Response of a polyvinyl chloride water pipe when transverse to an underlying pipe replaced by pipe bursting

J.A. Cholewa, R.W.I. Brachman, and I.D. Moore

Abstract: An existing deteriorated or hydraulically undersized pipe can be replaced with a new pipe by static pipe bursting. Cavity expansion during pipe bursting induces ground movements, which may potentially damage nearby buried utilities if they are in close proximity to the pipe bursting operation. A large-scale pipe bursting experiment was performed in an 8 m long, 8 m wide, and 3 m deep test pit filled with a well-graded sand and gravel soil. A polyvinyl chloride (PVC) pipe, crossing transversely and 0.45 m above the existing pipe being replaced, was instrumented with strain gages to quantify the response of that transverse utility to the ground movements associated with pipe bursting. In this paper, the measured strain and corresponding deflection of the PVC pipe are examined and compared with measurements of surface uplift. The maximum longitudinal strain measured in the pipe was less than 0.1% and its vertical diameter decreased by only 0.5%, suggesting that ground displacements induced by pipe bursting did not jeopardize the transverse water pipe's long-term performance, provided its joints were not damaged. A simplified design equation is introduced and shown to provide estimates of maximum longitudinal strain in the PVC pipe close to those measured during the laboratory experiment.

Key words: pipe bursting, adjacent utility, displacement, longitudinal strain, laboratory testing.

Résumé : Un tuyau existant trop petit ou détérioré peu être remplacé par un nouveau tuyau par la méthode de l'éclatement statique du tuyau. L'expansion de la cavité pendant l'éclatement du tuyau provoque des mouvements dans le sol qui peuvent potentiellement causer des dommages aux services enfouis s'ils sont près de l'opération d'éclatement du tuyau. Un essai à grande échelle d'éclatement du tuyau a été effectué dans une fosse d'essai de 8 m de longueur, 8 m de largeur et 3 m de profondeur remplie avec du sable non uniforme et du gravier. Un tuyau de chlorure de polyvinyle (« PVC ») placé 0,45 m (transversal) au-dessus du tuyau à changer a été instrumenté afin de quantifier le comportement de tuyaux de services transversaux lors de du remplacement d'un tuyau adjacent par la méthode de l'éclatement du tuyau. Les déformations mesurées et les déflections correspondantes sur le tuyau de PVC sont examinées et comparées aux mesures de soulèvement de la surface. La déformation longitudinale maximale mesurée sur le tuyau était inférieure à 0,1 % et son diamètre vertical s'est réduit de seulement 0,5 %, ce qui indique que les déplacements du sol causés par l'éclatement du tuyau n'ont pas mis en danger les performances à long terme du tuyau d'eau, en supposant que ses joints n'ont pas été endommagés. Une équation de conception simplifiée est présentée et démontre qu'elle permet d'obtenir des estimations des déformations longitudinales maximales dans le tuyau de chlorure de polyvinyle qui sont près de celles mesurées en laboratoire.

Mots-clés : éclatement de tuyau, services adjacents, déplacement, déformation longitudinale, essais en laboratoire.

[Traduit par la Rédaction]

Introduction

An existing deteriorated or hydraulically undersized pipe (made of brittle material) can be replaced with a new pipe by static pipe bursting (e.g., see Simicevic and Sterling 2001). As shown in Fig. 1, this process involves breaking (i.e., bursting) the existing pipe by using an expander that is pulled by a series of rods. The expander enlarges the soil cavity and displaces the broken pipe fragments out into the surrounding soil. The replacement pipe is attached to the rear of the expander and is pulled into place along the same trajectory as the existing pipe. Of specific interest in this work is the effect of the ground movements, caused by cavity expansion, on an adjacent utility running above and transverse to the existing pipe being replaced.

Physical pipe bursting experiments have been conducted to quantify the three-dimensional nature of surface and subsurface ground displacements (Rogers and Chapman 1995*a*; Lapos et al. 2004) and procedures have been developed for estimating the magnitude of these displacements as a result of cavity expansion (Nkemitag and Moore 2006). There have been limited experimental studies that investigate the response of an adjacent polyvinyl chloride (PVC) pipe to ground displacements caused by pipe bursting. Atalah (1998) monitored pressure in transverse PVC pipes in the vicinity of pipe bursting operations. During one particular test in sand, the PVC pipe crossing 300 mm above the clay pipe being upsized by 50% lost internal pressure, suggesting the

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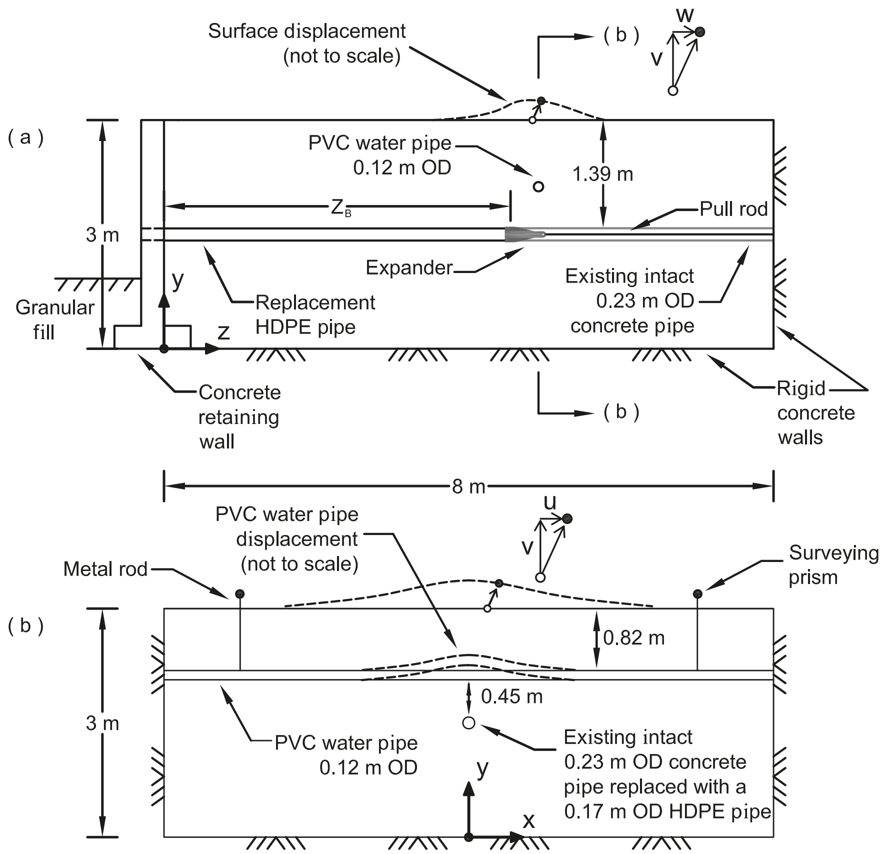
Fig. 1. (*a*) Axial and (*b*) transverse cross sections showing the test configuration. PVC, polyvinyl chloride; HDPE, high-density polyethylene; OD, outside diameter.



pipe was damaged. For cases when internal pressure was maintained, the short-term capacity of the pipe may not have been exceeded; however, of particular interest are the strains that developed in these pipes with respect to determining if long-term performance limits were exceeded. Currently, proximity charts are available to identify whether or not the integrity of grey cast iron pipes would be in jeopardy if pipe bursting operations were performed in their vicinity (Transco 1997). Note, however, that these charts have been developed on the basis of very limited field studies (Chapman et al. 2007).

The objective of this paper is to quantify the response of a PVC pipe, representing a utility in the vicinity of a pipe bursting operation. A large-scale pipe bursting experiment was performed, with the PVC pipe crossing transverse and 0.45 m above the pipe being replaced. The measured strain and corresponding deflection of the PVC pipe are presented. In addition, an equation for estimating the magnitude of maximum longitudinal strain in the adjacent utility is evaluated.

Experimental details

Test pit

A schematic of the static pipe bursting experiment is provided in Fig. 1. It was performed in an 8 m long, 8 m wide, and 3 m deep test pit with boundary conditions consisting of three rigid concrete walls at (*i*) z = 8 m, x = –4 to 4 m; (*ii*) x = –4 m, z = 0 to 8 m; and (*iii*) x = 4 m, z = 0 to 8 m, where x is the transverse direction and z is the axial direction. The fourth wall at z = 0 m, x = –4 to 4 m is a removable concrete retaining partition (i.e., the test pit is actually 16 m long) anchored to the concrete floor and buttressed with granular fill to reduce horizontal displacement at the top of the wall. Given the size of the test pit, the imposed restraint from boundary friction did not affect the ground displacements in the vicinity of the PVC pipe (Cholewa 2009). The expander and replacement pipe entered the test pit through a porthole located at x = 0 m and z = 0 m. The 8 m long replacement pipe was strung out in the adjacent partially empty pit and it was pulled towards another porthole at x = 0 m and z = 8 m.

Materials

A well-graded sand and gravel, having a coefficient of uniformity (C_u) of 20 and a coefficient of curvature (C_c) of 0.5, was used to fill the test pit. The material had a maximum and minimum dry unit weight of 24.1 18.3 kN/m^3, respectively. It was placed in 300 mm thick lifts and compacted, using a vibrating plate tamper (Wacker 1550 with an operating mass of 88 kg and a maximum centrifugal force of 15 kN), to an average as-placed dry unit weight of 20.9 ± 0.1 kN/m^3 at an average water content of 4.6 ± 0.9% (where ± is one standard deviation).

The unreinforced concrete pipe being burst, located along x = 0 m, had an outside diameter (OD) of 229 mm and an average wall thickness of 38 mm. It was replaced with a high-density polyethylene (HDPE) pipe, with an OD of

168 mm and an average wall thickness of 11 mm, using an expander with a maximum diameter of 202 mm (Fig. 2). Based on the pipe bursting geometry tested, the average outward radial displacement was 25 mm (maximum radius of the expander minus the inside radius of the concrete pipe), assuming the expander travels along the centreline of the unreinforced concrete pipe. Once the unreinforced concrete pipe was replaced with the HDPE pipe, the maximum inward radial displacement was 17 mm (maximum radius of the expander minus the outside radius of the HDPE pipe). Buried above and transverse to the concrete pipe along z = 4.92 m was a PVC pipe with an OD of 122 mm and an average wall thickness of 7 mm. There was 815 mm of cover above the PVC pipe (crown to the surface) and the vertical distance between the invert of the PVC pipe and the crown of the concrete pipe was 450 mm. The configurations of the PVC pipe and the concrete pipe are illustrated in Figs. 1 and 2.

Instrumentation

During the pipe bursting process, surface displacements directly above the PVC pipe and strains in the PVC pipe were monitored. Surface displacements (v and w in the y and z directions, respectively, as defined in Fig. 1) were measured using targets tracked with digital cameras and surveying prisms electronically tracked with a total station. Images obtained from the cameras were analyzed using the image-based deformation software, GeoPIV (White et al. 2003). The accuracy of the displacements obtained with the cameras and the total station are ±0.1 and ±0.3 mm, respectively.

The outside surface of the PVC pipe was instrumented at 13 separate sections along the length of the pipe with 52 uniaxial and rosette strain gages fixed at the crown, invert, and two springlines. The uniaxial (SHOWA N11-FA-5-120-11) and rosette (SHOWA N32-FA-5-120-11) foil strain gages had a gage length of 5 mm and were estimated to be accurate to within ±10 microstrain ($\mu\varepsilon$). These gages were used to measure strains in the longitudinal (x) and circumferential (θ) direction as defined in Fig. 3. Tensile longitudinal (ε_x) and circumferential (ε_θ) strains are taken as positive. The measured strain was multiplied by a modification factor of 1.2 to account for local gage stiffening. This factor wasbtained in a separate experiment by dividing strain calculated from independent deflection measurements by measurements with the strain gages during an unrestrained thermal expansion–contraction test from 0 to 30 °C. The strain gage readings were zeroed after backfilling of the PVC pipe was complete. Measurements of longitudinal strain in the PVC pipe were used to infer pipe displacements v and w shown in Fig. 2. To measure vertical movement of the PVC pipe's ends during the pipe bursting process, metal rods attached to the pipe crown at x = –3 and 3 m were extended up to and beyond the ground surface and a surveying prism was mounted at the top as shown in Fig. 1.

Method

Steel pull rods connected the expander to a hydraulic actuator, which was used to pull the expander and replacement HDPE pipe through the concrete pipe at a controlled displacement rate of 100 mm/min. The pulling process was paused for 15–20 min at various expander locations (denoted as Z_B in Fig. 1) to take measurements of surface displacements and pipe strains. For Z_B = 4.92 m, the expander was directly beneath the PVC pipe located at z = 4.92 m.

Fig. 2. Pipe bursting process showing the orientation of the PVC and concrete pipes. All dimensions in millimetres.

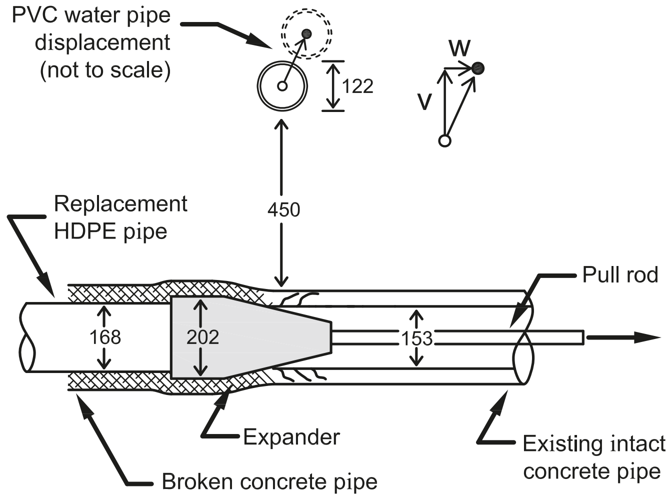
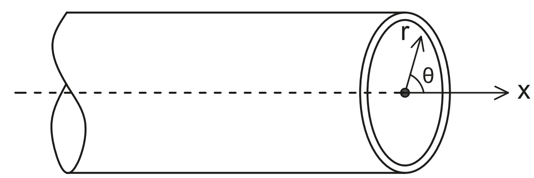


Fig. 3. PVC pipe notation. r, radius.



Results

Longitudinal strains in the PVC pipe

The distribution of longitudinal strains, ε_x, measured along the crown and invert of the PVC pipe for Z_B = 4.25 and 4.92 m are given in Fig. 4. In addition, the measured longitudinal strains at the crown and invert for various expander locations are given in Tables 1 and 2, respectively. Tensile strains are taken as positive. When the expander approached, bending developed in the PVC pipe near the centreline of the existing concrete pipe being burst (indicated by tensile strains measured along the crown and compressive strains along the invert). As expected, the strains measured on the crown and invert are nearly equal, but opposite and almost symmetric about x = 0. When the expander was directly beneath the PVC pipe (Z_B = 4.92 m), the maximum longitudinal strain of 880 $\mu\varepsilon$ was measured (corresponding to about 0.09% strain) at x = 0 m. Subsequent strain measurements at the crown and invert remained almost constant when the expander moved beyond the PVC pipe (i.e., from Z_B = 4.92 m to Z_B = 7.47 m).

The curvature, κ, of the PVC pipe can be calculated by

$$[1] \qquad \kappa = \frac{\varepsilon_c - \varepsilon_i}{D}$$

where ε_c is the strain measured at the crown, ε_i is the strain measured at the invert, and D is the outside diameter of the PVC pipe. The computed curvature of the PVC pipe when

Fig. 4. Distribution of longitudinal strain measured along the crown and invert of the PVC pipe when Z_B = 4.25 and 4.92 m.

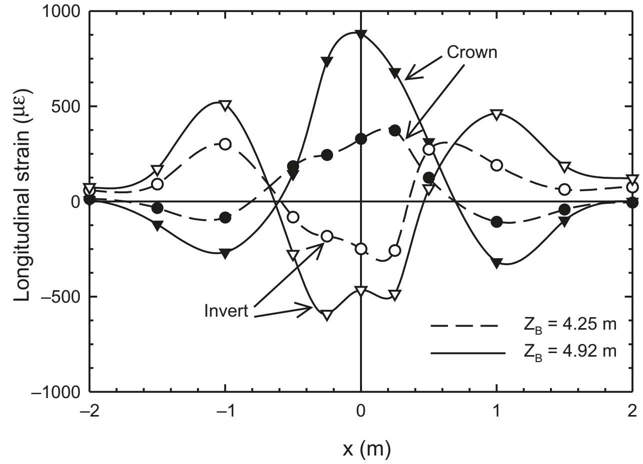


Fig. 5. Curvature of the PVC pipe when Z_B = 4.25, 4.92, and 5.43 m.

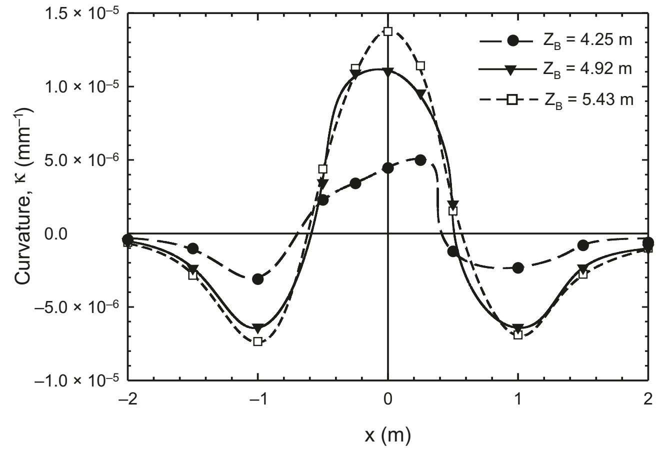


Table 1. Longitudinal strain (με) measured along the crown.

	Strain (με)				
Z_B (m)	x = –1 m	x = –0.25 m	x = 0	x = 0.25 m	x = 1 m
3.04	25	55	100	80	5
3.68	10	105	170	170	0
4.25*	–85	245	330	375	–110
4.60	–165	470	625	510	–210
4.92*	–270	740	880	680	–320
5.43	–290	705	855	670	–325
7.47	–260	700	860	675	–300

*Fig. 4.

Table 2. Longitudinal strain (με) measured along the invert.

	Strain (με)				
Z_B (m)	x = –1 m	x = –0.25 m	x = 0	x = 0.25 m	x = 1 m
3.04	55	40	50	50	25
3.68	130	10	–5	10	50
4.25*	300	–185	–250	–260	190
4.60	400	–340	–295	–375	320
4.92*	510	–590	–465	–485	460
5.43	595	–630	–805	–705	500
7.47	600	–565	–800	–685	505

*Fig. 4.

Z_B = 4.25, 4.92, and 5.43 m is given in Fig. 5. Here, it is further illustrated that the maximum bending (or maximum curvature) occurs at a portion of the PVC pipe located directly above the pipe being replaced (x = 0) and the maximum curvature of the PVC pipe occurs when Z_B = 5.43 m.

PVC pipe and surface displacements

Using conventional thin beam theory, the vertical displacement, v, of the PVC pipe's centroid can be related to its curvature, κ, by

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

Using this expression and integrating curvature twice (integration constants were determined by assuming the displacement at the ends of the PVC pipe were zero), the distribution of vertical displacement for the PVC pipe was calculated for different stages of the experiment as the expander approached and moved beyond the PVC pipe as given in Fig. 6*a*. Upward vertical displacements are taken as positive. The PVC pipe started to displace vertically when the expander was approximately 1.88 m away (i.e., the expander at Z_B = 3.04 m). As the expander approached, vertical displacement increased to a maximum of 5.1 mm when Z_B = 5.43 m, followed by a decrease to the residual vertical displacement as the expander proceeded to move away. The vertical displacements measured near the ends of the pipe at x = –3 and 3 m during the experiment reached a maximum of 0.1 and 0.3 mm, respectively, when Z_B = 5.43 m. These displacements decreased to 0 and 0.1 mm when Z_B = 7.47 m.

A transverse cross section showing the vertical displacement of the ground surface measured above the PVC pipe at z = 4.92 m is shown in Fig. 6*b*. The ground surface response to pipe bursting is similar to the response of the PVC pipe. Maximum vertical displacements increased until they reached a maximum when Z_B = 5.43 m, followed by a decrease in the residual displacement as the expander proceeded to move away. From the results given in Fig. 6, it can be seen that the distribution of vertical displacements for the surface and PVC pipe extend no more than 2 m on either side of the centreline (neglecting small deformations that could not be accurately measured by the instrumentation). Thus, the lateral boundaries of the 8 m wide pit were sufficiently far away to not impact the displacements.

In addition, Fig. 6 shows that the magnitude of vertical displacement is greater on the surface than for the PVC pipe. In fact, the maximum vertical displacement of the PVC pipe and the surface was 5.1 and 5.7 mm, respectively. This is further illustrated in Fig. 7, which plots the vertical displacement of the PVC pipe and the surface at the point where the centreline of the concrete pipe being burst intersects the PVC pipe (z = 4.92 m, x = 0 m). These vertical displacements, located above the centreline of the concrete pipe (at x = 0 m), correspond to the maximum vertical displacement of the PVC pipe and the ground surface. For various expander locations, the vertical displacement of the surface was on average 0.6 mm greater than the PVC pipe, but no greater than 1.4 mm.

Fig. 6. Vertical displacement of the (*a*) PVC pipe and (*b*) ground surface measured above the PVC pipe for various expander locations.

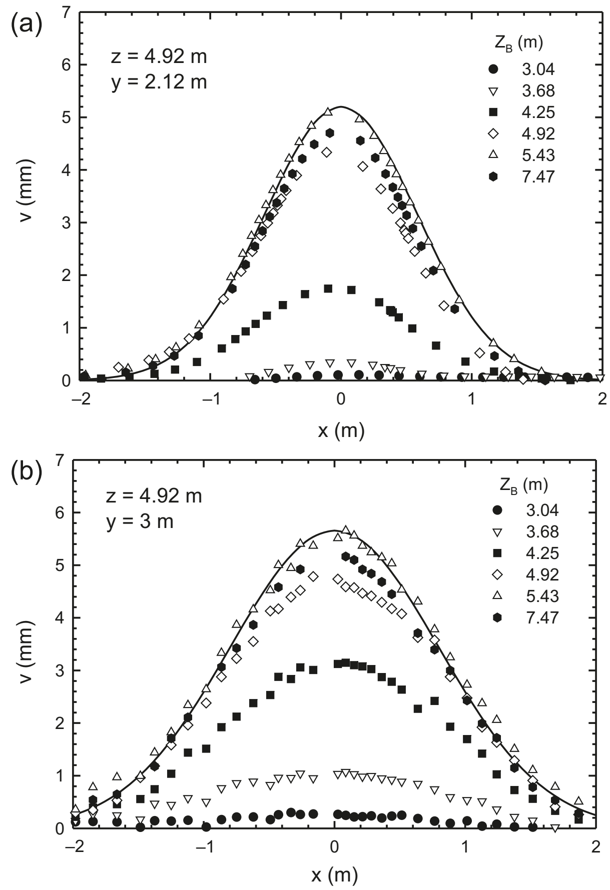


Fig. 7. Vertical displacement of the PVC pipe and the surface at the point where the centreline of the concrete pipe intersects the PVC pipe for various expander locations.

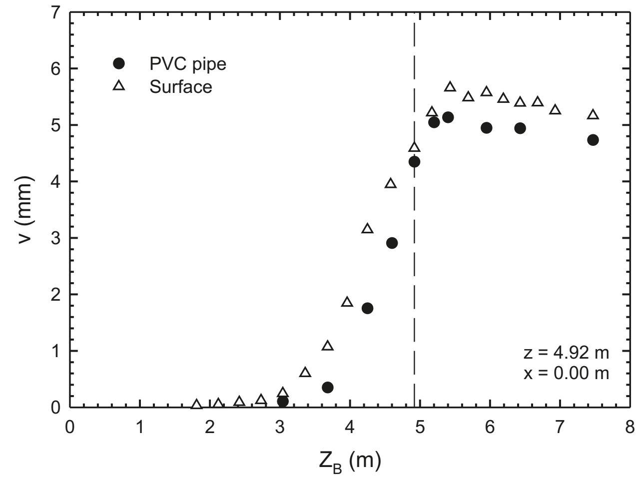
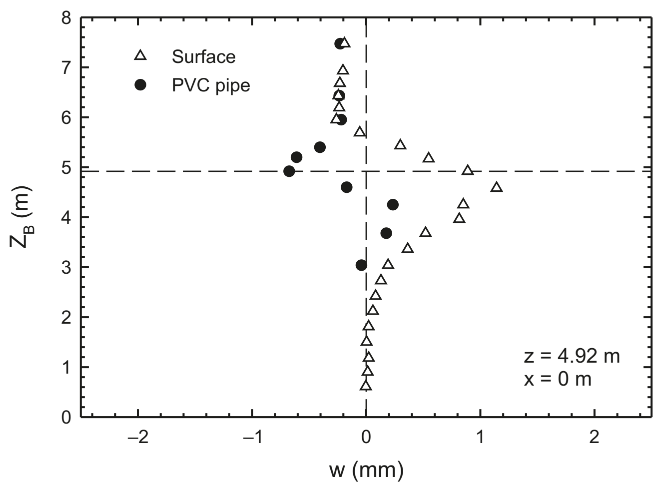


Fig. 8. Displacement in the *z* direction of the PVC pipe and the surface at the point where the centreline of the concrete pipe intersects the PVC pipe for various expander locations.

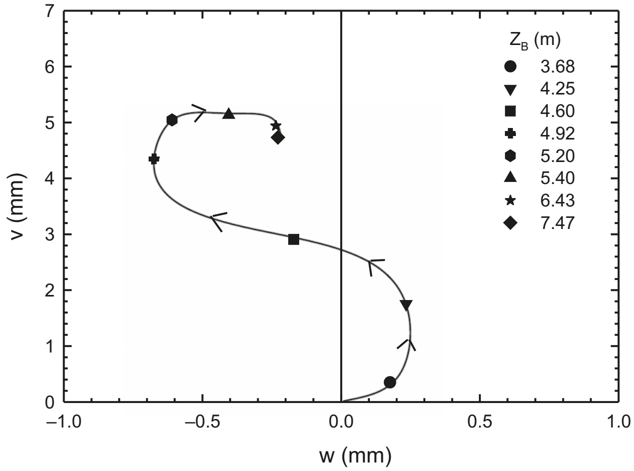


Due to the three-dimensional nature of ground displacements induced by pipe bursting, vertical surface displacements are accompanied by displacements w in the z direction that lead to bending of the PVC pipe in the x–z plane. Figure 8 shows w of the PVC pipe and the surface at the point where the centreline of the concrete pipe being burst intersects the PVC pipe (z = 4.92 m, x = 0 m). Forward displacements are taken as positive. As the expander approached, both the surface and the PVC pipe were displaced forward. The maximum forward displacement (positive w) of the PVC pipe was 0.2 mm when Z_B = 4.25 m, whereas the maximum forward displacement of the ground surface was 1.1 mm when Z_B = 4.60 m. As the expander progressed further, both the pipe and the surface began to move backwards (negative w). The backward displacement of the PVC pipe reached a maximum of –0.7 mm when Z_B = 4.92 m (when the expander was located directly beneath the pipe). As the expander proceeded to move away, the net movement of both the surface and the PVC pipe was backwards by –0.2 mm. Similar patterns of ground movements have been previously reported by Rogers and Chapman (1995*b*).

To further illustrate the response of the PVC pipe to ground movements induced by pipe bursting, the displacement trajectory in the z–y plane for a point along the PVC pipe at x = 0 is given in Fig. 9. Upward vertical (v) and forward (w) displacements are taken as positive. As the expander approached, the pipe displaced forward and upward. The maximum forward position was reached when the expander was roughly 0.67 m away from the pipe (Z_B = 4.25 m). When the expander advanced further into the soil (from Z_B = 4.25 m to Z_B = 4.92 m), the pipe moved backward and upward. Here, the incremental displacement in the z direction was –0.9 mm. The net displacement of the pipe (from Z_B = 0.00 to 7.47 m) was upward by 4.7 mm and backward by –0.2 mm.

Based on numerical simulations of ground movements during pipe bursting (Nkemitag and Moore 2006), the ground deformations were expected to be greatest in the vicinity of the expanded cavity and then attenuate outwards. However, the vertical displacements measured in the z direction at the ground surface during this particular experiment were greater than those of the PVC pipe (located only 0.45 m from the pipe being burst). This can be attributed to the flexural properties of the pipe versus the soil it replaces.

Fig. 9. Displacement trajectory of v and w for the PVC pipe at x = 0.



The flexural stiffness (EI, where E is the modulus of elasticity and I is the moment of inertia) of the PVC pipe and the soil it replaces was 5.0×10^9 and 2.2×10^9 N·mm^2, respectively. These values were calculated using a modulus of 1200 MPa for the pipe and 200 MPa for the soil. Based on large-scale triaxial testing on similar material, conducted at a range of confining stresses expected for this pipe bursting experiment (Scott et al. 1977), a soil modulus of 200 MPa is not overly conservative. Even when a conservatively low modulus is assumed for PVC, the flexural stiffness of the pipe is larger than the soil it replaces. Therefore, it appears that the PVC pipe stiffens the soil in its vicinity. Contours of the measured vertical surface displacements (v) when Z_B = 5.95 m are given in Fig. 10. Here, there is no discernible stiffening of the soil by the PVC pipe based on the measured surface response (i.e., there is no decrease in surface displacement above the PVC pipe), suggesting that the soil restraint is restricted to the zone immediately around the PVC pipe.

Circumferential strains in the PVC pipe

The measured circumferential strains in the PVC pipe at the crown, invert, and springlines at x = 0 m for various expander locations are given in Table 3. Tensile strains are taken as positive. Circumferential strains started to develop in the PVC pipe when Z_B = 3.04 m. When Z_B = 4.25 m, tensile circumferential strains of 330 and 510 $\mu\varepsilon$ were measured at the crown and invert, respectively, while compressive strains of –565 and –445 $\mu\varepsilon$ were measured at the springlines. This signifies that the pipe is predominately loaded along a horizontal axis though the springlines causing the vertical diameter (crown to invert) to increase and the horizontal diameter (springline to springline) to decrease. When the expander progressed further through the existing concrete pipe to Z_B = 4.92 m (directly below the PVC pipe), the axis of loading rotated to act predominately through the crown and invert. This is indicated here by compressive circumferential strains of –640 $\mu\varepsilon$ measured at the crown and invert and tensile strains of 960 and 720 $\mu\varepsilon$ at the springlines resulting in a decrease in the vertical diameter and an increase in the horizontal diameter. When the expander progressed beyond the PVC pipe (Z_B = 7.47 m), the circumferential strains measured at the springlines and invert decreased significantly; however, strains at the crown only decreased from –640 to –460 $\mu\varepsilon$.

Fig. 10. Contours of the measured vertical surface displacements when Z_B = 5.95 m.

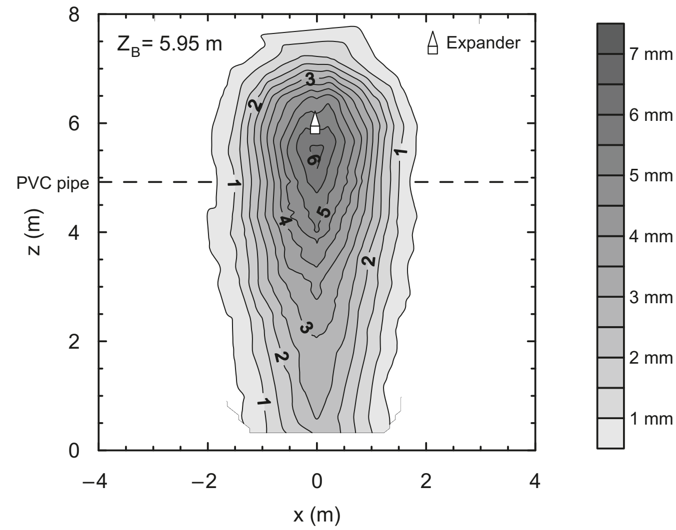


Table 3. Circumferential strain ($\mu\varepsilon$) measured around circumference at x = 0 m.

	Strain at θ (°)			
Z_B (m)	0 (springline)	90 (crown)	180 (springline)	270 (invert)
2.42	–5	–20	–50	5
3.04	–100	10	–135	40
3.68	–310	185	–355	260
4.25	–445	330	–565	510
4.92	960	–640	720	–640
5.43	60	–480	185	95
7.47	80	–460	95	95

Using conventional ring theory (Moore 2001), the change in pipe diameter can be related to circumferential strain, viz.

$$[3] \qquad \frac{\Delta D_v}{D} = \frac{\varepsilon_{\theta,\max} D}{D_f t}$$

where ΔD_v is the vertical diameter change of the PVC pipe, $\varepsilon_{\theta,\max}$ is the maximum circumferential strain, t is the pipe wall thickness, and D_f is an empirical strain factor relating longitudinal strain to bending deflection. If the circumferential strains measured when Z_B = 4.92 m (960 and 720 $\mu\varepsilon$) are interpreted using eq. [3], they correspond to changes in pipe diameter of 0.6% and 0.4%, respectively. These values were calculated using a D_f value of 3 because the PVC pipe was assumed to be an incompressible pipe subjected to pure bending (Brachman et al. 2008). For this particular experiment, the calculated change in pipe diameter, when the expander was directly beneath the PVC pipe (Z_B = 4.92 m), was much less than the conventional ring deflection limit of 7.5% for PVC pipe recommended in ASTM D3034 (ASTM 2006). This suggests that, for the specific conditions examined, pipe bursting in the vicinity of the PVC pipe did not jeopardize its long term performance, provided its joints were not damaged.

Simplified analysis

A schematic showing surface uplift and the deformed shape of the transverse utility is given in Fig. 11. Assuming the transverse utility can be represented as a beam under bending, the deformation pattern will feature inflection points where the moment (and curvature) is zero, each a distance i from the location of maximum longitudinal strain (or maximum curvature). Given that the points of inflection have zero moment, they can be represented as pin supports for a simply supported beam of length $2i$. The magnitude of vertical deflection relative to these inflection points (or supports) will be denoted as Δ. Values of i and Δ are dependent on pipe bursting geometries and soil materials. Using beam bending theory, the magnitude of maximum longitudinal strain (ε_{max}) in the beam is a function of i and Δ, viz.

$$[4] \qquad \varepsilon_{max} = \kappa_{max}\frac{D}{2} = f\frac{D\Delta}{i^2}$$

where κ_{max} is the maximum curvature, D is the outside diameter of the transverse utility, and the factor f is a function of the pattern of transverse loading applied to the beam. Now, the specific pattern of transverse loading imposed on the transverse utility is unknown, so the value of factor f is unknown. It would be reasonable to assume that the actual load configuration falls somewhere between a force concentrated at the centre of the beam for which f = 1.5 and a force distributed uniformly along the length of the beam for which f = 1.2 as illustrated in Fig. 12. These loading conditions serve as upper and lower bounds for the actual loading condition, which features a distributed load that is higher at the centre of the beam where the transverse utility passes over the pipe being replaced (Fig. 12).

To verify that eq. [4] satisfies beam theory, it was used to calculate ε_{max} at the centre of the PVC pipe in the large-scale pipe bursting experiment for the two simplified lateral loading configurations (point and distributed loading) shown in Fig. 12. Calculations of ε_{max} for the PVC pipe are compared with longitudinal strain values measured during the experiment shown in Table 4 for various expander locations (using values of i and Δ obtained from Fig. 6*a*). Generally, the measured longitudinal strain values are within the range of the calculated longitudinal strain values using f = 1.2 to 1.5, confirming the PVC pipe behaved similar to a beam under bending.

The beam approximation works well when values of i and Δ are known; however, of particular interest is the ability of eq. [4] to provide ε_{max} when values of i and Δ for a transverse utility are not readily available (as knowledge of its deflection is required). To approximate values of i and Δ for a transverse utility, values from surface uplift are used instead. Calculations of ε_{max} (based on the measured surface uplift provided in Fig. 6*b*) were compared with strain values measured along the crown of the PVC pipe (Table 1) to evaluate the effectiveness of eq. [4] at predicting maximum longitudinal strain in a transverse utility, using values of Δ and i for surface movement. The estimated strain values using the beam approximation together with the measured values are given in Table 5 for various expander locations. In general, the calculated maximum strain values using the beam approximation were less than measured values when surface uplift was used to approximate Δ and i. Most of the discrepancy between the calculated and measured strain can be attributed to the value of i used. Figure 11 shows that i increases at vertical locations further away from the expanded cavity and is greatest at the surface for a homogeneous soil with no close rigid boundaries. In fact, during this experiment i = 800 mm for the surface and i = 489 to 592 mm for the PVC pipe.

Although using surface uplift to approximate i for a transverse utility may be realistic for cases when pipe bursting operations are carried out in a narrow trench, where the vertical displacements are likely to be confined within the trench width (i.e., i for the surface and the pipe may be similar), further investigation appears to be required to relate

Fig. 11. Schematic of surface uplift and the deformed shape of a transverse utility in response to cavity expansion.

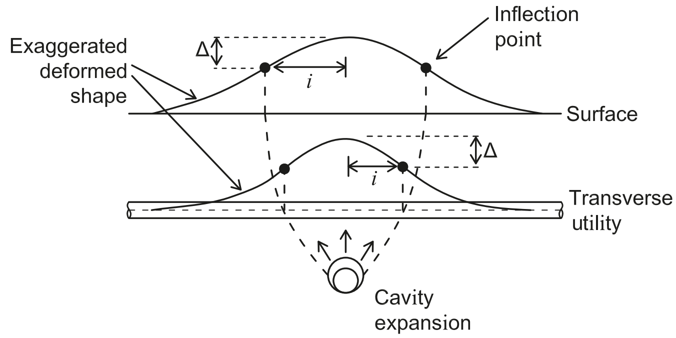


Fig. 12. Simply supported beam approximations. L, length of unsupported pipe; P, load; p, load per unit length.

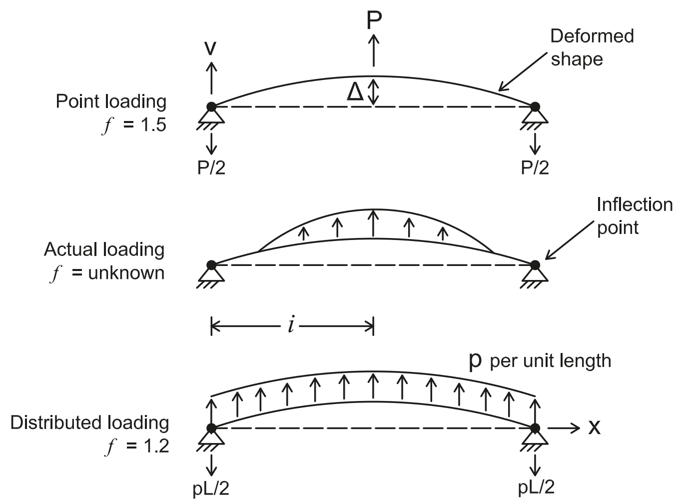


Table 4. Measured and calculated strain using actual PVC pipe deflections.

			ε_{max} ($\times 10^{-6}$)		
Z_B (m)	Δ (mm)	i (mm)	f = 1.2	f = 1.5	Measured strain ($\times 10^{-6}$)
3.68	0.2	489	102	127	170
4.25	0.6	554	298	372	330
4.92	1.6	549	756	944	880
5.43	2.0	592	833	1041	855
7.47	1.8	560	837	1047	860

Table 5. Measured and calculated strain using surface uplift to approximate PVC pipe deflections.

			ε_{max} ($\times 10^{-6}$)		
Z_B (m)	Δ (mm)	i (mm)	f = 1.2	f = 1.5	Measured strain ($\times 10^{-6}$)
3.68	0.4	800	92	114	170
4.25	1.2	800	275	343	330
4.92	1.6	800	366	458	880
5.43	2.4	800	549	686	855
7.47	1.8	800	412	515	860

transverse utility displacements (Δ and i) to surface displacements for varying pipe bursting geometries and soil materials. The results presented here could be used to evaluate the effectiveness of computer models or other procedures developed in the future.

Conclusions

Experimental results from a laboratory investigation of static pipe bursting in a well-graded sand and gravel soil were presented. The experiment was conducted in an 8 m long, 8 m wide, and 3 m deep test pit with an unreinforced concrete pipe (buried 1.385 m below the ground surface) being replaced by a HDPE pipe. The unreinforced concrete pipe had an outside diameter of 229 mm and a wall thickness of 38 mm, whereas the HDPE pipe had an outside diameter of 168 mm and a wall thickness of 11 mm. A PVC pipe instrumented with strain gages was buried 0.45 m above and transverse to the unreinforced concrete pipe. The PVC pipe had an outside diameter of 122 mm and a wall thickness of 7 mm. The nature of pipe bending that occurs as a result of the ground movements induced by pipe bursting operations were quantified, leading to the following conclusions specific to the conditions tested:

(1) The maximum longitudinal strain measured was 0.1%, corresponding to a peak vertical displacement of the pipe of 5.1 mm.

(2) As the expander approached the PVC pipe, a section located directly above the pipe being burst (x = 0) moved vertically upwards and axially forwards. The permanent pipe displacement (i.e., once the expander had passed) was 4.7 mm vertically upwards and 0.2 mm axially backwards from its original position.

(3) Displacements measured at the ground surface were greater than the displacements of the PVC pipe. This was attributed to the pipe having higher flexural stiffness than the soil it replaces.

(4) Based on measurements of circumferential strain, as the expander approaches the PVC pipe, the PVC pipe's vertical diameter increases and the horizontal diameter decreases. When the expander is located directly below the pipe, the vertical diameter decreases and the horizontal diameter increases.

(5) A simplified design equation based on beam theory provides a range of calculated longitudinal strain values that contains the strain measured in the PVC pipe. This may form the basis of a useful calculation procedure once more is learned about the effect of project geometry and materials on transverse pipe response.

(6) For the specific conditions examined, pipe bursting in the vicinity of the particular PVC pipe tested did not jeopardize its long term performance based on conventional ring deflection limits for PVC pipe, provided its joints were not damaged.

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References

ASTM. 2006. Specification for Type PSM poly (vinyl chloride) (PVC) sewer pipe and fittings. ASTM standard D3034-06. ASTM International, West Conshohocken, Pa.

Atalah, A. 1998. The effect of pipe bursting on near by utilities. Pavement and Structures. Technical Report: TT 98–01. Trenchless Technology Center, Louisiana Tech University, Ruston, La.

Brachman, R.W.I., Moore, I.D., and Munro, S.M. 2008. Compaction effects on strains within profiled thermoplastic pipes. Geosynthetics International, **15**(2): 72–85. doi:10.1680/gein.2008.15.2.72.

Chapman, D.N., Ng, P.C.F., and Karri, R. 2007. Research needs for on-line pipeline replacement techniques. Tunnelling and Underground Space Technology, **22**(5–6): 503–514. doi:10.1016/j.tust.2007.05.004.

Cholewa, J.A. 2009. Ground displacements and pipe response during pulled-in-place pipe installation. Ph.D. thesis, Department of Civil Engineering, Queen's University, Kingston, Ont.

Lapos, B., Brachman, R.W.I., and Moore, I.D. 2004. Laboratory measurements of pulling force and ground movement during a pipe bursting test,*In* Proceedings of NO-DIG 2004, New Orleans, La., 22–24 March 2004. North American Society for Trenchless Technology, Arlington, Va. Paper B-1-04.

Moore, I.D. 2001. Buried pipes and culverts. *In* Geotechnical and geoenvironmental engineering handbook. *Edited by* R.K. Rowe. Kluwer Academic Publishing, Norwell, Mass. pp. 541–567.

Nkemitag, M., and Moore, I.D. 2006. Rational guidelines for expected ground disturbance during static pipe bursting through sand. *In* Proceedings of NO-DIG 2006, Nashville, Tenn., 26–28 March 2006. North American Society for Trenchless Technology, Arlington, Va. Paper E-2-01.

Rogers, C.D.F., and Chapman, D.N. 1995*a*. An experimental study of pipe bursting in sand. Proceedings — Institution of Civil Engineers, **113**(1): 38–50.

Rogers, C.D.F., and Chapman, D.N. 1995*b*. Ground displacements caused by pipebursting. *In* Proceedings of Trenchless Asia '95, Singapore, 14–16 February 1995. International Society for Trenchless Technology, Singapore. pp. 5.4.1–5.4.12.

Scott, J.D., Bauer, G.E., and Shields, D.H. 1977. Triaxial testing on granular A aggregate. Ontario joint transportation and communications research program, Ont. Project O-1.

Simicevic, J., and Sterling, R.L. 2001. Guidelines for pipe bursting. U.S. Army Corps of Engineers, Vicksburg, Miss. TTC technical report No. 2001.02.

Transco. 1997. Damage control procedure for pipeline construction involving pipe splitting. Transco BG Plc (now part of National Grid Transco), London. Technical publication No. 4558/3250.

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. doi:10.1680/geot.53.7.619.37383.

List of symbols

C_c coefficient of curvature
C_u coefficient of uniformity
D outside diameter of the PVC pipe (mm)
D_f empirical strain factor
ΔD_v vertical diameter change of pipe (mm)
f factor that is a function of the pattern of the transverse loading applied to the beam
i distance between a point of inflection and location of maximum bending (mm)
L length of the unsupported pipe
P load
p load per unit length
t pipe wall thickness (mm)
u transverse displacement (mm)
v vertical displacement (mm)
w axial displacement (mm)
x transverse direction (m)
y vertical direction (m)
Z_B expander location or length of existing pipe replaced (m)
z axial direction (m)
Δ vertical deflection relative to a point of inflection (mm)
ε_c longitudinal strain measured at the crown
ε_i longitudinal strain measured at the invert
ε_{max} maximum longitudinal strain
ε_x longitudinal strains
ε_θ circumferential strain
$\varepsilon_{\theta,max}$ maximum circumferential strain
θ circumferential direction
κ curvature of the PVC pipe (mm^{-1})
κ_{max} maximum curvature of the PVC pipe (mm^{-1})