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Dynamic response of nanoparticle-water pipes buried in the soil subjected to far-fault earthquake using numerical method

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ABSTRACT

Presenting a mathematical model for seismic response of the water pipes buried in the soil is the main contribution of this study. The structure is subjected to far-fault earthquake load. The pipe is conveying water mixed by nanoparticles where the Navier–Stokes equation is used for considering the interaction of fluid and pipe. The surrounding soil medium is simulated by spring elements. Utilizing the cylindrical shell element, the pipe is modeled mathematically and the motion equation of the structure is derived by Hamilton's principal. Based on Galerkin and Newmark methods, the dynamic deflection of the structure is calculated. The effects of different parameters such as fluid velocity, soil medium, volume percent of nanoparticle in fluid, boundary condition and geometrical parameters of the pipe are shown on the dynamic deflection of the structure. Numerical results indicate that water pipe buried in the solid has lower dynamic deflection with respect to the pipe without soil foundation.

1. Introduction

Mathematical modeling of the structure is one of the interest subjects among the researchers recently. Among the structures, the buried pipes in the soil are one of the important subjects which is not modeled yet mathematically for seismic analysis of them. This is the main motivation of the authors to present this paper. Hence, we investigated dynamic response of the pipes buried in the soil conveying water mixed by nanoparticles subjected to earthquake load using numerical methods and computer programs [1-5].

In the field of seismic response of structures, Ai-wen et al. [6] presented a new shell finite element method (FEM) model with an equivalent boundary for estimating the response of a buried pipeline under large fault movement. Vazouras et al. [7] investigated the mechanical behavior of buried steel pipelines, crossing an active strike-slip tectonic fault. The fault was normal to the pipeline direction and moves in the horizontal direction, causing stress and deformation in the pipeline. A 3-D soil-pipe nonlinear finite element model with contact element was suggested by Zhao et al. [8] and the influences of the rupture mode, thickness and rigidity of overlying soil on the response of buried pipeline are analyzed. A fuzzy-rule-based semi-active control of building frames using semi-active variable orifice dampers (VODs) was presented by Ghaffarzadeh et al. [9]. Additionally, the consequences of well-known characteristics of near-fault ground motions, forward directivity and fling step, on the seismic response control was investigated. Using the spectrum method and theory of one-dimensional beam units, CAESAR II was used by Wy et al. [10] to perform a dynamic earthquake analysis for an oil pipeline in the XX earthquake disaster area. Shell element model of four nodes was used by Xue et al. [11] to simulate the buried pipeline, and the interaction between soil and pipeline was simulated by nonlinear soil spring, seismic response of buried variable-diameter pipeline under strike slip fault was analyzed by using finite element software ADINA. Behavior of a buried pipeline subjected to reverse fault displacement in the rock stratum was presented by Zhang et al. [12]. Effects of internal pressure, wall thickness, fault displacement and burial depth on the buckling mode and the axial strain of the buried pipeline are discussed. Numerical models using a FEM were developed by Naeini et al. [13] to analyze the buried High-Density Polyethylene (HDPE) pipelines subjected to the normal fault motions. Multi-hazard failure probability analysis of gas pipelines for earthquake shaking, ground failure and fire following earthquake was presented by Omidvar and Karimi Kivi [14]. To analyze buried pipelines subjected to reverse faults, a beam-shell coupling scheme was proposed by Xu and Lin [15] based on the Vector Form Intrinsic Finite Element (VFIFE or V-5) method. A finite-element model was established by Liu et al. [16] to evaluate the seismic responses of buried pipe networks. In the model, pipes were simulated as beams on elastic foundation, the joints of the segmented pipes were modeled by axial

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and rotational springs, and the pipe–soil interactions are simulated by springs. Safety of buried steel natural gas pipelines under earthquake-induced ground shaking was reviewed by Psyrras and Sextos [17].

Mathematical modeling of the structure for dynamic analysis has not been presented by the above works. In this regard, vibration and stability of concrete pipes reinforced with carbon nanotubes (CNTs) and Fe_2O_3 nanoparticles conveying fluid were presented by Zamani Nouri [18,19]. Vibration of nanoparticles reinforced-concrete pipes surrounded by soil medium and filled by fluid was presented by Zamani Nouri [20]. The nanoparticles were silica where the effective material properties of the structure were obtained by Mori–Tanaka model considering agglomeration of nanoparticles. In another work by Zamani Nouri [21] the seismic response of the fluid-conveyed concrete pipes surrounded by soil medium was presented.

With respect to the cited works, dynamic analysis of water pipes buried in the soil conveying fluid-nanoparticles subjected to far-fault earthquake has not been reported by researchers. In this paper, based on a mathematical model, the water pipe is simulated and the force of the fluid is calculated by Navier-Stokes equation. The soil medium is simulated by spring element. Applying Galerkin and Newmark methods, the dynamic deflection of the structure is obtained. The effects of the fluid velocity, soil medium, volume percent of nanoparticle in fluid, geometrical parameters of the pipe and boundary condition on the dynamic displacement of the water pipe are disused in detail.

2. Mathematical modeling

A schematic figure of this work is shown in Fig. 1 where a buried pipe in the soil conveying water mixed by nanoparticles subjected to earthquake load is presented. The pipe has length of L, radius of R and thickness of h.

2.1. Cylindrical shell model

Based on the refined higher order shear deformation theory, the displacement field can be written as [22]

$$U(x,\theta,z,t) = u(x,\theta,t) - z\frac{\partial}{\partial x}w_b(x,\theta,t) + z\left[\frac{1}{4} - \frac{5}{3}\left(\frac{z}{h}\right)^2\right]\frac{\partial}{\partial x}w_s(x,\theta,t), \quad (1)$$

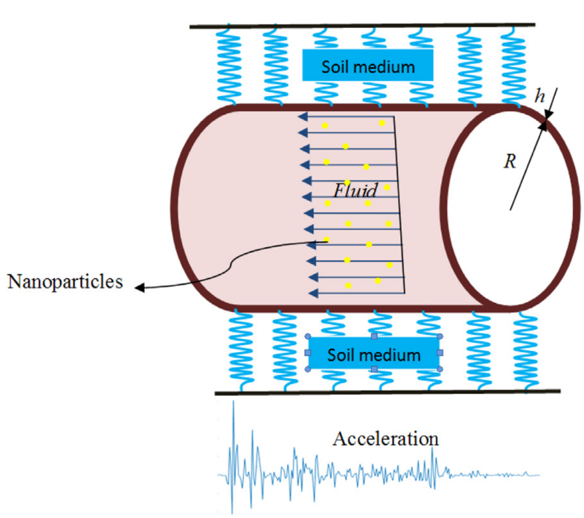

Fig. 1. A buried pipe in the soil conveying water mixed by nanoparticles subjected to earthquake load.

$$V(x,\theta,z,t) = v(x,\theta,t) - z\frac{\partial}{R\partial\theta}w_b(x,\theta,t) + z\left[\frac{1}{4} - \frac{5}{3}\left(\frac{z}{h}\right)^2\right]\frac{\partial}{R\partial\theta}w_s(x,\theta,t), \quad (2)$$

$$W(x,\theta,z,t) = w_b(x,\theta,t) + w_s(x,\theta,t), \quad (3)$$

where (u, v) are the displacement of a material point at (x, θ) on the mid-plane (i.e. $z = 0$); w_b and w_s are transverse bending and shear deflections, respectively. The strain-displacement relations can be obtained as

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w_b}{\partial x^2} - f\frac{\partial^2 w_s}{\partial x^2}, \quad (4)$$

$$\varepsilon_{\theta\theta} = \frac{\partial v}{\partial x} + \frac{w_b}{R} + \frac{w_s}{R} - z\frac{\partial^2 w_b}{R^2\partial\theta^2} - f\frac{\partial^2 w_s}{R^2\partial\theta^2}, \quad (5)$$

$$\gamma_{x\theta} = \frac{\partial v}{\partial x} + \frac{\partial u}{R\partial\theta} - 2z\frac{\partial^2 w_b}{R\partial x\partial\theta} - 2f\frac{\partial^2 w_s}{R\partial x\partial\theta}, \quad (6)$$

$$\gamma_{xz} = g\frac{\partial w_s}{\partial x}, \quad (7)$$

$$\gamma_{\theta z} = g\frac{\partial w_s}{R\partial\theta}, \quad (8)$$

where $f = -\frac{z}{4} + \frac{5}{3}z\left(\frac{z}{h}\right)^2$ and $g = \frac{5}{4} - 5\left(\frac{z}{h}\right)^2$.

2.2. Constitutive equations

The linear constitutive relations for the structure can be expressed as

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{\theta\theta}\\ \sigma_{\theta z}\\ \sigma_{zx}\\ \sigma_{x\theta}\end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 & 0 & 0\\ C_{21} & C_{22} & 0 & 0 & 0\\ 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{\theta\theta}\\ \gamma_{\theta z}\\ \gamma_{xz}\\ \gamma_{x\theta}\end{Bmatrix}, \quad (9)$$

where C_{ij} $(i, j = 1, 2, \ldots, 6)$ are elastic constants.

2.3. Energy method

For deriving the motion equations, the energy method is used. In this method, the potential and kinetic energies of the structure as well as work done by soil medium and fluid should be written. The strain energy of the structure can be written as

$$U = \frac{1}{2}\int_{\Omega_0}\left(N_{xx}\frac{\partial u}{\partial x} + N_{\theta\theta}\left(\frac{\partial v}{\partial\theta} + \frac{w}{R}\right) + Q_\theta\frac{\partial w_s}{R\partial\theta} + Q_x\frac{\partial w_s}{\partial x} + N_{x\theta}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{R\partial\theta}\right) + M_{xx}^b\frac{\partial^2 w_b}{\partial x^2} + M_{\theta\theta}^b\frac{\partial^2 w_b}{R^2\partial\theta^2} + M_{x\theta}^b\frac{\partial^2 w_b}{R\partial x\partial\theta} + M_{xx}^s\frac{\partial^2 w_s}{\partial x^2} + M_{\theta\theta}^s\frac{\partial^2 w_s}{R^2\partial\theta^2} + M_{x\theta}^s\frac{\partial^2 w_s}{R\partial x\partial\theta}\right)dxRd\theta, \quad (10)$$

where the stress resultant-displacement relations can be defined as

$$\begin{Bmatrix}N_i\\ M_i^b\\ M_i^s\end{Bmatrix} = \int_{-h/2}^{h/2}\begin{bmatrix}1\\ z\\ f\end{bmatrix}\sigma_i dz, \quad (i = xx, \theta\theta, x\theta) \quad (11)$$

$$Q_i = \int_{-h/2}^{h/2} g\sigma_i dz, \quad (i = xz, \theta z) \quad (12)$$

The kinetic energy of the pipe may be written as