Physical modeling of gap formation during soil-pipeline interaction

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ABSTRACT
The paper presents the results of centrifuge tests on reduced scale models of continuous pipes examining the soil-pipe interaction under normal faulting. Both pipe and soil displacements were measured using Particle Image Velocimetry (PIV).The semi-cylindrical pipe was placed at the Perspex wall of the centrifuge strong-box, so that digital images could be taken during the test for PIV analysis. The detailed data of sub-surface soil and pipe displacements and the calculated pipe bending moments are provided. The observed gap formation beneath the pipeline and its effect on pipe bending is illustrated.

RÉSUMÉ
Le document présente les résultats d'essais en centrifugeuse sur des modèles à échelle réduite pour les tuyaux en fonte en examinant l'interaction sol-tuyau pour des défauts normaux. Les déplacements de tuyaux et de sol ont été mesurés au moyen de la technique de vélocimétrie par imagerie de particules (PIV). Le tuyau semi-cylindrique a été placé sur le mur de Plexiglas de la boîte de la centrifugeuse telle que les images numériques puissent être prises pendant l'essai pour l'analyse des PIV. Les données détaillées des déplacements du sol sous la surface et des tuyaux ainsi que les calculs des moments de flexion des tuyaux sont fournies. La formation d'une cavité observée sous le pipeline et ses effets sur la conduite en flexion de l'oléoduc sont illustrés.

1 INTRODUCTION

Municipal engineers across North America and beyond are making replacement and repair decisions for deteriorated cast iron water and gas pipes. Statistics of the performance of water mains in Ontario show that about 70% of water main breaks are circular (i.e. circumferential) breaks. These breaks are caused by excess bending moments resulting from transverse permanent ground deformation where soil movement is perpendicular to the pipe axis. Transverse ground deformation is either due to surface faulting, landslide, liquefaction induced lateral spread, settlement in non-uniform ground, frost heave, or tectonic uplift or subsidence. Unfortunately, crossing areas which are susceptible to permanent ground movement is often unavoidable for water pipelines to connect both supply and demand regions.

Pipeline response under permanent ground deformation is a function of the amount of permanent ground deformation, the shear zone width, and the shape of soil displacements. The soil deformation pattern is not completely known and is usually described by an assumed shape function. Response of continuous pipeline to specially distributed transverse permanent ground deformation in which the ground movement towards the center of the permanent ground deformation zone is larger than that close to the margins is well studied by Liu et al. (1997), O'Rourke et al. (1999), and others. However, the study of the behaviour of buried pipeline under localized abrupt permanent ground deformation is limited to some recent experimental work: Klar and Soga (2006), Bransby et al. (2007), Choo et al. (2007), Abdoun et al. (2008), and Ha et al. (2008). The non-linear soil-pipeline interaction is complex and makes numerical analyses difficult.

The current design of buried pipelines for permanent ground deformation hazard is usually based on finite element simulation following ASCE guidelines (1984). The soil resistance is modeled as a Winkler foundation and the soil-support to the pipe is typically idealized as an elastic-perfectly-plastic spring. The formation of gap (separation of the pipe from the ground) is often ignored. The Winkler model has the advantage of simplicity and ease of application; however, as part of this simplicity it does not account for the interaction through the soil from location to location or the formation of gaps. The properties of the elastic-perfectly-plastic springs suggested in the ASCE guidelines (1984) are inferred from bearing capacity theory for footings, and pull-out capacity theory and laboratory tests on anchor plates and model buried pipes (eg. Vesic, 1969; Rowe and Davis. 1982; and Trautmann and O'Rourke,1983). The aim of this paper is to present preliminary results from an investigation into the behaviour of buried pipelines subject to transverse ground displacement using the geotechnical centrifuge testing technique and PIV image processing methods to measure the soil and pipe displacements.

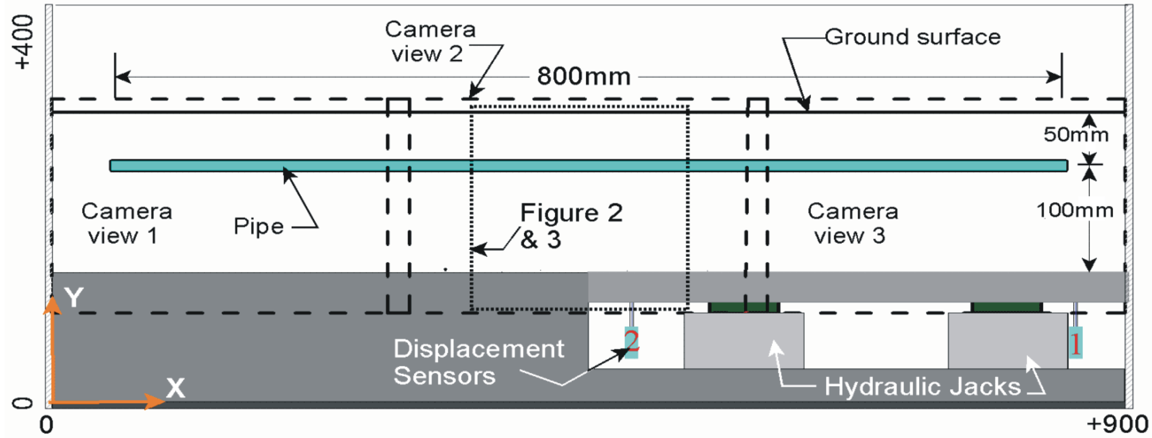

Figure 1. Test geometry (vertical section through the front face of the test box, parallel to the axis of the half-pipe).

2 CENTRIFUGE MODELING

Tests were carried out using the geotechnical centrifuge testing facility at C-CORE, NL (Phillips et al 1994). The test model geometry is illustrated in Figure 1. The centrifuge strong box which held the model containing soil, pipe, and the actuator had plan dimensions of 300 x 900 mm and was filled with soil to a depth of 150 mm. The front face of the box was made from Perspex to allow both pipe and soil displacements to be viewed. Tests were carried out at an acceleration of 30 times normal gravity so that all length dimensions were reduced by a factor of 30 relative to full scale.

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 test. Sand pluviation was used to prepare the soil sample with relative density of 80%.

The test pipe was a solid rod made of aluminium with diameter of 9.52 mm representing a 285 mm diameter cast iron pipe at full-scale. The pipe was split in half along its centre line to give a semi-circular cross-section. The pipe was then placed with the flat section in contact with the Perspex wall at elevation of 100 mm from the base plate.

Three 10-megapixel digital cameras were used to capture the entire visible view of the model. Particle Image Velocimetry (PIV) (White et al., 2003) was then applied to calculate the soil and pipe displacements.

To simulate the 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 have maximum stroke of about 12 mm before pouring sand and preparing the model test. During the test at 30g, the base plate was dropping 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. The PIV measurements of one step at model scale are presented in this paper. Two linear position transducers (LPs) were installed below the translating floor to measure the plate's displacement during the test. Further details on experimental model set up are reported by Saiyar et al. (2010).

3 EXPERIMENTAL RESULTS

Using the software developed by White et al. (2003), PIV analysis was performed for all three fields of view of the cameras. The results were then assembled to show the whole of the pipe deformation profile.

3.1 Free field soil test

A free field test in which no model pipe was included was performed first to measure the soil displacements. The free field test gives useful data regarding the effect of normal faulting on sand deformations. Figure 2 presents the soil displacement contours from PIV measurements at the given imposed vertical base displacement of 7.2 mm.

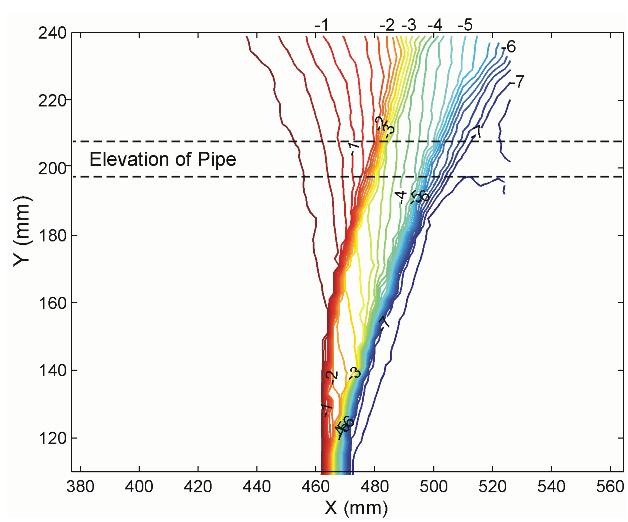

Figure 2. Soil displacement contours for the test without the half-pipe

The contours show the orientation of the shear zone in the sand and how it widens as it approaches the ground surface. This data indicates that the width of the zone of intense shearing at the elevation of the pipe is approximately 25 mm at model scale (0.75 m at prototype scale). The soil displacement at the pipe elevation is shown in Figure 3 (the half-pipe is not present in this free field test) for an imposed vertical fault displacement of 7.2 mm.

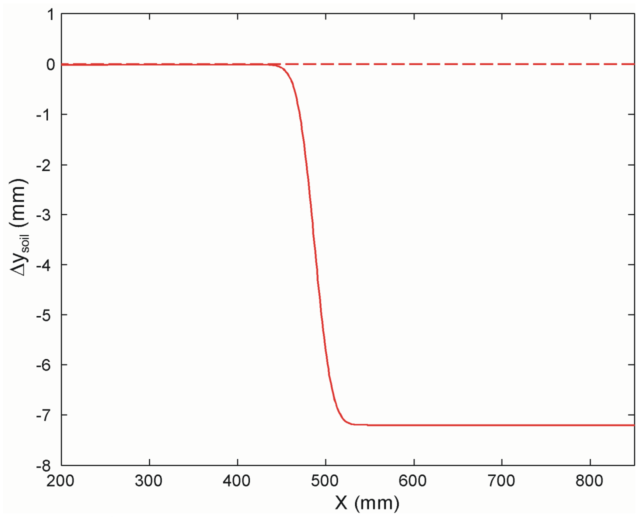

Figure 3. Soil displacements at pipe elevation in free field test

3.2 Pipeline test

Following the free field soil test, a second test was performed in which a soil model containing a model pipeline was subjected to the same imposed vertical base displacement of 7.2 mm. The 800 mm long model pipe was buried at depth of 50 mm from the ground surface. Considering the box length of 900 mm, the distance from the pipe ends to the box side walls was 50 mm and was chosen to prevent boundaries affecting the behaviour of the pipe. At full scale, this pipe represents a 285 mm (11¼”) diameter cast iron pipe with thickness of 10 mm which is buried at depth of 1.5 m from the ground surface.

Figure 4 presents the soil displacement contours for the pipe test at the given imposed vertical base displacement of 7.2 mm. As shown, the soil below the pipe experienced wider shear zone, especially near the pipe, while there is no obvious shear zone in the soil above the pipe. This is due to the bridging effect of the pipe on the overlying soil.

Figures 5 and 6 show the central part of the digital photographs taken before and after the test. Figure 6 clearly shows that a gap formed beneath the pipe during the test. When a gap forms below a pipeline, it is no longer supported along its invert in that area. This is of particular concern, since if influences the bending behaviour of the pipe under any future imposed loading conditions. Sometimes gap formation is considered in numerical analysis by setting the uplift capacity for the soil. However, there is no experimental data available in the literature regarding the loading conditions for which a gap forms beneath a pipeline crossing a normal fault.

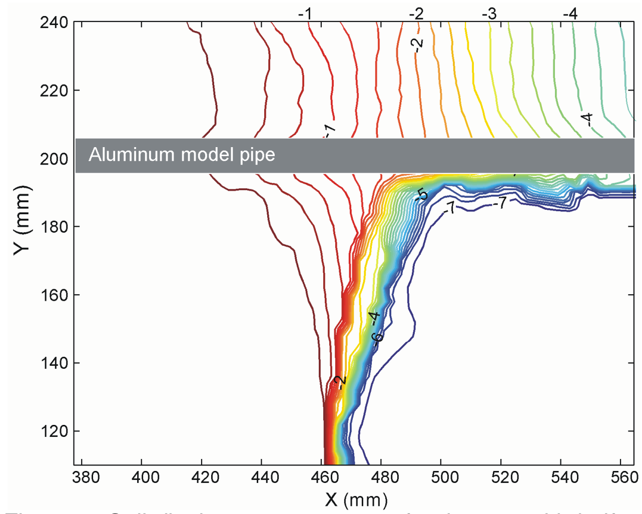

Figure 4. Soil displacement contours for the test with half-pipe

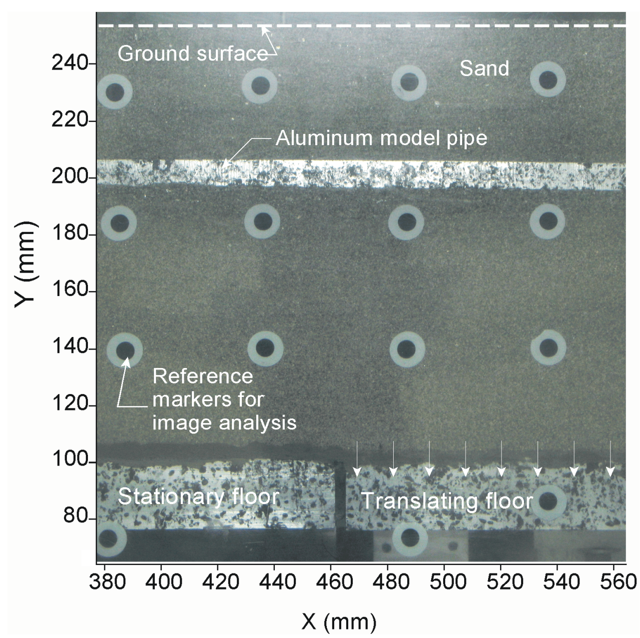

Figure 5. Digital photograph from central view of the test model before starting the test

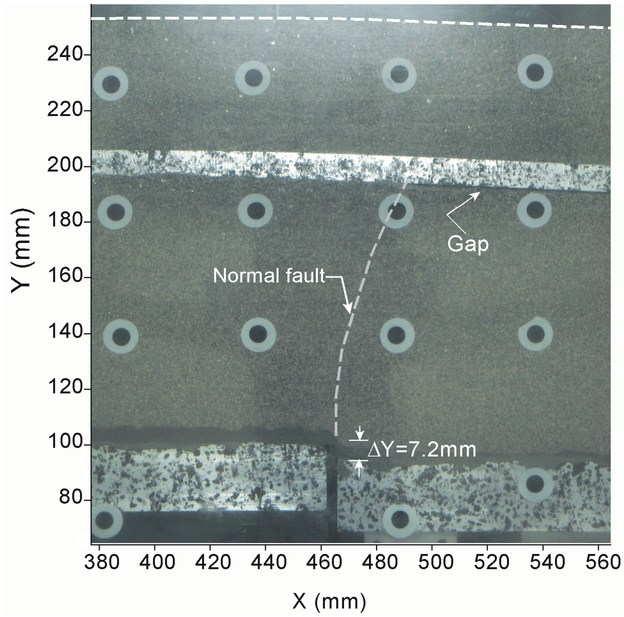

Figure 6. Digital photograph from central view of the test model after the test

The pipe displacement profile obtained from PIV analysis is presented in Figure 7. The relative soil-pipe displacement, $\Delta y = y_{soil} - y_{pipe}$, which is the vertical displacement of the pipe relative to the free-field vertical displacement of the soil is shown in Figure 8.

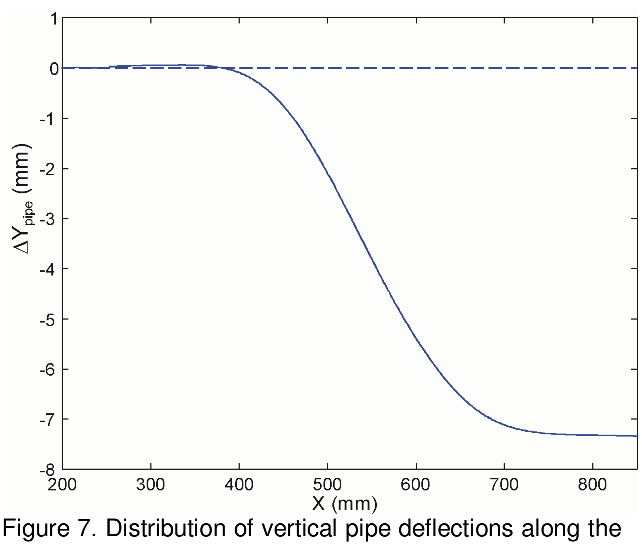

Figure 7. Distribution of vertical pipe deflections along the pipe

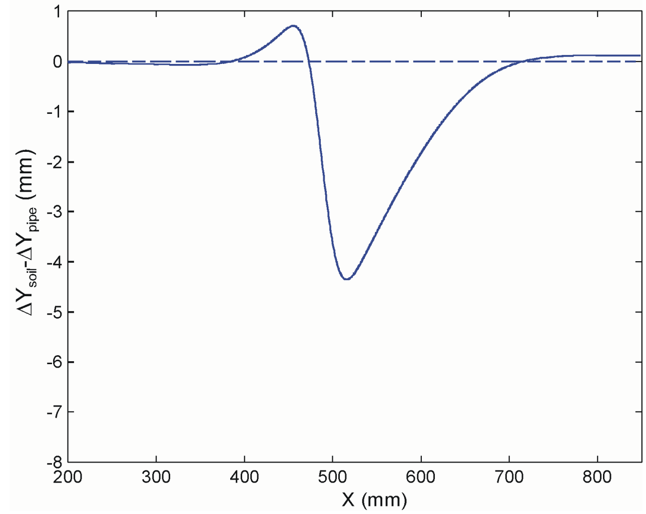

Figure 8. Distribution along the pipe of vertical pipe displacement relative to the soil

The distribution of pipe bending moments, M(x), along the length of the pipe was derived from beam theory (Equation 1) and the vertical displacement data of the pipe, y(x), obtained from PIV analysis.

$$M(x) = EI \frac{d^2y}{dx^2} \qquad [1]$$

where x is the horizontal axis illustrated in Figure 1, and EI is the flexural stiffness of the pipe. Because PIV data contains a small (but non-zero) noise content, any interpolation method that fits a curve passing through all PIV data points will provide a noisy curvature profile. To suppress the impact of this noise, a low-pass Butterworth filter with order of nine was used. The detailed process of filtering is described by Saiyar et al. (2010).

The calculated bending moments using the flexural stiffness of the full pipe section are presented in Figure 9 (these moments are normalized using the flexural rigidity, and therefore represent the curvature change in the pipe). Positive bending moments occur in sagging and cause tension along the pipe invert. As the figure shows, the bending moment distribution is not symmetric. In the hogging zone, it appears that a bearing capacity mechanism dominates the soil-pipe interaction demand on the pipe as the pipe experiences the largest curvature in this region. In the sagging zone, the uplift capacity is the critical mechanism and the pipe experiences smaller bending moments compared to those in the hogging zone.

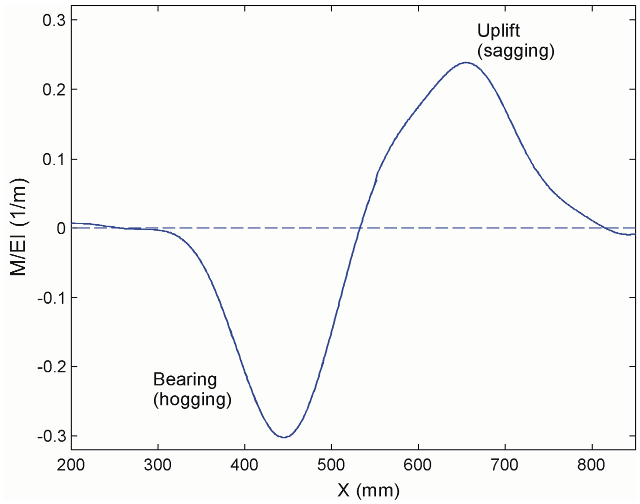

Figure 9. Bending moment distribution along the pipe (model scale)

4 SUMMARY AND CONCLUSIONS

The paper presents preliminary results from a series of centrifuge tests examining soil-pipe interaction during normal faulting. The pipe and soil displacement profiles were obtained using the PIV image processing technique. The pipe displacements relative to the soil were also obtained from PIV of soil and pipe displacements. A gap was observed to form beneath the pipe. The free field soil displacements were directly measured, and the pipe displacements relative to the free field soil were then calculated. The change in pipe curvature (bending moment divided by flexural rigidity) in the pipe were calculated by differentiating the displacement profiles twice. The bending moment distribution was observed to be not symmetric with respect to the fault due to gap formation and uplift. Work is currently underway to investigate the influence of relative pipe-soil stiffness on the observed soil-pipe interaction and to compare the experimental results to current prediction methods.

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