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# Artificial earthquake test of buried water distribution network

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ABSTRACT

In this study, a 24 m × 24 m buried pipeline network is constructed and an artificial earthquake test is performed with explosives in the field. The buried pipeline network is composed of segmented ductile cast-iron pipelines that are connected by bell-and-spigot joints and welded steel pipelines. The test preparation process is illustrated in detail, including the laying of the pipeline network and sensor deployment. The test process and test phenomena are then described. Test results of ductile cast-iron pipelines are also obtained and analyzed, including those for field acceleration, joint deformations, pipe strains, and pipe-soil relative slippages. Finally, the relationships among field deformation, joint deformation, pipe-soil relative slippage, and pipeline strain are analyzed and explained.



## 1. Introduction

Water distribution networks (WDNs) are important components of urban lifeline systems. However, many previous earthquake investigations indicate that WDNs are fragile when subjected to earthquakes. During the American Northridge earthquake ($M_L$=6.6) in 1994, about 1400 breaks appeared in the WDNs; as a result, water was not supplied to roughly 40,000 customers. Moreover, the water supply had to be cut off for seven days in the epicentral area because water leakage interrupted traffic [1,2]. To repair the WDNs after the earthquake, 440 million USD were spent [3]. In addition, in the Wenchuan Earthquake ($M$=8.0) in 2008, about 2000 breaks appeared on 380 km long water pipelines of the WDN in Dujiangyan and the leakage rate exceeded 65% (i.e. 35% of water reaches customers and 65% through leakage) [4].

The importance of WDNs has motivated researchers to address this issue. In 1967, Newmark [5] first suggested that pipeline strain subject to seismic wave propagation is identical to the strain of the soil surrounding the pipeline. The peak field strain was estimated by assuming that the seismic wave spreads as a traveling wave. However, this method does not consider the relative slippage between the pipeline and the surrounding soil, especially in the case of severe soil deformation. Thus, it does provide an upper bound for pipe strain. In 1979, Shinozuka and Koike [6] introduced a transfer coefficient whose value is smaller than 1 to describe the slippage between the pipeline and the surrounding soil. Moreover, these researchers suggested that the pipeline and soil work together, i.e., the transfer coefficient equals 1.0, when field strain is smaller than $10^{-4}$ while slippage occurs when the field strain reaches $10^{-3}$–$10^{-2}$. Wang and Chen [7] established static equilibrium equations in the same year and presented joint deformations according to theory of beam on elastic foundations. Wang et al. [8] considered the influence of pipeline stiffness further on the basis of this method. The axial seismic response of a buried pipeline was analyzed by Qu and Wang in 1993 using a Fourier series expansion method according to dynamic equations for beams on elastic foundations and in consideration of the spatial correlations among seismic waves [9]. Finite element method [10] has also been used to analyze the seismic response of pipelines at present.

Many tests, including on-spot artificial earthquake tests, indoor pull-out tests, and shaking table tests, have been performed to verify theoretical methods. In 1971, Nasu et al. [11] employed a buried pipeline that was 1.2 m in diameter and 84.0 m long to perform a field test. During this test, ground displacement, pipeline displacement, and strain were recorded upon the excitation of five artificial vibration sources, namely, explosions, the dropping of heavy weights, air guns, piling and running cars. The test results indicated that the pipeline moved in sync with the ground, and no appreciable relative slippage was observed between them. In 1975, Ye et al. [12] discussed the relationship between soil and pipe deformation based on the results of blast vibration tests. In 1992, Li et al. [13] generated continuous impulses using high-pressure gas

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and solid fuel to simulate seismic waves. These researchers determined the transfer coefficient between soil and pipe strains. In 2006, Ashford et al. [14] performed an experiment on two gas transmission lines in Tokaehi Harbor of Hokkaido Island, Japan. The pipelines were instrumented with strain gages, and their performance were examined under lateral spreading. Unfortunately, the objectives of all of these tests were single continuous pipelines.

Many indoor static tests have been conducted to determine the mechanical parameters of the joints between pipe segments, including the force–displacement relationships of joints [15,16], joint strength [16,17], and the leakage–displacement relationships of joints [18]. However, these tests cannot reflect the mechanical property of joints in ground motions because of the limitations imposed by a static loading condition.

Shaking table and centrifuge tests have also been performed to study the performance of buried pipelines. Such tests are controllable, repeatable, and low cost. In 2002, Zhou et al. [19] determined the dynamic response of buried pipelines in saturated sand through a shaking table test. Choo et al. [20] conducted a centrifuge test on buried pipelines subjected to significant displacement in 2007. In 2008, Meng [21] tested buried pipelines on two different shaking tables to simulate non-uniform seismic excitation. Qiao et al. [22] studied the earthquake damage to buried pipelines under severe deformation as a result of sand liquefaction on a shaking table. Although shaking table and centrifuge tests are the main approaches currently, the test objectives are all single continuous pipelines or concrete pipelines with rigid joints.

A full-scale field test that measures the dynamic response of buried pipelines in actual earthquakes is crucial to the present study. In 1969, Sakurai and Takahashi [23] measured the strains on soil and pipelines subjected to the successive earthquakes in Matsushiro. These researchers suggest that the pipelines may have vibrated in sync with the surrounding soil. In 1991, Katayama [24] arranged a series of sensors to record the displacements and strains of soil and buried pipelines subjected to actual earthquakes. In small earthquakes, the axial strains on the pipelines were almost similar with those of the surrounding soil. Nonetheless, this method is not always feasible because of the rare observation opportunities and high test cost. Moreover, all of the measurements still focus on single continuous pipelines.

In consideration of the significance of WDNs and the scarcity and necessity of field dynamic testing, a full-scale artificial earthquake test is conducted on a buried pipeline network for the current study. Ground motion is generated by detonating TNT explosives. The pipeline network consists of segmented ductile cast-iron pipelines and welded steel pipelines. Field acceleration, joint deformation, pipeline strain and pipe-soil relative slippage are measured during the tests. The test process is detailed in the paper, and the test results are analyzed.

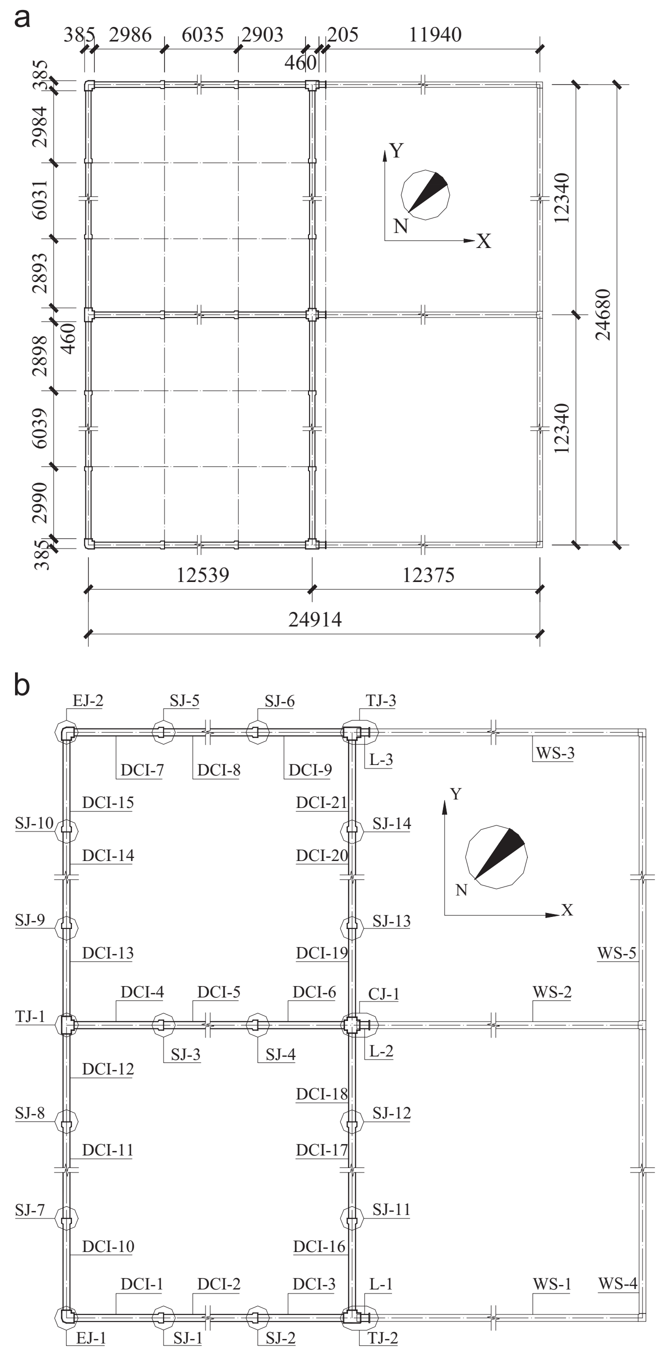


**Fig. 1.** Layout of pipeline network (a) size of pipeline network and (b) components of pipeline network.

## 2. Overview of the test

### 2.1. Test design

#### 2.1.1. Pipeline network

The pipeline network is designed as 24 m × 24 m in consideration of actual site conditions. Fig. 1 shows the layout of the network; specifically, the size of the network is shown in Fig. 1a, and the components are displayed in Fig. 1b. Pipelines DCI-1–DCI-21 denote the segmented ductile cast-iron pipelines that constitute a small WDN, whereas pipelines WS-1–WS-5 are the welded steel pipelines that represent a small gas network. In this study, only the responses of segmented ductile cast-iron pipelines are analyzed and reported; those of welded steel pipelines will be presented in the future.

The ductile cast-iron pipelines, elbows, tees and cross are connected by bell-and-spigot joints. A rubber ring gasket compressed as the spigot end is inserted into the joint. In Fig. 1b, SJ-1–SJ-14 are the bell-and-spigot joints between two adjacent ductile cast-iron pipelines. EJ-1 and EJ-2 are the elbows. Each elbow has a pair of bells, and two adjacent pipelines with spigots are inserted into these bells. TJ-1–TJ-3 are the tees, and each tee connects three adjacent pipelines. The welded steel pipelines WS-1 and WS-3 are connected to TJ-2 and TJ-3 through short, ductile cast-iron pipelines L-1 and L-3. Spigots are positioned at one end of L-1 and L-3 each. These spigots are inserted into the tee. The opposite ends of these pipelines contain flanges that are fixed to the flanges of the steel pipelines by bolts. Fig. 2 shows the connection of TJ-3. CJ-1 is a cross