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Seismic wave propagation effects on buried segmented pipelines

Peixin Shi [a]

[a] School of Urban Rail Transportation, SooChow University, Suzhou 215012, China

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ABSTRACT

This paper deals with seismic wave propagation effects on buried segmented pipelines. A finite element model is developed for estimating the axial pipe strain and relative joint displacement of segmented pipelines. The model accounts for the effects of peak ground strain, shear transfer between soil and pipeline, axial stiffness of the pipeline, joint characteristics of the pipeline, and variability of the joint capacity and stiffness. For engineering applications, simplified analytical equations are developed for estimating the maximum pipe strain and relative joint displacement. The finite element and analytical solutions show that the segmented pipeline is relatively flexible with respect to ground deformation induced by seismic waves and deforms together with the ground. The ground strain within each pipe segmental length is shared by the joint displacement and pipe barrel strain. When the maximum ground strain is higher than 0.001, the pipe barrel strain is relatively small and can be ignored. The relative joint displacement of the segmented pipeline is mainly affected by the variability of the joint pullout capacity and accumulates at locally weak joints.

1. Introduction

Extensive damage to buried pipelines has been observed and documented during previous earthquakes. Examples of such earthquakes include: the 1906 San Francisco [1], the 1964 Niigata [2], the 1976 Tangshan [3], the 1985 Michoacan [4], and the 1994 Northridge earthquake [5], as well as the 2010–11 Canterbury Earthquake Sequence [6]. The damage to buried pipelines can be induced by either permanent ground deformation (PGD) or seismic wave propagation (WP). The PGD, associated primarily with liquefaction, surface faulting, and landslides, causes concentrated, locally severe damage to underground pipelines. The WP, generated by the passage of seismic waves, can disturb an entire network, damaging lifelines at locations of weak joints and corroded and/or deteriorated pipe wall. For example, Ayala and O'Rourke (1989) [4] reported that most water pipeline damage during the 1985 Michoacan earthquake was caused by the WP hazard. Investigations focused on the 1994 Northridge earthquake [5] showed that the WP damage in the Los Angeles water distribution network was widespread, with serious effects on trunk line joints that were vulnerable to pullout under seismic wave interaction.

Buried pipelines can be either segmented (e.g., cast iron pipelines (CI) and jointed concrete cylinder pipelines) or continuous (e.g., steel pipelines with welded slip joints). The CI pipeline is one of the oldest and most commonly used segmented pipelines for water and gas transportation in North America. For example, Jeon and O'Rourke (2005) [7] reported that CI mains comprise 7740 km, or 72% of the water distribution system operated by the Los Angeles Department of Water and Power (LADWP). The CI pipelines sustained extensive damage during previous earthquakes. After the 1994 Northridge earthquake 1013 repairs were identified in the LADWP system [7] of which approximately 71% were in CI pipelines. The seismic damage to CI pipelines was also extensive during other earthquakes (e.g., 1971 San Fernando, 1987 Whittier Narrows, and 1989 Loma Prieta earthquakes). This paper focuses on the behavior of CI pipelines under seismic wave interaction.

The seismic WP effects on buried pipelines have received extensive attention in the past decades. Newmak (1967) [8], Shinozuka and Koike (1979) [9], Wright and Takada (1980) [10], Hwang and Lysmer (1981) [11] and O'Rourke and Liu (2012) [12], et al. proposed different models for predicting the response of buried pipelines to the WP effects. Previous research [12,13] showed that the ground strain induced by seismic waves along segmented pipelines is accommodated by a combination of pipe strain and relative axial displacement at pipe joints. Since the axial stiffness for pipe barrels is typically much larger than that for the joints, the ground strain results primarily in relative displacement of joints, and hence, one principal failure mode of segmented pipelines is axial pullout at the joints.

This paper deals with seismic WP effects on buried segmented pipelines. Both finite element (FE) and analytical models are developed for estimating the axial pipe strain and relative joint displacement of CI pipelines. Following the introduction, the characteristics of the CI pipeline and joints are discussed in Section 2. Section 3 describes the seismic waves and seismic

E-mail address: pxshi@suda.edu.cn

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loadings on buried pipelines. Section 4 focuses on the seismic responses of CI pipelines. An FE model for estimating the pipe strain and relative joint displacement is developed. Simplified analytical equations are developed for estimating the maximum pipe strain and relative joint displacement to facilitate the computations. The conclusions are made in Section 5.

2. Characteristics of CI pipelines

The CI pipelines are typically composed of 3 (10) to 6 m (20 ft) long pipe segments, jointed together with bell-and-spigot lead caulked joints. Fig. 1 shows a schematic drawing of the joint, which is constructed by: (1) packing oakum, which is a hemp yarn, into the joint; (2) pouring lead into the joint; and (3) ramming and tamping the lead into the joint with a caulking tool. Fig. 2 summarizes axial force vs. displacement data after Prior (1935) [14] from a comprehensive testing program of lead-caulked joints for water trunk and distribution pipelines. The test data correspond to the internal pipe diameters of 450 and 600 mm. The axial force is expressed in terms of kN per circumferential distance. Two force-displacement models are provided corresponding to rigid and elasto-plastic behavior, respectively. Both models show that a very small axial displacement, 0 for rigid and 2.5 mm for elasto-plastic model, is needed to mobilize the full axial tensile capacity of the joints. The joints can sustain a fair amount of axial slip and keep the tensile resistance constant after reaching its tensile capacity. The axial slip which the joint can sustain without reducing its tensile resistance depends on the depth of oakum packing, which typically ranges from 50 to 75 mm (2–3 in.).

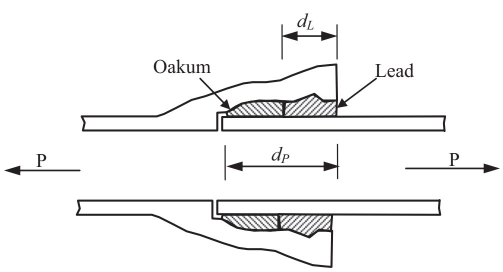

Fig. 1. Schematic Drawing of Bell-and-Spigot Lead Caulked Joint.

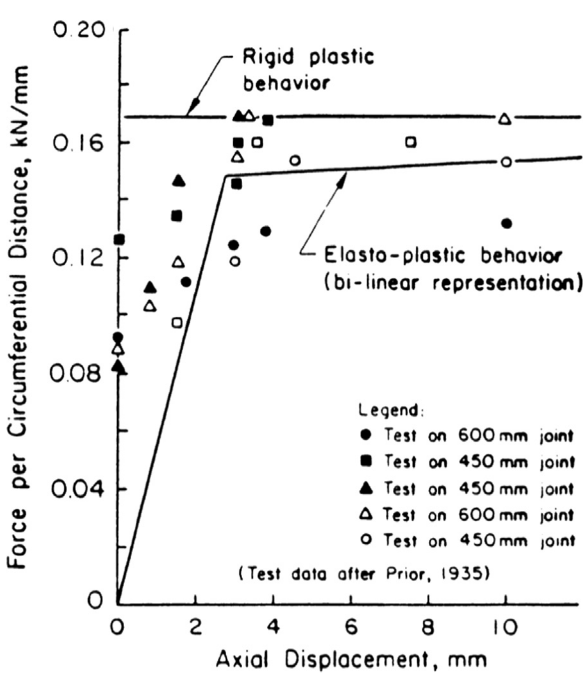

Fig. 2. Axial Force vs. Displacement Data for Lead Caulked Joints (after Prior, 1935 [14]).

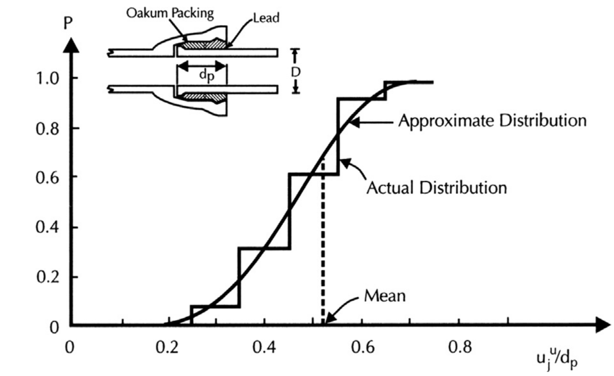

Fig. 3. Relationship between Probability of Leakage and Normalized Joint Pullout Displacement (after Eh Hmadi and O'Rourke, 1989 [13]).

The pullout capacity of the joint in terms of axial displacement to cause leakage depends on how much movement can occur before the lead caulking loses its compressive seal. Eh Hmadi and O'Rourke (1990) [13] summarized the available information on joint performance and established a cumulative distribution for leakage as a function of the normalized joint axial displacement u_j^u/d_P, as shown in Fig. 3, where u_j^u is the joint opening and d_P is the joint depth. This figure shows the mean value of joint opening corresponding to leakage is $0.52d_P$ with a coefficient of variation of 10%. Hence, Eh Hmadi and O'Rourke(1990) [13] suggested a relative joint displacement corresponding to 50% of the total joint depth to cause leakage. The total joint depth typically ranges from 100 to 140 mm (4–5.5 in.) for pipe diameter ranging from 41 cm (16 in.) to 122 cm (40 in.), resulting in an axial pullout movement of 50–70 mm (2–2.75 in.) to cause leakage.

3. Seismic waves

There are two types of seismic waves, body waves and surface waves. The body waves include P-waves (compressional waves) and S-waves (shear waves). P-waves, whose ground motion is in the same direction as the WP, generate alternating compressive and tensile ground strain. In contrast, the ground motion of S-waves is perpendicular to the direction of WP. Since S-waves carry much more energy and generate larger ground motion amplitudes than P-waves, only the S-waves are considered herein.

Surface waves include Rayleigh waves (R-waves) and Love waves (L-waves). The particle motion of the L-waves is along a horizontal line perpendicular to the direction of propagation, while the particle motion of the R-waves follows a retrograde ellipse in a vertical plane with a horizontal motion component parallel to the direction of propagation. Previous studies [12] have shown that pipeline strains induced by L-waves are significantly less than those generated by R-waves, so only R-waves are considered herein. Compared with body waves, surface waves have a much lower apparent WP velocity, which causes higher ground strain. Under the appropriate conditions, therefore, surface waves can be more hazardous to buried pipelines than body waves. Severe damage to water supply pipelines related to surface wave traveling effects has been recorded during previous earthquakes, such as the 1985 Michoacan earthquake in Mexico City [4]. As such, the surface waves are used as examples for analyzing the seismic response of segmented pipelines in this paper.

The seismic loads on buried pipelines imposed by WP are typically characterized by ground strains, ε_g, which can be calculated as the ratio of ground particle velocity, V, to apparent wave propagation