \varepsilon_{x\theta}\end{bmatrix}, \tag{7}$$

where C_{ij} are elastic constants.

The strain energy can be written as

$$U = \int_V \left(\sigma_{xx}\varepsilon_{xx} + \sigma_{\theta\theta}\varepsilon_{\theta\theta} + \sigma_{x\theta}\gamma_{x\theta}\right) dV, \tag{10}$$

By substituting Eqs. (4)- (6) into (10) yields

$$\begin{aligned} U = \int_A \Bigg(& N_x \left(\frac{\partial u}{\partial x} + 0.5\left(\frac{\partial w}{\partial x}\right)^2 \right) - M_x \frac{\partial^2 w}{\partial x^2} \\ & + N_\theta \left(\frac{\partial v}{R\partial\theta} + \frac{w}{R} + 0.5\left(\frac{\partial w}{R\partial\theta}\right)^2 \right) - M_\theta \frac{\partial^2 w}{R^2\partial\theta^2} \\ & + N_{x\theta} \left(\frac{\partial u}{R\partial\theta} + \frac{\partial v}{\partial x} + \frac{\partial w}{R\partial\theta}\frac{\partial w}{\partial x} \right) - 2M_{x\theta} \frac{\partial^2 w}{R\,\partial\theta\,\partial x} \Bigg) dA \end{aligned} \tag{11}$$

where

$$\begin{Bmatrix} N_x \\ N_\theta \\ N_{x\theta} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_\theta \\ \tau_{x\theta} \end{Bmatrix} dz, \tag{12}$$

$$\begin{Bmatrix} M_x \\ M_\theta \\ M_{x\theta} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_\theta \\ \tau_{x\theta} \end{Bmatrix} z dz, \tag{13}$$

The kinetic energy may be expressed as

$$K = \frac{\rho}{2}\int_v \left((\frac{\partial u_1}{\partial t})^2 + (\frac{\partial u_2}{\partial t})^2 + (\frac{\partial u_3}{\partial t})^2 \right) dV, \tag{14}$$

By substituting Eqs. (1)-(3) into (14) and defining the following term

$$\begin{Bmatrix} h \\ 0 \\ \dfrac{h^3}{12} \end{Bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} 1 \\ z \\ z^2 \end{bmatrix} dz, \tag{15}$$

We have

$$K = \int \left(\begin{aligned} & \frac{\rho}{2}\left(\frac{h^3}{12}\left((\frac{\partial^2 u}{\partial t\,\partial x})^2 + (\frac{\partial^2 w}{\partial t\,\partial\theta})^2 \right) \right. \\ & \left. + h\left((\frac{\partial u}{\partial t})^2 + (\frac{\partial v}{\partial t})^2 + (\frac{\partial w}{\partial t})^2 \right) \right) dA \end{aligned} \right). \tag{16}$$

The external work due to internal fluid is (Zamani Nouri 2017)

$$\begin{aligned} W_f = \int (F_{fluid}) w dA = \int \Bigg(& -\rho_f \left(\frac{\partial^2 w}{\partial t^2} + 2v_x \frac{\partial^2 w}{\partial x\,\partial t} + v_x^2 \frac{\partial^2 w}{\partial x^2} \right) \\ & + \mu\left(\frac{\partial^3 w}{\partial x^2\,\partial t} + \frac{\partial^3 w}{R^2\,\partial\theta^2\,\partial t} + v_x \left(\frac{\partial^3 w}{\partial x^3} + \frac{\partial^3 w}{R^2\,\partial\theta^2\,\partial x} \right) \right) \Bigg) w dA, \end{aligned} \tag{17}$$

Also, the external work due to outside fluid can be obtained as follows (Ghavanloo and Fazelzadeh 2011)

$$F_v = -\alpha \frac{\partial w}{\partial t}, \tag{18}$$

where

$$\alpha = \frac{2\nu_f \pi(\eta^2 - 1)}{(1-\eta^2 + (\eta^2+1)\ln\eta)} \quad and\ \eta = \frac{R_0}{R_1} \tag{19}$$

It should be noted that the parameter α is positive ($0<\eta<1$) Here, R_0 is shell outer radius and R_1 is the distance from the center line to the position where the induced viscous flow vanished. To couple the elastic deformation of the shell and the viscous flow of the external fluid, it is assumed that the surface traction of the external fluid along the interface is equal to external force exerted on the shell.

$$q = F_v \tag{20}$$

The external work due to the earthquake loads can be computed as below

$$W_s = \int \underbrace{(ma(t))}_{F_{Seismic}} w dA, \tag{21}$$

where m and $a(t)$ are the mass and the acceleration of the ground.

The governing equations of the structure are derived using the Hamilton's principle which is considered as follows

$$\int_0^t (\delta U - \delta K - \delta W) dt = 0. \tag{22}$$

Now, by applying the Hamilton's principle, three equations of motion can be derived as follows

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_{x\theta}}{R\partial\theta} = \rho h \frac{\partial^2 u}{\partial t^2}, \tag{23}$$

$$\frac{\partial N_\theta}{R\partial\theta} + \frac{\partial N_{x\theta}}{\partial x} = \rho h \frac{\partial^2 v}{\partial t^2}, \tag{24}$$

$$\begin{aligned} & \frac{\partial^2 M_x}{\partial x^2} + \frac{2\partial^2 M_{x\theta}}{R\,\partial x\,\partial\theta} + \frac{\partial^2 M_\theta}{R^2\,\partial\theta^2} - \frac{N_\theta}{R} + N_x \frac{\partial^2 w}{\partial x^2} + N_\theta \frac{\partial^2 w}{R^2\partial\theta^2} \\ & + N_{x\theta} \frac{2\partial^2 w}{R\partial x\,\partial\theta} + F_V + F_{fluid} = \rho h \frac{\partial^2 w}{\partial t^2} + F_{Seismic}, \end{aligned} \tag{25}$$

By integrating the stress-strain relations of the structure and introduced Eqs. (12)-(13), we have

$$\begin{aligned} N_x = h\Bigg(& C_{11}\left(\frac{\partial u}{\partial x} + 0.5\left(\frac{\partial w}{\partial x}\right)^2 \right) \\ & + C_{12}\left(\frac{\partial v}{R\partial\theta} + \frac{w}{R} + 0.5\left(\frac{\partial w}{R\partial\theta}\right)^2 \right) \Bigg), \end{aligned} \tag{26}$$

$$\begin{aligned} N_\theta = h\Bigg(& C_{12}\left(\frac{\partial u}{\partial x} + 0.5\left(\frac{\partial w}{\partial x}\right)^2 \right) \\ & + C_{22}\left(\frac{\partial v}{R\partial\theta} + \frac{w}{R} + 0.5\left(\frac{\partial w}{R\partial\theta}\right)^2 \right) \Bigg), \end{aligned} \tag{27}$$

$$N_{x\theta} = h\left(C_{66}\left(\frac{\partial u}{R\partial\theta} + \frac{\partial v}{\partial x} + \frac{\partial w}{R\partial\theta}\frac{\partial w}{\partial x} \right) \right), \tag{28}$$

$$M_x = \frac{h^3}{12}\left(C_{11}\left(-z\frac{\partial^2 w}{\partial x^2}\right)+C_{12}\left(-z\frac{\partial^2 w}{R^2\,\partial\theta^2}\right)\right), \tag{29}$$

$$M_\theta = \frac{h^3}{12}\left(C_{12}\left(-z\frac{\partial^2 w}{\partial x^2}_{x}\right)+C_{22}\left(-z\frac{\partial^2 w}{R^2\,\partial\theta^2}\right)\right), \tag{30}$$

$$M_{x\theta} = \frac{h^3}{12}C_{66}\left(-2z\frac{\partial^2 w}{R\,\partial\theta\,\partial x}\right). \tag{31}$$

3. Solution method

Based on Navier method, the dynamic amplitudes can be written for simply supported boundary conditions as

$$d=\begin{Bmatrix} u \\ v \\ w \end{Bmatrix}=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\begin{Bmatrix} A_1\cos(\frac{m\pi x}{a})\cos(n\theta)\cos(\omega t) \\ A_2\sin(\frac{m\pi x}{a})\sin(n\theta)\cos(\omega t) \\ A_3\sin(\frac{m\pi x}{a})\cos(n\theta)\cos(\omega t) \end{Bmatrix}, \tag{32}$$

where ω represents vibration frequency of the pipe, m and n are half axial and circumferential wave numbers, respectively. Substituting Eq. (32) f into motion equations yields

$$[K][d]+[C]\omega+[M]\omega^2=0, \tag{33}$$

where $[K]$, $[C]$ and $[M]$ are stiffness, damp and mass matrixes, respectively; $[d]=[A_1,A_2,A_3]$ is the dynamic vector. Finally, using Newmark method, we have (Simsek 2010)

$$K^*(d_{i+1})=Q_{i+1}, \tag{34}$$

$K^*(d_{i+1})$ and Q_{i+1} are the effective stiffness matrix and the effective load vector in time of i+1 which can be presented as

$$\begin{aligned} K^*(d_{i+1}) &= K_L + K_{NL}(d_{i+1}) \\ &+\alpha_0 M + \alpha_1 C, \end{aligned} \tag{35}$$

$$\begin{aligned} Q^*_{i+1} &= Q_{i+1}+M\left(\alpha_0 d_i+\alpha_2\dot{d}_i+\alpha_3\ddot{d}_i\right) \\ &+C\left(\alpha_1 d_i+\alpha_4\dot{d}_i+\alpha_5\ddot{d}_i\right), \end{aligned} \tag{36}$$

and

$$\begin{aligned} &\alpha_0=\frac{1}{\chi\Delta t^2}, \quad \alpha_1=\frac{\gamma}{\chi\Delta t}, \quad \alpha_2=\frac{1}{\chi\Delta t}, \\ &\alpha_3=\frac{1}{2\chi}-1, \quad \alpha_4=\frac{\gamma}{\chi}-1, \\ &\alpha_5=\frac{\Delta t}{2}\left(\frac{\gamma}{\chi}-2\right), \quad \alpha_6=\Delta t\,(1-\gamma), \\ &\alpha_7=\Delta t\,\gamma, \gamma=0.5, \chi=0.25 \end{aligned} \tag{37}$$

Eq. (33) is solved at any time step and modified velocity and acceleration vectors are calculated as follows

$$\ddot{d}_{i+1}=\alpha_0(d_{i+1}-d_i)-\alpha_2\dot{d}_i-\alpha_3\ddot{d}_i, \tag{38}$$

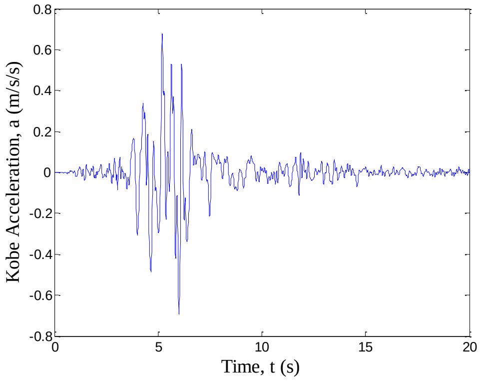

Fig. 2 The acceleration of Kobe Earthquake

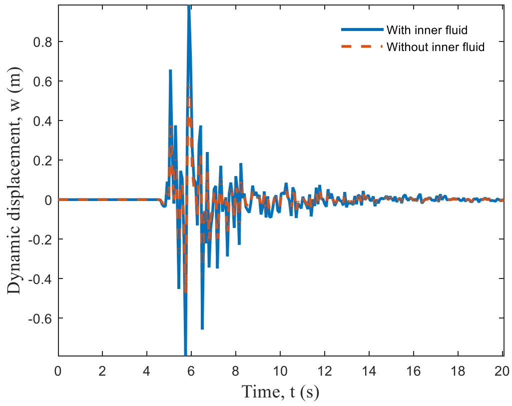

Fig. 3 The effect of internal fluid on the dynamic displacement of the structure

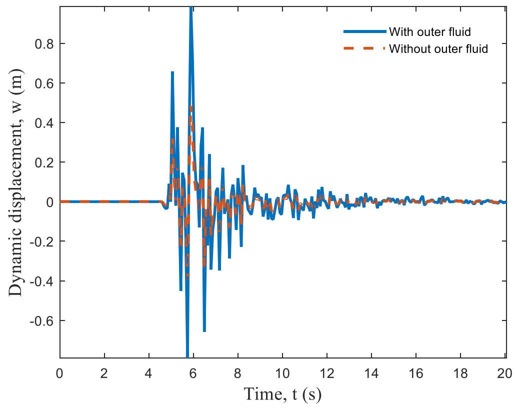

Fig. 4 The effect of external fluid on the dynamic displacement of the structure

$$\dot{d}_{i+1}=\dot{d}_i+\alpha_6\ddot{d}_i+\alpha_7\ddot{d}_{i+1}, \tag{39}$$

these modified velocity and acceleration in Eqs. (38) and (39) are considered in next time step and all these procedures mentioned above are repeated.

4. Numerical results

A concrete pipe with Young's modulus of E=20 GPa and Poisson's ratio of 0.3 is considered. The location of earth quake is Kobe with acceleration shown in Fig. 2.

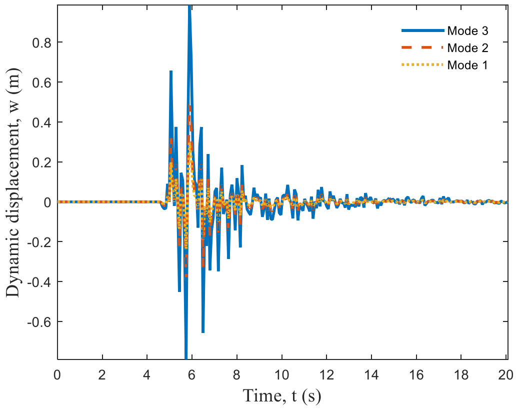

Fig. 5 The effect of mode number on the dynamic displacement of the structure

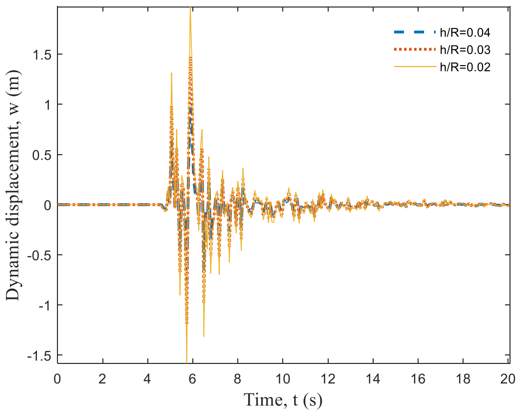

Fig. 6 The effect of thickness to radius ratio on the dynamic displacement of the structure

Figs. 3 and 4 show the effect of internal and external fluid on the dynamic deflection of the structure, respectively.

It can be found that considering internal and external fluid, the dynamic deflection increases since the with assuming internal and external fluid, the forces of the pipe increases. The changes of deflection versus time for various mode numbers are shown in Fig. 5. It can be seen that with increasing the mode numbers, the dynamic deflection increases.

Figs. 6 and 7 indicate the effect of the thickness to radius ratio and length to thickness ratio on the concrete pipe on the dynamic deflection versus time. As can be seen, by increasing the thickness to radius ratio and decreasing the length to thickness ratio, the dynamic deflection of system decreases. It is because the structure becomes stiffer with increasing the thickness to radius ratio and decreasing the length to thickness ratio.

5. Conclusions

Dynamic analysis of submerged concrete pipe conveying fluid subjected to earthquake load was studied. The structure was simulated by classical shell model. Using energy method and Hamilton's principle, the motion

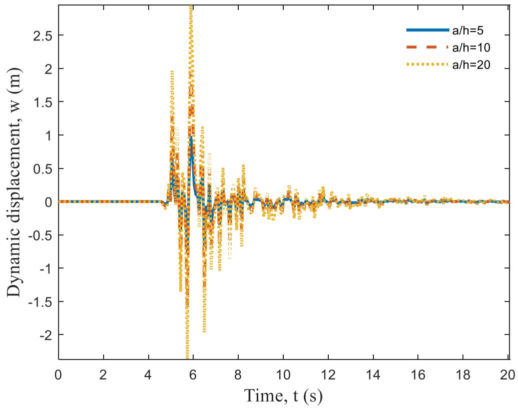

Fig. 7 The effect of length to thickness ratio on the dynamic displacement of the structure

equations were derived. Applying Navier and Newmark methods, the dynamic deflection of the structure was obtained and the effects of mode number, internal and external fluid and geometrical parameters of the pipes are considered. It can be found that considering internal and external fluid, the dynamic deflection increases. In addition, by increasing the thickness to radius ratio and decreasing the length to thickness ratio, the dynamic deflection of system decreases. Furthermore, with increasing the mode numbers, the dynamic deflection increases.

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