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RESPONSE OF A PVC WATER PIPE DURING CONCRETE SEWER REPLACEMENT BY BURSTING

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ABSTRACT: Pipe replacement using bursting involves cavity expansion and ground movements in the vicinity. While influence charts from technology developers British Gas provide guidance on acceptable proximity of other infrastructure to bursting operations, there are no published measurements available to evaluate the effectiveness of those guidelines and the actual response of flexible pressure pipes in the vicinity. A pipe bursting experiment is reported where replacement of a concrete sewer line passes under a PVC water pipe running transversely. Strain gages fixed to the PVC waterline provide information on the longitudinal bending that results, and the pattern of pipe deformation is compared to uplift observed at the ground surface above. A design equation is developed for estimating the maximum longitudinal strain that develops in a flexible pipe transverse to the pipe being replaced. Comparisons with measured strains indicate that the design equation provides effective estimates of the response of the transverse utility.

1. INTRODUCTION

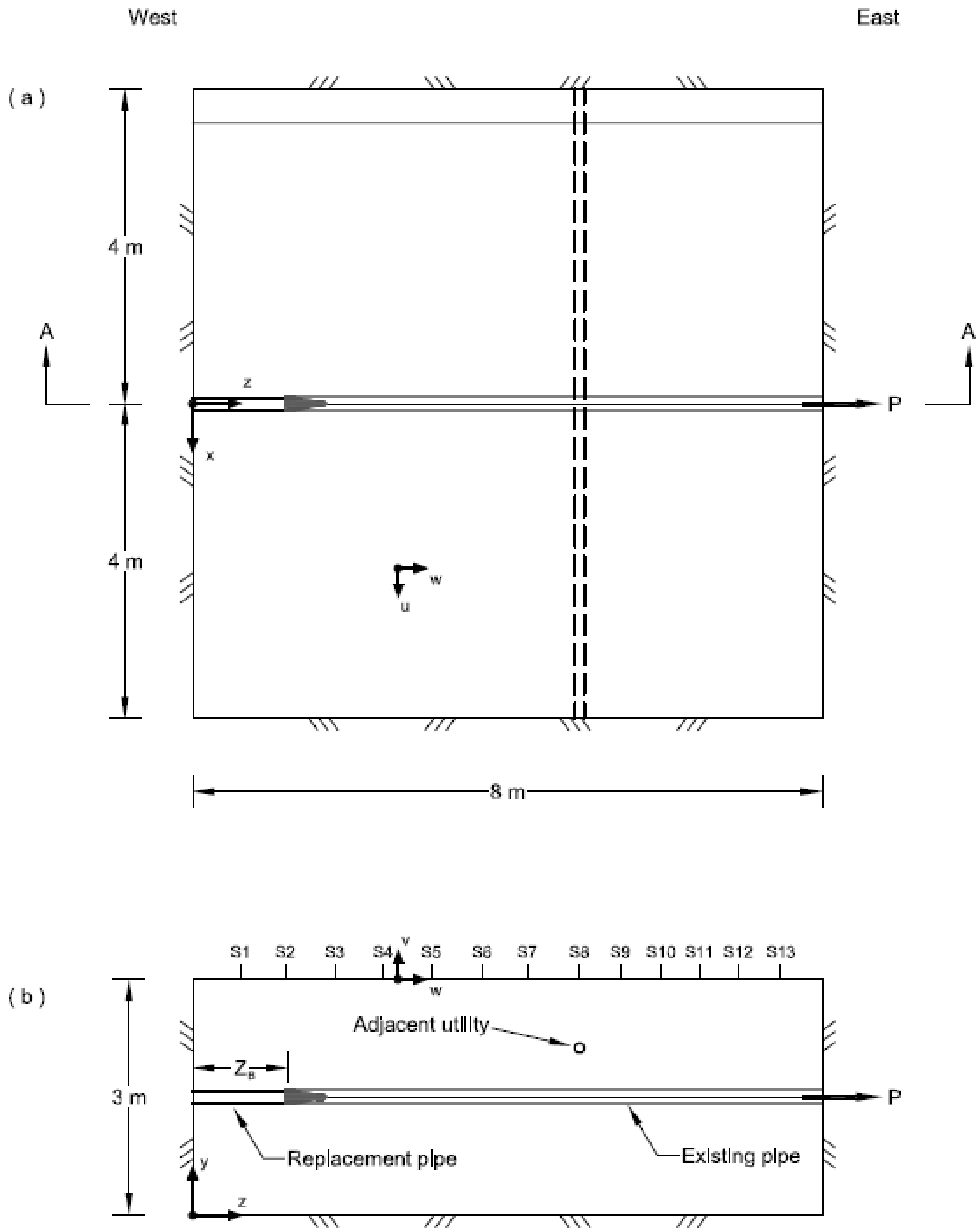
One important consideration during the design and implementation of a pipe bursting operation is the effect on adjacent utilities of the ground movements that result. In particular, the integrity of pressure pipes buried in the vicinity of the pipe being replaced needs to be maintained. While researchers have measured and explained the pattern of ground movements as the bursting head or expander is drawn through the old pipe (Chapman and Rogers, 1991; Lapos et al., 2004) and have developed procedures for estimating uplift of the ground surface as a result of the expansion of the soil cavity (Nkemitag and Moore, 2006), the assessment of adjacent utilities has relied on so-called proximity charts developed on the basis of very limited field studies, Chapman et al. (2007). The authors know of no reported study where a pressure pipe has been monitored to determine the effect of a pipe replacement operation in the vicinity.

A large scale pipe bursting experiment has therefore been conducted as part of a research project studying bursting operations. The experiment monitors the impact of replacing an unreinforced concrete pipe running transverse and below a typical PVC pressure pipe. Strain gages fixed to the PVC pipe indicate the pattern and magnitude of bending that is induced during pipe bursting. Details of the large scale experiment are reported, focussing on the measured response at the ground surface and the strain patterns observed in the PVC pipe. An approximate equation for estimating the magnitude of the longitudinal strains is then presented, and the procedure is used to examine the laboratory test case. A comparison of the measured and calculated strains is used to determine the effectiveness of the approximate procedure.

2. LARGE SCALE PIPE BURSTING EXPERIMENT

Figure 1 defines the experiment geometry using a plan view (Figure 1a) and an elevation (section A-A, Figure 1b). Half of the test pit at Queen's University was employed, giving total lateral dimensions of the experiment of 8m by 8m, and total depth of 3m.

A graded granular soil material was used throughout the experiment. After preparing the bedding material, Figure 2a, an unreinforced concrete pipe of external diameter 229 mm and wall thickness 38mm



a. Plan view (PVC pipe shown with dashed lines) b. Elevation along section A-A parallel to bursting
Figure 1. Layout of the large scale test in an 8m by 8m section of the Queen's University test pit.

was placed in a shallow trench, Figure 2b. Backfill placement continued, with 450 mm of material placed over the concrete pipe before the ‘adjacent utility’, a plain PVC water pipe of outside diameter 122mm and wall thickness 7mm, was placed transverse to the concrete pipe, Figure 2c, at the location illustrated in Figure 1. Additional soil was then placed, to bring the cover depth over the concrete pipe to 1385 mm, and over the PVC pipe to 815 mm.

The PVC pipe was instrumented with 52 biaxial strain gages or rosettes placed on its outside surface (120 ohm gages with 5mm gage length; using a System 5000 DA system and quarter bridge configuration, these have been found to be accurate to ±4 microstrain). Gages were fixed at the crown, the invert, and the two springlines, at 13 separate locations along the pipe length, Figure 2c. The PVC pipe also had two metal rods attached near its ends, and running up past the ground surface, Figure 2d. Reflective prisms attached to these rods above the final ground surface were monitored during the experiment, and these confirmed that movements of the ends of the pipe were negligible during the pipe bursting process (and that the width of the experiment was sufficient to eliminate boundary effects).

The ground surface was monitored using a servo-controlled total station monitoring 30 reflective prisms arranged over the surface, and two digital cameras photographing a series of 350 wooden blocks placed on the ground surface, Figure 2e. The digital images were analyzed after the tests using the particle image velocimetry software GeoPIV of White et al. (2003).

Static pipe bursting was employed, using the burst head shown in Figure 2f. The outside diameter of the burst head is 202 mm, and the new HDPE pipe pulled into place featured an external diameter of 168 mm. An MTS actuator with 500mm stroke and 200 tonne capacity was used to pull the burst head through the old pipe, steadily recovering a series of steel rods connected together and inserted through the concrete pipe being replaced. In subsequent sections, measurements of bending strain and ground surface movements are presented to establish the response of the PVC pipe. Details of the loads measured during the pipe bursting process, and more extensive details of the ground movements observed during the pipe replacement operation will be reported elsewhere.

3. MEASUREMENTS

3.1 Uplift measurements at the ground surface

Figure 3 presents the measurements of vertical surface movement v (uplift) made along a line directly above the PVC pipe. Lateral distributions of the surface uplift are presented as a function of horizontal position x defined in Figure 1. Results are presented for the burst head at a number of different locations z_B along the concrete pipe being replaced. These show the steady development of surface movements as a result of the progressive fracture and outward expansion of the concrete pipe being replaced and the soil surrounding it.

Surface movements are approximately symmetric about x=0. Figure 3 has been augmented to show distance W_z from x=0 to the inflection point, and the levels of peak uplift above the inflection points $\Delta_{4.92}$ and $\Delta_{5.43}$ where burst head is at z_B=4.92m, and at z_B=5.43m (burst head location producing maximum uplift). Parameters W_z and Δ are discussed in more detail in a subsequent section.

3.2 Longitudinal bending strains in the PVC pipe

Figure 4 presents the distributions of longitudinal strain measured along the crown of the PVC pipe for the burst head at various locations z_B. The ten different distributions provided illustrate the steady development of bending in the PVC pipe as the burst head approaches along the concrete pipe positioned below and transverse to the PVC pipe. Of particular interest are results for the burst head at two specific locations, that is at z_B=4.92m (denoted Section 8 or S8 in Figure 1b), and at z_B=5.43m (denoted Section 9). Subsequent measurements of crown strain remain almost constant (e.g. Section 13 corresponding to measurements as the burst head exits the test pit). Strains at the crown are almost symmetric about the center of the pipe, though prior to the burst head reaching z_B=5.43m (Section 9) the strains are higher to the right of center.

Peak values of longitudinal strain at the crown of the PVC pipe are about 320με and 700με for these two burst head positions, (sections 8 and 9 respectively). Peak strains are achieved after the burst head has passed below the PVC pipe and are then maintained (results for sections 9 and 13 are almost identical).

a. Preparation of bedding material.


b Concrete pipe to be replaced


c. PVC pipe with gages.


d. Rod to monitor pipe uplift


e. Surface instruments


f. Burst head & new pipe

Figure 2. Preparation for the large scale pipe bursting experiment.

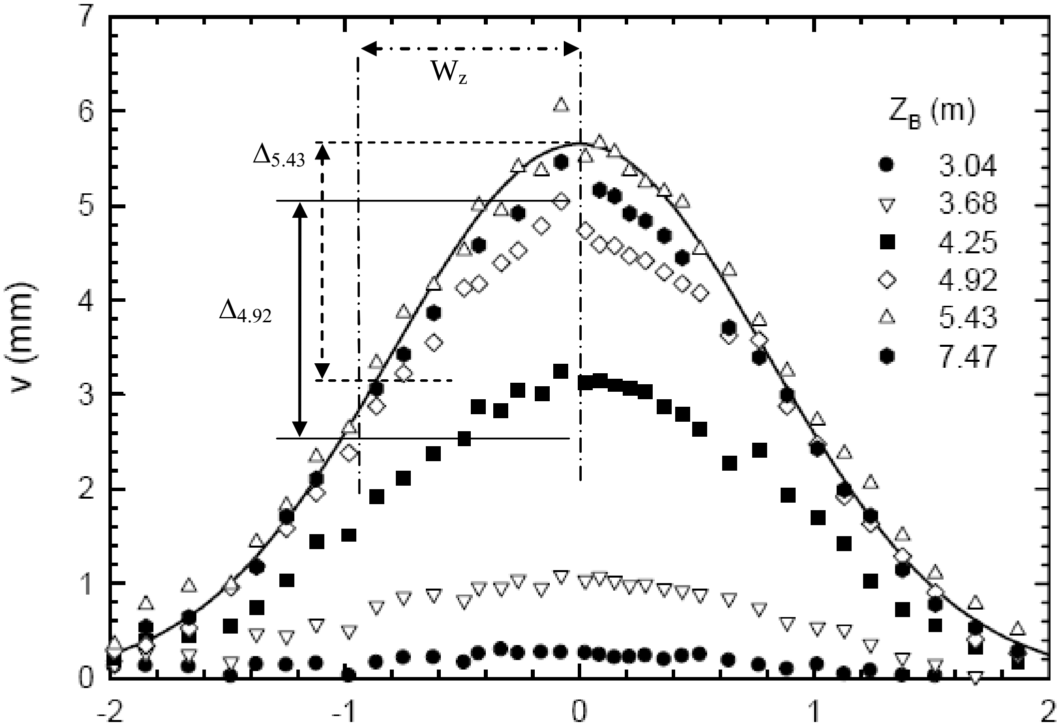


Figure 3. Distributions of surface uplift directly over the PVC pipe (*z*=4.92m); results for different burst head positions $Z_{B.}$

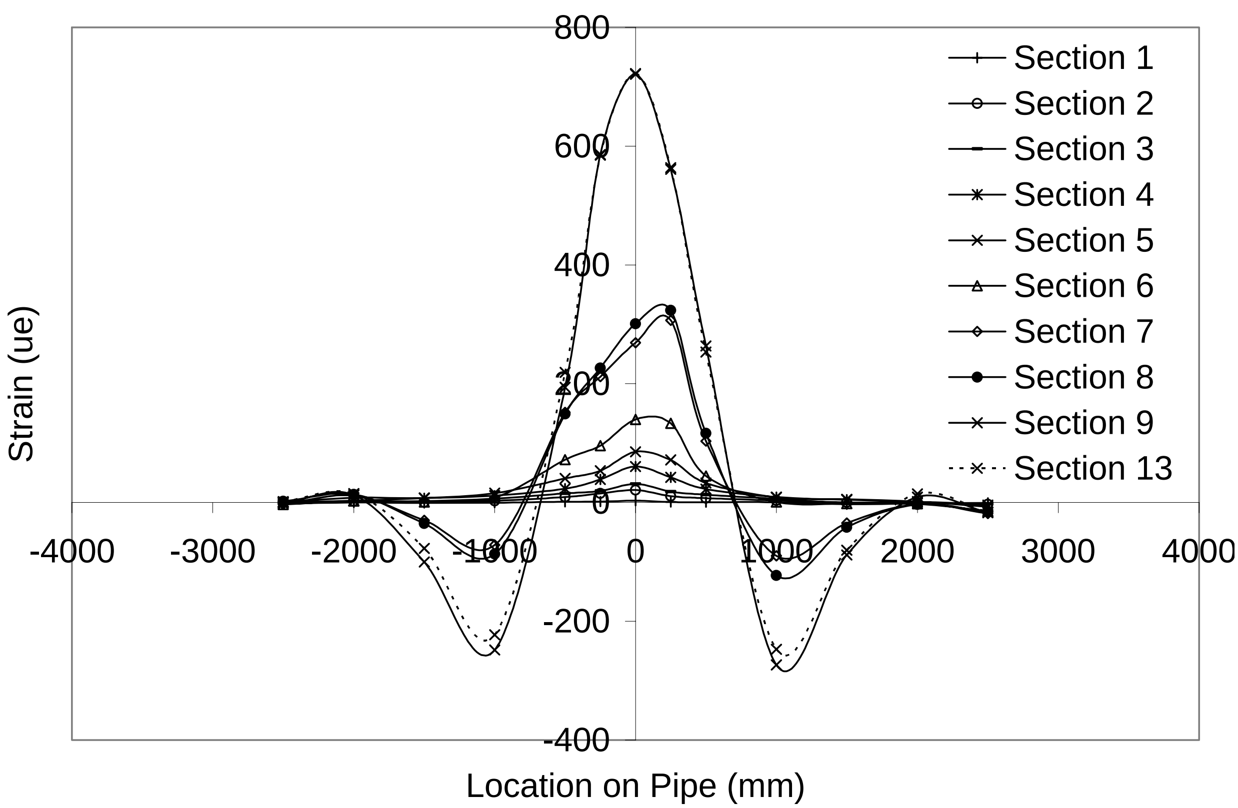


Figure 4. Distribution of longitudinal bending strains along the PVC pipe for burst head at ten locations.

4. BEAM APPROXIMATION FOR BENDING OF A TRANSVERSE UTILITY PIPE

Consider the utility pipe running transverse to the pipe being replaced as a beam under bending, Figure 5. The point of maximum bending induced in the beam is expected at a location directly over the pipe being replaced. The beam will feature inflection points where moment is zero (marked in red on Figure 5), and the distance of these points from the point of minimum radius of curvature is denoted W_z. The magnitude of maximum bending (or minimum radius of curvature) will be some function of the amount of deflection of the beam Δ relative to those inflection points. Beam bending theory is used here to develop an expression for the maximum longitudinal bending strain ε in the utility pipe over the pipe being replaced as an approximate function of Δ and W_z.

Figure 6 shows two beam bending approximations used to calculate this expression for ε as a function of Δ and W_z. Given that the points of inflection have zero moment, these can be represented as points of support for a simply supported beam of length $2W_z$.

The first, Figure 6a, represents an upper bound limit, where the lateral force causing bending P is concentrated at the center of the beam. The second, Figure 6b, represents a lower bound limit where the lateral force causing bending is distributed uniformly along the beam. The real loading condition should be between these limits, featuring a distributed load on the transverse utility pipe that has maximum magnitude where the transverse utility passes over the pipe being replaced.

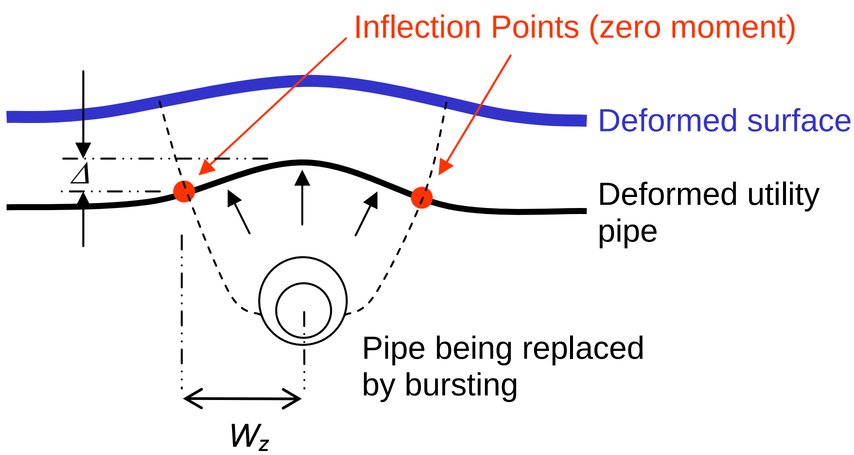


Figure 5. Kinematics of problem, including longitudinal bending of the transverse utility pipe

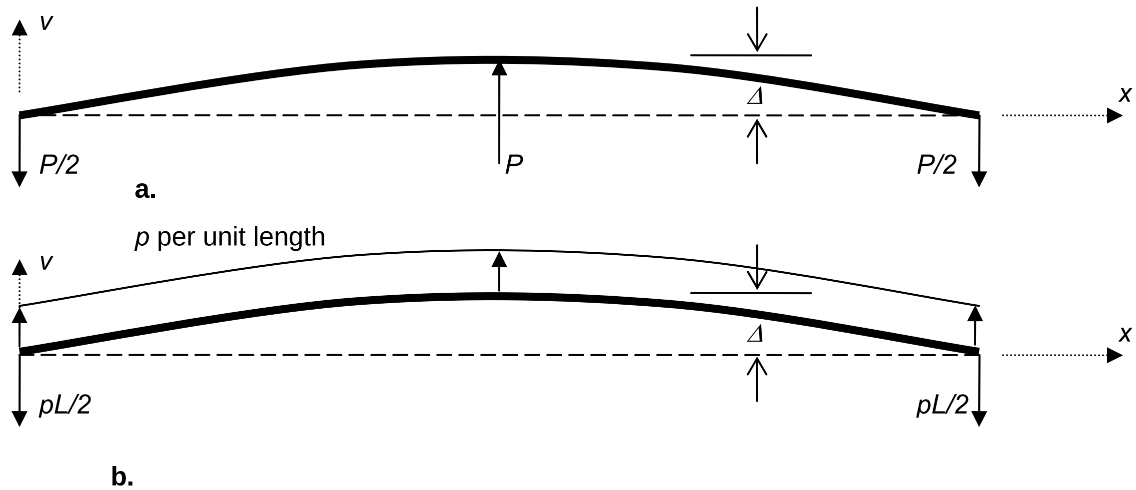


Figure 6. Simply supported beam approximations, Beam under a. single central load, b. distributed load

Conventional thin beam theory indicates that curvature κ is related to lateral pipe deformations *v* by

$$\kappa = \frac{d^2 v}{dx^2} \qquad [1]$$

Using solutions for the two simplified beam loading configurations, this expression for curvature can be used to calculate the maximum longitudinal bending strain at the center of the beam as a function of the deflection at the center of the beam relative to its 'ends' (the points of zero moment), $\Delta = v$ at $x = W_z$

$$\varepsilon = \kappa_{\max} \frac{D_{pipe}}{2} = f \frac{D_{pipe}\Delta}{W_z^{\,2}} \qquad [2]$$

where factor f takes values of 1.5 and 1.2 for the point load (Figure 6a) and distributed load (Figure 6b) cases respectively.

5. COMPARISON OF BEAM APPROXIMATION RESULTS WITH MEASURED STRAINS

The effectiveness of equation [2] developed in Section 4 is evaluated here using the values of longitudinal strain measured along the crown of the PVC pipe during the large scale pipe bursting experiment.

Table 1 contains calculations of design strain ε. Parameter W_z in equation [2] was estimated considering the pipe strain distributions presented in Figure 4, since it is expected that the crown strains are primarily the result of the bending illustrated in Figure 5.

Parameter Δ is more difficult to infer, since it requires knowledge of the PVC pipe deflections. Since these pipe deformations are not directly available, values of deflection of the ground surface were used instead. These are expected to provide movements reasonably close to those of the PVC pipe buried below since the flexible PVC pipe will not restrain the soil movements, and finite element calculations of vertical soil movements are nearly uniform with depth at locations more than a few pipe diameters above the pipe being burst and expanded, Nkemitag (2007).

Table 1 shows calculations and measurements for two different burst head locations:

1. For burst head directly under the PVC pipe, z_B=4.92m, the calculated strain is approximately double that measured at the crown of the PVC pipe
2. For burst head beyond the PVC pipe, z_B=5.43m, the calculated strain is close to that measured at the crown of the PVC pipe (the strain of 700 corresponds to factor f of 1.4)

Deflection monitoring of the ground surface included measurement of changes in horizontal positions in addition to the uplift measurements presented earlier in Section 3.1. While full details of those horizontal soil movements will be presented elsewhere, the key observation is that the ground above the pipe replacement operation displaced in the z direction (the direction of movement of the burst head) when the burst head was located at z_B=4.92 (directly below the PVC pipe). Strain gages attached to the springlines of the PVC pipe gave longitudinal strain values that echo bending associated with this forward movement. It appears that some or most of the discrepancy between calculated and measured strain shown in the second row of Table 2 is because when the burst head is still under the PVC pipe, the crown of the PVC pipe is not the location of peak tensile strain (the PVC pipe deformation is not confined to the vertical plane running along its axis). Instead, the PVC pipe bends upwards and forwards, and the strain readings indicate that the peak strains occur at a point located between the crown and the springline. It may be that the strain calculated from [2] is a reasonable estimate of the maximum longitudinal strain at this shoulder position on the PVC pipe.

In any case, peak measured strain once the burst head had passed corresponded to equation [2] with f value of 1.4. It appears that this equation can be used to provide useful estimates of bending in the transverse utility pipe above the pipe being replaced. Work is ongoing to develop guidance on expected values of Δ and W_z for different pipe bursting geometries and soil materials.

Table 1. Strain estimated using beam approximation [2] together with measured values.

bursting head location z_B (m)	Δ (mm)	W_z (mm)	f	ε_{max} ($x10^{-6}$)	measured strain ($x10^{-6}$)
4.92 m	2.5	800	1.2 to 1.5	570 to 720	320
5.43 m	2.6	800	1.2 to 1.5	590 to 740	700

6. CONCLUSIONS

A large scale laboratory test has been reported, where measurements of ground surface movement were made above a concrete pipe replaced using static pipe bursting. A typical flexible PVC pressure pipe located at shallower depth and running transverse to the pipe being replaced was instrumented with strain gages. The measured distributions of longitudinal strains along the crown of the PVC pipe were used to explain the nature of pipe bending that occurs as a result of the ground movements induced by pipe bursting operations. A simplified design equation for pipe bending was then developed.

Estimates of maximum bending strain using the new design equation are close to those measured during the laboratory experiment. These estimates were obtained using the pattern of surface uplift as approximations for the pipe deformation (since measurements of pipe deformation are not available). Further work is underway to interpret the complete set of PVC pipe strain measurements, and to finish development and evaluation of design procedures for estimating the effect of pipe bursting operations on adjacent utilities.

7. ACKNOWLEDGEMENTS

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