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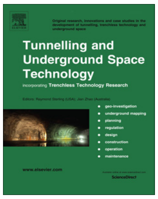

Post-failure fracture angle of brittle pipes subjected to differential ground movements

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ABSTRACT

Centrifuge testing of four glass pipe models has been used to measure the kinematics associated with cast iron pipe fracture and the relative rotation of the pipeline on either side of the fracture when fracture is induced by a normal ground fault. The model pipelines were fabricated at 1/30th scale using solid glass rod of semi-circular cross-section. After placing each model against the transparent sidewall of a test box, the pipe was buried and the tested at 30 g. Movements of the soil and the model pipe were monitored using particle image velocimetry, and analysis was used to examine both the curvature distributions before fracture, the fracture pattern (i.e. the fracture locations) expected for cast iron pipes passing across a normal ground fault, and the post-test rotations across the fractures. The depth of soil cover was observed not to make a significant difference to the amount of initial fracture angle for the range of covers investigated in this study (1.125–2.25 m in prototype scale). The fracture angle was shown to be well represented by the slope of the pipe displacements at the inflection point. The use of normalized peak curvature to estimate the fracture angle (rotation across the fracture) was demonstrated. The estimated magnitude of rotation after the pipe breaks can then be used to estimate the local stresses and strains that would develop in a polymer liner inserted within the cast iron pipeline before fracture initiates and which is therefore subjected to longitudinal bending stresses after the cast iron pipe fractures, values of 'demand' that can then be evaluated against measurements of liner strength (i.e. its stress and/or strain limits). The initial angle of rotation directly across the fractures after they form is approximately the same regardless of when the pipe initially breaks, and regardless of the soil cover depth and soil density. However, the magnitude of the vertical ground displacement across the normal fault needed to induce fracture varies considerably for the different burial conditions that were considered, and the rotation angle increases steadily after fracture if the amount of vertical ground displacement continues to grow.

1. Introduction

Most of the water mains installed in North America during the first half of the 20th century were cast iron. Statistics of the performance limits of these pipes show that an average of 70% of water main breaks are circular (Rajani et al., 1996), also known as circumferential or ring fractures. Circular fractures are mostly the result of longitudinal bending that occurs as a result of differential ground movements due to frost action (Trickey and Moore, 2005), construction effects associated with static pipe bursting (Cholewa et al., 2009; Shi et al., 2013) or tunneling (Klar et al., 2008), reactive soils (Gallage et al., 2009), soil liquefaction (Takada et al., 2001), or strike-slip fault rupture (O'Rourke, 2009). The crack initiation risk for cast iron pipes increases with their age as a result of corrosion (O'Day et al., 1986 and Seica and Packer, 2004). One of the challenges engineers are facing these days is the repair and rehabilitation of these aging pressure pipes. One rehabilitation method available for this purpose involves the use of polymer liners. However, it is not expected that a polymer liner will provide additional strength sufficient to resist the development of circular fractures (since the polymer modulus is low compared to the cast iron).

After the old pipe has ruptured, the ring fracture will open at the top or bottom as one segment of cast iron pipe rotates relative to the other. If a liner has been installed, it will need to resist the strains that develop where it spans across a pipe fracture that

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permits rotation (e.g. Allouche et al., 2005; Brown et al., 2014). Consideration needs therefore to be given to liner design so that it has the ability to resist the longitudinal stress and strain induced where it crosses a ring fracture. Provided the magnitude of expected rotations can be established, the local stresses and strains that develop can be evaluated against measurements of liner strength like those provided by Brown et al. (2008). However, currently there is no experimental or analytical data available in the literature for predicting the angle of rotation that develops across the pipe fracture.

Given that the timing and location of fracture events in the field is hard to predict, the majority of experimental data to date regarding other soil-pipeline interaction phenomena has come from physical model tests. Due to the inherent scale effect associated with testing reduced-scale models (Guo and Stolle, 2005), tests need to either be performed at full scale (e.g. Takada, 1984; Trautmann and O'Rourke, 1985) or using the centrifuge modeling technique in which tests have been successfully performed to investigate offshore problems (e.g. Dingle et al., 2008) and onshore issues such as tunnel-pipeline interaction (e.g. Marshall et al., 2010), and the behaviour of continuous (e.g. Bransby et al., 2007; Ha et al., 2008) and jointed pipelines (Saiyar et al., 2015) crossing faults with different patterns of permanent ground motion. However, no experimental study to date has addressed the quantification and prediction of post-failure fracture angle. The objective of this paper is to address this lack of data by using the centrifuge modeling technique to induce curvature and measure fracture angles in pipelines subject to normal faulting permanent ground motion. As the angle of rotation at failure is an important input in liner design, an approach for estimating the fracture angle is developed and the calculated fracture angles are compared to the experimental data.

2. Centrifuge modeling of pipe fracture under normal faulting

Using the 11 m diameter geotechnical centrifuge testing facility at C-CORE, Newfoundland and Labrador, Canada (Phillips et al., 1994), a series of small-scale tests were conducted at acceleration of 30 times normal gravity so that all length dimensions were reduced by a factor of 30 relative to full scale.

The test geometry is illustrated in Fig. 1. The centrifuge strong box which held the model containing soil, pipe, and the actuator had plan dimensions of 300 mm × 900 mm. The elevation of the pipe was kept constant (100 mm) for all tests. To study the effect of the soil cover (distance from the pipe centreline to the soil surface), three different soil covers were tested: 37.5 mm, 50 mm, and 75 mm. The test soil was Fraser River Delta sand with specific gravity of 2.71, uniformity coefficient of 1.88, coefficient of curvature of 0.92, mean grain size, D_{50}, of 0.26 mm, effective grain size, D_{10}, of 0.17 mm, maximum void ratio, e_{max}, of 0.94, and minimum void ratio, e_{min}, of 0.62 (Wijewickreme et al., 2005). Sand pluviation was used to prepare the soil sample. The sand pouring apparatus was calibrated to achieve the relative densities of 80% and 60%. Standard density of 80% was used for all tests except for one test in which the soil above the pipe elevation had density of 60% to model the loose backfill condition (Table 1).

To simulate a normal fault, two hydraulic cylinders were installed on one side of the box and under the supporting base. The cylinders were pressurized up to 6.9 MPa to their maximum stroke of about 12.7 mm before pouring sand and preparing the model. During the test at 30 g, the base plate was dropped down step by step by discharging the hydraulic oil from the cylinders. The amount of discharge was controlled by the amount of time the cylinder valve was kept open. Two linear position transducers (LPs) were installed below the translating floor to measure the

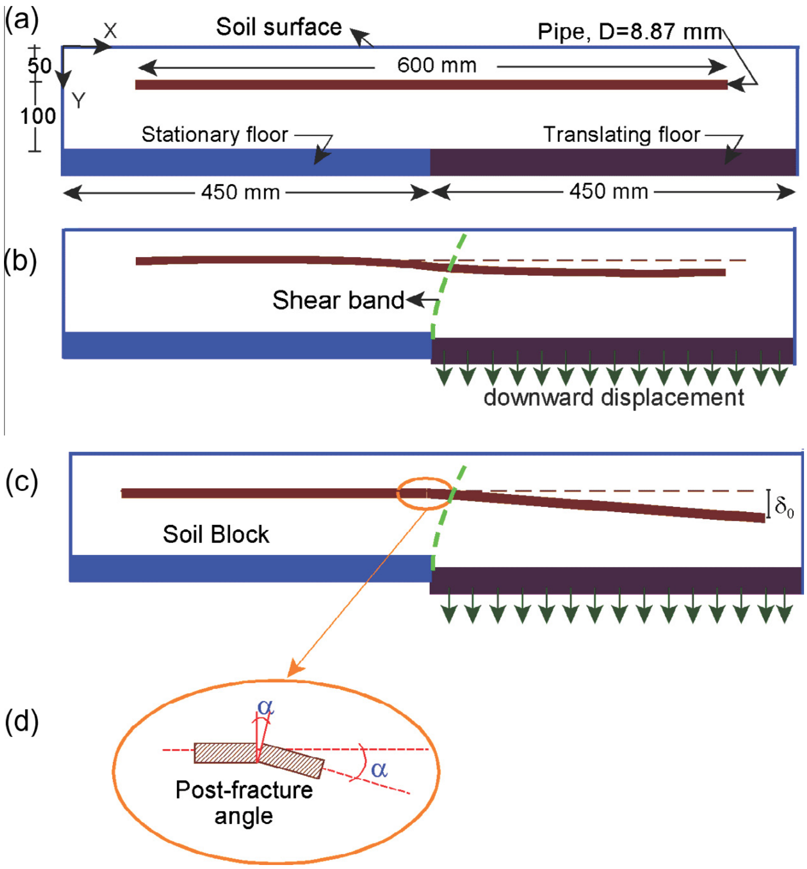

Fig. 1. Test geometry (dimensions in mm): (a) pipe initial position; (b) pre-fracture behaviour and (c) Post-fracture behaviour; definition of post-fracture angle.