Soil Dynamics and Earthquake Engineering 106 (2018) 41–52

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

The stiffness of axial pipe–soil springs and axial joint springs tested by artificial earthquakes

Wei Liu[a,b,*], Huiquan Miao[b], Chuang Wang[b], Jie Li[a,b]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[b] Department of Structural Engineering, Tongji University, Shanghai 200092

A R T I C L E I N F O

Keywords:
Axial pipe–soil spring
Axial joint spring
Artificial earthquake test
Buried pipes

A B S T R A C T

This study proposes an experimental method to obtain the stiffness of axial pipe–soil and axial joint springs in time and frequency domains. The proposed method can determine axial pipe–soil spring stiffness by using the pipe strains and slippages between pipes and soil. It can also determine axial joint spring stiffness by utilizing pipe strains and joint deformations. The pipe–soil spring stiffness values of ductile cast iron (DCI) and welded steel (WS) pipes are obtained and analyzed through artificial earthquake tests on a 24 m × 24 m buried pipe network. Artificial earthquakes are produced with trinitrotoluene explosives. Three theoretical models are discussed, and their results are compared with the test results. The comparisons indicate that the proposed experimental method is valid to obtain the stiffness of axial pipe–soil and axial joint springs. The stiffness values can be a benchmark to study the pipe–soil interaction and flexible joints. The effects of axial pipe–soil spring stiffness on the joint deformations of DCI pipes and pipe strains of WS pipes are also discussed.

1. Introduction

The interaction between pipes and soil is an important mechanism that significantly affects the seismic responses of buried pipes. Many researchers have focused on this interaction. In 1967, Newmark [1] suggested that pipe strain is equal to the strain of the surrounding soil, which means there is no interaction between pipe and soil. Shinozuka and Koike [2] introduced a transfer coefficient in 1979 to describe pipe–soil slippage. They suggested that no slippage occurs when the field strain is less than 10^{-4} (i.e., the transfer coefficient is equal to 1), whereas slippage occurs when the field strain reaches 10^{-3} to 10^{-2} (i.e., the transfer coefficient is less than 1). However, these models can only provide some rough estimations. In 1979, Wang and Cheng [3] presented a quasi-static analysis model, in which the interaction between pipes and soil is perceived as an elastic spring. Wang [4] further summarized spring stiffness values obtained from different pipes and soil types in 1983. This model is widely adopted by many researchers [5–10] and seismic guidelines in different countries [11–13]. Therefore, how to accurately determine spring stiffness has become a highly important research topic.

Many theoretical methods have been proposed to obtain the stiffness of pipe–soil springs in the axial direction. These methods include Mindlin solution [14,15], and wave equation [16] and so on. The method proposed by Matsubara and Hoshiya [16] fully considers the influence of different factors on the stiffness of axial pipe–soil springs. However, the method was not validated by experiments. Another popular theoretical model is bilinear soil spring representation in the major pipe design guidelines of American Lifelines Alliance [12,13]. However, representations of the axial pipe–soil springs are derived from pile shaft load transfer theory [17]. Although this model is commonly accepted, several discrepancies exist between laboratory tests and the established equations [18]. Considering the limitations of laboratory tests, the model should be validated through full-scale dynamic tests similar to those in engineering practice.

Axial pipe–soil spring stiffness values are essentially the slope of the soil resistance–slippage relationship curve on the pipe–soil contact surface [19] and can be obtained through static and dynamic tests. For static tests, in 1976, Takada and Hassani [20] observed soil resistance as static displacement exerted on pipes by oil pressure jacks. In 1998, Cappelletto et al. [21] conducted a field test to consider longitudinal pipe–soil interaction with different soil types. In 2011, Weerasekara [22] performed five pullout tests on large-scale medium-density polyethylene pipes buried in Fraser River Sand. Static tests are generally easy to conduct, but they ignore the fact that an earthquake is a type of dynamic loading, and the soil resistance in a dynamic situation is different from that in a static situation [4,20]. Therefore, dynamic tests are more appropriate than static tests. In 1976, Takada [20] conducted a dynamic experiment and obtained hysteretic loops between soil

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China.
E-mail addresses: liuw@tongji.edu.cn (W. Liu), miaohq@126.com (H. Miao), 1110098@tongji.edu.cn (C. Wang), lijie@tongji.edu.cn (J. Li).

https://doi.org/10.1016/j.soildyn.2017.12.014
Received 31 May 2017; Received in revised form 31 October 2017; Accepted 5 December 2017
0267-7261/

resistance and pipe displacement under 2 Hz excitation. The experiment results indicated that the dynamic soil resistance is about 70% of the static soil resistance. Meng et al. [23] performed a shaking table test on buried pipes subjected to non-uniform seismic wave excitation in 2008. The researchers suggested that the relationship between shear stress and pipe–soil slippage can be described by a bilinear model. However, these tests have two drawbacks. First, the soil in these tests is disturbed and thus different from in situ undisturbed soil. Second, soil movement is restrained, and the boundary condition is different from that in the field [24].

The best method to test the axial pipe–soil spring stiffness is in situ experiments with real earthquakes. However, this method requires long preparation and observation periods because earthquake occurrences are random, and their intensities are unpredictable. A popular example is Isenberg et al.'s work [25], in which two pipes with anchors crossing a fault were tested. The expected earthquake did not occur even after the test began 15 years. Adopting artificial earthquakes produced by explosives in full-scale tests is an effective alternative. Several field tests have been conducted with artificial earthquakes [26,27]. However, reports about obtaining the stiffness of axial pipe–soil springs through in situ full-scale tests under artificial earthquakes are rare because testing the pipe–soil slippage in in situ dynamic experiments is difficult.

Aside from axial pipe–soil springs, the joints of ductile cast iron (DCI) pipes can also be modeled by axial and rotational springs. Several theoretical methods, such as the finite element method [28], and experiments under static [29–32] and dynamic [33–35] loads have also been applied to determine the stiffness of axial joint springs.

This paper is a further work based on the achievement of Refs. [24,36]. However, it should be noted that Refs. [24,36] mainly focused on the responses of buried pipes. The former discussed the field deformation and the joint deformation of segmented pipes while the later concentrated on the behaviors of continuous steel pipes. In this paper, an experimental method to obtain the stiffness of axial pipe–soil springs and axial joint springs are presented. Three artificial earthquake tests are used to determine the spring stiffness. Also, three different models of axial pipe-soil springs are validated by the experimental results. The axial pipe–soil spring model proposed by Matsubara and Hoshiya [16] is validated, and the recommended pipe–soil spring models in the Chinese code and American guidelines are discussed. In this study, because the soil surrounding pipes in the site is still in elastic state in three artificial earthquake tests, the pipe–soil spring in axial direction can also be seen as in elastic state. Actually, the elastic deformation limit for the axial pipe-soil spring is assumed as $x_u/2$, where x_u is 0.2–0.4 in. for stiff to soft clay, namely 5.08–10.16 mm for stiff to soft clay [12]. Therefore, the elastic deformation limit for the axial pipe-soil spring is about 2.54–5.08 mm for stiff to soft clay. In the tests, the maximum pipe-soil relative slippage is only 0.44 mm. Thus, it can be seen as in elastic state. Therefore, the stiffness shown in this paper does not consider the influence of soil nonlinearity when higher level of strains are reached in the soil.

The remainder of this paper is organized as follows. The experimental method to obtain the stiffness of axial pipe–soil springs and axial joint springs is introduced in Section 2. Artificial earthquake tests conducted on a buried pipe network are introduced briefly in Section 3. In Section 4, the stiffness values of axial pipe–soil springs are obtained from tests using the proposed method. Section 5 discusses the model proposed by Matsubara and Hoshiya [16], and those in the Chinese code [37] and American guidelines [12]. The stiffness values of axial joint springs are obtained and discussed in Section 6. Section 7 focuses on the influence of axial pipe–soil springs on the joint deformations of DCI pipes and pipe strains of welded steel (WS) pipes in the tested pipe network. Section 8 presents some conclusions.

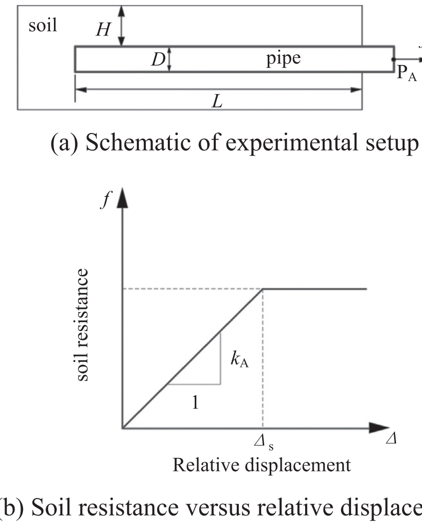

Fig. 1. The classic method to obtain the stiffness of axial pipe–soil springs.

2. Experimental method to obtain the stiffness of axial pipe–soil springs and axial joint springs

2.1. Classic method to obtain the stiffness of axial pipe–soil springs

Fig. 1(a) shows a schematic of the common experimental setup to obtain the stiffness of axial pipe–soil springs. Load f is generally implemented and recorded by several load cells at the end of the tested pipe (i.e., point P_A). The displacement, Δ, of point P_A, is recorded by displacement sensors [22]. The force–displacement relationship is illustrated in Fig. 1(b) [19], which can be expressed as:

$$f = F_{\Delta}(\Delta) \tag{1}$$

In Fig. 1(b), f_m is the maximum value of f; Δ_s is the displacement when f arrives at f_m. F_Δ is a force–displacement function. Then the stiffness of axial pipe–soil springs, k_A, can be determined as follows:

$$k_A = \frac{f_m}{\Delta_s} \tag{2}$$

If the length of the pipe contacting with the soil is L, then the stiffness per unit length should be:

$$k_{AL} = \frac{f_m}{\Delta_s L} \tag{3}$$

Obviously, this method neglects the pipe deformation due to the significantly higher axial stiffness of pipe segments than that of soil–-pipe interface. The displacement at point P_A is thought as just the pipe–soil slippage. The slippage along the pipe is the same. However, the displacement at point P_A cannot represent pipe–soil slippage because the soil and pipe will deform along the pipe during the experiment. Therefore, the classic method to obtain the force–displacement relationship cannot provide the exact stiffness. A more precise method to obtain spring stiffness involves measuring the soil resistance and slippage in a relatively short segment. Given this consideration, a new experimental method is proposed.

2.2. Method to obtain the stiffness of axial pipe–soil springs

2.2.1. Time domain method

For the pipe element shown in Fig. 2(a), the following can be derived when the inertia force of the pipe is ignored:

$$F_f(t) = F_{p2}(t) - F_{p1}(t) \tag{4}$$

$$F_{p1}(t) = \varepsilon_{p1}(t)\cdot E_I\cdot A_I \tag{5}$$