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Behavior of a branched buried MDPE gas distribution pipe under axial ground movement

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ABSTRACT
Medium density polyethylene pipes (MDPE) are widely used for gas distribution systems in Canada and worldwide. These pipes are often exposed to relative ground movements resulting from landslides and earthquakes. The effects of the relative ground movement on the pipes are influenced by the presence of lateral branches and the tee-joint connecting the branch. Only a limited study is currently available in the literature on studying the behavior of branched pipe subjected to ground movements. This paper presents an experimental investigation of a branched MDPE pipe subjected to axial ground movement. A test with a 60.3 mm diameter gas distribution pipe is conducted using the laboratory facility at Memorial University of Newfoundland. Pipe wall strains and soil pressures around the pipe are measured to capture the mechanism of soil-pipe interaction. Test results reveal that the pullout force and pipe wall strains are significantly influenced by the tee-joint. The elongation of the flexible MDPE pipe also contributes to the pipe deformations and wall strains.

RÉSUMÉ
Les tuyaux en polyéthylène à moyenne densité (MDPE) sont largement utilisés pour les systèmes de distribution de gaz au Canada et dans le monde entier. Ces tuyaux sont souvent exposés aux mouvements relatifs du sol résultant de glissements de terrain et de tremblements de terre. Les effets du mouvement relatif du sol sur les tuyaux sont influencés par la présence de branches latérales et du joint en T qui relie la branche. Seule une étude limitée est actuellement disponible dans la littérature sur l'étude du comportement des tuyaux ramifiés soumis aux mouvements du sol. Cet article présente une étude expérimentale d'un tuyau MDPE ramifié soumis à un mouvement axial du sol. Un essai avec un tuyau de distribution de gaz de 60.3 mm de diamètre est réalisé dans le laboratoire de l'Université Memorial de Newfoundland. Les contraintes de la paroi du tuyau et les pressions du sol autour du tuyau sont mesurées pour saisir le mécanisme de l'interaction sol-tuyau. Les résultats du test révèlent que la force d'arrachement et les contraintes sur la paroi du tuyau sont influencées de manière significative par le joint en T. L'allongement du tuyau flexible en MDPE contribue également aux déformations du tuyau et aux contraintes exercées sur les parois.

1 INTRODUCTION

The performance of gas distribution pipelines exposed to relative ground movements resulting from landslides and earthquakes has been a significant concern to the utility companies. The damage of these structures due to these geotechnical hazards may pose severe threats to human lives and the surrounding environment adjacent to the area where damage can occur. Branched pipe systems comprising of tee-joint and lateral branches, being common in gas distribution networks, may magnify the effects of these ground movements on the trunk mains as well as the branches.

A considerable amount of studies are available in the literature on exploring the mechanism of soil-pipe interaction subjected to ground displacements (Trautmann and O'Rourke 1985; Wijewickreme et al. 2009; Meidani et al. 2017). Most of these studies focus on investigating the behavior of buried steel transmission pipes. Currently, polyethylene pipes, especially medium density polyethylene (MDPE) pipes, are being widely used for gas distribution piping systems in Canada and worldwide. The failure mechanisms of the polyethylene piping systems are expected to be different from those of steel transmission pipelines due to the higher flexibility and lower deformation stiffness (Weerasekara 2007). Presence of joints and frequent bends in the distribution system makes the problem more complex. However, studies on the behavior of buried polyethylene (PE) gas distribution pipes are very limited.

Early research on full-scale laboratory testing of soil-pipe interaction focused on axial, lateral and uplift loadings on steel pipelines in sand due to relative ground movement (Trautmann and O'Rourke 1983, 1985; Karimian 2006). These studies established equations to predict maximum pullout resistance per unit length of pipe. Based on the findings, design guidelines were developed for the assessment of the pipelines subjected to ground movements (ASCE 1984; ALA 2001; PRCI 2017). In the design guidelines, use of the maximum pullout resistance per unit length is recommended to estimate the spring constants for analysis of pipes considering the soil as a Winkler medium. Several studies were conducted to examine the applicability of the design guidelines and explore soil-structure interaction for MDPE and high density polyethylene (HDPE) pipes (Anderson et al. 2004; Weerasekara and Wijewickreme 2008; Bilgin and Stewart 2009ab). The studies revealed that the soil-pipe interaction for PE pipes is significantly different from that for steel pipes. The PE pipes elongate significantly and undergo diameter reduction under the pulling forces, which influence the soil-pipe interaction. Weerasekara (2007) conducted pullout tests of MDPE pipes and developed closed-form solutions based on several assumptions to explain the nonlinear stress-strain behavior observed during the tests. Considering the lack of experimental evidence on the interaction of soil and polyethylene pipe, Reza et al. (2019ab) and Reza and Dhar (2020) have recently conducted full-scale tests of MDPE gas distribution pipes subjected to movements with respect to backfill soil in a test box. The study revealed that the pullout behavior of the pipe depends on the viscoelastic response of the pipe material.

The soil-pipe interaction of PE pipe is further complicated by the presence of branches on the pipes, commonly observed in the gas distribution system. From full-scale laboratory testing of branched MDPE pipes, Anderson (2004) and Anderson et al. (2004) reported that during ground movement, branched pipes are subjected to a complex interaction with soil, beginning as a lateral movement and transitioning to an axial pullout. Weerasekara (2007) investigated the soil-pipe interaction of branched pipe through full-scale testing of different types of tee-junctions in MDPE pipes under pullout loadings. This study evaluated the impact of commonly used tee connections on a trunk pipe, with respect to additional resistance and induced localized strains for different trunk pipe sizes. The research suggested that the level of soil anchoring at the tee would govern the movement of the tee, depending on the stiffness of the trunk pipe. Thus, special consideration has to be given to the local strain capacity of the tee, mainly if the adjoining branch pipe is stiff. However, the complex interactions of the pipe, tee-junction and the branch with surrounding soil are not well-understood.

The current research focuses on investigating the localized stresses and strains in the vicinity of the tapping tee and the pipe for an improved understanding of their interaction with the surrounding soil. A full-scale laboratory test with a 60.3 mm diameter MDPE pipe having a 15.9 mm diameter branch is conducted under relative ground movement in the axial direction of the pipe. The study includes measurement of soil pressures at pipe-soil interface both before and during the pullout displacement, and pipe wall strains during the pullout. The primary objectives of the study are to investigate the effect of an axial landslide on the MDPE gas distribution pipe with tee-joint and understand the associated mechanics of soil-pipe interaction. The research attempts to identify the contribution of the branch and the tee-joint to the soil resistance.

2 SOIL RESISTANCE IN BRANCHED PIPE

A branched pipe includes a trunk main, a jointing element (tapping tee) and a branch pipe. Soil resistance for the branched pipe depends on the interaction of these components with the surrounding soil, which is expected to be very complex. Weerasekara (2007) proposed to isolate the contribution of each component, considering them independent of each other. The total soil resistance was divided into the frictional resistance caused by the axial movement of the trunk pipe, anchoring resistance of the tapping tee and resistance due to the branch pipe movement (Weerasekara 2007). Frictional resistance due to axial movement of trunk pipe is considered as the one given by the axial pullout forces for straight pipe, without giving any consideration for any coupling effect. For the lateral resistance due to the tapping tee (F_t), it is suggested to employ the lateral bearing capacity of pipes or vertical anchors proposed in ASCE (1984), as shown in Eq. 1

$$F_t = \left(N_q\,\gamma\,H\right) A_t \qquad [1]$$

where A_t = projected tee area in a plane perpendicular to the direction of the movement, H = soil cover depth, γ = soil density and N_q = lateral bearing capacity factor calculated from ASCE (1984) design graph for H/D ratios and friction angles. According to these guidelines, the tee displacement (y_h) at the ultimate bearing capacity is estimated as y_h = 0.02 H, based on which the forces at any other displacements were calculated. The applicability of the ASCE (1984) method for lateral bearing capacity of pipes or anchor plates to the forces due to tapping tee was not investigated. In the current study, earth pressure in front of the tapping tee is measured to examine the forces due to the tapping tee.

Weerasekara (2007) proposed an empirical method to approximate the contribution of the branch pipe (F_b) to the pullout resistance as a function of the displacement (x) of the tapping tee, where the branch is connected. The contribution of the branch is separated experimentally using testing of pipe with a tapping tee only and a pipe with a branch along with the tapping tee.

The objective of the current study is to explore the effects of tapping tee and branch through measurements of local strains on the pipe and stresses within the soil around the pipe, including the tapping tee.

3 TEST METHOD

3.1 Test Pipe

This paper presents the results of a test conducted as a part of a laboratory testing program being carried out to investigate the MDPE branch pipes subjected to ground movement along the longitudinal direction of the trunk pipe. The test pipe is a 60.3 mm diameter trunk pipe with a 15.9 mm diameter branch. The branch is connected to the trunk pipe using a tapping tee of 91.4 mm height and 38.1 mm diameter. Figure 1 shows the tee-joint used to connect the branch. The thickness of the trunk pipe and the branch pipe was ~6 mm and ~3.2 mm, respectively. Anderson et al. (2004) and Weerasekara et al. (2006) earlier conducted tests with similar pipe (60 mm diameter trunk pipe with a tee connection and branch) buried in Fraser river sand. They reported significant strain concentration on the trunk pipe near the tapping tee. However, the soil stresses around the pipe and within the vicinity of tapping tee were not measured.

Figure 1. Tee-joint used for branch connection

3.2 Test Facility

The test facility at Memorial University of Newfoundland is a steel tank with inside dimensions of 4 m length, 2 m width and 1.5 m depth (Murugathasan et al. 2020). The tank has two circular openings of adjustable sizes on two opposite walls in the longitudinal direction that allow pulling of pipes with different diameters. The MDPE pipe was buried in well-graded sand in the test box at a depth of 0.6 m, a depth commonly used in the gas distribution system (Weerasekara 2007). The ends of the pipe extend beyond the test box through the openings to allow longitudinal movement when pulled. The openings in the tank walls are slightly larger than the outer diameter of the pipe. The gap is filled with lubricant (grease) to minimize the friction between the pipe and the face of the openings. A steel connector is used to connect one end of the pipe to a hydraulic actuator for axial pulling. The actuator was attached to a 22.25 kN capacity load cell. The load cell measured the pullout force applied to the pipe, which is the same as the soil resistance against the pipe movement. The end of the pipe nearer to the actuator is referred to as the "leading end" and the other end of the pipe is referred to as the "trailing end". A linear variable differential transducer (LVDT) was attached to the trailing end of the pipe to measure the axial movement during the pullout test. A pulling rate of 0.5 mm/min was applied during the test, which was the minimum rate that could be applied in the laboratory setting.

3.3 Backfill Sand

A locally available well-graded sand (USCS classification: SW) containing ~1.30% of fines was used as the backfill material for the pipe. About 9.6 m^3 of sand was required to achieve the soil cover depth of 0.6 m for the test. The sand was compacted in layers with a tamping plate at every 2 m^3 of placement. Saha et al. (2019) measured the maximum dry density of this sand as 18.8 kN/m^3 using laboratory Standard Proctor Compaction tests. The dry density of the sand in the tank was measured as 20.9 kN/m^3 using the sand cone method (ASTM D1556-07). Thus, the relative compaction of the backfill material was 111% of the Standard Proctor maximum dry density.

3.4 Instrumentation

The test instrumentation included six soil pressure sensors used at different locations within the soil and the pipe-soil interface. These sensors are named 'null pressure sensors' as they work on the principle involving nullification of deformation of diaphragm by internally applied pressure (Talesnick et al. 2014). In this method, the stiffness of the diaphragm inside the sensor does not interfere with the pressure measurements as the diaphragm is kept undeflected by applying internal air pressure in the sensor. This internal air pressure is equivalent to the pressure within the soil. The diameter of the sensor is 50 mm, which can measure the localized stress within the soil. Figure 2 shows a typical earth pressure sensor used.

Figure 2. Soil pressure sensor used in the test

Two of the pressure sensors were intended to measure soil parameters and placed at a depth of 0.3 m below the pipe springline. The influence of the pipe at this depth is considered insignificant on the earth pressures for the pipe with 60 mm diameter that allows a depth to diameter ratio of ~5. The sensors were placed horizontally and vertically in the soil to measure the vertical and lateral soil pressure, respectively. The other pressure sensors were placed to measure the soil stresses around the pipe and near the tapping tee. A sensor is placed at a distance of 200 mm from the tapping tee to measure the earth pressure due to the connection.

Figure 3 shows the details of the instrumentation employed during the test. Five electronic strain gauges were placed at the crown of the pipe along the pipe length to measure the pipe wall strains. Earth pressure sensors MU1 and MU2 were used to measure the vertical and horizontal stresses, respectively, in the soil away from the pipe to understand the behavior of the backfill soil. Sensors MU3 and MU4 measured the horizontal stresses near the pipe in the lateral and longitudinal directions, respectively. Sensor MT1 measured the lateral earth pressure in front of the tapping tee and sensor MT2 measured the vertical earth pressure at the invert of the pipe. Three LVDTs (LVDT 1, 2 and 3) were used to measure the soil strains within the test cell (the results are not reported here for the sake of brevity).

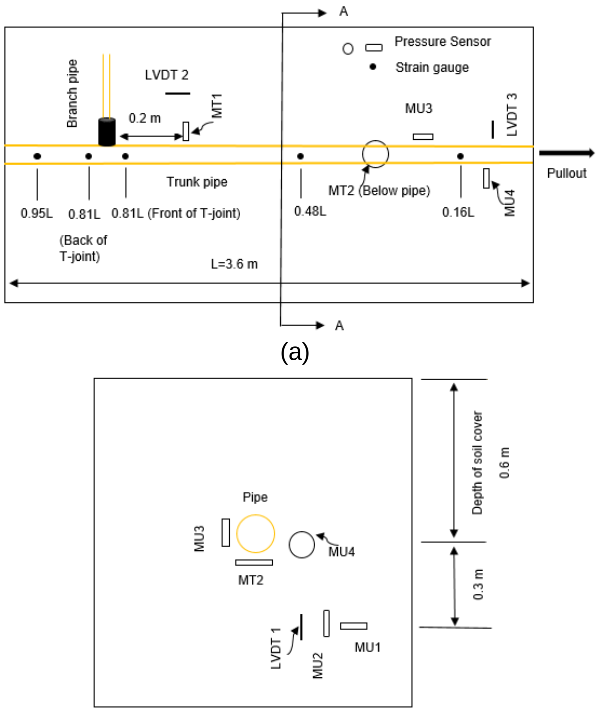

Figure 3. Test instrumentation (a) plan view (b) section A-A

4 RESULTS AND DISCUSSIONS

4.1 Soil Pressures during Installation

Earth pressures during placement of soil and pipe in the test box are examined to understand the mechanics of load transfer in the soil during installation. Figure 4 shows the measured earth pressures during installation. Soil cover above the sensors and the corresponding calculated geostatic stresses are also included in the figure for comparison. Note that the height of soil cover is estimated based on the approximate volume of the sand placed, except for the final soil cover, which was measured after completion of installation. During backfilling, the sand is first dumped at a place in the box and then spread to level the surface. As a result, the measured stresses change with time (the lines are not horizontal) for a particular cover depth, while the lines for the estimated soil cover depths (and the geostatic stresses) are horizontal in the figure.

Figure 4(a) shows the vertical soil pressure measured at a depth of 0.3 m below pipe (beyond the zone of influence by the pipe) using sensor MU1. In general, the measured earth pressure increases with the increase of soil cover. At the final soil cover depth, the measured earth pressure matches the calculated geostatic stress. This implies that even though no treatment was used to reduce the sidewall friction, the vertical stress was not reduced by the wall friction. This may be due to the fact that for the 2.0 m wide test cell, a shallow soil cover (0.3 m to 0.9 m) corresponds to a scenario similar to a wide trench installation condition of buried pipe (Moser and Folkman 1990) where the soil load is not reduced by the friction along the trench wall. The sensor used to measure horizontal stress at this depth (MU2) mulfuntioned and therefore data is not available.

For the sensors used to measure earth pressures in the vicinity of test pipe, vertical stresses under the invert of the pipe (measured by MT2) are higher than the corresponding geostatic stresses (Figure 4b). As shown in the figure (Figure 4b), at shallow cover (~0.1m) the measured vertical stress is almost the same as the geostatic stress. However, at the higher cover depths, the measured stresses are significantly higher than the calculated geostatic stresses. At the final covered depth, the measured vertical stress is 18.7 kPa, while the geostatic stress is 12.5 kPa. Thus, the measured stress is ~50% higher than the geostatic stress. The sensor used to measure horizontal stress normal to the pipe surface at the springline (MU3) did not work properly. The stress normal to the pipe surface (vertical stress at the invert) is significantly higher than the corresponding geostatic stresses due to soil−pipe interaction. This phenomenon has also been observed in other pullout tests. This high stress is not considered in the calculation of pullout force using conventional design equations (ASCE 1984; ALA 2001).

However, the horizontal stresses measured in the longitudinal direction of the pipe and test cell (measured by sensor MU4) are less than the calculated vertical stresses and increase consistently with soil cover (Figure 4c). At the final cover depth, the horizontal earth pressure in the longitudinal direction is 2.5 kPa, which provides a coefficient of lateral earth pressure of 0.2 based on the calculated geostatic vertical stress of 12.5 kPa. This coefficient of lateral earth pressure (K = 0.2) is equal to the coefficient of earth pressure at rest calculated using a Poisson's ratio of 0.17, which is considered reasonable for the dense sand in the test box. Thus, the earth pressure in the longitudinal direction is not affected by the presence of the pipe and can be calculated as the lateral earth pressure at rest.

The horizontal soil stresses measured in front of the tapping tee are less than the geostatic vertical stress at this point (Figure 4d). However, the coefficient of lateral earth pressure (i.e., 0.46) is higher than the coefficient of earth pressure calculated in the longitudinal direction, indicating that the earth pressure is affected by the presence of the relatively rigid tapping tee.

4.2 Earth Pressure during Pipe Pullout

Figure 5 shows the changes in the earth pressures measured during axial pulling of the trunk pipe having the lateral branch. Figure 5(a) shows that the vertical stress at the depth of 0.3 m below the pipe is not affected by the axial pullout of the pipe (sensor MU1). The vertical stress at that point remains the same as the vertical overburden pressure. All other sensors located near to the pipe experienced stress increase during the pulling of the pipe due to movement of the soil (or dilation) near the pipe.

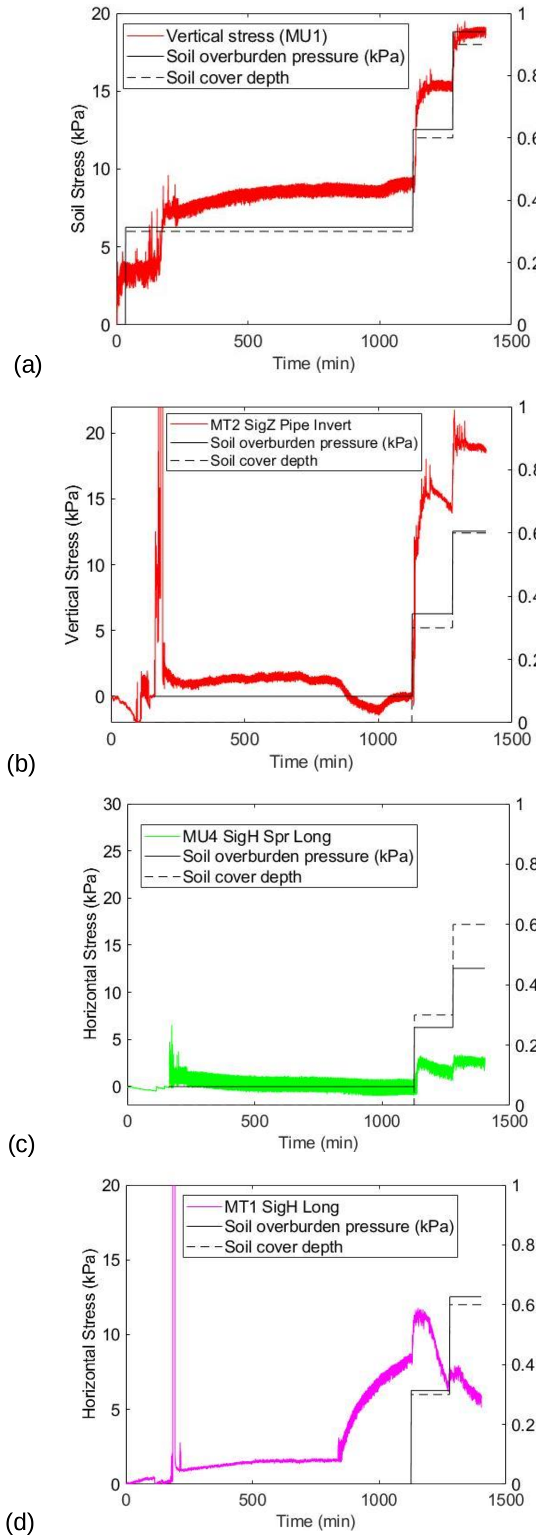

Figure 4. Earth pressure measurements during installation at (a) 300 mm depth below springline (b) pipe invert (c) pipe-soil interface (d) 200 mm in front of the tee

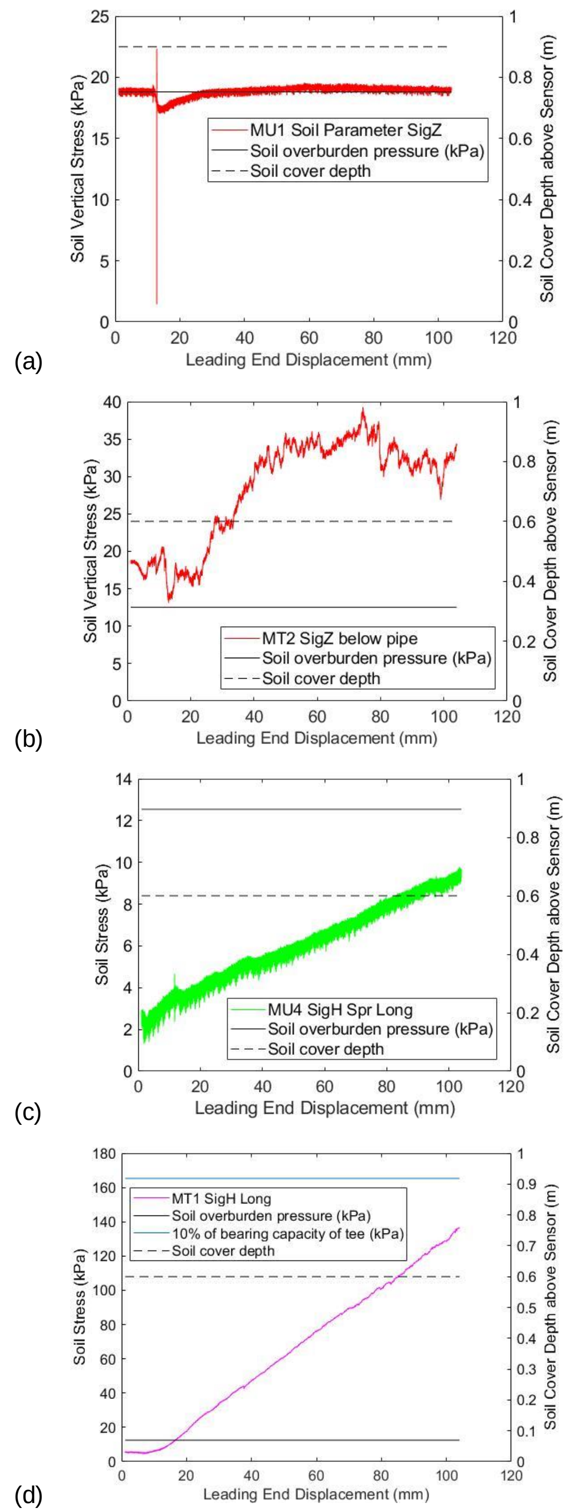

Figure 5. Earth pressure measurements during pullout of pipe at (a) 300 mm depth from pipe springline (b) pipe invert (c) pipe-soil interface (d) 200 mm in front of the tee

The increase of normal stresses to the pipe (vertical stress at the invert in Figure 5b and horizontal stress in the longitudinal direction at the springline in Figure 5c) is less significant up to a leading end displacement of around 20 mm beyond which the stress is increased steadily until the maximum values are reached. Thus, the effect of dilation or soil movement is insignificant during elongation of the pipe up to the leading end displacement of 20 mm. The measurements of strains discussed later in the paper reveal that strain gauge right behind the tee start reading a compressive strain at the leading end displacement of 20 mm while the other strain gauges in front of the tee continue to read tensile strains. The change of sign of the strain from the front to the back of the tapping tee indicates a bending mechanism. Thus, the earth pressure increase beyond 20 mm of leading end displacement is associated with the bending mechanism of the pipe that is caused by the presence of the tapping tee (Figure 7). The earth pressure increase is stabilized beyond the leading end displacement of 80 mm. The maximum stress is almost double of the initial values (before pulling).

The horizontal soil stress in front of the tapping tee (MT1) does not change up to a leading end displacement of ~10 mm beyond which it increases almost linearly with the increase of leading end displacement (Figure 5d). At the leading end displacement of around 10 mm, the strain right in front of the tee starts increasing (discussed later), indicating that the axial force is mobilized to that position. Beyond that displacement, the axial force is mobilized to the tapping tee. Thus, the stress increase in MT1 is due to the movement of the tee that applies horizontal bearing pressure to the soil. The maximum horizontal pressure measured at the end of the test (104 mm of leading end displacement) was 140 kPa. This pressure is almost half of the lateral bearing capacity calculated using Eq. 1. The test was discontinued at the leading end displacement of 104 mm and therefore, the maximum bearing pressure due to the tapping tee could not be examined during the test. However, as discussed further below, tapping tee displacement was greater than the lateral displacement (i.e., 12 mm) recommended in ASCE (1984) for mobilization of maximum lateral resistance for pipes or vertical anchor plates (i.e., $y_h/H=0.02$). Thus, ASCE (1984) recommendation for the lateral displacement may not be applicable for the tapping tee considered in this study.

4.3 Pullout Force and Pipe Responses

The pulling force or the soil resistance to pipe pulling is plotted against the leading end displacement in Figure 6. The maximum pullout resistance of 9.3 kN was observed during the test at the leading end displacement of 104 mm. As mentioned above, the pulling resistance is contributed by the frictional resistance along the length of the pipe and the anchoring resistance of the tee-joint and the branch. The frictional resistance along the pipe length can be separated into two components: one for the pipe length in front of the tee and the other for the pipe length behind the tee (Figure 7). The test program was designed to have a shorter length (19% of the total length of the pipe as shown in Figure 3a) behind the tee to have minimum frictional contribution for this part of the pipe. The mobilization of axial force (hence the soil resistance) along the length of the pipe is examined through the measurement of axial strains during the test.

Figure 8 shows the axial strains measured at various points along the length of the pipe. Since the axial force in the pipe is gradually mobilized from the leading end toward the trailing end during pipe pulling, the strain gauge closest to the leading end first shows strain increase followed by the subsequent strain gauges. Strain just in front of the tee joint (identified as 0.81L) starts increasing at the leading end displacement of 10 mm, implying that axial force (and the frictional resistance) is mobilized over the pipe length in front of the tee at this displacement. The pullout resistance at the displacement of 10 mm is found as 3.0 kN from Figure 6. Thus, the frictional resistance for the pipe length in front of the tee can be assumed as 3.0 kN. This value tends to match the frictional resistance of 3.1 kN that occurred in a similar pullout test without any branch (Reza and Dhar 2020). The frictional resistance for the pipe length behind the tee can be assumed to be negligible as the strain reading is zero at this portion of the pipe (identified as 0.95L). Thus, the maximum anchoring resistance can be estimated through the frictional resistance from the maximum pullout resistance. The anchoring resistance is thus calculated as 6.3 kN.

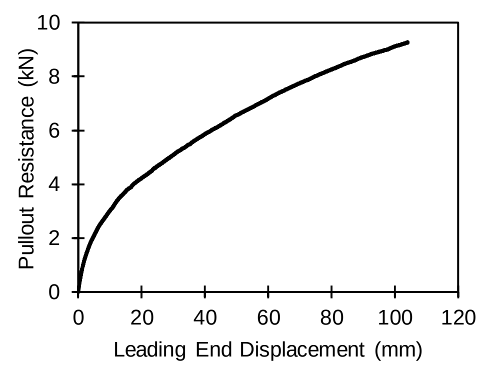

Figure 6. Pullout response of the test

For the leading end displacement of beyond 10 mm, the anchoring effect of the tee and the branch comes into effect. Then, the lateral soil force on the tee causes a bending moment to the trunk main. Due to the bending effect, strain right behind the tee joint is compressive at the pipe crown. Tensile strain in front of the tee is also increased at a higher rate due to the bending effect. Deflected shape of the pipe subjected to the bending is shown using a dotted line in Figure 7.

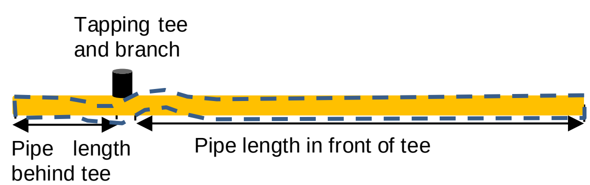

Figure 7. Contributors to pullout resistance

The bending mechanism can be examined further using the distribution of axial strain along the length of the trunk pipe at various leading end displacements (Figure 9).

Figure 9 shows that at low leading end displacement (up to 10 mm), pipe strain decreases linearly from the leading end to zero. The strain behind the tee is zero. With the increase of leading end displacement beyond 10 mm, strain increases at a higher rate toward the trailing end while compressive strain develops right behind the tee due to the bending action. Finally, the axial strain right in front of the tee becomes significantly higher than the leading end strain, which may lead to rupture in the pipe. Rupture was not observed during the test at the maximum strain encountered (i.e., 3%).

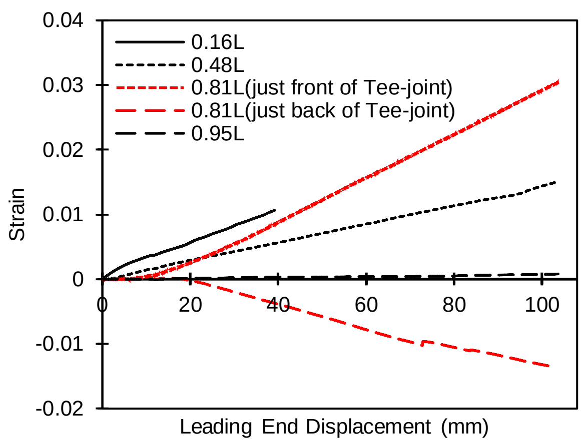

Figure 8. Pipe wall strain at different locations

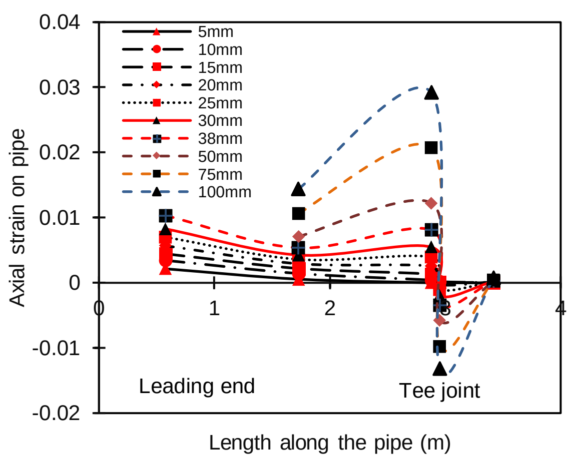

Figure 9. Strain distribution along the trunk pipe

Movement of the tee joint could not be measured during the test in order to develop force-displacement relation for the anchor force. However, since the pipe strain behind the tee is zero, elongation for that part of the pipe can be assumed to be zero. Thus, the trailing end movement can be considered same as the movement of the tee joint. The trailing end movement was measured during the test using an LVDT. Figure 10 plots the trailing end displacement along with overall pipe elongation calculated as the difference between the leading end displacement and the trailing end displacement. It shows that the maximum trailing end displacement of 20 mm was obtained during the test. As mentioned earlier, this displacement is greater than the displacement recommended in ASCE (1984) for mobilization of lateral soil resistance. However, peak pullout force was not reached during the test.

5 CONCLUSIONS

This research explores the mechanism of soil-pipeline interaction in the buried branched pipe subjected to axial ground movement using a full-scale laboratory test. Pipe strains and soil stresses are measured during the test to capture the mechanics of soil-pipe interaction. The main findings of the study are summarized below:

- Test box can effectively be used to investigate soil-pipe interaction without any requirement for sidewall treatment to reduce friction. For the 2 m wide test cell, vertical soil stress was not reduced due to wall friction.
- Soil stress at a depth of 300 mm from the pipe is not affected by the presence of the pipe and can be calculated as the geostatic stress. However, the soil stress near the pipe is significantly affected by the pipe.
- The stress normal to the pipe surface (vertical stress at the invert) can significantly be higher than the corresponding geostatic stress even under static condition. This high stress is not considered in the calculation of pullout force using conventional design equations.
- The axial pulling increases the normal stresses further due to the effect of dilation of soil. These stresses should be properly accounted for calculating the pipe wall stress.
- The lateral stress in front of tapping tee is influenced by the movement of the tee. ASCE (1984) guideline might be useful for calculating the maximum lateral force on the tee. However, ASCE (1984) recommendation for the lateral displacement for mobilization of maximum lateral resistance may not be applicable for the branched MDPE pipe.
- Soil reaction force on the tee connection can induce a bending moment to the trunk main that can cause very high strain on the pipe wall in front of the tee.

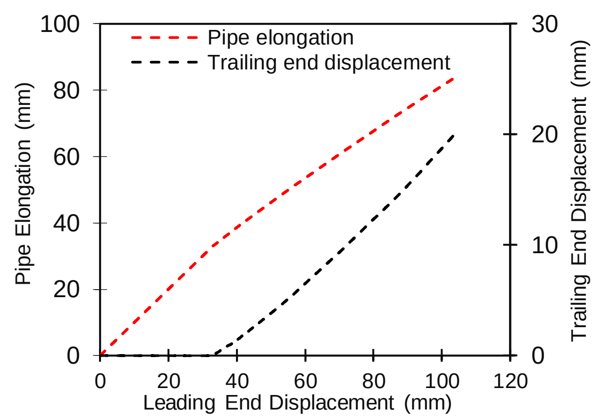

Figure 10. Pipe elongation and trailing end displacement

6 ACKNOWLEDGEMENTS

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