Vol. 14, No. 40, Fall 2024, Pages 65-78

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

Research article

Analysis of the nanoparticles' effect on the stability of buried porous concrete pipes containing fluid flow using the numerical method

Mahmood Rabani Bidgoli[1]*

1- **Dept. of Civil Engineering, Jaseb Branch, Islamic Azad University, Jaseb, Iran**

(Received: *January 2024* , Accepted: *May 2024*)

DOI: *10.22034/ANM.2024.21132.1621*

Keywords

Buried concrete pipe
Navier-Stokes equation
Silica nanoparticles
Porosity
High-order shear theory

English Extended Abstract

Summary

Considering the widespread applications of perforated concrete pipes containing fluid flow in civil engineering, providing a suitable mathematical model for analyzing their stability and dynamic performance is essential. In this regard, a buried concrete pipe is formulated, taking into account the permeability of concrete materials and the surrounding soil, reinforced with silica nanoparticles. The structure is modeled using cylindrical shell elements and by employing the theory of elasticity. To calculate the force induced by the fluid flow inside the pipe, the Navier-Stokes equation is utilized. The influence of nanoparticles in the pipe is modeled using a mixing model, and the soil bed is simulated using vertical springs and shear layers. Finally, by applying Hamilton's principle, the governing equations of the structure are extracted. The Bezier finite element method is employed for structural analysis, and the effects of parameters such as the volume fraction of nanoparticles, concrete permeability, soil bed, fluid inside the pipe, and geometric parameters are investigated. The results of the analysis indicate that with an increase in the volume fraction of nanoparticles from zero to 3%, the maximum frequency and critical fluid velocity increase by 35% and 38%, respectively. Additionally, as the concrete permeability increases from zero to 6.0, the maximum frequency and critical fluid velocity decrease by 26% and 18%, respectively. These findings can contribute to the improvement and optimization of the design of concrete pipes containing fluid flow, enhancing our understanding of the dynamic behavior of these structures.

Introduction

Buried porous concrete pipes, which are used with fluid flow underground or in porous environments, are one of the vital innovations in subsurface structures. However, the stability and optimal performance of these pipes in the face of fluid flow are related to multiple issues including chocolate change, corrosion, and structural resistance reduction. In recent years, with the advancements in the field of nanotechnology, adding nanoparticles to the concrete environment to improve various properties has become one of the strategies to study and improve the stability of buried porous concrete pipes.

Cylindrical shells containing fluid flow are one of the most important fields in structural engineering, which has become a subject of attention in the field of structural engineering research due to the wide variety of applications. These structures are used as cylindrically shaped thin shells in various architecture and industries, including tanks, pipes, storage tanks, and oil structures. The analysis and design of these types of shells are of particular importance because their mechanical and dynamic characteristics are affected by fluid flow, external loads, and variable environmental conditions. This article deals with the study of cylindrical shells containing fluid flow and uses analytical and numerical methods to improve the understanding and

*Corresponding author: E-mail: *m.rabanibidgoli@yahoo.com*

Vol. 14, No. 40, Fall 2024, Pages 65-78

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

control of the performance of these structures. Considering the importance of these structures in industry and construction, it is very important to investigate the effect of fluid flow on the mechanical and dynamic characteristics of cylindrical shells, and the results of this research can help to optimize the design and use of these structures in practice. In the field of structural mechanics and fluid-structure interaction, the dynamic behavior of pipes containing fluid has been considered. An accurate understanding of the complex dynamics of these structures is crucial for various engineering applications. This introduction provides an overview of key research that has contributed to the understanding of the dynamic response of fluid-bearing pipes under varied loading conditions. Sadeghi and Karimi Dana [1] presented a study on the dynamic behavior of a tube containing fluid under the influence of moving mass. From the finite element method and a state space approach, they investigated the complex interactions between fluid flow and structural response and shed light on the effects of dynamic loading. Mirramzani et al. [2] investigated the non-local vibrations of shell-type tubes containing carbon nanotubes governing the internal and external flow. Their study considered sliding conditions and elaborated on the vibrational characteristics of fluid-carrying carbon nanotube-based structures. This work helps to understand the combined effects of internal and external flows on the vibration behavior of the shells of such structures. Sheng and Ng [3] characterized the nonlinear response of cylindrical shells containing fluid with variable properties in combination with mechanical and thermal loading. This study investigated the behavior of shells with variable properties and helped to understand the effects of functional materials on the response of cylindrical structures containing fluid. Dormos et al. compared and analyzed the free vibration of the pipe with composite materials containing fluid located on the soil with a two-parameter model [4]. Ma et al. [5] analyzed the stability of a pipe containing fluid located on a two-parameter foundation with elastic support boundary conditions. The vibration isolation analysis of the pipe containing piezoelectric fluid consisting of layered composite materials reinforced with fibers was performed by Liang et al [6]. They concluded that the use of a piezoelectric feedback control system increases the natural frequency and stability of the pipe containing fluid. to be Fu et al. [7] analyzed the dynamic behavior of axial functional graduated tubes containing liquid-gas two-phase flow. A three-dimensional analysis of vibration in curved pipes containing fluid with curved fluid elements and straight pipe was done by Ven et al. [8].

Methodology and Approaches

Figure (1) shows a porous concrete pipe reinforced with nanoparticles buried in a soil bed containing fluid flow. The length of the concrete pipe is L, the average radius, and the thickness of the pipe. The soil bed is modeled with Winkler vertical springs and a Pasternak shear layer.

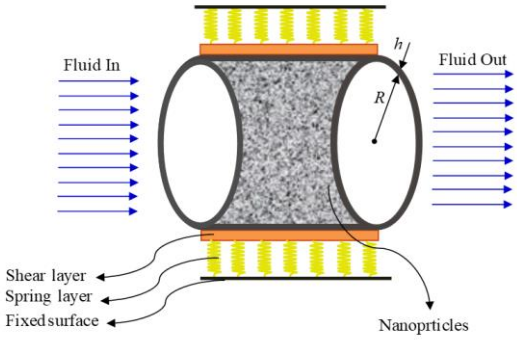

Fig. 1. Schematic of buried porous concrete pipe reinforced with nanoparticles containing fluid flow

According to the high-order shear deformation theory, the stress-strain relations are in the following form:

$$\sigma_{xx}=C_{11}\left[\frac{\partial U}{\partial x}+\frac{1}{2}\left(\frac{\partial W}{\partial x}\right)^2+z\frac{\partial \phi_x}{\partial x}+z^3\frac{-4}{3h^2}\left(\frac{\partial \phi_x}{\partial x}+\frac{\partial^2 W}{\partial x^2}\right)\right]+C_{12}\left[\frac{\partial V}{R\partial\theta}+\frac{W}{R}+\frac{1}{2}\left(\frac{\partial W}{R\partial\theta}\right)^2+z\frac{\partial\phi_\theta}{R\partial\theta}+z^3\frac{-4}{3h^2}\left(\frac{\partial\phi_\theta}{R\partial\theta}+\frac{\partial^2 W}{R^2\partial\theta^2}\right)\right], \tag{1}$$

$$\sigma_{\theta\theta}=C_{21}\left[\frac{\partial U}{\partial x}+\frac{1}{2}\left(\frac{\partial W}{\partial x}\right)^2+z\frac{\partial \phi_x}{\partial x}+z^3\frac{-4}{3h^2}\left(\frac{\partial \phi_x}{\partial x}+\frac{\partial^2 W}{\partial x^2}\right)\right]+C_{22}\left[\frac{\partial V}{R\partial\theta}+\frac{W}{R}+\frac{1}{2}\left(\frac{\partial W}{R\partial\theta}\right)^2+z\frac{\partial\phi_\theta}{R\partial\theta}+z^3\frac{-4}{3h^2}\left(\frac{\partial\phi_\theta}{R\partial\theta}+\frac{\partial^2 W}{R^2\partial\theta^2}\right)\right], \tag{2}$$

Vol. 14, No. 40, Fall 2024, Pages 65-78

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

$$\sigma_{x\theta}=C_{66}\left[\frac{\partial V}{\partial x}+\frac{\partial U}{R\partial\theta}+\frac{\partial W}{\partial x}\frac{\partial W}{R\partial\theta}+z\left(\frac{\partial\phi_x}{R\partial\theta}+\frac{\partial\phi_\theta}{\partial x}\right)-\frac{4z^2}{h^2}\left(\phi_x+\frac{\partial W}{\partial x}\right)-\frac{4z^3}{3h^2}\left(\frac{\partial\phi_\theta}{\partial x}+\frac{\partial\phi_x}{R\partial\theta}+2\frac{\partial^2 W}{R\partial x\,\partial\theta}\right)\right], \tag{3}$$

$$\sigma_{xz}=C_{55}\left[\phi_x+\frac{\partial W}{\partial x}-\frac{4z^2}{h^2}\left(\varphi_x+\frac{\partial W}{\partial x}\right)\right], \tag{4}$$

$$\sigma_{\theta z}=C_{44}\left[\phi_\theta+\frac{\partial W}{R\partial\theta}-\frac{4z^2}{h^2}\left(\phi_\theta+\frac{\partial W}{R\partial\theta}\right)\right]. \tag{5}$$

where C_{ij} is the elastic constant of the nanoparticle-reinforced tube. Considering that the concrete pipe is porous, therefore the elastic constants and the density of the pipe change according to the following relations:

$$C_{ij}(z)=C_{ijc}\left[1-e_0\psi(z)\right], \tag{6}$$

$$\rho(z)=\rho_c\left[1-e_m\psi(z)\right], \tag{7}$$

where ρ_c and C_{ijc} are the maximum density and elastic constants, respectively, e_0 and $e_m=1-\sqrt{1-e_0}$ are the porosity constants in the structure. Considering that the concrete pipe is reinforced with silica nanoparticles, therefore, the mixing model is used to calculate the equivalent properties of the structure. According to the mixing law, we have:

$$C_{ijc}=\left(1-V_N\right)C_{ijP}+V_N C_{ijN}, \tag{8}$$

$$\rho_c=\left(1-V_N\right)\rho_P+V_N\rho_N, \tag{9}$$

where P and N indices are for tube and nanoparticles, respectively, and VN indicates the volume percentage of nanoparticles.
Hamilton's principle is used to obtain the governing equations of the structure. Hamilton's principle is:

$$\int_0^t(\delta U-\delta K-\delta W_F-\delta W_S)dt=0. \tag{10}$$

Now, with the help of the finite element Bezier and the eigenvalue method, the real and imaginary part of the frequency can be calculated and the unstable velocity of the structure can be determined.

Results and Conclusions

Figures (2) and (3) respectively show the influence of the volume percentage of silica nanoparticles on the dimensionless frequency (imaginary part of the response) and damping (real part of the response) of the tube against the dimensionless fluid velocity. These graphs clearly show that the higher the volume percentage of silica nanoparticles, the higher the frequency and critical velocity of the fluid, because the rigidity of the structure increases with the addition of nanoparticles. For example, by increasing the volume percentage of nanoparticles from zero to 3%, the maximum frequency and critical velocity of the fluid increase by 35% and 38%, respectively.

*Corresponding author: E-mail: m.rabanibidgoli@yahoo.com

Vol. 14, No. 40, Fall 2024, Pages 65-78

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

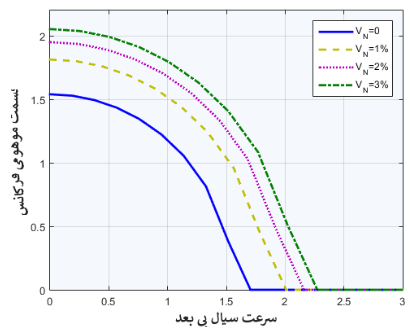

Fig. 2. The effect of the volume percentage of silica nanoparticles on the imaginary part of the dimensionless frequency against the dimensionless fluid velocity

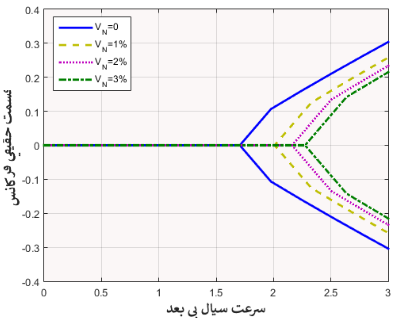

Fig. 3. The effect of the volume percentage of silica nanoparticles on the real part of the dimensionless frequency against the dimensionless fluid velocity

Figs. (4) and (5) depict the effect of concrete porosity on the imaginary and real part of the structure's frequency with changes in the dimensionless fluid velocity. As it is clear, considering the porosity leads to the reduction of the stiffness of the structure, and the maximum frequency and the critical velocity of the fluid are also reduced. This issue is particularly important because porosity is continuously present in concrete pipe structures. For example, with the increase of concrete porosity from zero to 0.6, the maximum frequency and critical velocity of the fluid decrease by 26% and 18%, respectively. These results clearly show the significant effect of porosity on the dynamic characteristics of the structure and how it reacts to changes in fluid velocity.

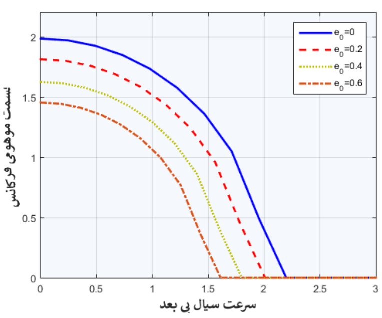

Fig. 4. The effect of the porosity on the imaginary part of the dimensionless frequency against the dimensionless fluid velocity

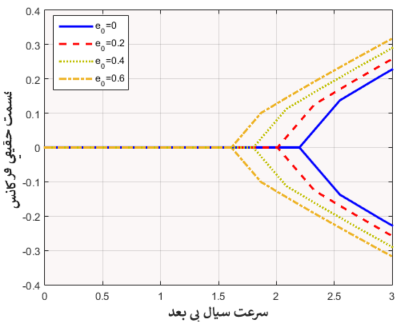

Fig. 5. The effect of the porosity on the real part of the dimensionless frequency against the dimensionless fluid velocity

Conclusions

Instability analysis of buried porous concrete pipes is investigated in this article. The tube is reinforced with nanoparticles and modeled with a high-order cylindrical shell model. The equivalent properties of the pipe were calculated using the law of mixing, and the energy method and Hamilton's principle were used to obtain the governing equations of the system. Using Bezier's finite element numerical method, the equations of motion were analyzed and the critical velocity of the fluid was obtained. The results showed:

- By increasing the volume percentage of nanoparticles from zero to 3%, the maximum frequency and critical velocity of the fluid increases by 35% and 38%, respectively.
- With the increase of concrete porosity from zero to 0.6, the maximum frequency and critical velocity of the fluid decrease by 26% and 18%, respectively. These results clearly show the significant effect of porosity on the dynamic characteristics of the structure and how it reacts to changes in fluid velocity.
- The presence of soil around the pipe increases the frequency of the structure by 21% and the critical velocity of the fluid by 29%.

Vol. 14, No. 40, Fall 2024, Pages 65-78

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

References

[1] Morteza H. Sadeghi, Mohammad H. Karimi-Dona, Dynamic behavior of afluid conveying pipe subjected to a moving sprung masse An FEM-state space approach, International Journal of Pressure Vessels and Piping 88 (2011) 123e131.

[2] Mehran Mirramezani, Hamid Reza Mirdamadi, Mostafa Ghayour, Nonlocal vibrations of shell-type CNT conveying simultaneous internal and external flows by considering slip condition, Comput. Methods Appl. Mech. Engrg. 272 (2014) 100–120.

[3] G.G. Sheng, X. Wang, Nonlinear response of fluid-conveying functionally graded cylindrical shells subjected to mechanical and thermal loading conditions, Composite Structures 168 (2017) 675–684.

[4] Durmus, D., Balkaya, M., Kaya, M.O. 2021. Comparison of the free vibration analysis of a fluid-conveying hybrid pipe resting on different two-parameter elastic soils. Int. J. Press. Vessel. 193, 104479.

[5] Ma, Y., You, Y., Chen, K., Feng, A. 2022. Analysis of vibration stability of fluid conveying pipe on the two-parameter foundation with elastic support boundary conditions. JOES. https://doi.org/10.1016/j.joes.2022.11.002.

[6] Liang, F., Chen, Z-Q., Xu, W-H. 2023. Vibration isolation of a self-powered piezoelectric pipe conveying fluid composed of laminated fiber-reinforced composites. Appl. Ocean Res. 138, 103664.

[7] Fu, G., Wang, X., Wang, B., Su, J., Wang, K., Sun, B. 2024. Dynamic behavior of axially functionally graded pipe conveying gas–liquid two-phase flow. Appl. Ocean Res. 142, 103827.

[8] Wen, H., Yang, Y., Li, Y., Tao, J. 2023. Three-dimensional vibration analysis of curved pipes conveying fluid by straight pipe-curve fluid element. Appl. Math. Model. 121,270-303.

*Corresponding author: E-mail: *m.rabanibidgoli@yahoo.com*