International No-Dig 2010
28th International Conference and Exhibition

Singapore
8-10 November 2010

Paper #43

JOINTED PIPELINE SUBJECTED TO DIFFERENTIAL GROUND MOVEMENTS

Masoumeh Saiyar[1], Ian D. Moore[1], and W. Andrew Take[1]

[1]GeoEngineering Centre at Queen's - RMC, Queen's University, Kingston, ON Canada

ABSTRACT: One of the major causes of cast iron water pipeline failure is excess bending moments resulting from differential ground movement due to either frost, reactive soil, reverse fault rupture, or liquefaction. Liners inserted within these structures may need to be designed considering the strains that develop where the liner spans the joint or ring fractures that develop after the liner is installed. Although cast iron water pipes are usually built using discrete sections jointed together with semi-rigid or flexible joints, the difficulties associated with modeling the joints has limited the study of these types of failures to theoretical investigations or experimental work on continuous pipelines. This paper reports on reduced scale centrifuge testing of pipes simulating jointed cast iron pipes subjected to differential ground movements. To avoid difficulties and complexities associated with joint modeling and properties in a centrifuge test, a simplified joint model with representative flexural properties was used. Image processing techniques have been applied to observe the deformation profile of the pipe and consequently assess rotation at joints. A simplified conservative joint rotation calculation is also reported.

1. INTRODUCTION

A number of procedures have been developed for repair of pressure pipes using polymer liners, and researchers have identified various potential limit states that need to be considered during design of such systems (e.g. Allouche et al., 2005). North American design practice outlined in ASTM F1216-07b examines liner ability to resist internal pressure for two conditions

i. No support provided to the outside surface of the liner by the old water pipe, so that simple hoop tension develops in the liner, and
ii. Continuous external support provided by the old water pipe, except where the liner spans across circular perforations

However, other loading conditions may also result in failure of the liner, and one of those is the focus of the present study (limit state denoted LS4 by Allouche et al. 2005, as defined in Figure 1). Many failures of cast iron water pipes involve development of ring fractures, generally as a result of longitudinal bending caused by differential ground movements, movements associated with

a. frost, Trickey and Moore (2005)
b. reactive soils, Gallage et al. (2009)
c. Soil liquefaction or reverse fault rupture, O'Rourke (2009).

NEXT PAGE

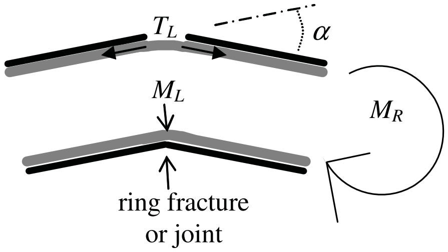


Figure 1. Kinematics of liner design limit state LS4 of Allouche et al. (2005); rotation angle α is defined.

Since it is not expected that a polymer liner will provide any additional strength to resist those fractures (since the polymer modulus is low compared to the cast iron), ring fractures may occur during the service life of the repaired water pipe. 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, Figure 1. Alternatively, liners may span across a pipe joint that permits rotation. Consideration is therefore being given to liner design so that it has the ability to resist the longitudinal stress and strain induced where it crosses a ring fracture or joint experiencing rotation. 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).

Centrifuge tests conducted at 1:30 scale are being used to measure the magnitude of rotations α, so these can be used as input to liner design. The centrifuge experiments are described, as are the processes used to model a jointed cast iron water pipe. One set of measurements is provided, quantifying rotation angle for one specific pattern of joints and differential ground movements. The resulting rotations provide a preliminary idea of the magnitude of rotations that need to be considered during design.

2. CENTRIFUGE TEST

Geotechnical centrifuge testing involves small scale modeling of the ground system, say at reduced scale of 1:*N*. Since the strength and stiffness of soil is a direct function of the earth pressures that are acting, it is important to reproduce the same stress conditions as would be expected at prototype scale. This is achieved by undertaking the testing at acceleration of $N g$ (where g is the acceleration due to earth gravity, 9.8 m/s^2). The tests described here were all performed at 30 g (i.e. N=30).

Figure 2 shows the test box used in the experiments. The box has length of 900 mm, height of 450 mm and width of 300 mm. Also shown are the three digital SLR cameras (Canon EOS G7) used to capture images through the front face of the box which is transparent.

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
- minimum void ratio, e_{min}, of 0.62.

Sand pluviation was used to prepare the test sand with a relative density of 80%.

Figure 3 shows a close-up view of the pipe used to represent the jointed pipe. One half of a solid aluminum pipe of diameter D of 9.525 mm was prepared, and cut into segments of length 100 mm. These segments were joined by a series of steel rods (UNC#2) with a distance of 5 mm left between the ends of consecutive pipe segments, Figure 3. The steel rod was chosen so as to provide a ratio of longitudinal bending stiffness of the joint to that of the pipe of about 10% .

The pipe model was selected so that the longitudinal bending stiffness of the pipe to the soil $EI_{pipe}/EI_{soil}=1300$ was similar to that for a cast iron pipe buried in silty backfill, where $EI_{soil}=E_{soil}\pi D^4/64$. A total of six joints were prepared along the aluminum test pipe.

This model pipe was used so that the vertical cross-section (parallel to the vertical diameter of the pipe) could be placed against the transparent front wall of the test box, and its movements tracked in a series of digital images.

The test pipe was buried at a depth of 50 mm from the ground surface, and a total height of 100 mm above the elevated base of the box. The base was split into two 450 mm long halves (subsequently denoted left and right hand halves consistently for all illustrations of the apparatus and results):

a. The left hand half held at fixed elevation
b. The right hand half supported on two jacks, that can be controlled during centrifuge operation ('in-flight') to prescribe different levels of base movement down from its initial elevation

As the right hand half of the base is moved downwards, differential ground movements occur in the soil surrounding the pipeline, and these result in rotation of some of the pipe segments, and angular movements across the joints connecting them.

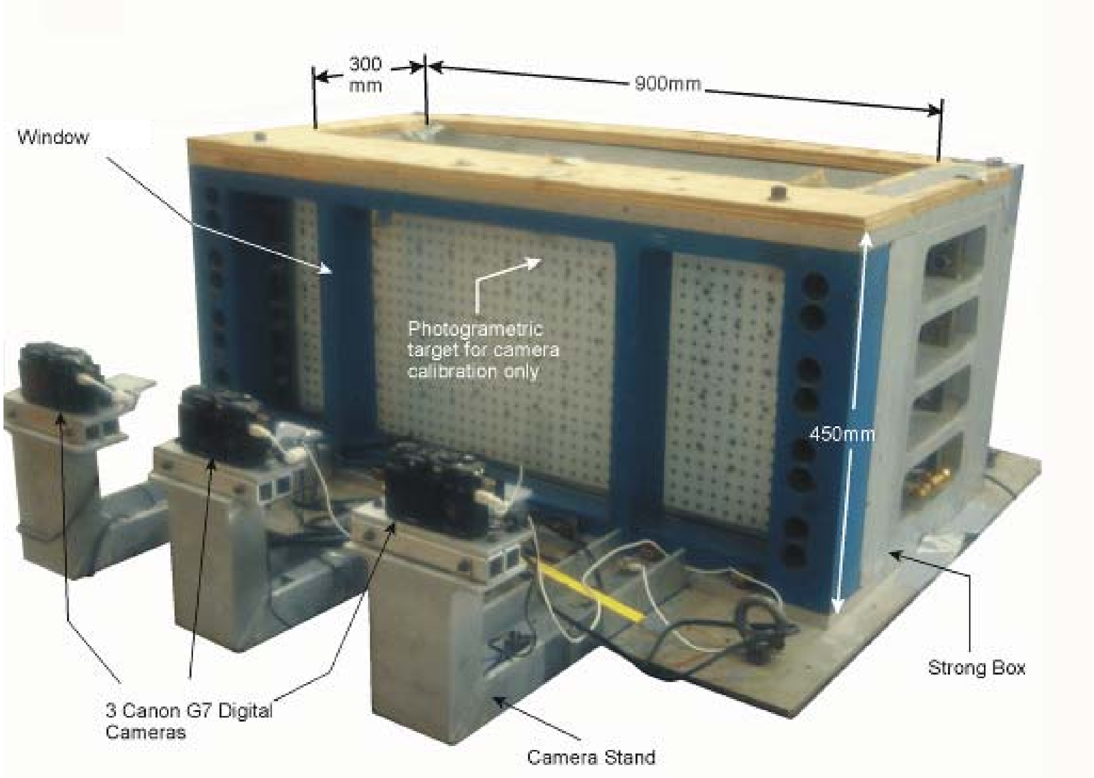
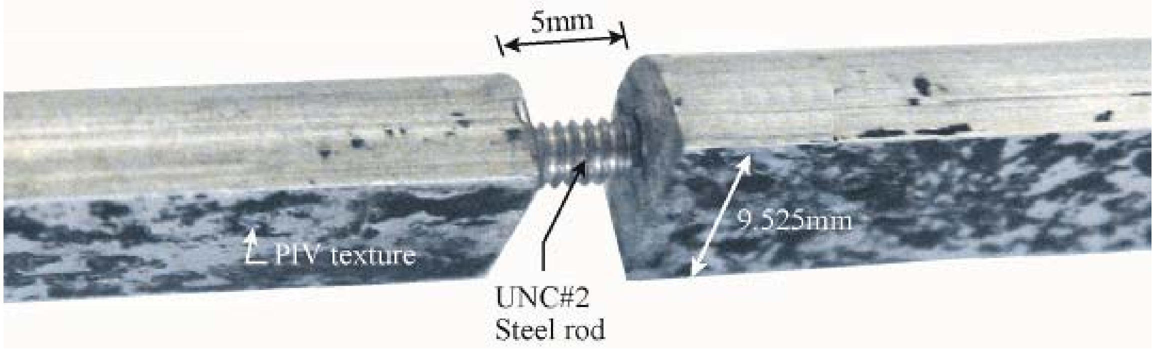
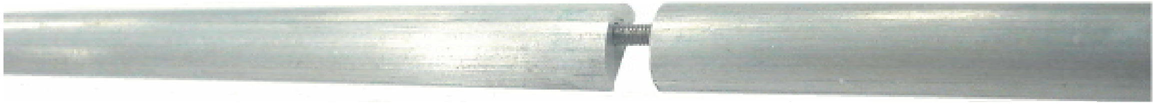


Figure 2. Test box for the C-CORE centrifuge; arrangement of cameras for capturing digital images for post-processing using Particle Image Velocimetry.



a. Close-up showing textured 'diameter' and the steel rod used to model joint stiffness



b. A larger view of two segments of aluminum half-pipe and the steel rod representing the joint.

Figure 3. Detail showing joint between aluminum half-pipes; image also shows painted texture on the pipe centreline for tracking with Particle Image Velocimetry.

NEXT PAGE

The flat surface of the half-pipe was painted with a texture, permitting use of Particle Image Velocimetry (PIV), as developed by White et al. (2003). This enabled the deflections of the pipe to be determined from the series of images collecting during the experiment (an example is shown in Figure 4).

Figure 5 summarizes the test data where base movement was almost 8 mm. First, it shows the distribution of vertical soil movements captured at the position where the pipe was to be located, but in a preliminary test where no pipe was present (denoted the free-field response Δy_{soil}, Figure 5a). Next, it provides the distribution of vertical movements determined along the pipe, Δy_{pipe}, Figure 5b. Lastly, it provides the pattern of pipe movements relative to the soil, Δy_{pipe}- Δy_{soil}, Figure 5c. These results indicate that:

a. the soil response Δy_{soil} features shear zone in the soil where differences in vertical ground movement concentrate between axial positions 420 and 495 mm
b. the vertical pipe response is distributed between axial positions 370 and 590 mm
c. the pipe largely responds as a series of straight-line segments between joints, with most of the curvature concentrated at three of the joints (those at axial positions 370, 480, and 590 mm).

Figure 6 provides angles of rotation between consecutive pipe segments (across each of the six joints), plotted relative to the axial positions of each of the joints (positive rotation angle is associated with positive change in slope). This clearly shows that most of the rotation was focused in three of the joints 3.3, -2.3, and -1.2 degrees. The remaining 0.2 degrees of rotation is distributed amongst the other three joints (if curvature in the pipe segments is neglected and if the end segments of the pipe remain horizontal, then the total sum of the joint rotation angles should be close to zero).

Now, the base movement imposed here is approximately 80% of the pipe diameter. For a 200mm (8 inch) cast iron pipe, this represents 160mm, a believable value of vertical pipe movement associated with the action of frost, or of moisture change in reactive soils. The rotation angles seen in these experiments, therefore, could occur in real jointed pipes responding to differential ground movement.

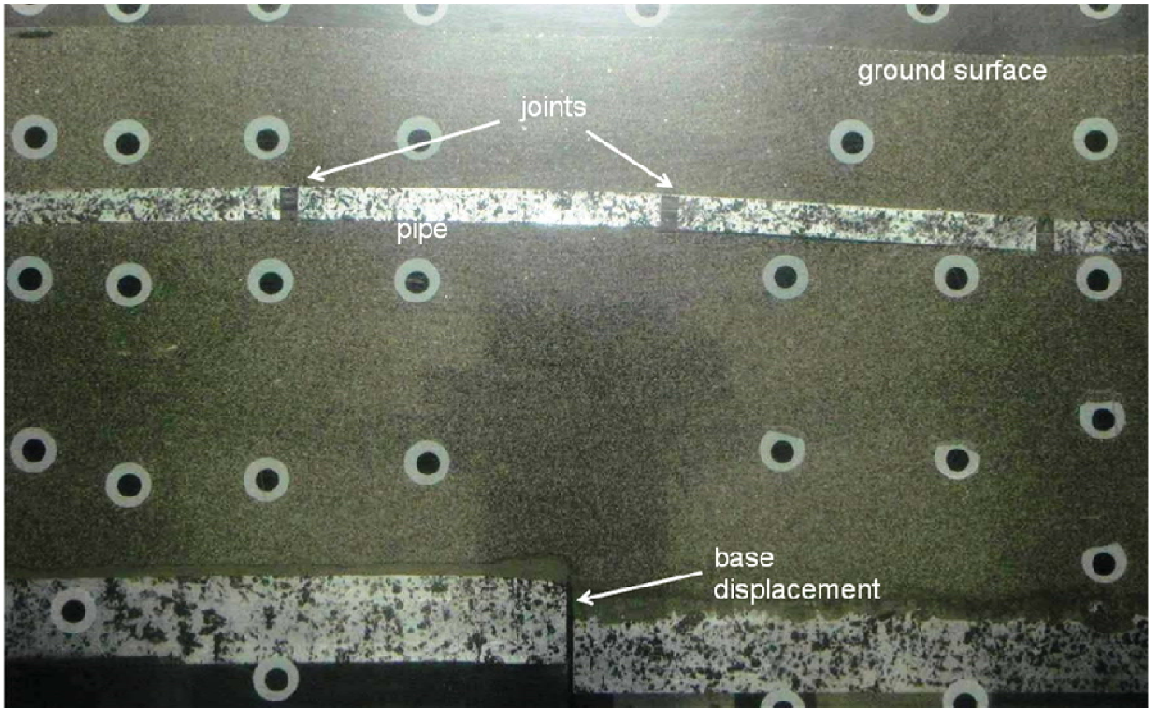
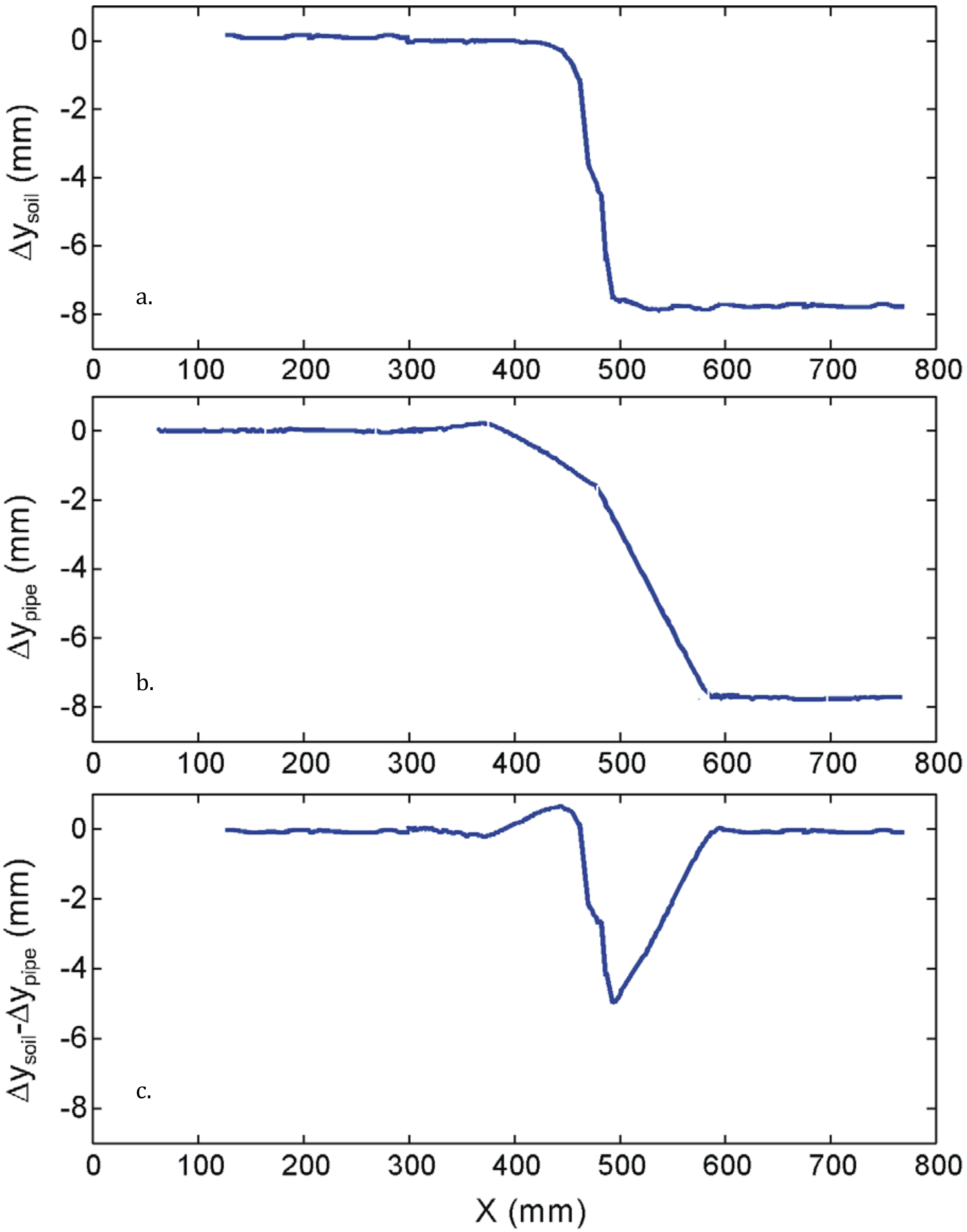


Figure 4. Image captured through the transparent side of the centrifuge test box showing the jointed pipe, the ground surface, the movable base, and the painted textures tracked by PIV.



a. Free field response of soil. b. jointed pipe response, and c. displacement of soil relative to pipe.

Figure 5. Response of aluminum test pipe with joint of length 5 mm; results are presented for differential base movement δy of 7.846 mm.

NEXT PAGE

3. SIMPLIFIED ESTIMATE OF ROTATION ANGLE

An assessment of the kinematics shown in Figure 5 indicates that a simplified, conservative estimate of the maximum angle of joint rotation results when there is one single segment of pipe that is not horizontal (assuming that rotations of $+\alpha$ and $-\alpha$ occur on each end of that single segment, Figure 7).

For the case examined in Figures 4 to 6, the angle of rotation can be assessed from the simplified geometry shown in Figure 7 as

$$\alpha = \sin^{-1}(\delta y/L) = \sin^{-1}(7.846/100) = 4.5 \text{ degrees.} \qquad [1]$$

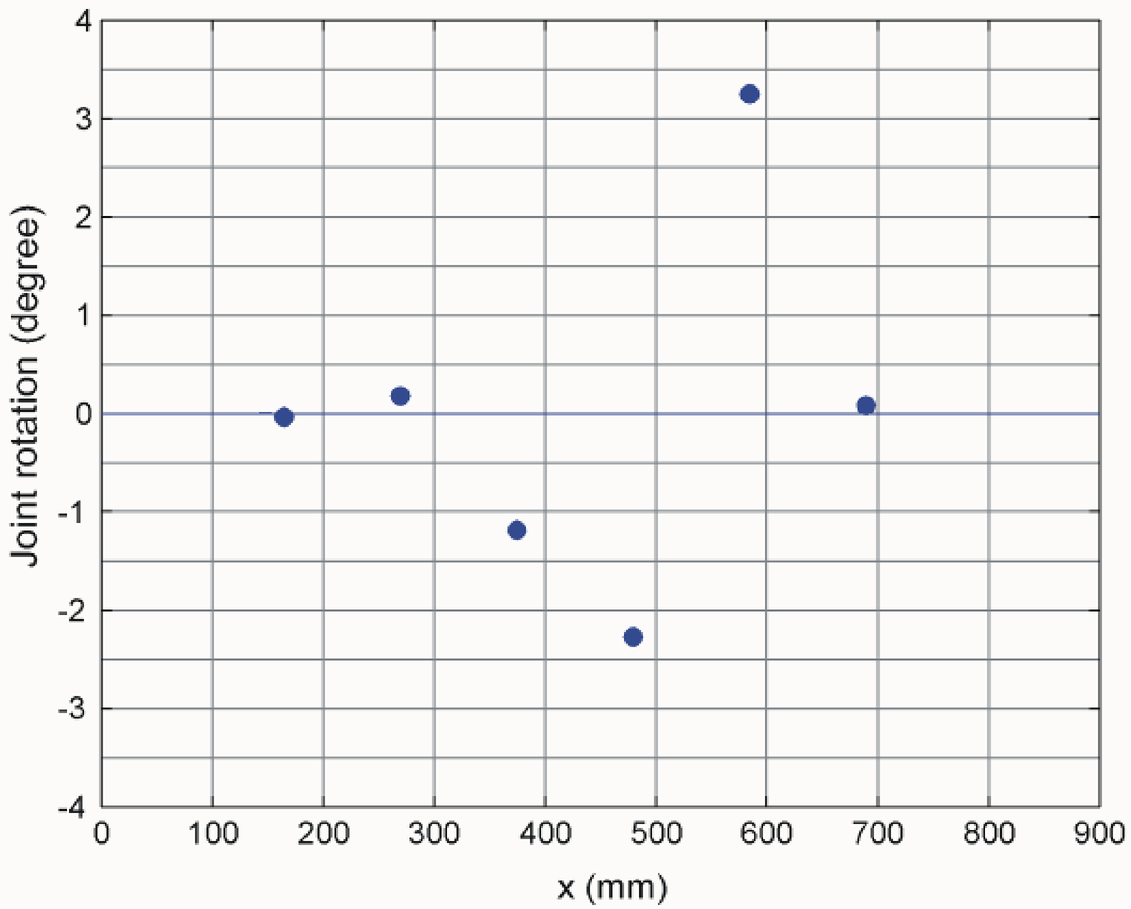


Figure 6. Joint rotations in aluminum test pipe with joint of length 5 mm length and base movement δy of 7.846 mm.

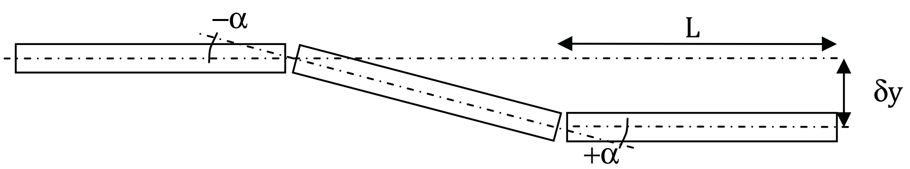


Figure 7. Simplified kinematic model to estimate maximum potential angle of joint rotation (pipe length between joints of L; elevation difference of δy; rotation angles of $+\alpha$ and $-\alpha$).

NEXT PAGE

This is 38% higher than the value measured in the centrifuge experiment where the differential ground movement was actually accommodated with significant rotations at 3 joints (rather than the two assumed in the simplified model), and where some curvature did develop in the model pipe segments. The value of joint rotation obtained from equation (1) appears to be a reasonable and conservative estimate.

Strains in the polymer liner as a result of these rotations are still to be estimated. Work is underway to examine interaction between the liner and the host pipe for a set value of rotation across a joint or new ring fracture.

4. CONCLUSIONS

It is well known that joints are introduced into pipelines to release moments associated with the longitudinal bending that results from differential ground movement. However, there has been almost no data on rational positioning of joints with respect to the ground deformations, or the magnitude of the expected rotations that result. A scale model was therefore developed for a jointed pipe, and tested at 30 *g* in a geotechnical centrifuge. This has established the pipe kinematics for one specific case of differential ground movement.

The maximum angle of rotation measured across any specific joint in the model pipe was 3.3 degrees. A simplified expression for joint rotation was developed by assuming that just one segment of the jointed pipeline would experience rotations and cease being horizontal. An estimate of the maximum angle of joint rotation was made on that basis, and it provided an estimate of rotation angle that was 38% higher than the observed value. Until more sophisticated methods are available to estimate this variable, this simple approach is useful as a measure of expected joint rotation for specific input values of differential ground movement.

5. ACKNOWLEDGEMENTS

This research was conducted using Discovery Grant support to Drs Moore and Take from the Natural Sciences and Engineering Research Council of Canada, in addition to a Major Resources Support grant to Dr Take and various collaborators for access to the C-CORE centrifuge. The assistance of Ryan Phillips, Gerry Piercey, Don Cameron and Derry Nicholl at C-CORE as the tests were conducted is gratefully acknowledged.

6. REFERENCES

Allouche, E.N., Bainbridge, K. and Moore, I.D. (2005) Laboratory examination of a cured in place pressure pipe liner for potable water distribution system, *No-Dig 2005*, Orlando, Florida, April 24-27, 2005.

ASTM F1216-07b Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube, *ASTM International*, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA

Brown, M., Fam, A. and Moore, I.D. (2008) Material characterization of a composite polymer liner for rehabilitation of pressure pipelines, *Polymer Engineering and Science*, Vol. 48(7), 1231-1239.

Gallage, C. and Chan, D. and Gordon, S.R. and Kodikara, J. (2009) Behaviour of an in-service cast iron water reticulation pipe buried in expansive soil In: Ozwater '09 : Australia’s National Water Conference and Exhibition, 16-18 March, 2009, Melbourne, Victoria.

O`Rourke, T.D. (2009). Geohazards and large, geographically distributed systems, *Géotechnique*, Volume 60, Issue 7, pages 505 –543.

Trickey, S.A. and Moore, I.D. (2005) Numerical study of frost-induced ring fractures in cast iron water pipes, *Canadian Geotechnical Conference*, Saskatoon, September, paper number GS665, 8pp.

White D.J., Take W.A. and Bolton M.D. 2003. Soil deformation measurement using particle image velocimetry and photogrammetry. *Géotechnique* 53 7:619-631.

TO INDEX