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An accurate and efficient time-domain model for simulating water-cylinder dynamic interaction during earthquakes

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ABSTRACT

Seismic analysis of many offshore structures is the three-dimensional (3D) water-cylinder dynamic interaction. The cylinder is commonly modeled as a beam by finite elements. If the 3D infinite water layer is also modeled by the finite elements, the high computational costs are unacceptable in engineering practice. Therefore, an accurate and efficient time-domain model is proposed to replace the 3D infinite water layer in the water-cylinder interaction analysis. Firstly, based on the frequency-domain analytical solution, the exact dynamic stiffness relationship between the hydrodynamic pressure and the structural displacement is constructed on the water-cylinder interface. Secondly, this relationship is transformed into a high-order approximation in time domain by using the temporal localization method. Thirdly, the high-order approximation is represented as a mechanical model system consisting of the spring, dashpot and mass elements, which is implemented into the finite element software ABAQUS by the user element subroutine. Finally, numerical examples are given to indicate the effectiveness of the proposed time-domain model and investigate the effect of hydrodynamic pressure on the seismic responses of the cylinder.

1. Introduction

The seismic analysis of the offshore structures should consider water-structure dynamic interaction because it may affect the structural responses significantly. To save the computational costs, the water is modeled as the seismic hydrodynamic pressure on the structure instead of as a real medium domain. The research on the seismic hydrodynamic pressure has begun with the gravity dam [1] and the cylindrical tank [2].

The Morison equation is originally used to estimate the wave force acting on the pile [3,4]. Then, it is introduced to calculate the hydrodynamic pressure on the offshore tower subjected to strong earthquake motion [5]. In the recent years, the Morison equation is expanded to calculate the seismic hydrodynamic pressure caused by the inner water of the hollow pier [6]. A simplified method for the seismic hydrodynamic pressure acting on the slender structure is also proposed based on the Morison equation [7]. However, the Morison equation is applicable to only the relatively slender structure due to that the effect of the structure on the water is not considered. In addition, the Morison equation has the empirical inertia and drag coefficients.

The seismic hydrodynamic pressure on a circular cylinder varying uniformly from the bedrock to the water surface can be derived strictly from the seismic water-cylinder interaction model, where the cylinder can be assumed as rigid and flexible, respectively. In fact, the flexible cylinder considers the effect of the flexible motion of the cylinder on the water but the rigid does not. The researches on the rigid circular cylinder are as follows. By modeling the compressible water as a real medium domain, a finite difference scheme is developed to derive the seismic hydrodynamic pressure acting on the rigid circular cylinder [8]. The analytical solution is modified and simplified to obtain the seismic hydrodynamic pressure of the outer and inner water acting on the hollow rigid circular cylinder [9]. A time-domain simplified formula is proposed for the seismic hydrodynamic pressure on the rigid circular cylinder [10]. This formula is expressed in the form of the added mass in low frequency and the added mass and damping in high frequency, due to the consideration of the water compressibility.

The effect of the hydrodynamic pressure on the seismic response of the flexible circular cylinder is investigated initially in [11] by the analytical method in frequency domain. If the water is incompressible, the seismic hydrodynamic pressure is a kind of inertia force that is equal to a product of the constant mass of water and the acceleration of cylinder. In this case, the water can be replaced and modeled by the so-called added mass model. The added mass can be implemented easily in the time-domain analysis. However, if the water is compressible, the

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seismic hydrodynamic pressure is equal to a product of the frequency-dependent mass of water and the acceleration of cylinder. It cannot be used directly in the time-domain analysis. The studies conducted by Liaw and Chopra [11] indicated that the water compressibility is important for the squat cylinder and it can be negligible for the slender cylinder under the low-frequency load. The studies on the surface wave condition indicate that the surface condition can be significant at the very low frequency. In a word, the water compressibility should be considered and the surface wave condition can be negligible under the earthquake action. The similar conclusion is drawn by Tanaka and Hudspeth [12] that the water compressibility is relative more important at the dimensionless frequency greater than unity, where the term "dimensionless frequency" is defined as ω/ω_1, where ω and ω_1 denote the loading frequency and fundamental frequency of the water layer. In the case of neglecting the water compressibility and the surface wave condition, a highly accurate added mass model is presented by Han and Xu [13] for computing the natural vibration frequencies of the flexible circular cylinder. By modeling the compressible water as a real medium domain, the hybrid finite-difference and finite-element scheme is used by Chen [14] to analyze the water-cylinder interaction, due to the absence of the time-domain hydrodynamic pressure model of simulating the water. In addition, other different water-cylinder models have been also considered [15–28].

In this paper, the flexible cylinder with circular section varying uniformly from the bedrock to the water surface is considered. For the compressible water without the surface wave condition, the seismic hydrodynamic pressure can be obtained in frequency domain just as in [11], but it is implemented difficultly into time domain for the nonlinear structure analysis. The simplified hydrodynamic pressure method has a low accuracy, which will result in the unreal structure response due to the hydrodynamic pressure method imposed directly on the structure. Therefore, based on the basis of the author's preliminary work in [29–32], an accurate and efficient time-domain hydrodynamic pressure model is proposed to replace the compressible water layer in this paper. The highlight in this paper is that the dynamic stiffness coefficient for the three-dimensional layer is written as a nested form of the dynamic stiffness coefficients of the two-dimensional full space and layer.

2. Problem statement

The seismic water-cylinder interaction problem in the 3D space is shown in Fig. 1. The signs (r,θ,z) and t denote the cylindrical coordinate system and time, respectively. The circular cylinder varies uniformly from bedrock to water surface. The cylinder may represent an engineering structure or its substructure. The radius of the circular section is a and the water is a horizontally infinite layer of the constant depth h. The rigid bedrock has a horizontal earthquake motion of the displacement time history $u_0(t)$ along the direction of paralleling the plane $\theta = 0$ or has two normal horizontal earthquake motions. The cylinder is fixed on the rigid bedrock. The water-cylinder interaction system is initially at rest. A nomenclature is shown in Table 1.

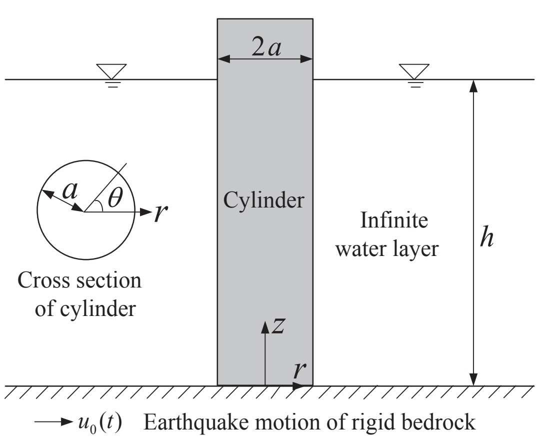

Fig. 1. Seismic water-cylinder interaction problem.

Table 1
Nomenclature.

a	radius of the cylinder
h	water depth
H	cylinder height
E	elasticity modulus
ρ_s	mass density of cylinder
μ	Poisson's ratio
c	acoustic velocity in water.
p	hydrodynamic pressure.
u	displacement of the cylinder
ρ	mass density of water
ω	circular frequency
ω_m	natural circular frequency of water layer
λ_m	natural circular wave number of water layer
t	time
z	vertical coordinate
b	the reciprocal of the wave number)
N	order number of the rational function

The cylinder can be modeled as a beam and may contain the material and geometry nonlinearities. It can be solved by the finite element method in time domain. After the spatial discretization to the cylinder, the finite element equation can be written as the partitioned matrix form as follow

$$\begin{bmatrix} \mathbf{M}_I & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_B \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}_I \\ \ddot{\mathbf{u}}_B \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_I & \mathbf{C}_{IB} \\ \mathbf{C}_{BI} & \mathbf{C}_B \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{u}}_I \\ \dot{\mathbf{u}}_B \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_I & \mathbf{K}_{IB} \\ \mathbf{K}_{BI} & \mathbf{K}_B \end{bmatrix} \begin{Bmatrix} \mathbf{u}_I \\ \mathbf{u}_B \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{f}_B \end{Bmatrix} \quad (1)$$

where the subscripts B denotes the nodes of the cylinder immersed in water and I denotes the nodes of the cylinder in vacuum, respectively; $\mathbf{u}$ is the total or absolute motion vector with the given bedrock motion u_0; the dot over variable denotes the derivative to time; and $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the lumped mass, damping and stiffness matrices, respectively.

The discrete hydrodynamic force vector of the water acting on the cylinder is

$$\mathbf{f}_B = \int_0^h \mathbf{N}^{\mathrm{T}} f \, dz \quad (2)$$

where $\mathbf{N}$ is a row vector of the global shape function of the one-dimensional finite elements for the transverse displacement degrees of freedom immerged in the water; and the superscript T denotes the matrix transpose. The continuous hydrodynamic force can be obtained from the hydrodynamic pressure acting on the cylinder surface as

$$f = -\int_0^{2\pi} pa\cos\theta \, d\theta \quad (3)$$

where p is the hydrodynamic pressure.

From the scientific point of view, the problem considered in this study belongs to a wave scattering problem, because the seismic wave is commonly coming from the far field of the rock foundation [33]. Under the assumption of a rigid rock foundation, the acceleration input motions can be approximately applied along the rock base. This means that both the wave scattering effect in the rock foundation [34] and the water-foundation interface [35] are neglected in this study.

The water is modeled as the acoustic media controlled by the scalar wave equation. The control equation represented by the hydrodynamic pressure in the cylindrical coordinates is

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} + \frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \quad (4)$$

where c is the acoustic velocity in water. The boundary condition on the water surface is

$$p = 0 \quad (5)$$