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Surface wave propagation effects on buried segmented pipelines

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ABSTRACT

This paper deals with surface wave propagation (WP) effects on buried segmented pipelines. Both simplified analytical model and finite element (FE) model are developed for estimating the axial joint pullout movement of jointed concrete cylinder pipelines (JCCPs) of which the joints have a brittle tensile failure mode under the surface WP effects. The models account for the effects of peak ground velocity (PGV), WP velocity, predominant period of seismic excitation, shear transfer between soil and pipelines, axial stiffness of pipelines, joint characteristics, and cracking strain of concrete mortar. FE simulation of the JCCP interaction with surface waves recorded during the 1985 Michoacan earthquake results in joint pullout movement, which is consistent with the field observations. The models are expanded to estimate the joint axial pullout movement of cast iron (CI) pipelines of which the joints have a ductile tensile failure mode. Simplified analytical equation and FE model are developed for estimating the joint pullout movement of CI pipelines. The joint pullout movement of the CI pipelines is mainly affected by the variability of the joint tensile capacity and accumulates at local weak joints in the pipeline.

1. Introduction

Buried pipelines constitute a key component of critical lifeline systems, such as water supply, gas and liquid fuel, sewage disposal, electricity supply, telecommunication. Soil-structure interaction triggered by seismic waves has an important effect on pipeline behavior, and when integrated over an entire network of pipelines, on system performance (O'Rourke, 2010). Surface waves are generated by the reflection and refraction of body waves at the ground surface. Surface waves can be more destructive to buried pipelines than body waves by generating larger ground strain caused by their low phase velocity. Severe damage to buried pipelines generated by the surface wave propagation (WP) effects has been documented during previous earthquakes, e.g. the 1985 Michoacan earthquake in Mexico City (Ayala and O'Rourke, 1989). Soil-structure interaction analyses of surface WP effects on buried pipelines have practical significance for both pipe damage estimation and system response evaluation of critical lifelines.

Buried pipelines can be categorized into continuous pipelines (e.g. steel pipelines with welded slip joints) and segmented pipelines (e.g. jointed concrete cylinder pipelines (JCCPs) and cast iron (CI) pipelines). Observations from previous earthquakes show that the principal failure mode of segmented pipelines is axial pullout at joints (O'Rourke and Liu, 2012).

The WP effects on buried segmented pipelines have received extensive attention in the past decades. Wang (1979), Iwamoto et al. (1984), El Hmadi and O'Rourke (1990), O'Rourke et al. (2004), and O'Rourke and Liu (2012) proposed different models for analyzing the interaction of segmented pipelines with WP. Previous research showed that the ground strain induced by WP along segmented pipelines is accommodated by a combination of pipe strain and relative axial displacement at pipe joints. Since the axial stiffness of pipe barrels is typically much larger than that of the joints, the ground strain results primarily in relative displacement of joints, and the maximum joint displacement can be approximately estimated by multiplying the maximum ground strain and the pipe segmental length.

This paper deals with the surface WP effects on buried segmented pipelines, including the JCCPs composed of joints with brittle tensile failure mode, and CI pipelines composed of joints with ductile failure mode. Both analytical and finite element (FE) models are developed for estimating the joint pullout movement of JCCPs and CI pipelines under the surface WP effects. Following the Introduction, the surface wave characteristics are briefly described in Section 2. Sections 3 and 4 present the models for the surface WP effects on JCCPs and CI pipelines, respectively. In Section 5, the conclusions are made.

2. Surface wave characteristics

In general, there are two types of seismic waves, i.e. body and surface waves. Surface waves are generated by the reflection and

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refraction of body waves, and travel along the ground surface. Two major types of surface waves are Love (L-) and Rayleigh (R-) waves. The R-waves generate alternating compressive and tensile axial strains along pipelines. The L-waves generate bending strains in pipelines that are typically 2–3 orders of magnitude less than the axial strains induced by R-waves (O'Rourke and Liu, 2012). Thus this paper focuses on the R-wave effects.

Body wave reflection and refraction in large sedimentary basins (several km wide with soil depths $\leq$ 1 km) can cause R-waves that amplify the ground motion significantly (Papageorgiou and Kim, 1993). The amplification effects can be demonstrated by the strong motion records, as shown in Fig. 1, at station Central de Abastos—Oficinas, located in the sedimentary basin in Mexico City where the surface waves were generated during the 1985 Michoacan earthquake (Ayala and O'Rourke, 1989). Fig. 1 shows that the peak ground velocity (PGV) was typically lower than 20 cm/s during the first 60 s of excitation which was primarily affected by the body waves, while the PGV went up to be higher than 30 cm/s between 60 s and 90 s of excitation which was primarily generated by the surface waves. The surface waves were similar to sinusoidal waves with similar amplitude and predominant period that can be estimated as about 3.5 s based on the time-history records. The phase velocity of the surface waves was estimated as 120 m/s corresponding to the predominant period of 3.5 s based on the dispersion curves developed for this station by Ayala and O'Rourke (1989).

The seismic loads on buried pipelines imposed by WP are typically characterized by ground strains, ε_g, calculated as the ratio of ground particle velocity, V, to apparent WP velocity, C_a, i.e. $\varepsilon_g = V/C_a$ (Newmark, 1967). For surface waves, C_a is equal to the phase velocity, C_{ph}, since surface waves travel along the ground surface. To calculate the ground strain along the axial direction of a pipeline, it is necessary to resolve the ground particle and apparent WP velocities into components parallel to the pipeline axis. For a pipeline orientated at an angle, α, with respect to the particle velocity, V, as shown in Fig. 2, the ground strain along the pipe axial direction can be calculated as

$$\varepsilon_g = \frac{V\cos\alpha}{C_a/\cos\alpha} = \frac{V}{C_a}\cos^2\alpha = \frac{V}{C_{ph}}\cos^2\alpha \quad (1)$$

The ground strain along the pipe axis reaches its maximum, V/C_{ph}, when the pipeline is parallel to the ground particle and phase velocities of surface waves.

3. Surface wave propagation effects on JCCPs

The JCCPs are typically composed of reinforced concrete and steel cylinders that are coupled with mortared, rubber gasket bell-and-spigot joints. Severe damage to JCCPs has been documented during previous earthquakes. For example, Ayala and O'Rourke (1989) reported that there were 60 repairs, concentrated at the joints, in Federal District JCCP transmission lines, resulting in a relatively high repair rate of 1.7 repair/km after the

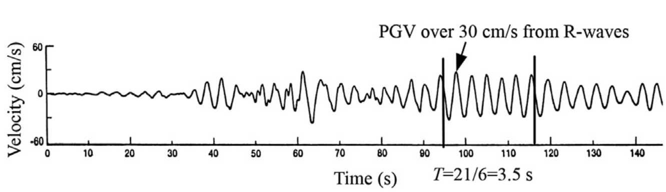

Fig. 1. Strong motion velocity histories during the 1985 Michoacan earthquake (modified from Ayala and O'Rourke, 1989).

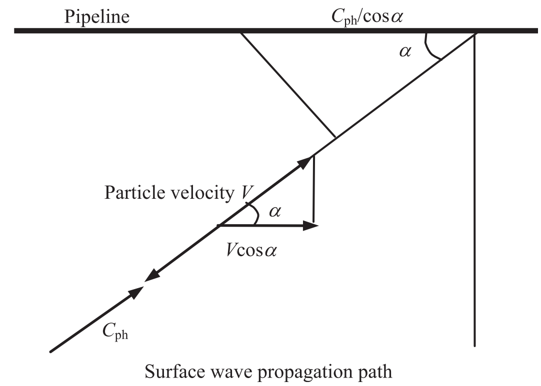

Fig. 2. Resolution of particle and phase velocities along the pipeline axial direction for R-waves.

1985 Michoacan earthquake. They further pointed out that the water system damage was primarily caused by the seismic WP effects.

The performance of JCCPs is affected by rubber-gasket bell-and-spigot connections. Fig. 3 shows an as-built drawing of a JCCP joint. The rubber gasket is often 18–22 mm wide when compressed to form a water-tight seal. Cement mortar is poured in the field to further seal the joint. The pullout capacity of the joints relies on the tensile resistance of the cement mortar which has a very low tensile strain limit, ranging from 0.00005 to 0.00015 (Avram et al., 1981). When the tensile strain limit is exceeded, the cement mortar cracks and the joint tensile capacity drops to almost zero, resulting in a brittle tensile failure mode. Furthermore, it is not uncommon for the mortar at the JCCP joints to be cracked and separated as a result of shrinkage during curing as well as subsequent operational loads and movement in the field. The pullout capacity of the joint, in terms of axial slip to cause leakage, depends on how much movement can occur before the rubber gasket loses its compressive seal. The design and as-built drawings examined by O'Rourke et al. (2004) show that axial movement between 15 mm and 60 mm is typically required to pull the gasket out of the horizontal portion of the bell into the flared end adjacent to the mortar filling. Most frequently, the slip capacity is 25 mm.

3.1. Surface wave interaction with JCCPs

O'Rourke et al. (2004) developed both FE and analytical models for estimating the axial strain in a continuous pipeline and relative displacement of an unrestrained joint under seismic

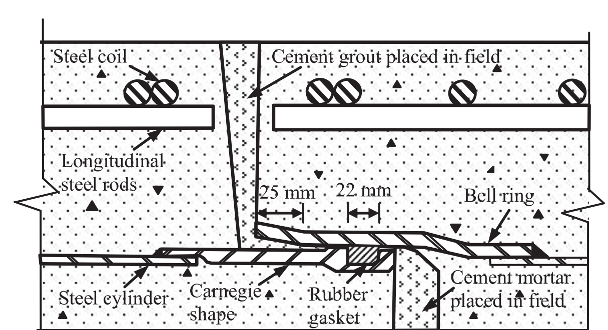

Fig. 3. Schematic view of JCCP joint.