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Experimental validation of a model for seismic simulation and interaction analysis of buried pipe networks

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ABSTRACT

A finite-element model is established to evaluate the seismic responses of buried pipe networks. In the model, pipes are simulated as beams on elastic foundation, the joints of the segmented pipes are modeled by axial and rotational springs, and the pipe–soil interactions are simulated by springs. The seismic wave acts on one end of the soil springs to induce the seismic responses of the pipe networks. The test results of a buried pipe network subjected to an artificial earthquake is adopted as benchmark to validate the model. The tested pipe network has a size of 24 m × 24 m and consists of ductile cast iron and welded steel pipes. The artificial earthquake is produced by 30 kg of TNT explosives. Two important responses are compared, i.e., the joint deformations of the ductile cast iron pipes and the strains of the welded steel pipes. Results indicate that the model can evaluate the seismic responses of the buried pipe networks well. The pipe interactions are analyzed using the model by comparing the seismic responses of the single pipe and its counterpart in the pipe network.

1. Introduction

Buried pipe networks are important components of lifeline engineering systems, which are indispensable for people's daily lives and industrial activities [1]. Buried pipe networks suffered extensive damages during almost all strong earthquakes in the recent 20 years. For example, after the Wenchuan Earthquake ($M = 8.0$) in 2008, about 2000 breaks appeared on 380 km-long water pipes, with leakage rate as high as 65%, in Dujiangyan [2]. More than 800 leaks in gas pipes were found in Mianyang, and the gas supply pressure decreased from 0.25 MPa to 0.1 MPa after the earthquake [3,4]. Notably, secondary disasters caused by the damaged pipe networks may be very serious. A classic example is the fires caused by the San Francisco earthquake in 1906. The fires burned for more than 3 days because of lack of water, and about 22,400 buildings were destroyed [5]. Therefore, the performance of buried pipes under earthquakes is an important research field.

Newmark [6] is the pioneer in the field of seismic evaluation of buried pipes. In 1967, he suggested that pipe strain under seismic wave excitation is equal to the strain of soil surrounding the pipe. Since then, many researchers have proposed different models to study the seismic responses of buried pipes; these models include the elastic foundation model [7,8], shell model [9], and finite-element model [10]. However, these studies only focused on single pipes and neglected the interaction between pipes. As such, some researchers [11–15] studied simple pipe networks or a pipe with several branches. In addition to straight pipes, buried pipe networks consist of many components, such as tees, elbows, crosses, and other fittings. All these components comprise an entire pipe network. To study the seismic responses of an entire pipe network, Liu et al. [16] developed a finite element model for buried pipe systems subjected to seismic wave propagation; they also established a nonlinear stochastic seismic analysis program for buried pipe systems by using a probability density evolution method. However, the theoretical results of these studies were not validated. Hence, Wang et al. [17] and Miao et al. [18] carried out an artificial earthquake experiment to study the seismic behavior of a 24 m × 24 m buried pipe network. The test uncovered different deformation patterns of pipes interacting with other pipes. The test can also be used as benchmark for validating the seismic evaluation method of pipe networks [16]. Herein, the test [17,18] is used to validate the suggested numerical model presented in literature [16]. Meanwhile, the interaction influence of the buried pipe network, especially presented by some deformed pipes, such as tees and elbows, is also studied in this new paper by the suggested numerical model.

This paper briefly introduces the finite element model proposed by Liu et al. [16] for entire pipe networks, including modeling for buried pipes, joints, and pipe–soil interactions. An artificial earthquake test of a buried pipe network is performed. The model of the test pipe network is established especially for elbows, tees, and cross. Furthermore, the

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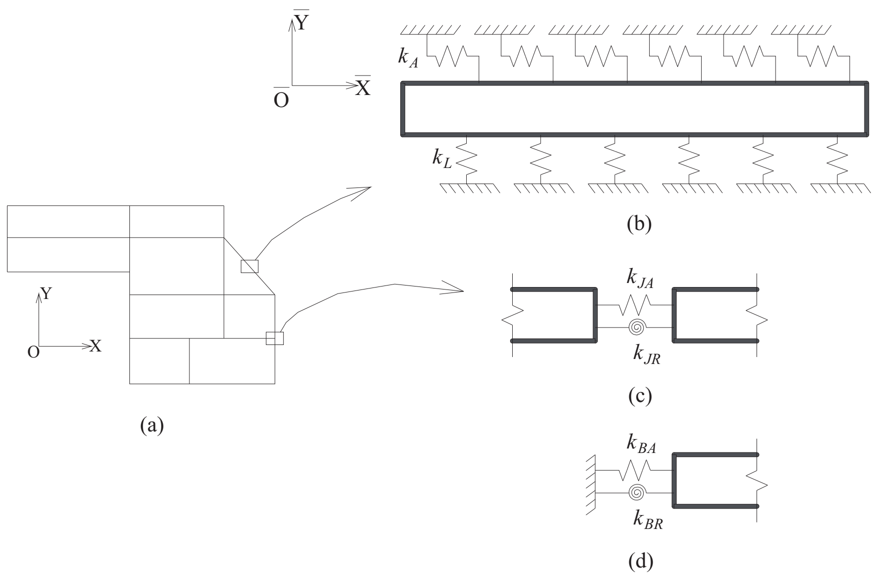

Fig. 1. Modeling of pipe networks.

model parameters are derived from the test results. The seismic responses provided by the finite element model are compared in detail with those obtained from the test. Finally, the seismic responses of some single pipes are compared with those of their counterparts in the network to illustrate interactions in the pipe network.

2. Modeling for buried pipe networks

In 2015, Liu et al. [16] established a finite element model to analyze the seismic responses of buried pipe networks. This model is verified in the present paper. Fig. 1a shows a simple pipe network. A buried pipe is usually idealized as a beam on elastic foundation (Fig. 1b), and seismic responses can be determined by a quasi-static method [19]. For the pipe in Fig. 1b, the axial and lateral motion equations can be described as follows:

$$EA\frac{\partial^2 u(x,\,t)}{\partial x^2} - k_A u(x,\,t) = -k_A u_g(x,\,t) \tag{1}$$

$$EI\frac{\partial^4 v(x,\,t)}{\partial x^4} + k_L v(x,\,t) = k_L v_g(x,\,t) \tag{2}$$

where EA and EI are the axial and bending stiffness of the pipe, respectively; k_A and k_L are the spring stiffness per unit length of soil surrounding the pipe along the axial and lateral directions, respectively (Herein, the axial direction is the longitudinal direction of the pipe and the lateral direction is the transverse horizontal direction of the pipe); $u(x,t)$ and $v(x,t)$ are the axial and lateral displacements of the pipe, respectively; $u_g(x,t)$ and $v_g(x,t)$ are the axial and lateral displacements of ground motion, respectively; and x is the coordinate.

When the pipe is discretized as many elements, the element stiffness matrix can be described as follows:

$$[\boldsymbol{K_P}] = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ & & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ & Symmetric & & \frac{EA}{L} & 0 & 0 \\ & & & & \frac{12EI}{L^3} & \frac{6EI}{L^2} \\ & & & & & \frac{4EI}{L} \end{bmatrix} \tag{3}$$

where L is the element length.

The interaction between the pipe and soil can be modeled as axial springs and lateral springs, and the corresponding stiffness matrix can be written as follows [16]:

$$[\boldsymbol{K_S}] = \begin{bmatrix} \frac{1}{3}\alpha & 0 & 0 & \frac{1}{6}\alpha & 0 & 0 \\ & \frac{13}{35}\beta & \frac{11}{210}L\beta & 0 & \frac{9}{70}\beta & -\frac{13}{420}L\beta \\ & & \frac{1}{105}L^2\beta & 0 & \frac{13}{420}L\beta & -\frac{1}{140}L^2\beta \\ & Symmetric & & \frac{1}{3}\alpha & 0 & 0 \\ & & & & \frac{13}{35}\beta & -\frac{11}{210}L\beta \\ & & & & & \frac{1}{105}L^2\beta \end{bmatrix} \tag{4}$$

where $\alpha = k_A DL$ and $\beta = k_L DL$. D is the pipe diameter.

An ideal elastic model is adopted to describe the interaction between the pipe and soil in the axial and lateral directions considering the relatively small soil deformation in the artificial test. Section 4.1 introduces the method for obtaining the parameters k_A and k_L.

The pipe joint can be simulated by a joint element consisting of an axial spring and a rotational spring (Fig. 1c). For segment pipes, one segment is inserted into another segment, thereby restraining lateral movement. The segments cannot move in the lateral direction, which is then simulated by a spring with infinite stiffness. The element stiffness matrix of a joint can be described as follows:

$$[\boldsymbol{K_J}] = \begin{bmatrix} k_{JA} & 0 & 0 & -k_{JA} & 0 & 0 \\ & k_\infty & 0 & 0 & -k_\infty & 0 \\ & & k_{JR} & 0 & 0 & -k_{JR} \\ & Symmetric & & k_{JA} & 0 & 0 \\ & & & & k_\infty & 0 \\ & & & & & k_{JR} \end{bmatrix} \tag{5}$$

where k_{JA} and k_{JR} represent the axial and bending spring stiffnesses of the joint, respectively; and k_∞ takes a large value and represents a lateral spring with infinite stiffness.

Generally, the axial joint spring behaves differently in tension and compression and is usually described separately by a perfectly plastic model for tension and an elastic model for compression [20]. The relationship between the axial force and the displacement is shown in Fig. 2, where P_u is the ultimate axial resistant force, Δu_1 is the ultimate axial deformation at the elastic phase, and Δu_{max} is the maximum axial deformation.

Sometimes, the pipe ends are connected to other underground instruments. The connection between the pipe and the instrument can be regarded as springs, such as axial and rotational springs (Fig. 1d).