Soil Dynamics and Earthquake Engineering 113 (2018) 180–192

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Seismic responses of deep buried pipeline under non-uniform excitations from large scale shaking table test

Kongming Yan[a], Jianjing Zhang[a,*], Zhijia Wang[b,*], Weiming Liao[a], Zuoju Wu[c]

[a] *Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, School of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan Province 610031, PR China*
[b] *College of Civil Engineering and Architecture, Hainan University, Haikou, Hainan Province 570228, PR China*
[c] *Sichuan Vocational and Technical College of Communications, Chengdu, Sichuan Province 611130, PR China*

ARTICLE INFO

Keywords:
Non-uniform seismic excitation
Shaking table test
Buried pipeline
Similarity design
Response analysis

ABSTRACT

The seismic response of long deep buried pipeline under non-uniform excitation is very important for suitable seismic design. However, due to restriction by excitation devices, few model tests have been carried out. In this study, a large-scale shaking table model test for a long deep buried pipeline was carried out, where two controlled-independent tables were used to excite two model containers and the excitations for the two tables are in the three directions and non-uniform. From the model test, the strains and deformations of the pipeline and the accelerations of the soil in containers were measured and evaluated. Some results were achieved: (1) non-uniform seismic excitation has great influence on the acceleration amplification in soil and the strain and displacement of the pipeline; (2) the deep buried pipe in ground has few impact on ground surface acceleration response, but has greater impact on the acceleration response of the soil surrounding the pipe; (3) the bending stain and permanent displacement under uniform excitation are negligible, but not neglected for non-uniform excitation; (4) the model test proves that there is obvious rotation of the pipeline in addition to horizontal and vertical displacements under non-uniform excitation.

1. Introduction

With the development of industrialization and urbanization, the role of urban tunnels, buried pipelines and other underground structures become more important in mobility of urban population, transportation of energy commodity, and discharges of municipal wastes. In that, the buried pipeline displays many advantages in transportation of fresh water and natural gas between cities. For a long linear structure, such as buried pipelines, it has some features, such as large span, low lateral stiffness and vulnerability when suffered natural disasters. As a potential disaster occurred in many areas, earthquakes instantly threat the safety of the long underground structures. Some seismic damages of pipelines in the San Francisco (1906) [1,2], Great Kanto (1923) [3], Mexico (1985) [4,5], Northridge (1994) [6], Chichi (1999) [7], and Wenchuan Earthquakes (2008) [8] indicate that buried pipelines are vulnerable in earthquakes and difficult to be quickly fixed, as a result, it is necessary to strength seismic response study of pipelines. Normally, the failure of the buried pipelines caused by earthquakes is divided into two types, one being joint failure and the other being segment failure. For segment failure, the types of failure has longitudinal and transverse cracks, pipeline buckling [9]. The possible reasons for the above failures may be due to different ground movements (including amplitude and direction) at different points on ground, which is called non-uniform seismic excitation [10–12]. Based on an amount of seismic damage investigations, researchers have realized that non-uniform ground motions can cause significant variations of ground motion in amplitude or phases along the linear structures, which is also true for the similar structures [13]. Some researchers put forward that ground motion spatial variability triggered by earthquake waves in the longitudinal direction of the underground structure has a huge impact on its deformations and studied the mechanism of the response variability of underground structure triggered by ground motion spatial variability [14–18]. Yu et al. [19] and Park et al. [20] utilized three-dimensional numerical model to analyze the deformations of long tunnels under different seismic excitations and revealed that non-uniform seismic excitations had a significant influence on the seismic response of tunnels in the longitudinal direction. Based on the above studies and using three-dimensional numerical analysis, Li et al. [21] discussed that the longitudinal axial and bending deformations of long tunnels under asynchronous waves, while incident angles of the input motions are different.

Although some researchers have discussed the characteristics of

---

[*] Corresponding authors.
E-mail addresses: Jianzhang1102@swjtu.edu.cn (J. Zhang), 993041@hainu.edu.cn (Z. Wang).

https://doi.org/10.1016/j.soildyn.2018.05.036
Received 17 October 2016; Received in revised form 7 February 2018; Accepted 31 May 2018

ground motions under non-uniform excitation, few model tests have been done to explore the seismic responses of pipelines under non-uniform excitation, and the reason may be due to limitation of experimental facilities. However, large scale model test is an efficient way for reproducing the seismic responses of pipelines under seismic excitation, especially for non-uniform seismic excitation. With the development of shaking table technology in recent years, inputting non-uniform seismic excitation in model test has been realized. For example, Chen et al. and Jiang et al. [22,23] studied the seismic responses of a rectangular utility tunnel and discussed the failure modes of the tunnel joint by inputting non-uniform one-dimensional seismic excitation to two shaking tables, but generally speaking, few model tests have been carried out for buried pipeline under non-uniform seismic excitation.

In this paper, a shaking table model test was carried out to explore the seismic responses of a deep buried pipeline under uniform and non-uniform excitations in the three directions. The shaking table facility consists of two controlled-independent tables, and the non-uniform excitations were selected from earthquake records and generated from our proposed multi-point ground motion generation model [24]. In the model test, the accelerations in soil, the strains and displacements of the pipeline were measured, and some results were obtained regarding of the axial strain, bending strains and permanent displacements of the deep buried pipeline and acceleration amplification in soil under non-uniform excitation.

2. Experimental program

2.1. The two-tables shaking facility used in the model test

The model test was performed on a shaking table array, consisting of two controlled-independent six-degree-of-freedom shaking tables. For the two shaking tables, one is fixed, called Table A, and the other is movable, called Table B (see Fig. 1). The space between the two tables is adjustable in a range of 2–20 m and the size of each table is 3 m × 6 m. The maximum acceleration of each table acted by hydraulic device is ± 1 g, the maximum horizontal and vertical displacements are ± 150 mm and ± 100 mm, respectively, the maximum weight taken is 35 t, and the maximum over-turning moment taken is 70 t m. The two tables have three work modes: (1) each table independently works; (2) two tables work together and are excited by the same input motion; (3) two tables work together, but are excited by different input motions. The third work mode was adopted in the model test.

2.2. Absorbing boundaries for the test containers

Normally the rigid boundaries of a test container will produce boundary effect, which will pollute experimental results in a dynamic test. The reason is that the size of the test container is limited, rather than infinite half space, and in this situation, if the boundaries are rigid, the waves, which should propagate into infinite half space in practices, will be reflected back into the soil in the test container by the rigid boundaries, and as a result, the wave field in the test container is disturbed. To reduce the boundary effect on experimental results, the boundaries of the test container should be deal with. In the model test, some foam cushions with 3 cm thick were glued on the internal wall of the test container (see Fig. 2), and in the case, the soil in the test container can move in horizontal x and y directions.

Fig. 1. Photo of double-table shaking system.

Fig. 2. Photo of experimental model container.

2.3. Similitude design of model test

The prototype size of the tested buried pipeline is φ1420 × 10 mm, and its buried depth in average is 3 m, namely the pipeline is classified as deep buried pipeline. The shear wave velocity of the prototype site is 266.8 m/s, its characteristic period is 0.5 s according to China design code [25], and the elasticity modulus of the buried pipeline is 2.05×10^5 MPa. According to similitude design of other shaking model test [26–28], based on the prototype pipeline size, site conditions, and test container size, the similitude ratio was determined by similitude law and listed in Table 1.

2.4. Model soil and pipeline

Based on Table 1, the unit weight and moisture content of the model soil are 21 kN/m^3 and 14%. To keep the consistence of the dynamic property of the prototype soil and model soil in the shaking table test, the dynamic stress-strain relation of the prototype soil and model soil should be same as possible. Therefore, based on the G/G_{max}-γ relation of the prototype soil and by using trial and error approach, the model soil with the G/G_{max}-γ relation being close to that of the prototype soil was made, as shown in Fig. 3. Finally the model soil was made from the

Table 1
Similitude ratios of the model test.

Number	Physical quantity	Dimension (MLT)	Similarity constants (prototype/model)
1	Physical dimension (L)	[L]	$C_L = 10$
2	Density (ρ)	$[M][L]^{-3}$	$C_\rho = 1$
3	Input acceleration (a)	$[L][T]^{-2}$	$C_a = 1$
4	Stress (σ)	$[M][L]^{-1}[T]^{-2}$	$C_\sigma = C_L = 10$
5	Strain (ε)	1	$C_\varepsilon = 1$
6	Force力 (F)	$[M][L][T]^{-2}$	$C_F = C_L^3 = 1000$
7	Velocity (*v*)	$[L][T]^{-1}$	$C_v = C_L^{1/2} = 3.162$
8	Time (t)	[T]	$C_t = C_L^{1/2} = 3.162$
9	Displacement (*u*)	[L]	$C_u = C_L = 10$
10	Bending rigidity	$[M][L]^3[T]^{-2}$	$C_{EI} = 10^5$
11	Axial rigidity	$[M][L][T]^{-2}$	$C_{EA} = 10^3$
12	Frequency (*ω*)	$[T]^{-1}$	$C_\omega = C_L^{-1/2} = 1/3.162$
13	Dynamic shear modulus ratio (G/G_{max})	1	$C_G = 1$
14	Shear strain (γ)	1	$C_\gamma = 1$
15	Damping ratio (λ)	1	$C_\lambda = 1$
16	Internal friction angle (φ)	1	$C_\varphi = 1$
17	Friction coefficient of pipe-soil (μ)	1	$C_\mu = 1$