BEHAVIOR OF BRANCHED BURIED MDPE GAS DISTRIBUTION PIPES UNDER RELATIVE AXIAL GROUND MOVEMENTS

by

© Sudipta Chakraborty

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ABSTRACT

The performance of medium density polyethylene (MDPE) gas distribution pipes subjected to relative ground movements has been a significant concern to the utility owners and companies. The tee-joints (tapping tee) and the lateral branches, common in gas distribution piping systems, may increase the effects of ground movement caused by various geohazards such as landslides, earthquakes etc. Most ground movement scenarios depict leak/stress concentration near the tapping tee of the branched pipe system. However, limited studies are currently available in the literature on the soil-pipe interaction of branched pipes during ground movement. Thus, the complex interactions of the pipe, the tee-junction, and the branch with surrounding soil are not well-understood. This thesis presents an experimental investigation of different configurations of 42.2-mm and 60.3-mm diameter branched buried MDPE pipes under relative axial ground movement. Tests with different positions of the tee-joint with respect to the pulling end of the pipe and varying densities of sand are conducted using the laboratory facility at Memorial University of Newfoundland. Pipe wall strains and soil pressures around the pipes are measured during the tests to capture the mechanism of soil-pipe interaction. Subsequently, an additional test is done with the tapping tee only (without the branch pipe) to identify the contribution of the branch pipe to soil resistance and pipe wall strain. The study explores the contribution of the trunk pipe, the tapping tee, and the branch pipe separately on the axial pulling force. Test results reveal the possibility of localized strain occurring on the trunk pipe near the tee. The anchoring effects of the tee and the branch significantly affect the soil resistance and the strain distribution on the trunk pipes.

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A_t projected tee area in a plane perpendicular to the direction of the movement

C_c coefficient of curvature

C_u coefficient of uniformity

D diameter of the trunk pipe

F_b branch pipe resistance

F_t lateral resistance due to the tapping tee

H soil cover depth

K coefficient of lateral earth pressure

L length of the trunk pipe inside the test cell

N_q lateral bearing capacity factor

x displacement of the tapping tee and the pipe

y_h tee displacement

γ soil density

CHAPTER 1 : Introduction

1.1 Background and Motivation

The performance of gas distribution pipelines exposed to relative ground movements resulting from landslides and earthquakes has been a significant concern to 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 tee-joints and lateral branches, being common in gas distribution networks, may increase the effects of these ground movements on the trunk mains as well as the branches.

A significant amount of studies are available in the literature on exploring soil-pipe interaction mechanisms in buried pipes subjected to relative ground movements (Trautmann and O'Rourke 1983, 1985; Weerasekara and Wijewickreme 2008; Bilgin and Stewart 2009a, 2009b; Wijewickreme et al. 2009; Meidani et al. 2017). Most of these studies focus on investigating the interaction behavior of buried steel transmission pipes with surrounding soil (Trautmann and O'Rourke 1983, 1985; Karimian 2006; Katebi et al. 2019). Polyethylene pipes (PE), especially medium density polyethylene (MDPE) pipes, are 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 (Anderson et al. 2003; Weerasekara 2007; Muntakim and Dhar 2021; Reza and Dhar

2021a, 2021b). The presence of joints and frequent bends in the distribution system makes the problem more complex (Anderson et al. 2004; Weerasekara et al. 2006). Consequently, leak/stress concentration mainly occurs near the joints of the branched pipe system during ground displacements. Previous studies also suggested that the trunk pipe may experience significant localized stress and strain concentration near the tee-joint of the branched pipe system due to anchoring of the tee connection and the branch pipe (Anderson 2004; Weerasekara 2007). However, studies on the pipe-soil interaction behavior of branched buried MDPE gas distribution pipelines are limited. Thus, the complex interactions of the pipe, tee-junction, and the branch with surrounding soil are not well-understood.

With this background, the current research conducts a full-scale laboratory testing program to investigate the buried MDPE branched pipes subjected to ground movement along the longitudinal direction of the trunk pipe. A relative axial ground movement is simulated by pulling a buried pipe through static soil in the test facility. The test pipes include 42.2-mm and 60.3-mm trunk pipes with a 15.9-mm branch connected with a tee-joint (tapping tee) to the trunk pipe, which are commonly used in gas distribution systems. The tee-joints tested in this study are typically used for service connection to households.

1.2 Objectives

The primary objective of the study is to develop a database on the behavior of branched buried MDPE gas distribution pipes under axial ground movement. An experimental program was undertaken to explore the soil-pipe interaction. The specific objectives of this research are to:

- Investigate the effect of axial landslide on the MDPE gas distribution pipes with tee-joint and understand the associated mechanics of soil-pipe interaction.
- Explore the effects of tee connection and branch through measurements of local strains on the pipe and stresses within the soil around the pipe.
- Examine the force due to the tapping tee by measuring lateral earth pressure in front of the tee connection.
- Identify the contribution of the trunk pipe, tapping tee, and branch pipe separately to the axial soil resistance of the branched pipe system.

1.3 Thesis Organization

The outcome of this research is presented in five chapters in this thesis.

Chapter 1 presents the background and motivation, objectives, and significant contributions of the research undertaken.

Chapter 2 is a literature review that presents an overview of the previous studies on buried steel pipes and medium density polyethylene (MDPE) pipes subjected to relative ground movements, including the full-scale laboratory tests and numerical and analytical modeling.

Chapter 3 describes the tests conducted with 60.3-mm trunk pipes with a 15.9-mm diameter branch. This chapter describes the test method and instrumentation, pipe pullout responses, earth pressure and soil strain results. The discussion and interpretation of the test results are also presented. The discussion includes the determination of the contribution of tapping tee and branch to the pullout resistance.

Chapter 4 presents the tests conducted with 42.2-mm trunk pipes and a 15.9-mm branch. The pipe pullout responses, soil pressure measurements, and calculation of tapping tee and branch contribution to pullout resistance were discussed.

Chapter 5 presents the overall summary of the study with recommendations and suggestions for future research.

1.4 Significant Contributions

The following technical papers were published from the study presented in this thesis.

Conference Papers

- Chakraborty, S., Dhar, A.S., Talesnick, M., and Muntakim, A.H. 2020. "Behavior of a Branched Buried MDPE Gas Distribution Pipe under Axial Ground Movement." *In* Proceedings of 73rd Canadian Geotechnical Conference, GeoVirtual 2020, Canada, September 14-16.
- Chakraborty, S., Dhar, A.S., and Reza, A. 2021. "A Laboratory Investigation of Buried 42-mm Diameter MDPE Branched Pipes under Relative Axial Ground Movements." *In* Proceedings of 74th Canadian Geotechnical Conference, GeoNiagara 2021, Niagara Falls, ON, Canada, September 26-29.

1.5 Co-Authorship Statement

All the research presented in the conference papers was conducted by the author of this thesis, Sudipta Chakraborty, under Dr. Ashutosh Sutra Dhar's supervision. The first draft of the manuscripts was also prepared by Sudipta Chakraborty and subsequently revised based on the co-authors’ feedback and the peer-review process.

CHAPTER 2 : Literature Review

2.1 Introduction

This chapter presents an overview of the previous research on buried steel pipes and medium density polyethylene (MDPE) pipes subjected to relative ground movements, including the full-scale laboratory tests and numerical and analytical modeling. The review describes the current understanding and design practices regarding soil-pipe interaction during permanent ground displacements. Only a limited study is currently available in the literature on studying the behavior of branched MDPE pipes. The findings from the existing studies would identify areas where further research is necessary.

2.2 Studies on Buried Steel Pipes

A considerable amount of studies are available in the literature on exploring the mechanism of soil-pipe interaction subjected to ground displacements for steel pipes. More details of these studies are available elsewhere (e.g., Audibert and Nyman 1977; Trautmann and O'Rourke 1985; Paulin et al. 1998; Wijewickreme et al. 2009; Meidani et al. 2017). 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. Some of the recommendations from these studies were incorporated in steel pipe design guidelines (i.e., ALA 2005, ASCE 1984, PRCI 2017). Using the theory of beams on elastic foundations

(Hetenyi 1946), closed-form solutions for longitudinal and lateral loading of pipes were derived (O'Rourke and Nordberg 1992; O'Rourke et al. 1995; Trigg and Rizkalla 1994; Rajani et al. 1995; Chan and Wong 2004). Inclusion of elasto-plastic characteristics of soil and pipe material in the closed-form solutions for the axial movement would prevent the design from being over-conservative (Trigg and Rizkalla 1994; Rajani et al. 1995).

Katebi et al. (2019) conducted a numerical analysis using the design recommendations in the guidelines to study the pipeline behavior during slow landslides at different at-risk landslide zones of Manitoba Pipeline Network. They compared the numerical analysis results with the instrumentation data and consequently recommended future monitoring programs in slow landslide areas. The study revealed that strain gauges could not capture the effect of the slow landslide on the pipe as they were installed on the pipe that has already reached the ultimate deformed state. The research findings suggested installing the strain gauges either on a pipe constructed newly or removing the soil cover over the entire pipe length in the active and the passive zone. Thus, the locked-in strain can be released before installing the strain gauges on the pipe. Jung et al. (2013a) evaluated pipe-soil interaction for uplift in granular soil using a two-dimensional, finite-element continuum model. The model results depicted excellent agreement with multiple full-scale tests measurements in corresponding force–displacement responses. Wham et al. (2016) numerically demonstrated the responses of jointed cast iron and ductile iron pipelines to tunneling-induced ground deformation, incorporating large-scale laboratory test results to characterize the joints.

Several field pullout tests reported in the literature were conducted on steel pipes to assess the soil-pipe interaction problem under real-life conditions. Audibert and Nyman (1977) conducted a field lateral pullout test on a 230-mm diameter pipe, whereas Rizkalla et al. (1996) and Cappelletto et al. (1998) performed field axial pullout tests on pipes buried under different backfill materials. Bruschi et al. (1996) and Bughi et al. (1996) presented detailed field monitoring results incorporated in numerical modeling of the actual pipe-soil interaction problem.

2.3 Studies on MDPE Pipes

Several studies were conducted to explore the soil-structure interaction for MDPE and high-density polyethylene (HDPE) pipes (O'Rourke et al. 1990; Stewart et al. 1999; Anderson et al. 2003; Weerasekara and Wijewickreme 2008; Bilgin and Stewart 2009a, 2009b). The interface friction behavior at the pipe-soil interface for MDPE pipes was investigated by O'Rourke et al. (1990). Stewart et al. (1999) experimentally investigated the thermal effects on the behavior of HDPE pipes under temperature-induced cyclic loading. Anderson et al. (2003) and Anderson (2004) conducted full-scale laboratory tests pulling MDPE pipe specimens axially through Fraser river sand backfill. The research included an instrumentation array and specialized installation procedures to observe and measure real-time pullout resistances, displacements, and strains along the pipelines (Anderson 2004). Pullout tests were conducted in both loose and dense sand backfill, and the results were compared with analytical models. 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. The strain, force, and mobilized frictional resistance of the pipe can be determined for a known ground deformation value using the closed-form solutions. The formulation can also predict the ultimate mobilized frictional length and the associated deformation value at failure.

Considering the lack of experimental evidence on the interaction of soil and polyethylene pipe, Reza et al. (2019a, 2019b) and Reza and Dhar (2021a) have recently conducted full-scale tests of MDPE gas distribution pipes subjected to axial 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 pipe wall strains developed almost linearly from the leading end to the trailing end when the shear strength was completely mobilized over the entire pipe length. The research highlighted the limitations of the current design method to calculate the maximum pullout force in MDPE pipes. These studies conducted axial pullout tests of 42.2-mm and 60.3-mm diameter MDPE pipes under different loading rates to examine the effect of strain rate on the pipe pullout behavior.

Recently Muntakim and Dhar (2021) employed three-dimensional finite element (FE) analysis to examine the soil-pipe interaction for MDPE pipes and proposed a soil-pipe interaction factor to account for the effects in calculating axial pullout forces due to ground movement. The study reported that the soil axial pulling resistance depends on the pipe stiffness relative to the surrounding soil and the soil shear strength parameters, considering the variation in normal stresses on the pipe surface. The normal stress becomes higher and nonuniform over the pipe length due to the elastoplastic behavior of the soil.

2.4 Research on Branched MDPE Pipes

The soil-pipe interaction for 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 branched pipes are subjected to a complex interaction with soil during ground movement, beginning as a lateral movement and transitioning to an axial pullout. The branched pipe system tested comprised two tee connections with corresponding branch pipes and was tested in dense and loose sand backfill conditions. The research developed an analyzing technique for branched pipe configurations by comparing the test results to available soil-pipe interaction models. The experimental study revealed that the trunk pipe is more vulnerable to damage than the branch in smaller diameter trunk pipes, in contrast to larger diameter trunk pipes where the branch pipe is more vulnerable during ground displacements. Figure 2-1 shows the axial strain distribution along the pipe length in the branched pipe test with 60-mm trunk pipe buried in dense sand (Anderson 2004). The figure shows that the local strains are significantly large in front of the tee, especially at the leading end displacements greater than 50 mm and have very steep gradients along the pipe length. The study indicated that the anchoring force of the tee connection causes this significant localized strain concentration in the trunk pipe. This research suggested that the performance of the branch was not significantly affected by the diameter of the trunk pipe.

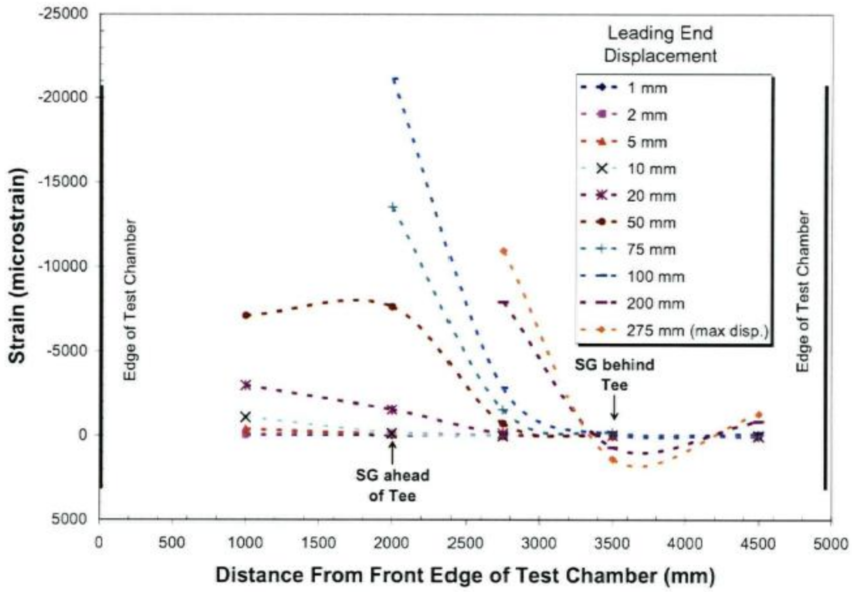


Figure 2-1: Axial strain distribution along the 60-mm trunk pipe in branched pipe tests of Anderson (2004)

Weerasekara (2007) investigated the soil-pipe interaction of branched pipe through full-scale testing of different types of tee-junctions in MDPE pipes under axial pullout loadings. The primary objectives of the research were to explore the key parameters influencing the behavior of branched MDPE pipes buried in soil and provide input contributing to building a suitable set of guidelines and criteria for ensuring the operational fitness of a given PE piping system with an increased level of confidence. 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 tests were conducted in both restrained and unrestrained conditions of the branch pipe ends buried in the backfill soil to simulate the real-life pipe installation scenarios. The experimental test results demonstrated that the physical location of vulnerability might depend on relative pipe sizes, soil density, and the type of tee-joint used. 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. The test results indicated the failure modes of the branched pipes and the critical locations of failure considering pipe configurations and associated tapping tee location. The results showed that the 60 mm diameter trunk pipes, when connected to 16 mm branch pipe, would experience large strains, as shown in Figure 2-2, primarily due to the anchoring of the tapping tee connection and the branch pipe. Anderson (2004) also depicted similar strain distribution along the trunk pipe in a branched pipe system (Figure 2-1).

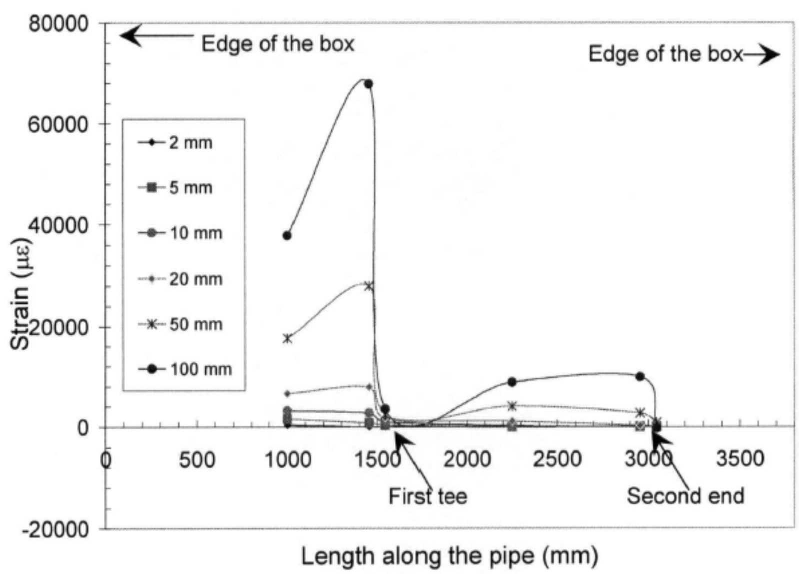


Figure 2-2: Axial strain distribution along the 60-mm trunk pipe in branched pipe tests of Weerasekara (2007)

Weerasekara (2007) proposed an empirical method to approximate the contribution of the branch pipe to the pullout resistance as a function of the displacement of the tapping tee, where the branch is connected. The contribution of the branch was also separated experimentally using testing of pipe with tapping tees only and pipe with two branches along with the tapping tees. The proposed soil-spring characteristics in that study are only valid for the specific soil and burial condition used.

2.5 Studies on Lateral Pipe Movement

Previous studies on branched pipe behavior, as mentioned above, revealed that branched pipes are subjected to a complex interaction with soil during ground movement, beginning as a lateral movement and transitioning to an axial pullout (Anderson 2004). As branched pipes buried in soil tend to be subjected to lateral movement at the start of the ground displacement, a brief overview of the studies conducted on the lateral pullout of pipes is presented here (e.g., Hansen 1961; Ovesen 1964; Audibert and Nyman 1977; Weerasekara 2007; Roy et al. 2016, 2018; Ono et al. 2017; Almahakeri et al. 2014, 2017, 2019). Hansen (1961) formulated an analytical method for shallow and deep failure mechanisms, considering the lateral movement of a rigid pile. Later, Ovesen (1964) predicted the lateral pullout resistance of pipes using pullout test results of vertical anchor plates and assuming a curved failure surface. The lateral soil resistances were reported to vary more than 200% depending on the corresponding pipe sizes, burial depths, and backfill conditions (Guo and Stolle 2005). In the initial stages of lateral pipe-soil interaction research, the lateral pullout behavior of pipes was predicted from model tests and centrifuge tests conducted on vertical anchor plates (e.g., Neely et al. 1973; Das and Seeley 1975; Dickin and Leung 1983).

Weerasekara (2007) conducted full-scale laboratory lateral pullout tests of MDPE pipes to obtain the required data for future numerical modeling. The study derived bending moment and tensile force distribution along the pipe length using strain gauge readings. Roy et al. (2016) simulated the force–displacement response for a wide range of lateral displacements of the pipe for different burial depths, pipe diameters, and soil properties using the modified Mohr–Coulomb model. The research revealed that mobilized internal friction angle and dilation angle vary along the length of the shear band (zone of inelastic shear deformation). Roy et al. (2018) proposed a simplified method to estimate the peak and the post-peak lateral resistances of buried pipes and vertical strip anchors, considering the strain-softening behavior of dense sand. The study recommended that the peak and the residual lateral resistances are higher for smaller diameter pipes and smaller height of anchors. The critical embedment ratio is also found higher for smaller diameter pipes. The research suggested that the transition from shallow to deep failure mechanisms occurs at a lower embedment ratio in pipes than in anchors. Almahakeri et al. (2014, 2019) conducted both experimental investigations and finite-element analyses for studying the bending behavior of buried steel pipes subjected to lateral soil loading. Almahakeri et al. (2017) presented numerical studies of longitudinal bending in buried glass-fiber-reinforced polymers (GFRP) pipes subjected to lateral earth movements. Jung et al. (2013b) numerically simulated the lateral soil-pipe interaction under plane-strain conditions in dry and partially saturated sand. Jung et al. (2016) presented multi-directional force–

displacement responses for underground pipes in sand, characterizing the responses for lateral and uplift movement of pipelines in soil. Besides these, several other numerical studies were conducted to investigate the lateral pullout behavior of pipes and vertical anchor plates (Rowe and Davis 1982; Ng 1994; Zhou and Harvey 1996; Yang and Poorooshasb 1997; Guo and Popescu 2002; Popescu et al. 2002).

Ono et al. (2017) investigated the soil-pipe interaction behavior in saturated sand with different effective stresses. The study conducted lateral loading tests on a model pipe buried in sand to examine the effect of initial effective stress on the lateral resistance and the lateral displacement relation. The research proposed a force–displacement relationship considering the change in soil unit weight with the excess pore water pressure ratio, the soil cover depth, the pipe length, and the diameter.

2.6 Summary

This chapter discusses the existing experimental and numerical studies on pipe-soil interaction in buried steel and MDPE pipes during longitudinal ground displacement. The findings from the literature review are summarized below:

- The mechanism of soil-pipe interaction in polyethylene pipes is different from that in steel pipes. This difference causes the existing design equations to be ineffective in explaining the behavior of buried polyethylene pipes in soil.
- The pullout behavior of the MDPE pipe significantly depends on the viscoelastic response of the pipe material.

- Branched pipes are subjected to a complex interaction with soil, beginning as a lateral movement and transitioning to an axial pullout during the event of relative ground movement.
- A smaller diameter trunk pipe is more vulnerable to damage than the branch pipe connected to it during axial ground movement. This scenario is the opposite of the larger diameter trunk pipe having a relatively smaller diameter branch.
- The physical location of vulnerability in branched pipe systems would depend on the relative pipe sizes, soil density, and the type of tee-joint used.
- The level of soil anchoring at the tee-joint would govern the movement of the tee depending on the stiffness of the trunk pipe. So, special consideration has to be given to the local strain capacity of the tee, especially if the adjoining branch pipe is stiff.

The above findings from the existing literature identify the research areas required to be investigated further thoroughly to characterize the soil-pipe interaction behavior in branched buried MDPE gas distribution pipes subjected to relative ground movements. Limited studies are currently available in the literature describing the ground movement effects on branched MDPE pipes. The current study will present the full-scale laboratory tests of buried small diameter (42.2 mm and 60.3 mm) branched MDPE gas distribution pipes based on these research needs identified. The research will investigate the localized strain concentration at the branch connection and compute the corresponding lateral soil forces. Two types of tapping tee connections are tested to investigate the effects of joints on pipe-pullout responses. The research will experimentally and analytically characterize the joint and the branch pipe contribution to the soil resistance during the ground movement.

CHAPTER 3 : Testing of 60.3-mm diameter trunk pipes with a lateral branch

3.1 Introduction

This chapter discusses experimental studies on the pullout behavior of 60.3-mm branched buried MDPE pipes subjected to axial ground movement. The research includes tests with different tapping tee positions with respect to the pulling end of the pipe and different sand densities using the full-scale laboratory testing facility at Memorial University of Newfoundland. Pipe wall strains and soil pressures around the pipes are measured to investigate the associated mechanics of soil-pipe interaction. The contribution of the trunk pipe, tapping tee, and branch pipe on the axial pulling force are identified separately.

A branched pipe system includes a trunk main, a connecting element (tapping tee), and a branch pipe. Soil resistance to the pipe movement 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 the one given by the axial pullout forces for straight pipe, without any consideration for any coupling effect. It was proposed to calculate the lateral resistance due to the tapping tee (F_t), as the lateral bearing capacity of pipes or vertical anchors proposed in ASCE (1984) and ALA (2005), as shown in Eq. 3-1

$$F_t = (N_q \gamma H) A_t \qquad [3\text{-}1]$$

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 the ASCE guideline of lateral soil spring, the tee displacement (y_h) at the ultimate bearing capacity is estimated as $y_h = 0.04\ (H + D/2) \leq 0.10D$ to $0.15D$, 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 was measured to examine the forces due to the tapping tee. Tests were also performed with the tapping tee only (without the branch pipe) to identify the contribution of the branch pipe to the soil resistance and the pipe wall strain.

Anderson (2004) conducted axial pullout tests of 60-mm diameter trunk pipes with 15-mm diameter branches in dense sand. The branches were connected to the pipe using tapping tees while the other end (far end) of the branches was set free to move. However, no considerable displacement of the free end of the branches was observed during the tests. Weeraseraka (2007) also conducted branched pipe tests with the far end of the branch in restrained or unrestrained conditions. No effect of branch end conditions (restrained or unrestrained) was observed in the pullout resistances for 60-mm and 114-mm trunk pipes with 16-mm diameter branches. However, the far end condition of the branch had a significant effect on the large diameter (42-mm diameter) branch. As this study involves testing of the small diameter branch pipe of 15.9 mm diameter, tests have been conducted with the branch pipe in unrestrained condition at the far end. Anderson (2004) and Anderson et al. (2004) reported elastic or plastic deformation of the trunk pipes during the pullout displacement in the tests with 60-mm diameter pipes. They observed that the 60-mm trunk main undergoes significant deformation in front of and in the vicinity of the tee-joint. The localized strains near the tapping tee appear to be much more critical for the 60-mm pipe than the 114-mm pipe, as the overall strain in the 60-mm diameter pipeline is relatively more considerable (Weerasekara et al. 2006; Weerasekara 2007). This chapter discusses the full-scale laboratory tests of 60.3-mm diameter trunk pipes with a 15.9-mm diameter branch, commonly used in gas distribution systems. Among these tests, a yellow tapping tee (tapping tee type II) was used in one test (with the near branch loose configuration), discussed later in more detail. All other tests used the black tapping tee (tapping tee type I) with different positions of the tee-joint from the pulling end. Two branch locations with respect to the pulling end of the trunk pipe were considered. Table 3-1 describes the tests conducted on 60.3-mm trunk pipes. In the table, “near branch” and “far branch” are defined based on the distance of the branch from the pulling end (leading end). The details of the distances are discussed later. The density of the backfill sand is denoted by “dense/loose”. The current study explores the effects of tapping tee and branch through measurements of local strains on the pipes and stresses within the soil around the pipes, including the vicinity of the tapping tee.

Table 3-1: Tests on 60.3-mm diameter MDPE branched pipes

Tests	Test name
Test 1	Far branch loose
Test 2	Near branch loose (Yellow tapping tee)
Test 3	Near branch loose (Black tapping tee)
Test 4	Far branch dense
Test 5	Near branch dense
Test 6	Near branch dense (tee only)

3.2 Test Method

3.2.1 Test Facility

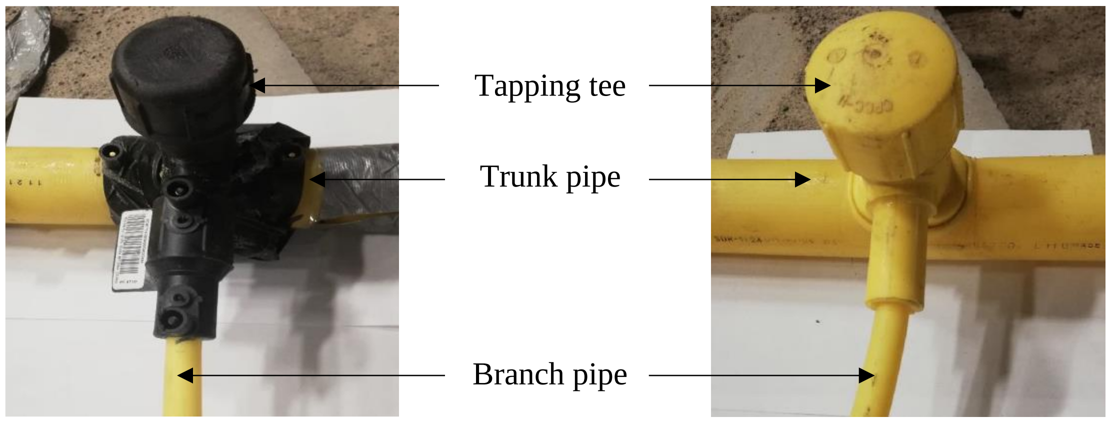
The test facility used was a steel tank with inside dimensions of 4 m length, 2 m width, and 1.5 m depth (Murugathasan et al. 2021; Reza and Dhar 2021a). The tank has two circular openings of adjustable sizes on two opposite walls in the longitudinal direction to allow the pulling of pipes with different diameters. The MDPE pipe was buried in well-graded sand in the test tank at a depth of 0.6 m, a depth commonly used in the gas distribution system (Weerasekara 2007). The pipe ends were extended 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 was filled using a rubber gasket with lubricant (grease) to minimize the friction between the pipe and the face of the openings. A steel connector connects one end of the pipe to a hydraulic actuator for axial pulling. Figure 3-1 shows the hydraulic actuator. The actuator, fitted with a reaction frame made of steel I-sections, 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 pipe end nearer to the actuator is referred to as the “leading end”, and the other end 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 (Figure 3-2). A pulling rate of 0.5 mm/min was applied during the tests, which was the minimum rate that could be applied in the laboratory setting.

Figure 3-1: The hydraulic actuator used for pulling the pipe

Figure 3-2: The LVDT used to measure the pipe trailing end movement

3.2.2 Test Pipe

As mentioned above, the test pipe used in each of the six tests is a 60.3-mm diameter trunk pipe with a 15.9-mm diameter branch. The thickness of the trunk pipe and the branch pipe were ~ 5.6 mm and ~ 2.28 mm, respectively. The standard dimension ratio (SDR, a ratio of the pipe outside diameter to wall thickness) of the trunk pipe tested is 11. The pipe, once tested, is never used in subsequent tests to avoid the effects of residual stresses. The branch connects to the trunk pipe using a butt-outlet tapping tee (Tapping tee type I, black) of 91.4 mm in height and 38.1 mm in diameter. The height and diameter of the yellow tapping tee (Tapping tee type II) are 82.55 mm and 38.1 mm, respectively. Figure 3-3 shows both types of tapping tees used in the tests, also commonly used in the field. Tapping tees type I and type II are designated as 'the black tapping tee' and 'the yellow tapping tee', respectively, in this thesis. In this test program, a test was also conducted with the tapping tee only, connected to the trunk pipe (without a branch pipe) to assess the tee-joint and the branch pipe contribution.



a) Tapping tee type I (Black)

b) Tapping tee type II (Yellow)

Figure 3-3: Tee-joints used for branch connection

3.2.3 Backfill Sand

The tests used a locally available well-graded sand (USCS classification: SW) containing ~ 1.30% of fines as the backfill material for the pipe. The coefficient of uniformity (C_u) and the coefficient of curvature (C_c) of the sand were 5.81 and 2.04, respectively. About 9.6 m^3 of sand was required to achieve the soil cover depth of 0.6 m for the tests. The sand was compacted in layers with a tamping plate every 100 mm of placement in the dense sand tests. 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 average dry density of the sand in the test box was measured as 19 kN/m^3 using the sand cone method (ASTM D1556-07) in the tests with the dense condition of the sand. Thus, the relative compaction of the backfill sand was ~ 101% of the Standard Proctor maximum dry density.

In the case of the loose sand tests, the sand was carefully spread over the test box without any compaction. The soil surface was leveled uniformly to minimize stress concentrations at potential localized hard spots before the pipe installation. For the loose sand, the average density of the sand was around 14.5 kN/m^3.

3.2.4 Pressure Sensor and Control System

The tests included several null soil pressure sensors at different locations within the soil and the pipe-soil interface. The diameter of the sensor is 50 mm, which can measure the localized stress within the soil. Figure 3-4 shows a typical earth pressure sensor used. This sensor is referred to as the 'null pressure sensor' as it works based on the principle of nullification of deformation of the diaphragm inside the sensor by internally applied pressure (Talesnick 2005; Talesnick et al. 2014). The significant advantage of this soil pressure measurement system is that it minimizes the effect of the instrument on soil behavior (Talesnick 2005). In this method, the diaphragm is kept undeflected by applying internal air pressure on the sensor, so the stiffness of the diaphragm does not interfere with the soil pressure measurements. The system measures this air pressure internally applied, which is equivalent to the pressure within the soil. The null gauge soil pressure sensors work with a control system, as shown in Figure 3-5, including air pressure regulators (control valves), air manifold, and pressure transducers (Talesnick et al. 2014). All these connect to a data acquisition system with custom-written nulling software installed. High-pressure air input is supplied to the air pressure regulator through the air manifold, and the air pressure regulator converts a voltage input into a regulated air pressure output. The pressure transducer gives the pressure readings.

Figure 3-4: Soil pressure sensor used in the tests

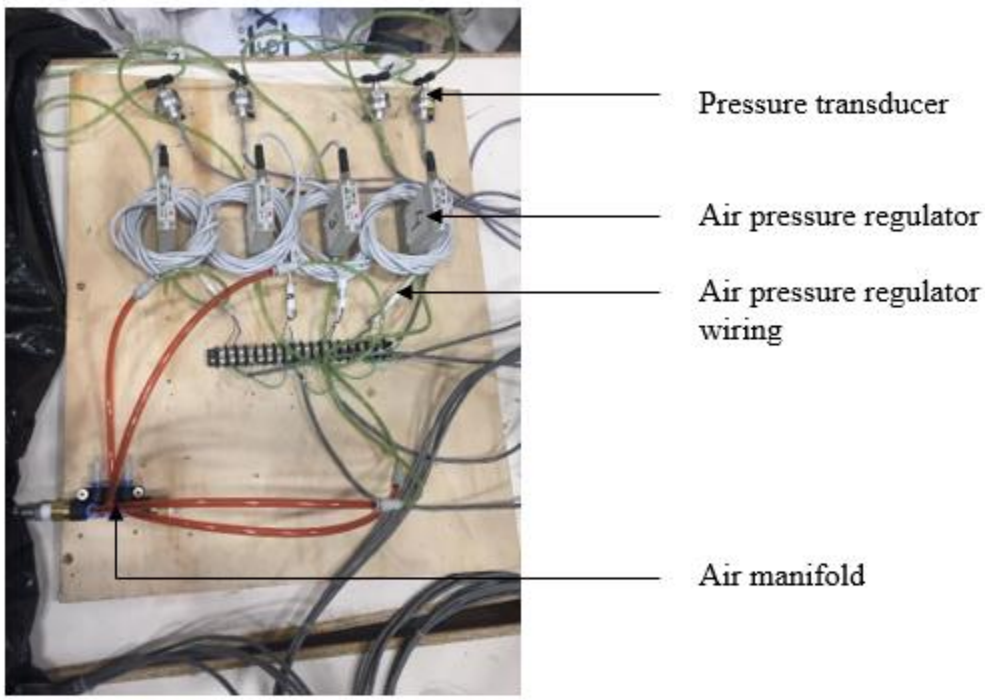


Figure 3-5: Control system setup used in the tests

3.2.5 Instrumentation

Electrical strain gauges were placed at the pipe crown along the length of the pipe to measure the pipe wall strains (Figure 3-6). Strain gauges were also placed on the top of the branch connection to examine the strain mobilization in the tapping tee. In Figure 3-6, "just front of T-joint" or "just back of T-joint" indicate the strains measured on the tee-joint (the black connector shown in the figure). "Front of T-joint" or "back of T-joint" refer to the trunk pipe wall strains before and after the tee connection.

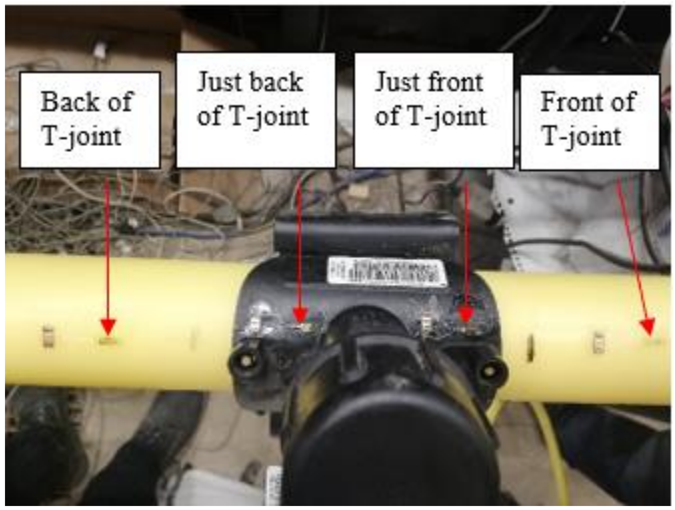
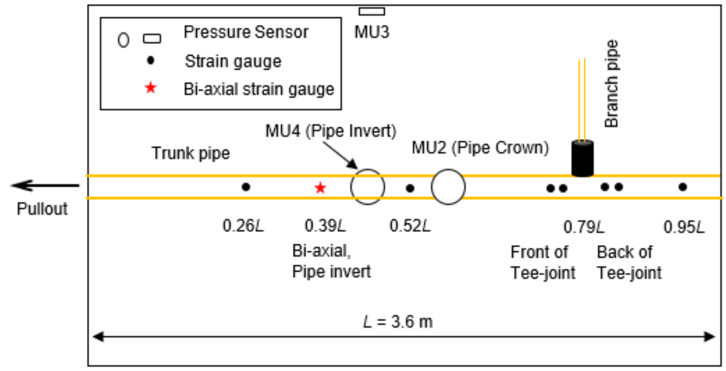
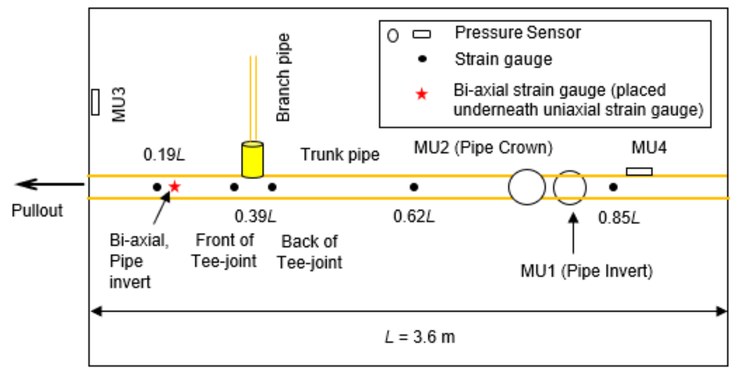


Figure 3-6: Placement of strain gauges on the pipe and the connector

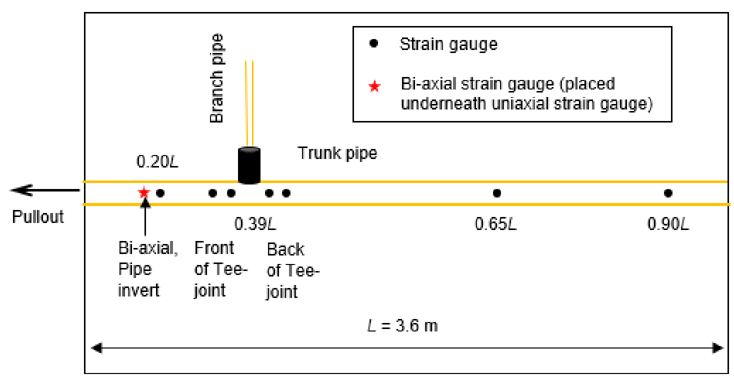
In the far branch loose test (test 1) and the near branch loose (yellow tee) test (test 2), pressure sensors were installed to measure the vertical stress at the crown and the invert of the pipe. The sensor MU3 measured the horizontal stress near the tank wall to examine the effect of sidewall stiffness on the pullout behavior of the pipes. Figure 3-7 indicates the instrumentation details employed during tests 1, 2, and 3, including the locations of the branch, the pressure sensors, and the strain gauges. For the "near branch" test in loose sand, the tee joint/branch was located at a distance of 39% of the length of the trunk pipe from the leading end. For the "far branch test", the branch was located at a distance of 80% of the length of the trunk pipe.



a) Test 1 (Far branch loose)



b) Test 2 (Near branch loose (Yellow tapping tee))

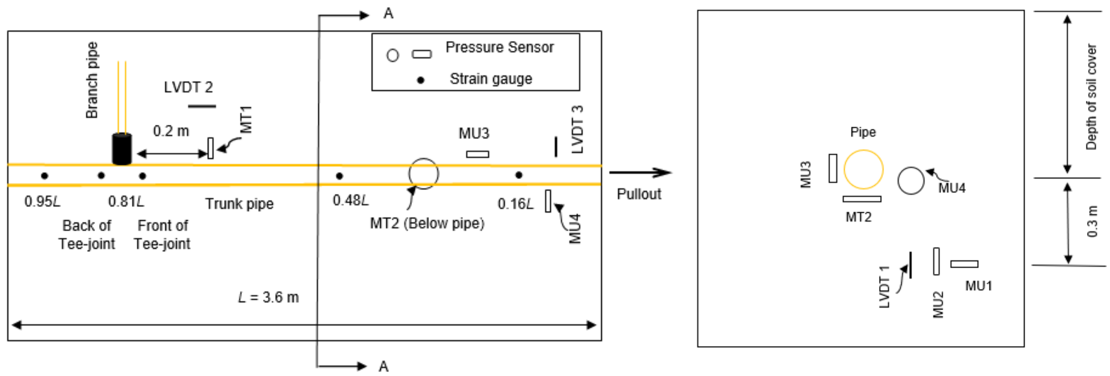


c) Test 3 (Near branch loose (Black tapping tee))

Figure 3-7: Test instrumentation in the loose sand tests with 60.3-mm trunk pipes

The far branch dense test (test 4) included six soil pressure sensors used at different locations within the soil and the soil-pipe interface. Two 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 distance to diameter ratio of ~ 5. The other pressure sensors measured the soil stresses around the pipe and near the tapping tee. A sensor was placed at a distance of 200 mm from the tapping tee to measure the earth pressure due to the connection. In the near branch dense test with tee-only configuration (test 6), the instrumentation included one soil pressure sensor at a distance of 200 mm from the tapping tee to measure the lateral earth pressure.

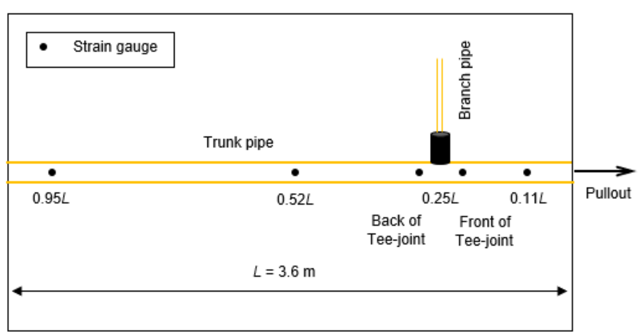
Figure 3-8 shows the details of the instrumentation employed during tests 4, 5, and 6. The tee joint/branch was located at a distance of around 25% of the length of the trunk pipe from the leading end for the “near branch” test in dense sand. For the “far branch test”, the branch was located at a distance of 80% of the length of the trunk pipe. In test 4, 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, in this test. 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 deformation within the test cell in the far branch dense test (test 4). Soil pressure sensor MU4 measured the lateral earth pressure in front of the tapping tee connection in test 6.



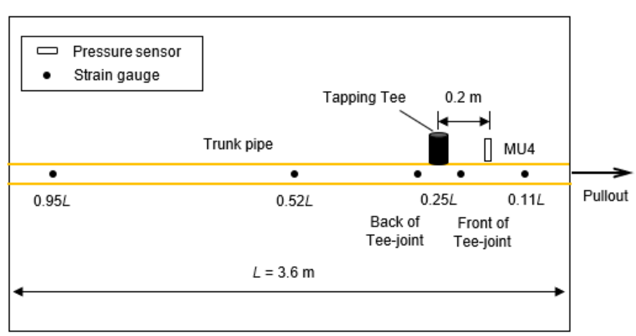
i) Plan view

ii) Section A-A

a) Test 4 (Far branch dense)



b) Test 5 (Near branch dense)



c) Test 6 (Near branch dense tee-only)

Figure 3-8: Test instrumentation in the dense sand tests

3.3 Results and Discussion

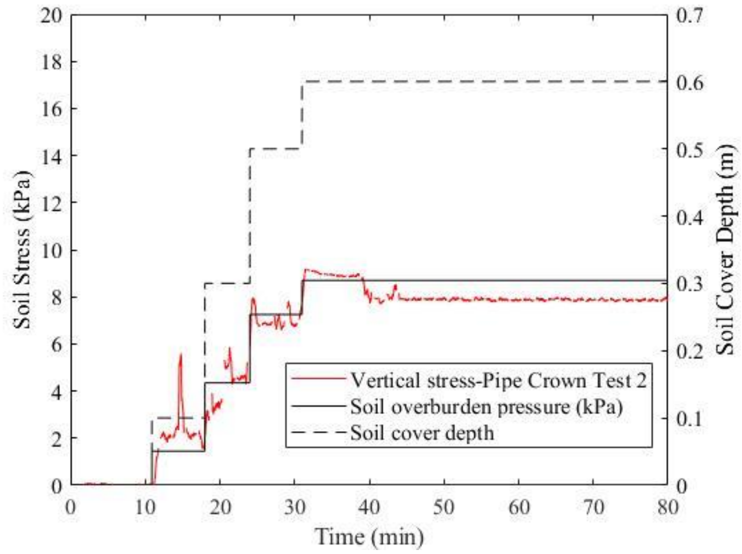
3.3.1 Soil Pressures during Installation

The behavior of the pipe subjected to ground movement may depend on the initial burial condition of the pipe before application of the pulling force. The initial condition can be defined by measuring the earth pressure in the ground and around the pipe during installation. During the placement of soil and pipe in the test box, earth pressures were examined to understand the mechanics of load transfer in the soil during installation and the condition surrounding the pipe after installation. It is, however, to be noted that earth pressures under the burial condition are very less and could not be measured using conventional earth pressure sensors. The earth pressure sensors (Null gauges) used in this study were also sensitive to the pressure levels. As a result, some of the pressure sensors did not work during the tests.

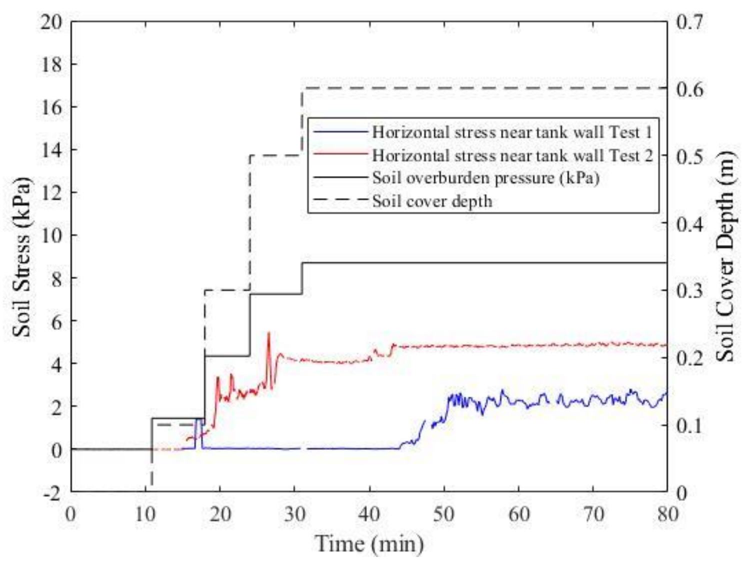
Figure 3-9 shows the measured earth pressures during installation of pipe in loose sand, i.e., test 1 (far branch loose) and test 2 (near branch loose-yellow tapping tee). The readings from the sensors that worked during the tests are only included in the figure. Soil cover above the sensors and the 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 the completion of installation. During backfilling, the sand was first dumped at a place in the box and then spread to level the surface. As a result, the measured stresses were changed 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 3-9(a) shows that at the end of the installation, vertical stress at the crown/center of the pipe was 8 kPa for test 2, while the calculated geostatic stress was 8.7 kPa for the soil cover of 0.6 m based on the unit weight of 14.5 kN/m^3 for the backfill soil. Thus, the measured stress is within 8% of the calculated earth pressure. The vertical earth pressure was increased with the increase of cover depth that is illustrated in the figure. It clearly shows that the earth pressure sensor was capable of measuring the earth pressure at the pipe crown. The vertical stress at the pipe crown is not affected by the presence of the pipe and the test cell boundary condition.

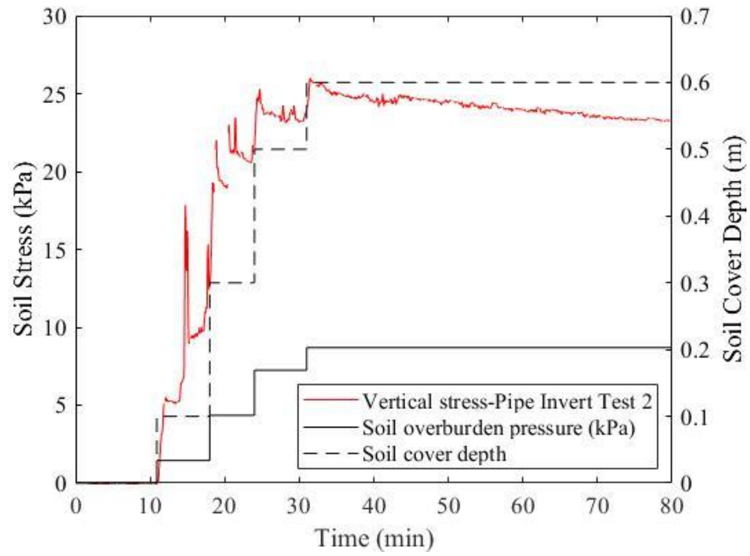
Horizontal stress was measured near the tank wall, and the mean values were found to be 2.4 kPa and 4.2 kPa, respectively, for tests 1 and 2 (Figure 3-9b). The horizontal stresses provide a coefficient of lateral earth pressure of 0.3 and 0.48, respectively, based on the geostatic vertical stress of 8.7 kPa. Figure 3-9(c) depicts that the vertical stress is 23 kPa at the invert of the pipe in test 2 at the completion of soil and pipe placement.



a) Vertical stress at pipe center



b) Horizontal stress near tank wall



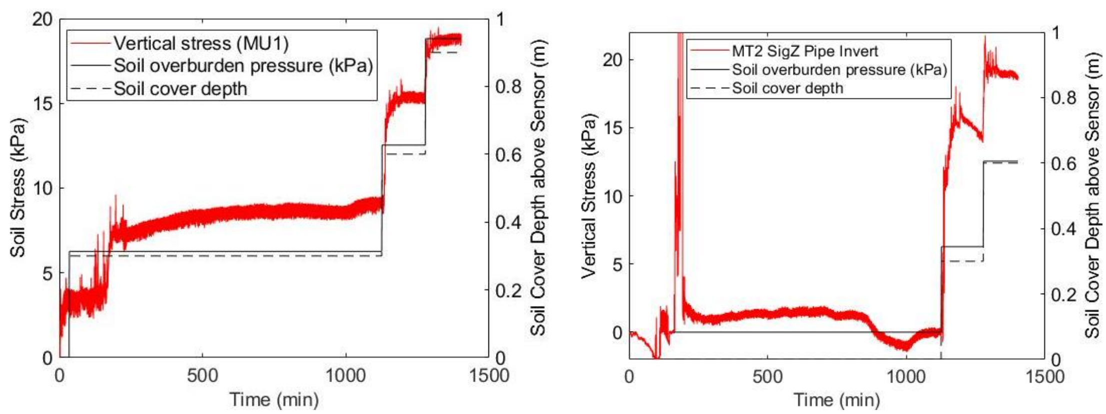
c) Vertical stress at pipe invert

Figure 3-9: Earth pressure measurements during installation for Test 1 and Test 2

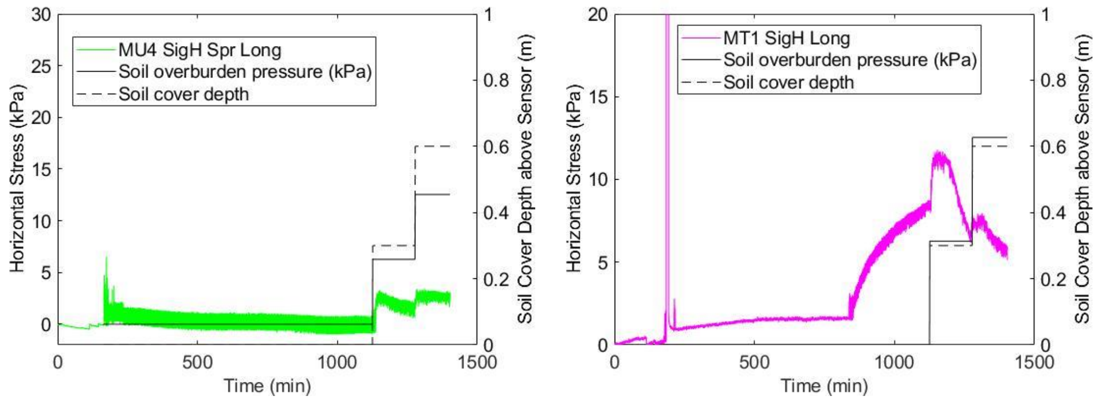
Figure 3-10 indicates the measured soil pressures during installation of a pipe in dense sand, i.e., test 4 (the far branch dense sand test). Figure 3-10(a) shows the vertical soil pressure measured at a depth of 0.3 m below the pipe (beyond the zone of influence by the pipe) using sensor MU1. In general, the measured earth pressure increased with the increase of soil cover. At the final soil cover depth, the measured earth pressure matched 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 friction along the trench wall does not reduce the soil load. The sensor used to measure horizontal stress at this depth (MU2) malfunctioned, and therefore data is not available for the test. Note that as the horizontal pressure is much less than the vertical pressure, pressure sensors were often unable to measure the horizontal earth pressure.

For the sensors used to measure earth pressures in the vicinity of the test pipe, vertical stresses under the invert of the pipe (measured by MT2) were higher than the corresponding geostatic stresses (Figure 3-10b). As shown in the figure (Figure 3-10b), at the shallow cover (~ 0.1m), the measured vertical stress was almost the same as the geostatic stress. However, the measured stresses were significantly higher at the higher cover depths than the calculated geostatic pressures. At the final covered depth, the measured vertical pressure was 18.7 kPa, while the geostatic stress was 12.5 kPa. Thus, the measured stress is ~ 50% higher than the geostatic stress. The sensor used to measure horizontal earth pressure 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 the inclusion of relatively rigid pipe with respect to the soil stiffness, resulting in negative arching (Moser and Folkman 1990). This high stress is not considered in calculating pullout force using conventional design equations (ASCE 1984; ALA 2005).

The horizontal stresses measured in the longitudinal direction of the pipe and the test cell (measured by sensor MU4) are plotted in Figure 3-10(c). The figure reveals that the horizontal stresses are less than the calculated vertical stresses. The stresses increased consistently with the soil cover (Figure 3-10c). At the final cover depth, the horizontal earth pressure in the longitudinal direction was 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. Based on the lateral earth pressure coefficient of 0.2, the angle of internal friction is calculated as 53° using Jaky (1944) equation. Considering that the effect of the overconsolidation ratio is neglected, the angle of internal friction corresponds to the value obtained for the dense condition of the sand in Saha et al. (2019).



a) 300 mm depth below pipe springline b) Pipe invert



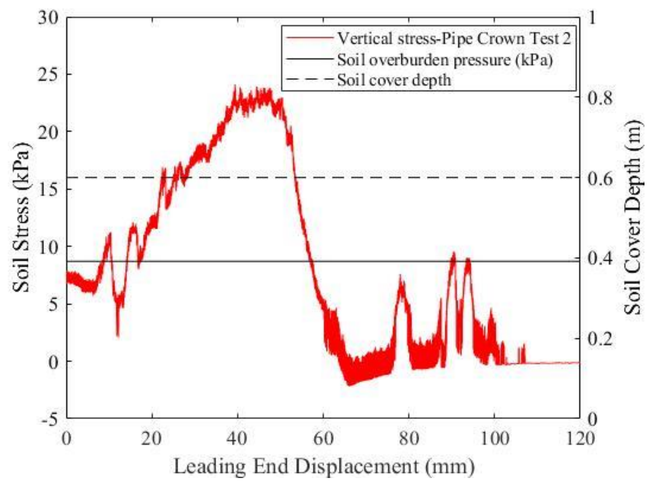
c) Pipe-soil interface d) 200 mm in front of the tee

Figure 3-10: Earth pressure measurements during installation for the far branch dense sand test (test 4)

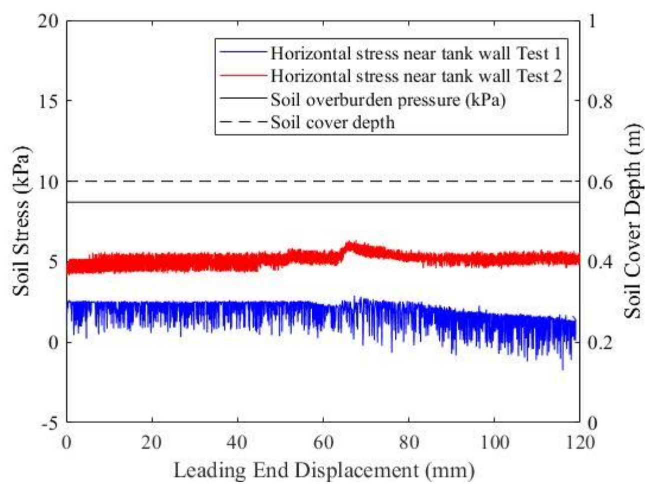
The horizontal soil stresses measured in front of the tapping tee were less than the geostatic vertical stress at this point (Figure 3-10d). However, the coefficient of lateral earth pressure (i.e., 0.46) is higher than the coefficient of earth pressure calculated in the longitudinal direction, indicating that the earth pressure is affected by the presence of the relatively rigid tapping tee.

3.3.2 Earth Pressure during Pipe Pullout

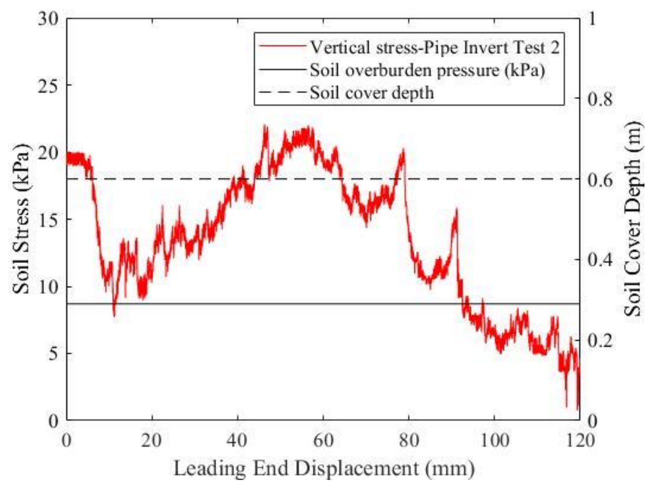
Figure 3-11 shows the earth pressure during the pipe pullout for the pipe in loose sand (tests 1 and 2). Vertical stress at the pipe crown in test 2 gradually increased from the displacement of ~ 10 mm up to a leading end displacement of 50 mm and reached 23 kPa. Then the vertical soil pressure rapidly decreased to zero (Figure 3-11a). The vertical stress at the pipe invert shows an opposite trend of decreasing initially beyond the displacement of 10 mm and increasing beyond the displacement of 50 mm. The opposite effect on the earth pressures at the crown and invert indicates a bending mechanism of the pipe resulting from the mobilization of force on the tee-joint. The horizontal stress near the tank wall did not appear to change during the pipe pullout (Figure 3-11b). Therefore, the effects of test cell boundaries on the pullout behavior of the pipe can be considered negligible.



a) Vertical stress at pipe-crown



b) Horizontal stress near tank wall



c) Vertical stress at pipe invert

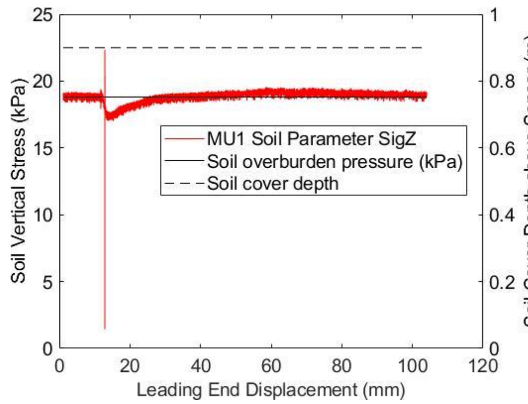
Figure 3-11: Earth pressure measurements during pipe pullout for Test 1 and Test 2

Figure 3-12 shows the earth pressures measured during axial pulling of the pipe buried in the dense sand. Figure 3-12(a) shows that the vertical stress at the depth of 0.3 m below the pipe was not affected by the axial pullout of the pipe (sensor MU1). The vertical stress at that point remained the same as the vertical overburden pressure. All other sensors located near the pipe experienced stress increase during the pulling of the pipe due to movement of the soil (or dilation) near the pipe.

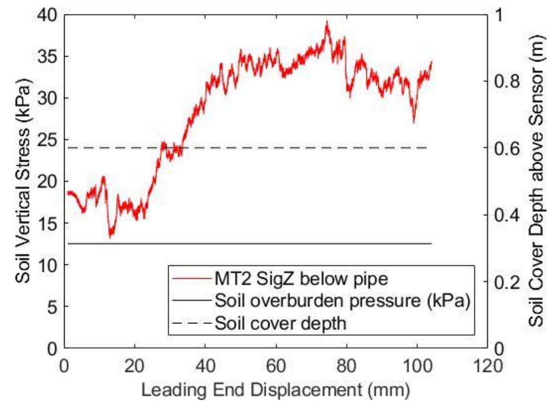
The increase of normal stresses to the pipe (vertical stress at the invert in Figure 3-12b and horizontal stress in the longitudinal direction at the springline in Figure 3-12c) was less significant up to a leading end displacement of around 20 mm beyond which the stress was increased steadily until the maximum values were reached. Thus, the effect of dilation or soil movement was insignificant during elongation of the pipe up to the leading end displacement of 20 mm. The measurements of strains discussed later in this chapter reveal that the strain gauge right behind the tee started reading a compressive strain at the leading end displacement of 20 mm while the other strain gauges in front of the tee continued 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 was associated with the bending mechanism of the pipe caused by the presence of the tapping tee (Figure 3-13). The earth pressure increase was stabilized beyond the leading end displacement of 80 mm. The maximum stress was almost double of the initial values (before pulling).

The horizontal soil stress in front of the tapping tee (MT1) did not change up to a leading end displacement of ~ 10 mm, beyond which it increased almost linearly with the increase of leading end displacement (Figure 3-12d). At the leading end displacement of around 10 mm, the strain right in front of the tee started increasing (discussed later), indicating that the axial force was mobilized to that position. Beyond that displacement, the axial force was mobilized to the tapping tee. Thus, the stress increase in MT1 was due to the movement of the tee that applied 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. 3-1. 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., 6 mm) recommended in ASCE (1984) for mobilization of maximum lateral resistance for pipes or vertical anchor plates (i.e., $y_h = 0.04\ (H + D/2) \leq 0.10D$ to

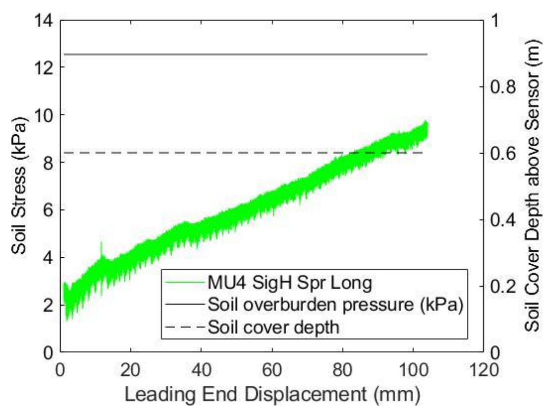
0.15*D*). Thus, ASCE (1984) recommendation for the lateral displacement may not be applicable for the tapping tee considered in this study.



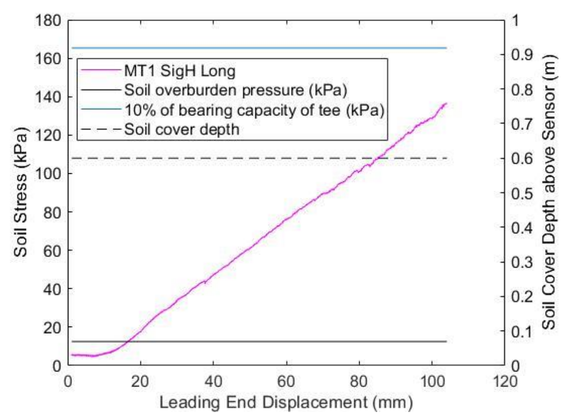
a) 300 mm depth from pipe springline



b) Pipe invert



c) Pipe-soil interface



d) 200 mm in front of the tee

Figure 3-12: Earth pressure measurements during pullout of pipe in the far branch dense sand test

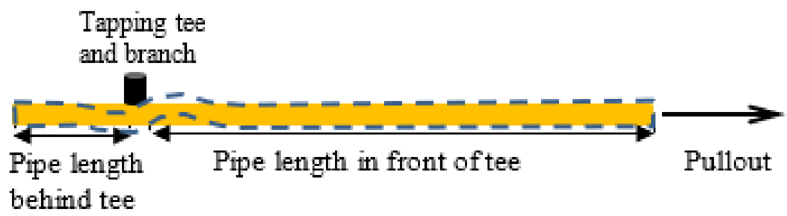


Figure 3-13: Contributors to pullout resistance

The increase of the lateral earth pressures in front of the tapping tee was measured during the pipe pullout of the near branch pipe in the dense tee-only test (test 6, Figure 3-14). The lateral earth pressures near the tapping tee gradually increased in this test with the applied relative axial displacement. The increase of earth pressure reached 90 kPa, where the earth pressure was stabilized. Thus, the pulling resistance of the tee-joint was fully mobilized at the earth pressure increase of 90 kPa.

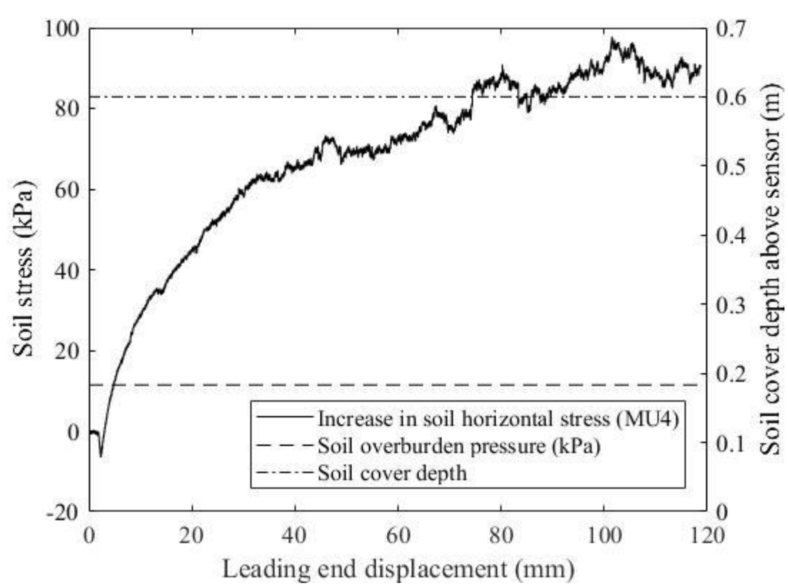
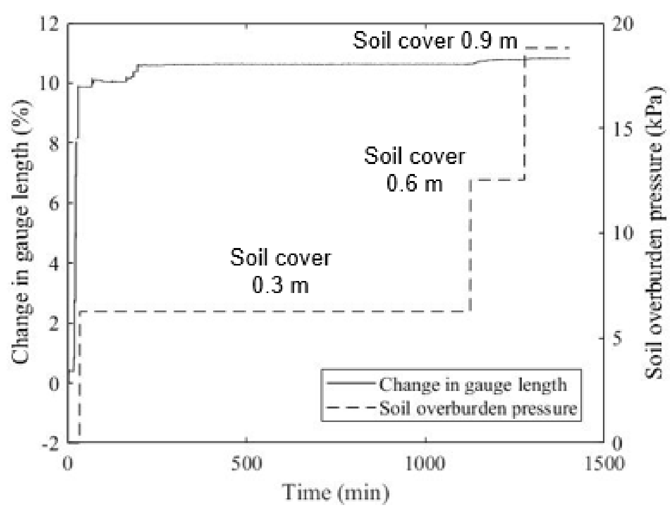


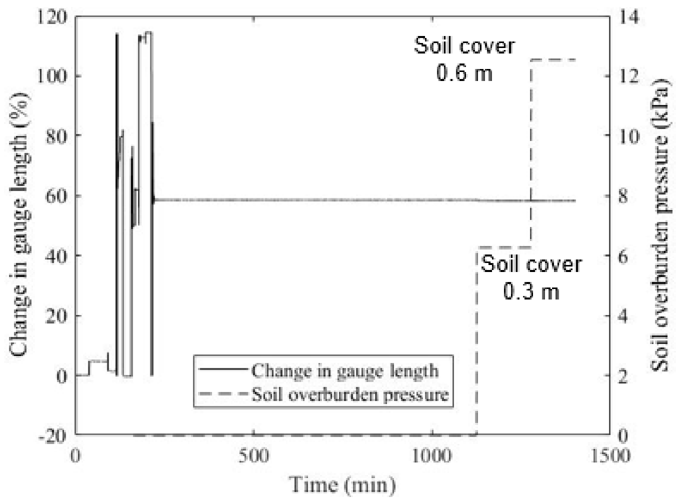
Figure 3-14: Increase in lateral earth pressure in front of the tee during pipe pullout in the near branch dense tee-only test

3.3.3 Soil Deformation Measurements

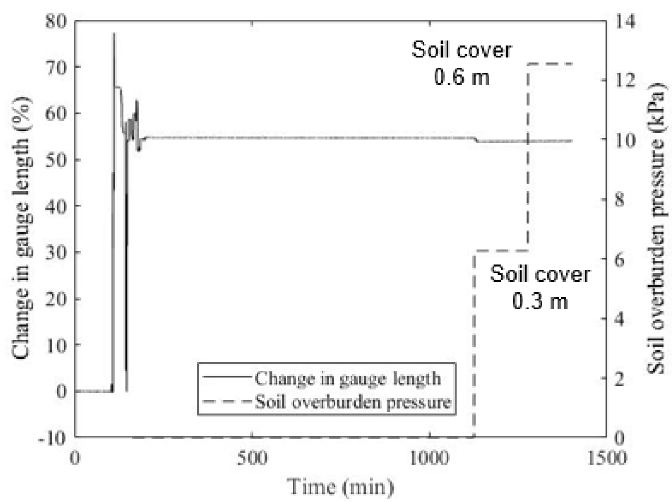
Soil displacement was measured during the soil and pipe placement and during the axial pulling using LVDT with a stroke length of 6 mm. The gauge length during installation ranged from 3 mm to 6 mm. The soil displacements were measured during the installation in the far branch dense sand test (test 4), as shown in Figure 3-15. Percent changes in gauge length are plotted in the figure. Soil deformations were measured at 300 mm depth below the pipe springline (Figure 3-15a), 200 mm in front of the tapping tee (Figure 3-15b), and the soil-pipe interface (Figure 3-15c). Figure 3-15 shows large strains in the backfill sand at all the locations during installation, which is due to the disturbance of the soil during the placement of soil and pipe. The final soil displacement at the end of the installation is constant.



a) 300 mm depth from pipe springline



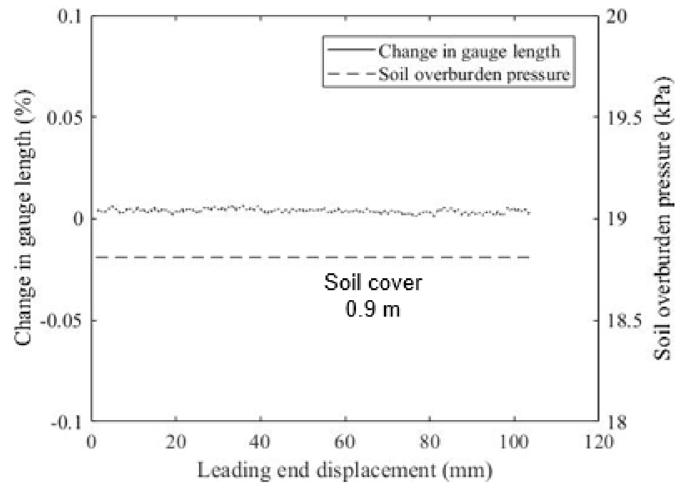
b) 200 mm in front of the tee-joint



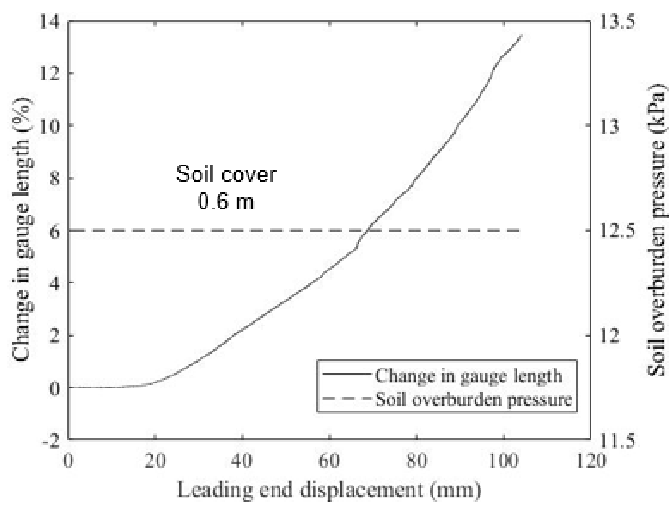
c) soil-pipe interface

Figure 3-15: Soil deformation measurements during installation for the far branch dense test

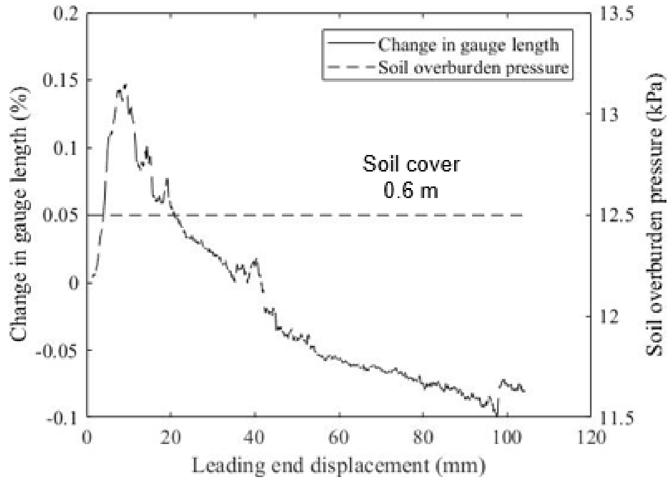
During axial pullout, the soil deformations were monitored. Percent changes in soil deformation with respect to initial length at the beginning of axial pullout are presented in Figure 3-16. The soil deformation at 300 mm depth below pipe springline is negligible during axial pullout (Figure 3-16a), indicating again that axial movement does not considerably affect the underlying soil at this depth. Figure 3-16(b) shows that the soil deformation at 200 mm in front of the tapping tee was initially zero up to a leading end displacement of ~ 20 mm when the tapping tee started to move. Trailing end of the pipe started moving at the leading end displacement of ~ 35 mm, indicating mobilization of axial force over the whole pipe length. The soil stress in front of the tee also increased at the leading end displacement of ~ 20 mm, which is associated with the movement of the tapping tee (Figure 3-12). The soil deformation increased beyond 20 mm of the leading end displacement as the pulling resistance was mobilized on the tapping tee. The soil displacement near the tee-joint reached about 13.5% at the end of the leading end displacement applied during the test. Figure 3-16(c) indicates that the soil deformation measured at the soil-pipe interface near the pulling end gradually increased to ~ 0.15% up to a leading end displacement of 10 mm. Thus, the interface soil was pushed away from the pipe during the axial pullout. However, the magnitude of soil movement was very less. Beyond 10 mm of leading end displacement, the interface soil deformation was reduced and became negative (beyond leading end displacement of ~ 35 mm), indicating a release of pressure to the soil by the pipe.



a) 300 mm depth from pipe springline



b) 200 mm in front of the tee-joint



c) soil-pipe interface

Figure 3-16: Soil deformation measurements during pipe pullout for the far branch dense test

3.3.4 Pullout Force and Pipe Responses

The pulling force or the soil resistance to pipe pulling is plotted against the leading end displacement in Figure 3-17 for the loose sand tests. The soil pullout resistances are similar for the far branch and the near branch configurations and for both types of tee (black and yellow). The maximum pullout resistances of 5.4 kN, 5.1 kN, and 5.5 kN were observed respectively during the far branch loose, the near branch loose-yellow tapping tee, and the near branch loose-black tapping tee tests at 120 mm relative displacement. Thus, yellow and black connections appear to have a similar effect on the pipe response. Figure 3-17 also reveals that for the pipe in loose sand, the pulling force for the near branch pipe is similar to the pulling force for the far branch pipe. However, bending mechanism can be different for the pipes, discussed later. In general, the load-displacement response in Figure

3-17 was relatively stiffer up to a displacement of around 10 mm, until the anchoring effect of the connection was fully mobilized. After full mobilization of the anchoring effect, the load-displacement response flattened. Anchoring force was mobilized at the same leading end displacement in all tests in the loose sand.

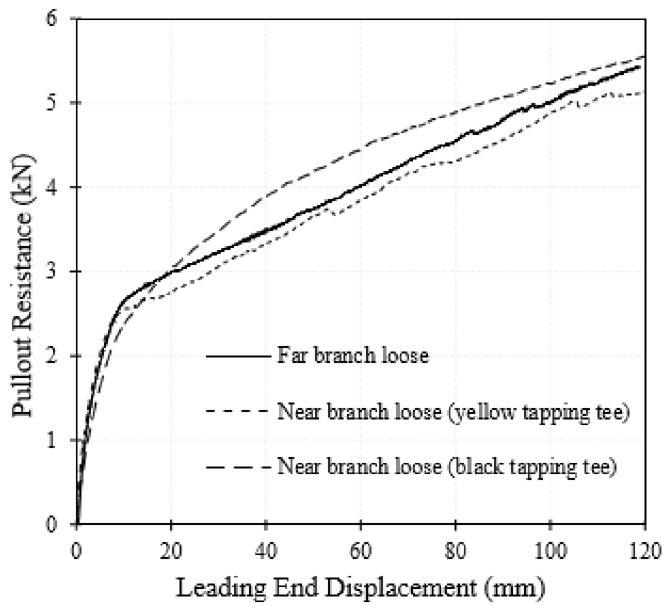


Figure 3-17: Load-displacement responses for the tests in loose sand

The load-displacement responses for far-branch and near-branch pipes in dense sand were different. Figure 3-18 plots the load-displacement responses for the pullout tests conducted in the dense sand. It shows that the mobilized pulling resistance for near-branch tests was significantly higher than the mobilized resistance for the far-branch pipe. The near-branch pipes with and without branch (tee only) were consistent up to a leading end displacement of ~ 40 mm. Beyond that, the pullout force mobilized for the pipe with a branch was higher than the tee-only pipe, indicating the contribution of branch in pulling resistance. The maximum pulling forces during the test were 14 kN and 12.2 kN for the near branch pipe tests with tapping tee and branch (test 5) and with tee-only test (test 6), respectively, at the leading end displacement of 119 mm. Thus, the maximum branch contribution to the axial pullout resistance can be considered as around 1.8 kN (the difference between the forces). The maximum pullout resistance of 9.3 kN was observed during the far branch test (test 4) at 104 mm leading end displacement.

The above results imply that the pulling forces in a buried branched pipe system depend on the tee-joint and the branch used, the distance of the joint from the pulling end, and the density of the backfill soil. The frictional resistance along the pipe length develops over the pipe length in front of the tee and the pipe length behind the tee (Figure 3-13). Test 4 (far branch dense test) was designed to have a shorter length (19% of the total length of the pipe as shown in Figure 3-8a) behind the tee to have minimum frictional contribution for this part of the pipe.

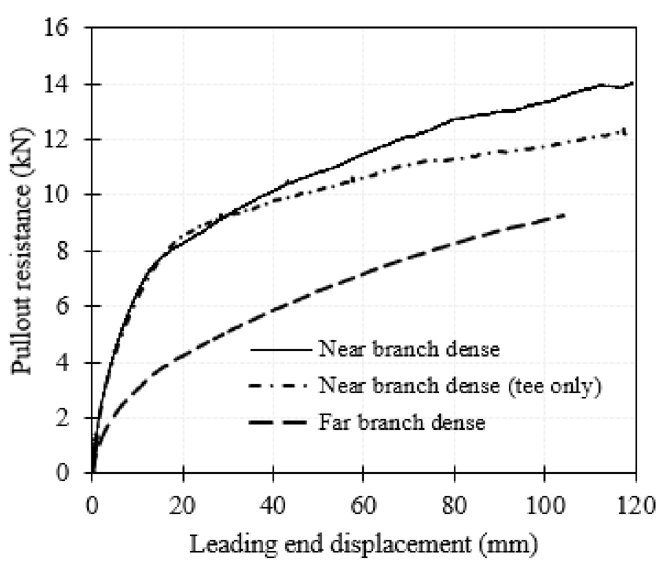
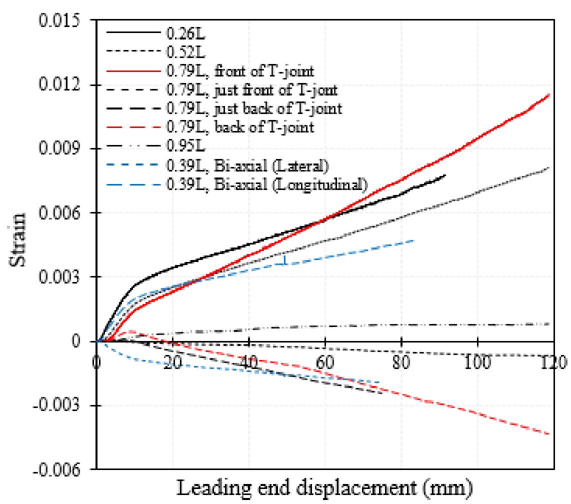


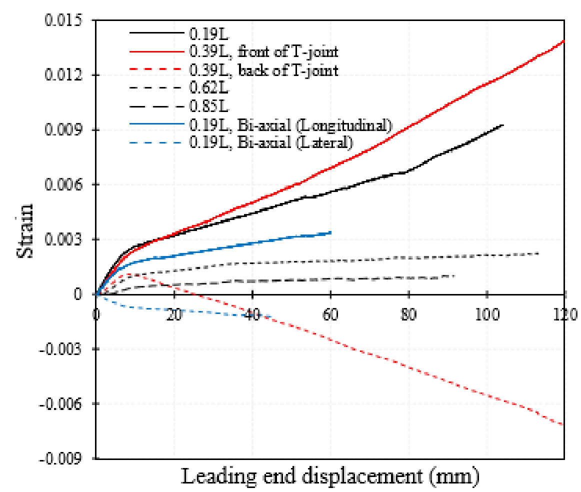
Figure 3-18: Load-displacement responses for the dense sand tests

The mobilization of axial force (hence the soil resistance) along the pipe length was examined through the measurement of axial strains during the tests. The axial strains measured at various locations along the length of the pipe are plotted in Figure 3-19. 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. In the near branch pipes in loose sand tests, the strain in front of the tee-joint started increasing at the leading end displacement of 0.9 mm and 0.4 mm, respectively, for the yellow and the black tapping tee (Figure 3-19 b,c), implying that the axial force (and the frictional resistance) was mobilized over the pipe length in front of the tee at these displacements. The corresponding pulling forces at these displacements were 0.7 kN and 0.3 kN, respectively, for the yellow and the black tapping tee (Figure 3-17). The strain in front of the tee-junction started increasing at the pullout displacement of 3.3 mm in the far branch pipe in loose sand test when the axial pullout force reached 1.5 kN (Figure 3-19a, Figure 3-17).

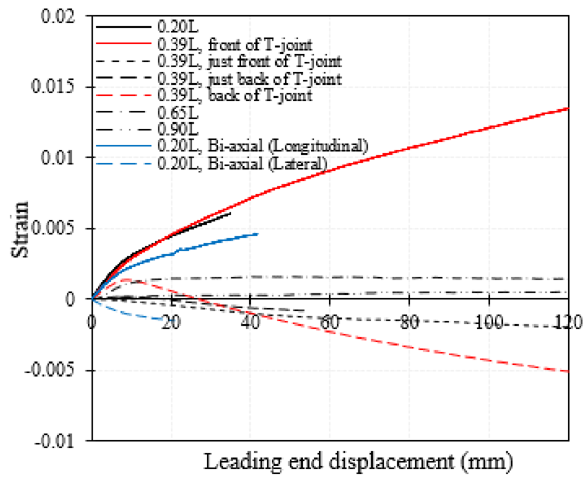
In the far branch dense test, strain in front of the tee-joint (identified as 0.81L) started increasing at the leading end displacement of 10 mm (Figure 3-19d). The pullout resistance at the displacement of 10 mm was found as 3.0 kN from Figure 3-18. Thus, the frictional resistance for the pipe length 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 2021a). The frictional resistance for the pipe length behind the tee can be assumed negligible as the strain reading was zero at this portion of the pipe (identified as 0.95L). Thus, the maximum anchoring resistance of the tee joint and the branch can roughly be estimated by subtracting the frictional resistance from the maximum pullout resistance. The anchoring resistance is thus calculated as 6.3 kN. Like the near branch tests in loose sand, strain in front of the tee-joint started increasing almost instantly after applying the pulling forces at the relative axial displacement of ~ 0.9 mm in the near branch dense tee-only test (Figure 3-19e). The strain near the pulling end (0.11*L*) could only be measured during the near branch dense (with branch) test (test 5), plotted in Figure 3-19(e). The plot shows that the presence of the branch pipe caused relatively higher pipe wall strains near the pulling end of the pipe than the corresponding tee-only test. Thus, the branch can also contribute to the pulling resistance of the pipe.



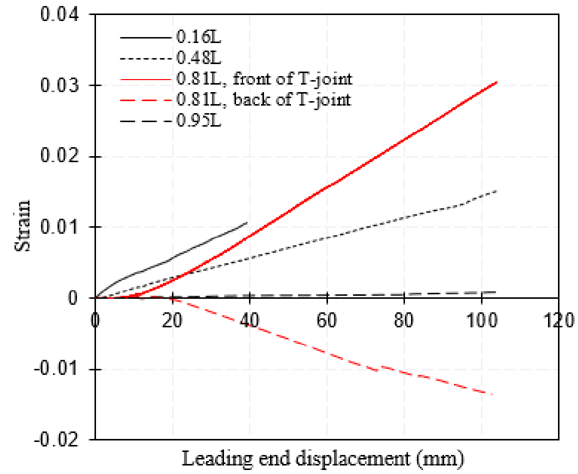
a) Test 1 (Far branch loose)



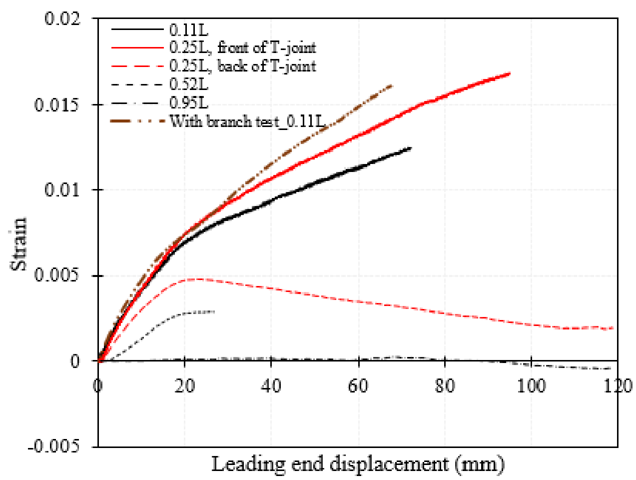
b) Test 2 (Near branch loose-yellow tee)



c) Test 3 (Near branch loose-black tee)



d) Test 4 (Far branch dense)



e) Test 6 (Near branch dense tee-only)

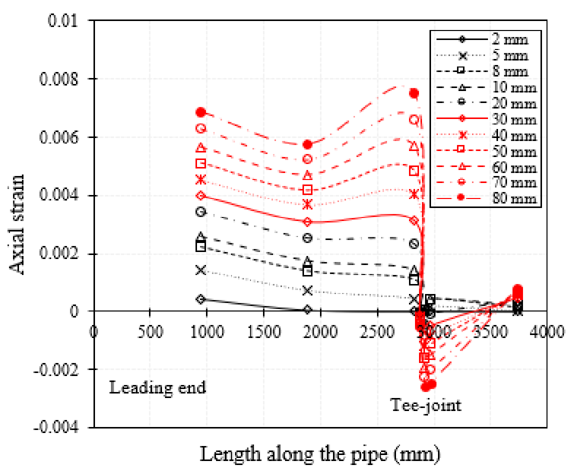
Figure 3-19: Pipe wall strain at different locations

Considerable localized strain occurred in all the tests in front of the branch connection, possibly caused by the geometric irregularity created in the pipes due to the presence of the tapping tee and the branch. A maximum of 3% strain was measured in front of the tapping tee in the far branch dense test, while a maximum of 1% strain was measured in front of the tee-junction in the far branch loose test at the same leading end displacement (i.e., 100 mm). Strain reading beyond 3% was not available as the strain gauge was detached at such a high strain. A significantly higher strain for the pipe in dense sand is due to a higher pullout resistance. The maximum strains on the pipes with black and yellow tee were the same and thus independent of the type of tapping tee used. In the near branch dense tests, the strains increased at a higher rate up to a leading end displacement of ~ 20 mm, when the anchoring resistance of the joint was fully mobilized. The rate of increase of strains was less beyond that displacement. However, the anchoring resistance was not fully mobilized for the far branch cases, and strain continued to increase at a higher rate in front of the tee-joint.

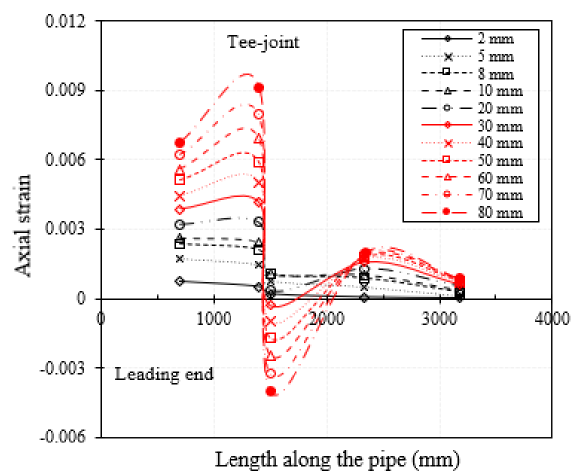
For the far branch dense test, the anchoring effect of the tee and the branch came into effect for the leading end displacement beyond 10 mm. Then, the lateral soil force on the tee caused a bending moment to the trunk main. Due to the bending effect, strain right behind the tee-joint was compressive at the pipe crown. Tensile strain in front of the tee 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 3-13. The plots of the measured pipe wall strains show that this bending phenomenon occurred in all the tests at the corresponding pullout displacements (Figure 3-19).

The bending mechanism can be examined further using axial strain distribution along the length of the trunk pipe at various leading end displacements (Figure 3-20). Figure 3-20 shows that pipe strain decreased from the leading end toward the trailing end at low leading end displacement when the pulling resistances of the tee were not mobilized. The strain behind the tee was zero at low leading end displacements. With the increase of leading end displacement, strain increased at a higher rate toward the trailing end while compressive strain developed right behind the tee due to the bending action. No compressive strains developed for the tee-only test (test 6), Figure 3-20(e), indicating a less effect of bending only for tee. However, the axial strain right in front of the tee became significantly higher than the leading end strain in all the tests performed due to the anchoring effect of the joint, which may lead to rupture in the pipe. Rupture was not observed during the tests at the maximum strain encountered in this study.

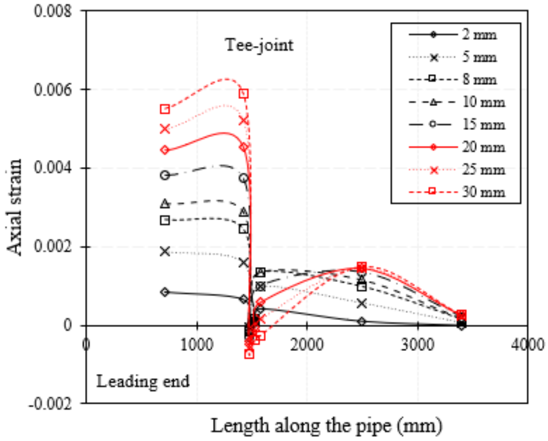
No significant branch pipe movement was observed in these tests with 60.3-mm pipes. This phenomenon implies that branch end boundary conditions will not significantly affect the pullout response for the 120 mm relative displacement applied in this study.



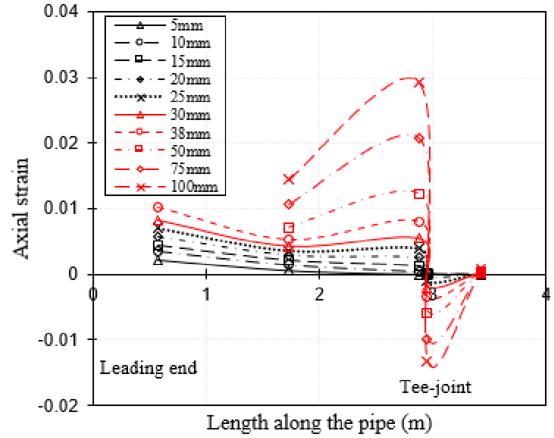
a) Test 1 (Far branch loose)



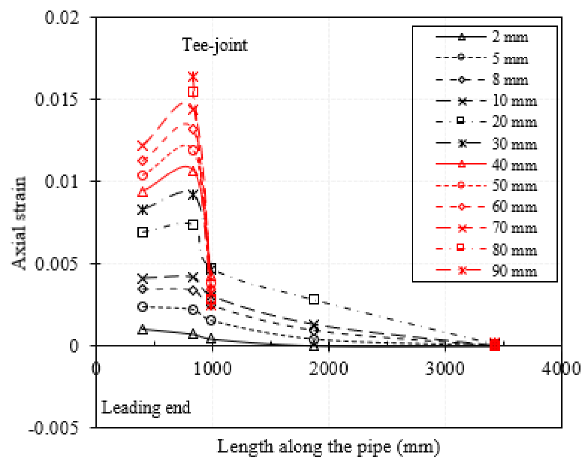
b) Test 2 (Near branch loose-yellow tee)



c) Test 3 (Near branch loose-black tee)



d) Test 4 (Far branch dense)



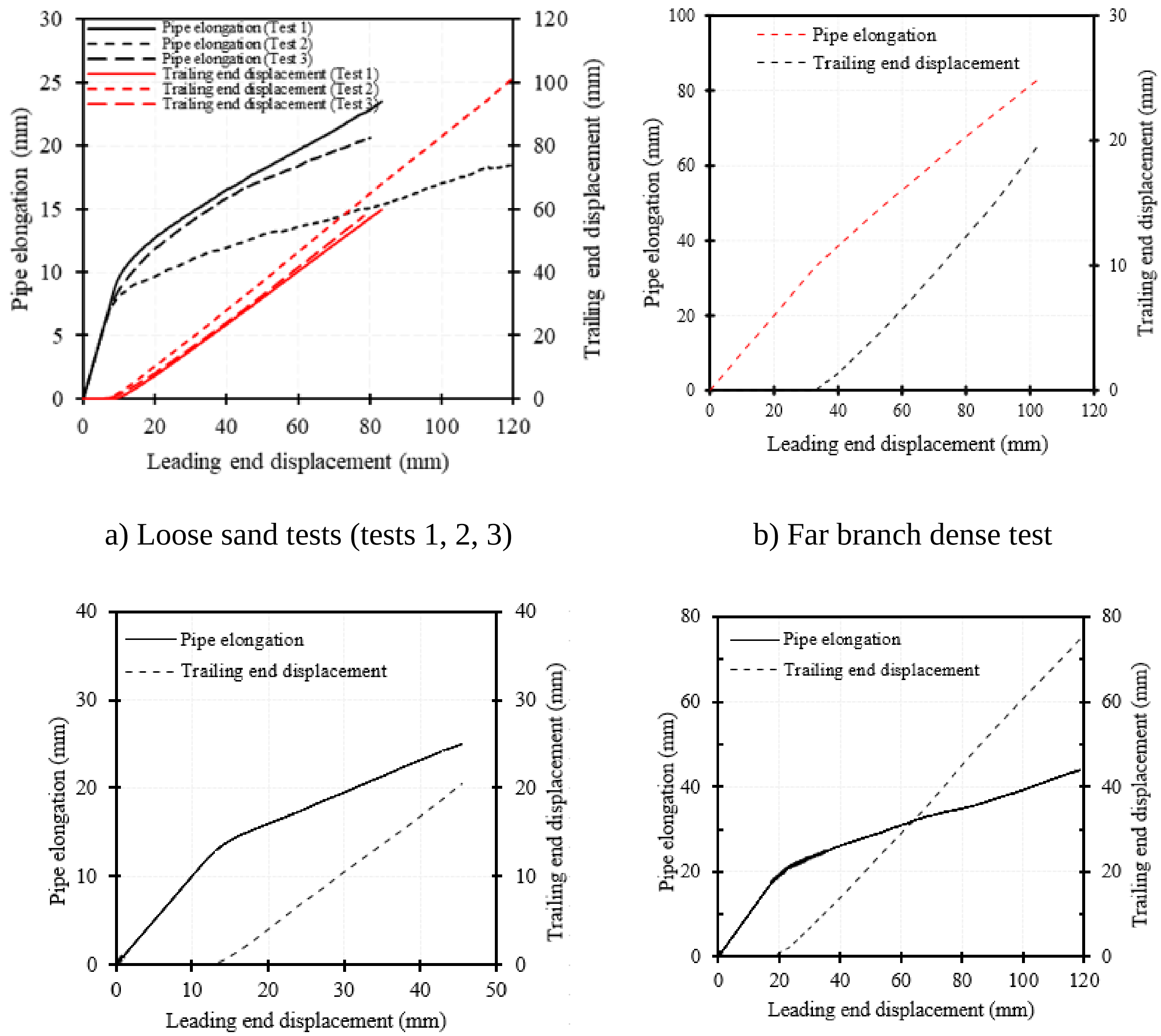
e) Test 6 (Near branch dense tee-only)

Figure 3-20: Strain distribution along the trunk pipe

As mentioned before, the test program for the far branch tests (tests 1 and 4) was designed to have a shorter length behind the tapping tee to minimize the frictional contribution for this portion of the pipe. Therefore, the frictional resistance for the pipe length behind the tee was assumed negligible when computing the frictional resistance contribution over the pipe length to the total soil resistance. However, the frictional resistance over the pipe length behind the tee-joint should be considered for the near branch tests. Thus, during pullout, the entire axial force mobilizes first, then when the trailing end starts to move, tapping tee and branch contribute to the pulling resistance.

The trailing end movement was measured during the test using an LVDT. Figure 3-21 plots the trailing end displacement along with overall pipe elongation calculated as the difference between the leading end displacement and the trailing end displacement. The trailing end began to move at ~ 10 mm leading end displacement in the tests conducted in loose sand (Figure 3-21a). The trailing end movement initiated at the leading end displacement of ~ 33.5 mm in the far branch dense sand test (Figure 3-21b). In the near branch dense test and the near branch dense tee-only test, the trailing end started to move at ~ 15 mm and ~ 20 mm relative axial displacement, respectively (Figure 3-21c,d). Higher leading end displacement for far-branch pipe is due to larger elongation of the portion of the pipe in front of the joint, which is longer than the near-branch pipe. Figures 3-21(b and c) show that when the trailing end started to move, pipe elongations were 30 mm and 12 mm for far-branch and near-branch pipes, respectively.

The tee-joint movement could not be measured during the tests to develop force-displacement relation for the anchor force. However, since the pipe strain behind the tee was zero in the far branch test, elongation for that part of the pipe can be assumed to be zero. Thus, the trailing end movement can be considered the same as the movement of the tee-joint. Figure 3-21(b) shows that the maximum trailing end displacement of 20 mm was obtained during the test for the far branch dense 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.



a) Loose sand tests (tests 1, 2, 3)

b) Far branch dense test

c) Near branch dense test

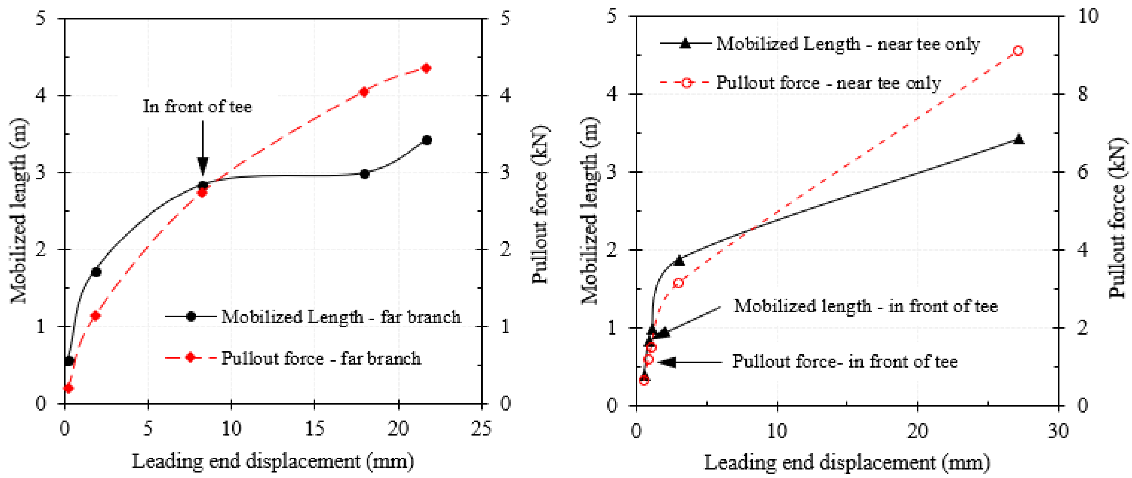
d) Near branch dense tee-only test

Figure 3-21: Pipe elongation and trailing end displacement

3.3.5 Axial Force Mobilization Length

Axial force mobilization along the pipe length was monitored using the strain measurements at different points along the pipe length. The axial force is assumed to be mobilized at a point when the strain gauge attached to this point starts reading (increasing).

The axial force mobilization length and the corresponding pullout force against the leading end displacement are shown in Figure 3-22 for the dense sand tests with 60.3-mm trunk pipe. It shows that the axial force was gradually mobilized with the increase of leading end displacement and hence the pulling force. Note that for the far-branch test, the axial force mobilization length increased non-linearly up to the front of the joint (tee-joint) and then stabilized (Figure 3-22a). This indicates that the anchoring effect of the tee was activated at this point of load to resist the pullout force applied. The corresponding leading end displacement was due to the elongation of the portion of the pipe in front of the tapping tee. Thus, about 8.2 mm of elongation (or leading end displacement) was due to the anchoring resistance of the tee and the frictional resistance in front of the tee. For the near-branch test (Figure 3-22b), the length of the pipe in front of the tee was less, resulting in a small elongation. For this test, axial force mobilization length is less than the length for the far-branch test. However, the corresponding pulling force is higher for the near-branch test. This is because, at the near-branch test, the anchoring effect of the tee is accounting for a large part of the pullout force.



a) Far branch test

b) Near branch tee-only test

Figure 3-22: Axial force mobilization length and the corresponding pullout force for the tests in dense sand

Figure 3-23 shows the axial force mobilization length and the corresponding pulling forces against the leading end displacement for the loose sand tests with 60.3-mm trunk mains. It shows that near-branch and far-branch test results are similar. This is due to a minimal anchoring effect of tee in the loose sand.

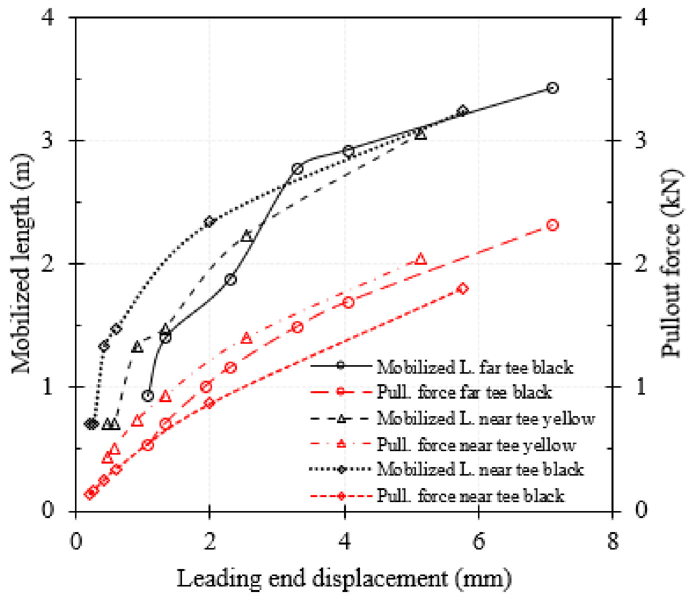


Figure 3-23: Axial force mobilization length and the corresponding pullout force for the tests in loose sand

3.3.6 Tapping Tee and Branch Pipe Contribution

For the near-branch pipe tests, pipe with a tee with branch and tee only pipes were used. From the difference of the pulling forces from the two tests, the contribution of the branch on the pulling resistance has been estimated. The contribution of the tee-joint with branch is also estimated based on the test results. The contribution of the frictional resistance of the pipe length is estimated based on the assumption that the axial force over the entire pipe length is mobilized when the trailing end starts to move. The corresponding pulling force is considered as the maximum frictional resistance of the pipe length. Pullout resistance beyond that pullout force is due to the anchoring effect of the tee (and the branch).

Figure 3-24 plots the axial pulling force versus the corresponding leading end displacement for the near branch dense tee-only test, indicating the initiation of the trailing end movement of the pipe. As discussed earlier, once the frictional resistance over the entire pipe length is mobilized, the trailing end of the pipe starts moving. Accordingly, Figure 3-24 shows that the axial pullout resistance was 8.5 kN when the trailing end started to move, which is the contribution of axial frictional resistance of the pipe. Subtracting this axial resistance from the total pulling force, the resistance due to the tapping tee is computed to be 3.7 kN at the relative axial displacement of 119 mm. The maximum lateral resistance of the tapping tee derived using Eq. 3-1 was relatively lower, shown in the inset of Figure 3-24. The tee-joint resistance was assumed to mobilize at 6 mm relative displacement based on the ALA (2005) guidelines for lateral soil spring. However, soil resistance for the MDPE pipe is expected to mobilize at a larger displacement. The soil resistance to pulling was also computed using the Terzaghi bearing capacity equation that provided a resistance of 2.3 kN in dense sand, which is lower than the resistance of the tee-joint observed during the test.

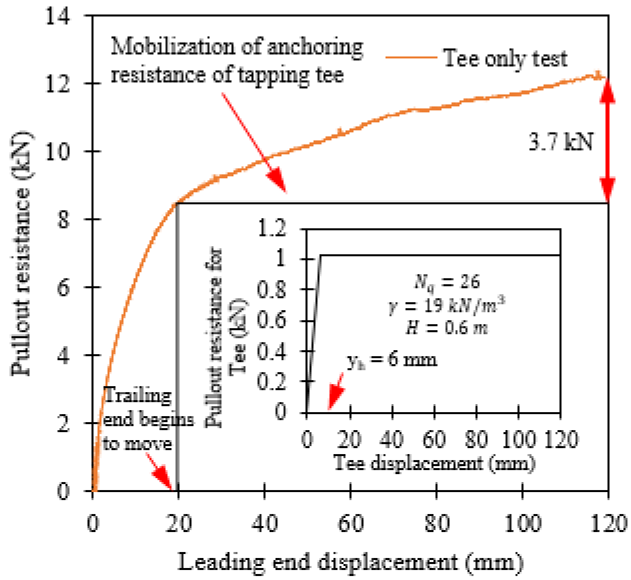


Figure 3-24: Anchoring resistance of tapping tee (dense sand)

It is difficult to identify the branch pipe contribution due to its small diameter (e.g., 16 mm). Any significant structural analysis is hardly possible due to the low stiffness and strength of the branch pipes (Chapman 1990). In this study, the branch pipe contribution to pullout resistance of soil is determined from the difference between the pulling forces for the branched pipe and the pipe without the branch (tee only). Figure 3-25 presents the branch contribution to the axial pulling resistance derived from the difference between the pulling forces in Test 5 (near branch dense) and Test 6 (near branch dense tee-only). This figure includes a fitted curve to estimate the branch pipe resistance (F_b) as a function of displacement (x) where x is the displacement of the tapping tee and the pipe, as shown in Eq. 3-2.

$$F_b = 0.0325x - 0.0001x^2 \qquad [3\text{-}2]$$

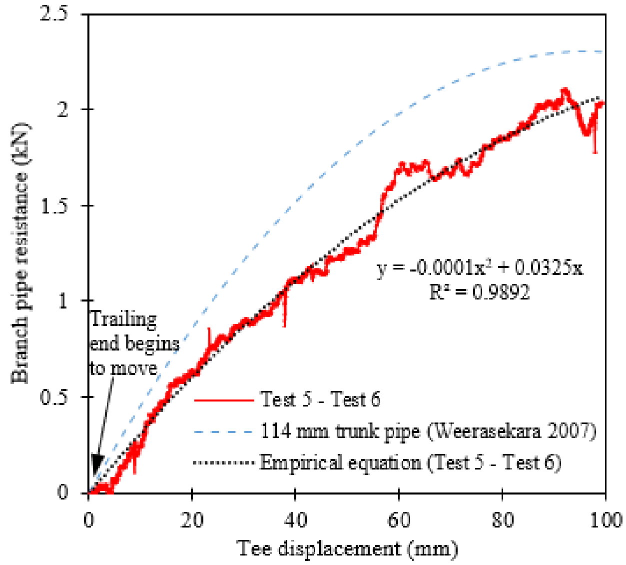
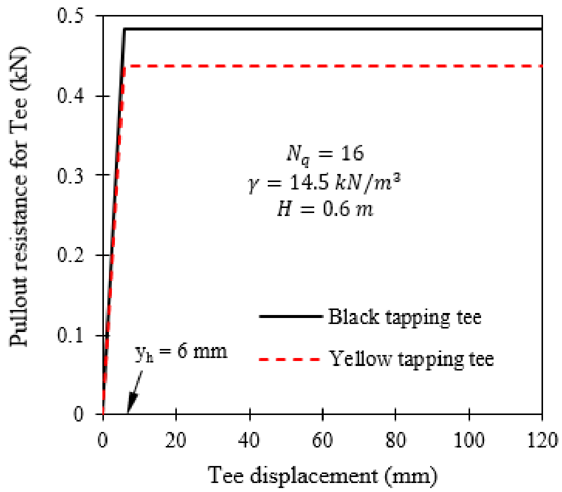


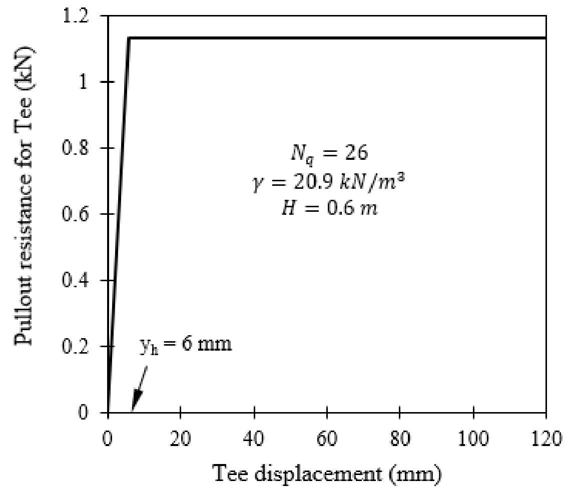
Figure 3-25: Contribution of the branch pipe to soil resistance (near branch dense test)

In the above equation, x is in mm and F_b in kN. Figure 3-25 also presents a similar empirical approximation (F_b = 0.048x – 0.00025x^2) derived from 114-mm pipes by Weeraserakara (2007). Weerasekara (2007) suggested the limiting value of the branch pipe contribution (F_b) as ~ 2.5 kN considering the possible failure of a 16-mm branch pipe from yielding beyond this point.

The lateral resistance due to the tapping tee is computed using ASCE (1984) and ALA (2005) design guidelines as presented in Eq. 3-1 and plotted in Figure 3-26 for the near branch loose tests and the far branch dense test. The ASCE design guideline calculates the anchoring resistance of the black and the yellow tapping tee buried in loose sand as 0.48 kN and 0.44 kN, respectively (Figure 3-26a). The lateral resistance of the black tapping tee used in the far branch dense sand test is computed as 1.1 kN (Figure 3-26b). The yellow and the black tapping tee vary negligibly in the anchoring resistance, implying that the use of these two different types of tapping tee will not significantly affect the associated pipe-soil interaction behavior.



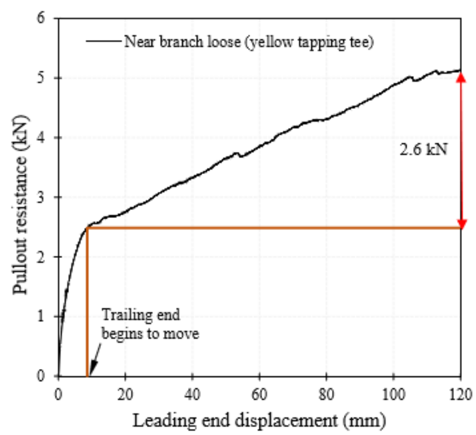
a) Near branch loose tests



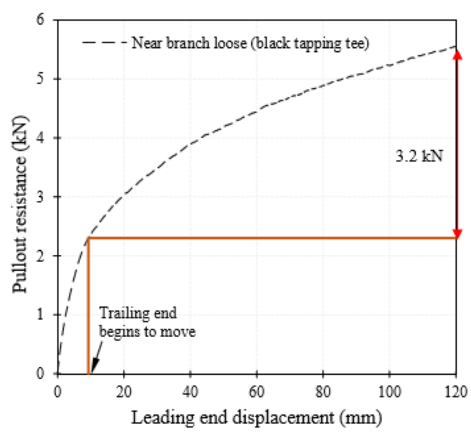
b) Far branch dense test

Figure 3-26: Anchoring resistance of tapping tee used with 60.3-mm trunk pipes

In the near branch loose sand test with yellow tapping tee, pipe trailing end started to move at 8.6 mm of leading end displacement (Figure 3-27a). The pulling force at this displacement was 2.5 kN. The frictional resistance due to the axial pipe movement thus contributed 2.5 kN to the total soil resistance. The combined anchoring resistance of the tee-joint and the branch is therefore calculated as 2.6 kN considering the total pullout resistance of the test. The branch contribution to the soil resistance is determined as 2.2 kN by subtracting the anchoring resistance of the yellow tapping tee (from Figure 3-26a). The proposed empirical equation (Eq. 3-2) computes the branch pipe resistance as 2.4 kN. The similar analysis is applied to the near branch loose (black tapping tee) test and the far branch dense test, as discussed below. Figure 3-27(b) shows that the trailing end began to move at 9.3 mm relative displacement of the pulling end and the corresponding axial pulling force was 2.3 kN. The combined anchoring resistance of the tee and the branch is thus found as 3.2 kN. Considering the anchoring resistance of the black tapping tee (0.48 kN from Figure 3-26a), the branch contribution to the total soil resistance is calculated as 2.7 kN. Eq. 3-2 calculates the branch contribution as 2.4 kN.



a) Test with the yellow tapping tee



b) Test with the black tapping tee

Figure 3-27: Combined contribution of the tee and the branch pipe to the soil resistance in loose sand tests

The trailing end movement started at 33.5 mm leading end displacement in the far branch dense test when the axial pullout force was 5.4 kN (Figure 3-28). The tapping tee and the branch thus combinedly contribute 3.9 kN to the soil pullout resistance. The total anchoring resistance of the tee and branch is computed as 6.3 kN for this test, as discussed earlier, assuming the pipe frictional resistance behind the tapping tee is negligible.

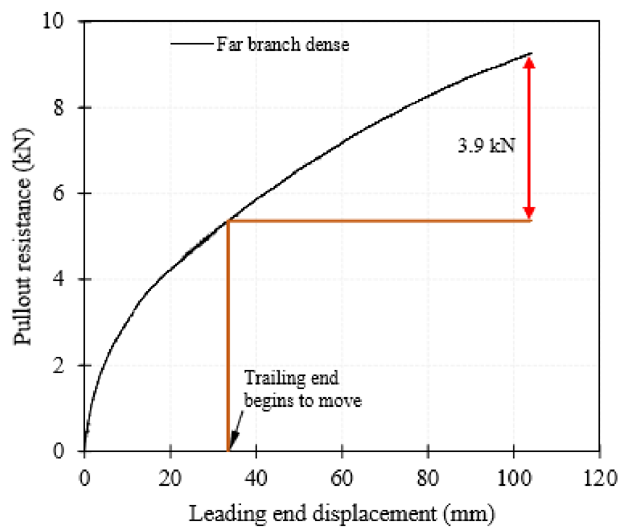


Figure 3-28: Combined contribution of the tee and the branch to the soil resistance in far branch dense sand test

The branch pipe resistance is calculated as 2.8 kN from the lateral resistance of the tapping tee (Figure 3-26b). The empirical equation (Eq. 3-2) determines the branch contribution as 1.8 kN.

3.4 Summary

This chapter explores the mechanism of soil-pipeline interaction in the buried branched 60.3-mm MDPE pipes subjected to axial ground movement using full-scale laboratory tests. Pipe strains and soil stresses are measured during the tests 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. The horizontal stress near the test tank wall does not also change significantly during the pipe pullout.
- 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.
- Earth pressure sensors used in this study are sensitive to pressure levels. As a result, some of the pressure sensors did not work during the tests when the soil pressures were less, identifying the limitation of the null pressure sensors used.
- The stress normal to the pipe surface (vertical stress at the invert) can be significantly higher than the corresponding geostatic stress even under static condition due to the presence of the pipe. 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 in calculating the pipe wall stress.

- The lateral stress in front of the tapping tee is influenced by the movement of the tee. ASCE (1984) and ALA (2005) guidelines might be useful for calculating the maximum lateral force on the tee. However, ASCE (1984) and ALA (2005) 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. Soil deformation can also increase considerably near the tapping tee due to this bending mechanism during the axial ground movement.
- Pullout resistance in a buried branched pipe system depends on the tee-joints and the branch pipes used, the distance of the joint from the pulling end, and the backfill soil density. Pullout forces for near branch pipes are significantly higher than the pulling forces for the far branch pipes.
- The mobilized soil resistance for the pipe with a branch is higher than that of the tee-only pipe, indicating the branch pipe contribution in the pullout. An empirical approximation has been developed to estimate the contribution of the branch pipe in the pulling resistance.
- The strain in front of the branch connection is higher for the far branch pipe than the corresponding strain on the near branch pipe.
- Less anchoring effect of the joint and the branch is observed in the pipes buried in loose sand compared to the pipes in dense sand.

CHAPTER 4 : Testing of 42.2-mm trunk pipes with a lateral branch

4.1 Introduction

Small diameter pipes with 42.2-mm diameter are often used in gas distribution networks. As the behavior of the joint may depend on the rigidity of the trunk main, branched pipes with 60.3 mm and 42.2 mm trunk main, commonly used in gas distribution system, were investigated in this research. The results for 60.3 mm diameter pipes are presented in Chapter 3. This chapter presents the results of investigation of 42.2-mm branched MDPE pipes under axial ground movement. Tests with different positions of the tee-joint with respect to the pulling end of the pipe and varying densities of sand were conducted using the laboratory facility at Memorial University of Newfoundland. Pipe wall strains and soil pressures around the pipes were measured to capture the mechanism of soil-pipe interaction. Tests were also conducted with the tapping tee only (without the branch pipe) to identify the contribution of the branch pipe to the soil resistance and the pipe wall strain. The study explores the contribution of the trunk pipe, tapping tee, and branch pipe separately on the axial pulling force. Test methods undertaken were similar to those for the 60.3-mm diameter pipes discussed in Chapter 3.

Table 4-1 describes the test program undertaken. In the table, “near branch” and “far branch” are defined based on the distance of the branch from the pulling end (leading end). “Dense/loose” denotes the density of the backfill sand. The details of the distances are discussed later.

Table 4-1: Tests on 42.2-mm diameter MDPE branched pipes

Tests	Test name
Test 1	Near branch dense
Test 2	Near branch dense (tee only)
Test 3	Far branch dense
Test 4	Near branch loose
Test 5	Far branch loose

4.2 Test Method

4.2.1 Test Pipe and Soil

The test pipe used in each of the five tests is a 42.2-mm diameter trunk pipe with a 15.9-mm diameter branch. The thickness of the trunk pipe and the branch pipe were ~ 4.22 mm and ~ 2.28 mm, respectively. The standard dimension ratio (SDR, a ratio of the pipe outside diameter to wall thickness) of the MDPE trunk pipe tested is 10. The branch is connected to the trunk pipe using a butt-outlet tapping tee (tee-joint) of 101.6 mm in height and 36.5 mm in diameter, commonly used in the field. Figure 4-1 shows the tee-joint used to connect the branch. Anderson et al. (2004) and Weerasekara et al. (2006) earlier conducted tests with 60-mm diameter trunk pipes with tee connections and branches buried in Fraser river sand. They reported significant strain concentration on the trunk pipe near the tapping tee. However, the full-scale laboratory test of 42.2-mm trunk pipe was not conducted, which is also common in local gas distribution networks. The test program was undertaken to investigate 42.2-mm diameter trunk pipes with a lateral branch in this study.

The sand discussed in Chapter 3 was used to backfill the 42.2-mm pipe. The dry density of the sand in the test box was measured using the sand cone method (ASTM D1556-07) during the tests. The average dry density for the dense condition of the soil was measured as 19 kN/m^3. The average density of the sand was around 14 kN/m^3 for the loose condition.

Figure 4-1: Tee-joint used for branch connection

4.2.2 Instrumentation

The instrumentation included several electrical strain gauges placed at the pipe crown along the length of the pipe to estimate the pipe wall strains. Strain gauges were also placed on the top of the branch connection.

The test instrumentation included one null soil pressure sensor at a distance of 200 mm from the tapping tee to measure the lateral earth pressure. Note that the null pressure sensor was found to be very sensitive, and some of the sensors malfunctioned. As a result, the earth pressures at limited locations could only be measured during the tests. Figure 4-2 shows the installation of the null pressure sensor in the tee-only test. Figure 4-3 displays the details of the instrumentation employed on the pipes, including the locations of the branch and the strain gauges. For the “near branch” test, the tee joint/branch was located at a distance of around 25% of the length of the trunk pipe from the leading end. For the "far branch" test, the branch was located at a distance of 80% of the length of the trunk pipe.

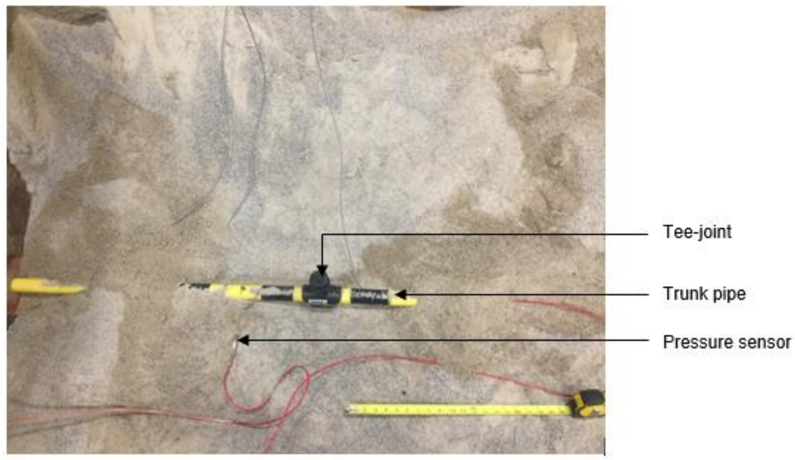
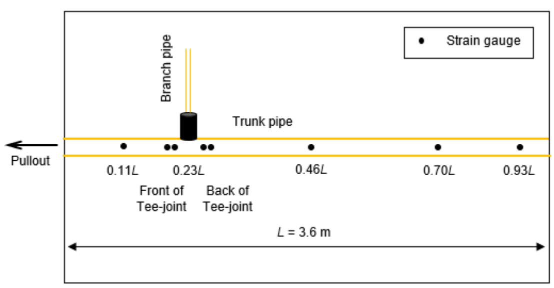
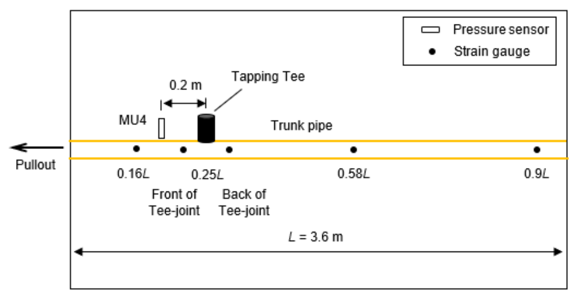


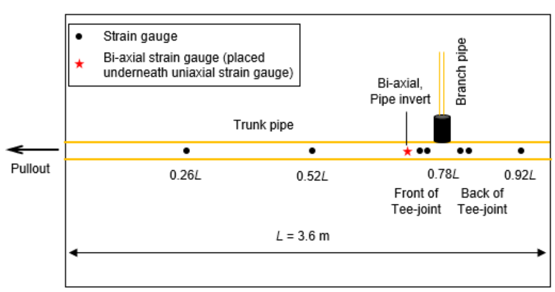
Figure 4-2: Pressure sensor installation in the tee-only test



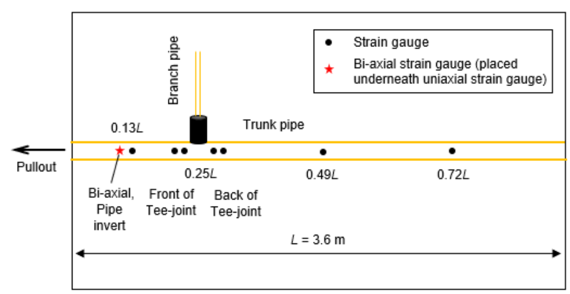
a) Test 1 (Near branch dense)



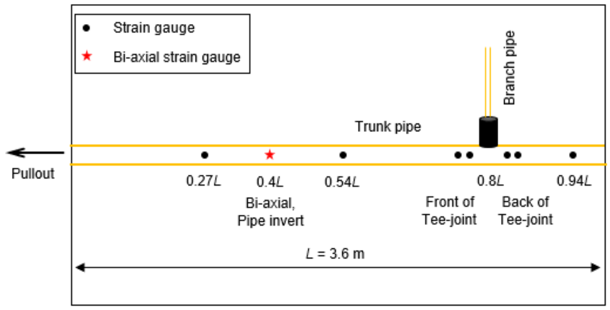
b) Test 2 (Near branch dense tee-only)



c) Test 3 (Far branch dense)



d) Test 4 (Near branch loose)



e) Test 5 (Far branch loose)

Figure 4-3: Test instrumentation in the tests with 42.2-mm trunk pipes

4.3 Results and Discussion

4.3.1 Pipe Pullout Responses

Figure 4-4 plots the load-displacement responses for the pullout tests conducted. It shows that the pulling resistance is the highest for the test with the branch near the pulling end (near branch test), followed by the pipe with the tee-joint only near the pulling end (tee-only test) and then the pipe with branch far from the pulling end (far branch test). Similar responses were measured for the 60.3 mm diameter pipes, discussed in Chapter 3. The anchoring effect of the tee-joint and the branch started earlier for the near-branch test than for the far-branch test, resulting in the higher pullout force in the "near branch" test. The branch pipe appears to contribute to the pulling resistance, resulting in about 2 kN lower pulling force for the tee-only test than for the near branch test. The maximum pullout loads of 6.5 kN, 4.5 kN, and 4.6 kN were observed for the pipes in the dense sand with the branch near the pulling end, tee-only near the pulling end, and the branch far from the pulling end, respectively, at the leading end displacement of 120 mm.

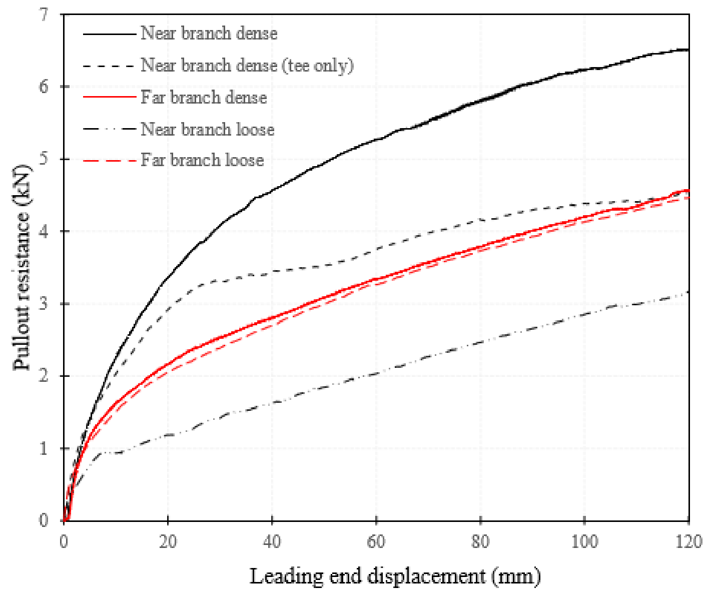
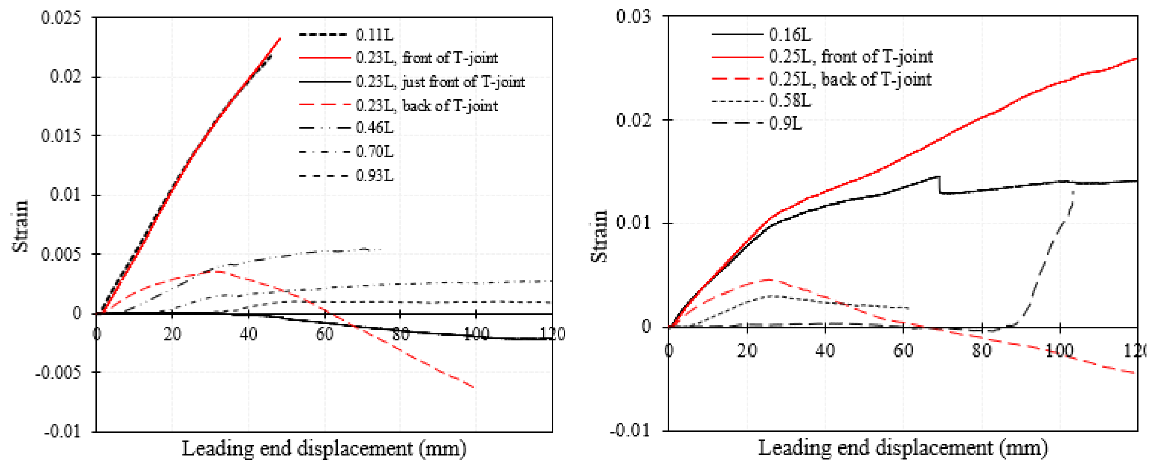


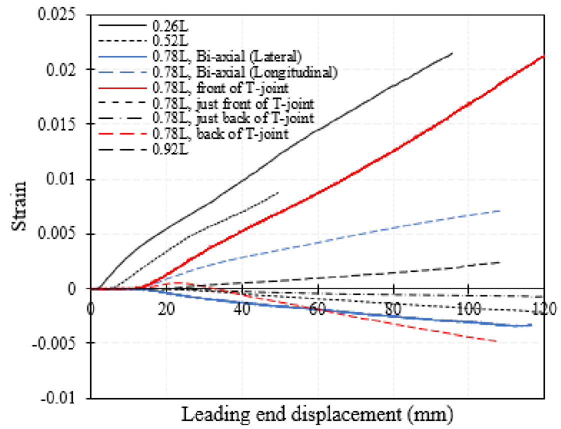
Figure 4-4: Load-displacement responses from different tests

The pulling forces for the pipes in the loose sand are less than the pipes in the dense sand (Figure 4-4). The maximum pulling forces for the pipes in loose sand were 3.2 kN and 4.5 kN for the branch near the pulling and far from the pulling end, respectively, at 120 mm of pullout displacement. Thus, the pullout resistance of the pipes depends on the presence of the tapping tee or branch used, the position of the tee-joint inside the box, and the density of the sand. Far branch dense and far branch loose tests showed similar load-displacement responses likely due to nonuniform levels of compactions during backfill soil placement. Additional tests are required to explore the mechanism of load transfer for the pipes in dense sand.

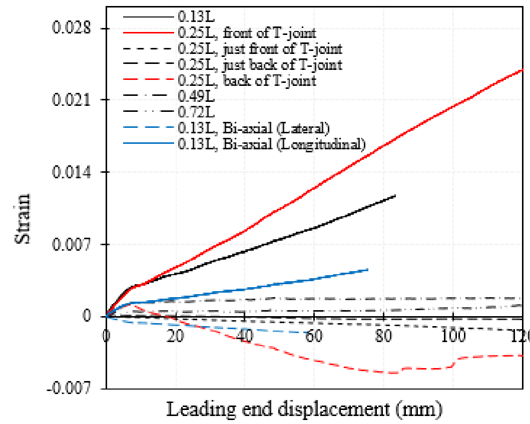
The mobilization of the axial force along the pipe length was examined by measuring axial strains during the tests. The axial strains measured at various points along the length of the pipe are shown in Figure 4-5. It shows that the strains first started at the locations of the gauge closest to the pulling end and then subsequently on the other strain gauge locations with the increase of leading end displacements. Thus, the pipe strains closest to the pulling end were the highest and decreased with the distance from the pulling end. However, the strains in front of the joint were significantly higher at large pulling end displacement. In the near branch tests, strain in front of the tapping tee started increasing almost instantly after applying the pullout load at the leading end displacement of ~ 1 mm. The strain in front of the tee-joint started increasing at the leading end displacement of ~ 10 mm in the far branch tests. Strain gauges malfunctioned after 40 mm of leading end displacement in Test 1.



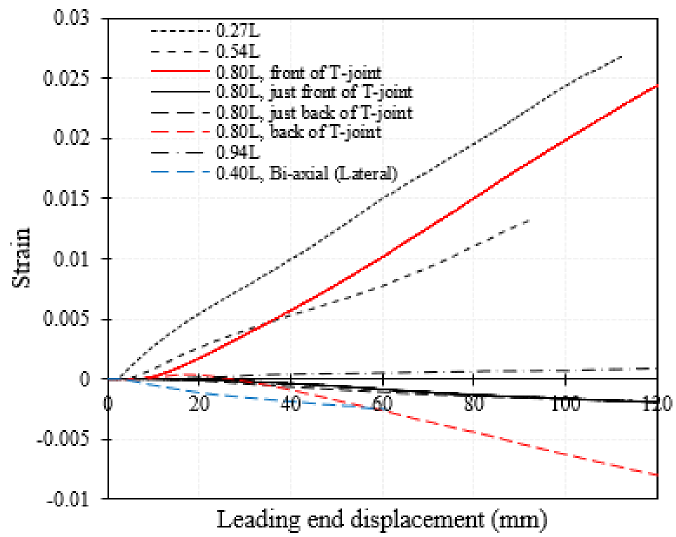
a) Test 1 (Near branch dense) b) Test 2 (Near branch dense tee-only)



c) Test 3 (Far branch dense)



d) Test 4 (Near branch loose)



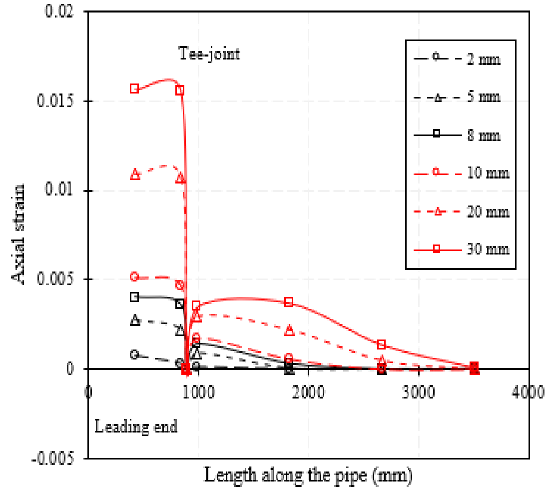
e) Test 5 (Far branch loose)

Figure 4-5: Pipe wall strain at different locations

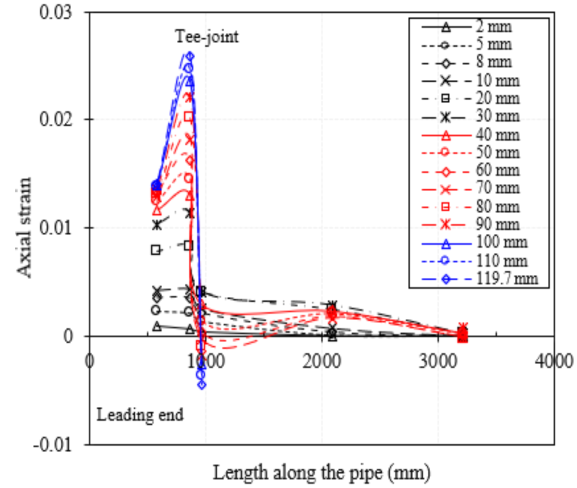
In Figure 4-5, "just front of T-joint" or "just back of T-joint" denote the strains measured on the black connector. "Front of T-joint" or "back of T-joint" indicate the pipe wall strains measured in front and behind the tapping tee connection, respectively. The strains on the connector are not significant, as shown in Figure 4-5. The connector is not monolithic with the pipe, rather a separate body. The negative strains that occurred on the joint in front of the tee can be due to the interaction between the connector and the pipe.

Figure 4-6 plots the axial strain distribution along the length of the trunk pipe at various leading end displacements during the pullout tests. This figure indicates that the trunk pipes experienced extensive strains in front of the tee-joint, particularly when the branch is located near the pulling force (near branch tests). Thus, the strain on the trunk (main) pipe in front of the tee-joint can be critical under axial ground movement.

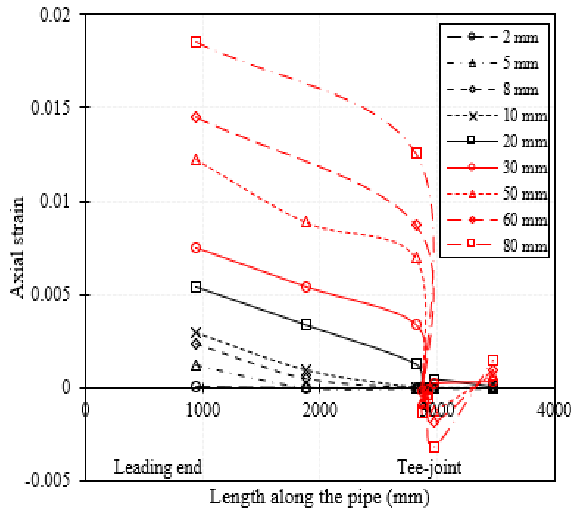
For the far branch tests, a large portion of the applied leading end displacement is the result of the elongation of a longer pipe length in front of the joint. Thus, the displacement of the tee-joint might be less. As a result, the anchoring force for the joint was not fully mobilized even at a larger leading end displacement, leading to the relatively lower pipe strains in front of the joint in Figures 4-6(c) and 4-6(e). For the near branch tests, the anchoring effect of the tee-joint is mobilized at a lower leading end displacement due to less elongation of the pipe length in front of the joint before mobilization of the axial force up to the joint. However, for the 60-mm diameter pipes discussed in Chapter 3, the strain was larger on the far-branch pipe than the strain on the near branch pipe. Thus, the load-transfer mechanism for the 60-mm diameter pipe and 42-mm diameter pipe might be different.



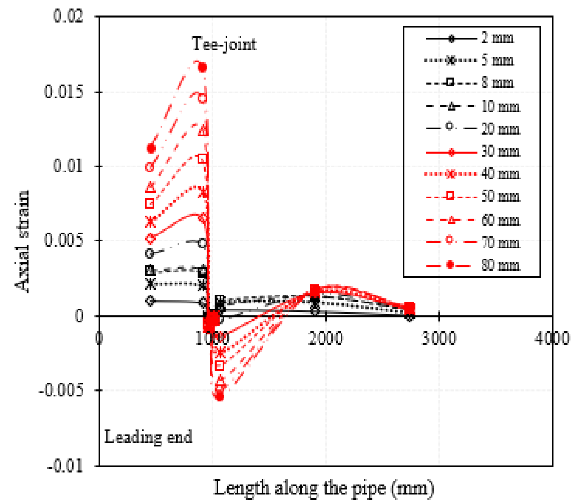
a) Test 1 (Near branch dense)



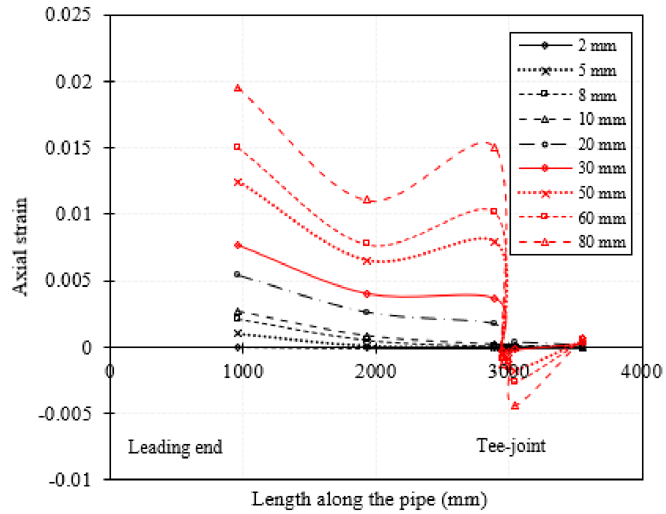
b) Test 2 (Near branch dense tee-only)



c) Test 3 (Far branch dense)



d) Test 4 (Near branch loose)



e) Test 5 (Far branch loose)

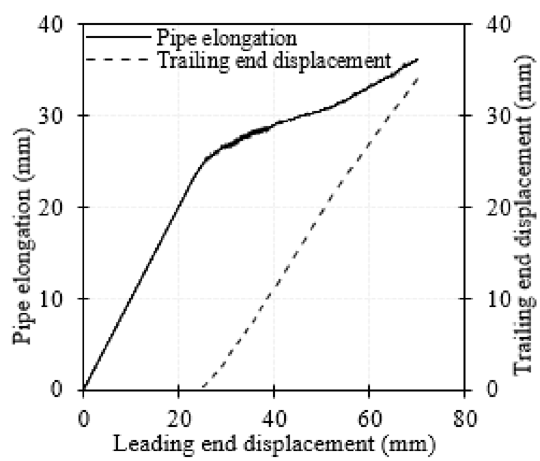
Figure 4-6: Strain distribution along the trunk pipe

As shown in Figure 4-5, the strain in front of the tee-joint continues to increase with increasing leading end displacement, implying that the tee-joint resistance may not be fully mobilized for the 120 mm relative displacement. The frictional resistance of the pipe length beyond the tee-joint can also contribute to the pulling resistance (Weerasekara 2007).

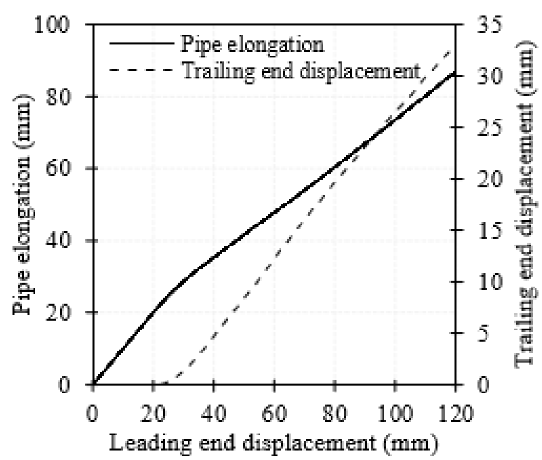
Once the frictional resistance over the entire pipe length is mobilized, the trailing end of the pipe starts moving. Figure 4-7 plots the displacement of the trailing end with the leading end displacement and the pipe elongation calculated as the difference between the leading end displacement and the trailing end displacement. The figure indicates that the trailing end displacement started at the leading end displacement of around 20 mm. The leading end displacement required for mobilization of trailing end movement is larger for the near branch test and for pipe in dense sand. This is consistent with the higher pulling force (and resulting elongation) for the near branch test in dense sand (Figure 4-4).

However, Figure 4-6 shows that the pipe strain behind the joint was very less. Thus, most of the pipe elongation occurred within the portion of the pipe in front of the joint. The tee-joint and the branch acted as an anchor. The anchoring effect is not symmetric about the pipe axis, resulting in a bending deformation of the pipe. The bending deformation was captured during the tests using the measurement of pipe strains at the crown and invert.

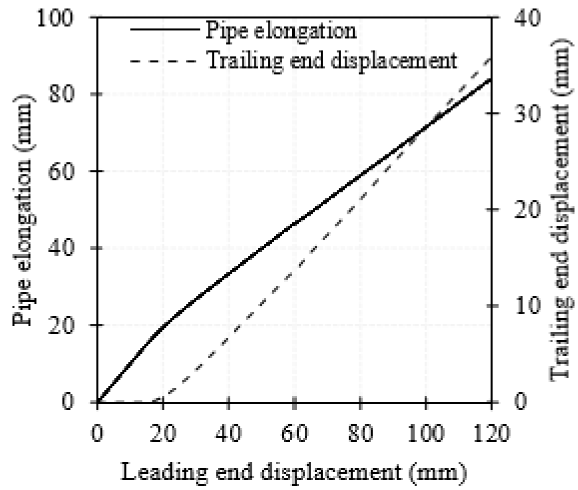
Figure 4-8 plots the crown and invert strains at a cross-section of the pipe near the tapping tee. This figure plots the strains measured in the far branch dense test. It is observed that beyond the leading end displacement of ~ 20 mm (when the trailing end starts to move), strain at the pipe crown was higher than the invert strain. The difference between the crown and invert strain started when the tee-joint began to contribute to pulling resistance and increased continuously with the increased displacement resulting from the anchoring effects of the tee-joint.



a) Test 2 (Near branch dense tee-only)



b) Test 3 (Far branch dense)



c) Test 5 (Far branch loose)

Figure 4-7: Pipe elongation and trailing end displacement

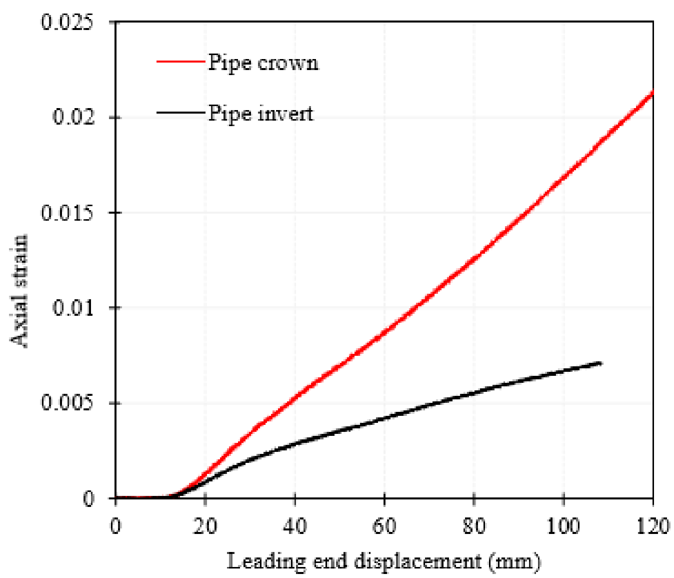


Figure 4-8: Strain at pipe crown and pipe invert near tapping tee (0.78*L*) in far branch dense test (Test 3)

Axial force (and the frictional resistance) is mobilized over the pipe length in front of the tee at the corresponding leading end displacement when strain in front of the tee-joint starts increasing. Beyond that leading end displacement, the frictional resistance of the remaining pipe length and the anchoring effect of the tapping tee and the branch come into effect. Then, the lateral soil force on the tee causes a bending moment to the trunk main. Thus, strain occurring on the pipe wall beyond that point is contributed from both axial strain and bending strain components.

4.3.2 Axial Force Mobilization Length

As discussed earlier, the strain gauge closest to the leading end first depicts strain increase followed by the subsequent strain gauges, as the axial force in the pipe is gradually mobilized from the leading end toward the trailing end during pipe pulling. The length of axial force mobilization could be estimated based on the strain measure (strain at a point increases if the axial force is mobilized to that point). Figure 4-9 plots the axial force mobilization length and the corresponding pulling force against the leading end displacement for the dense sand tests with 42.2-mm trunk mains. The straight portion in the mobilized length graph corresponds to the gradual mobilization of the axial soil resistance from the front to the back of the tapping tee. The strain gauges on the top of the tee-joint started reading after axial force mobilized over the whole pipe length (not shown in the figure). It implies that the tapping tee contributes to the soil resistance mobilization after the entire pipe length contributes to the frictional resistance. It is because a certain amount of deformation is required for the tapping tee for mobilization of the soil resistance. However, the movement of the tapping tee could not be measured during the test.

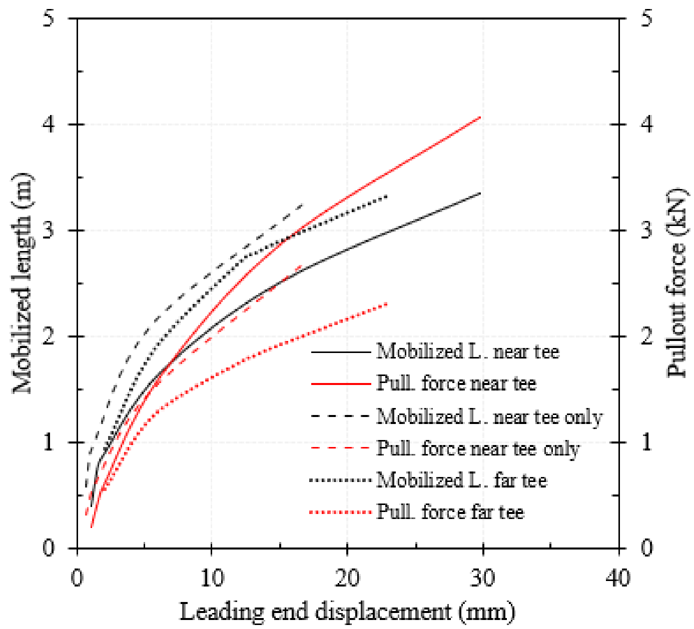


Figure 4-9: Axial force mobilization length and the corresponding pullout force for tests in dense sand

The axial force mobilization length and the corresponding pullout force against the leading end displacement for the loose sand tests with 42.2-mm trunk pipes are plotted in Figure 4-10. For the near branch loose test, axial force mobilizes over 72% of the pipe length at 4 mm of the leading end displacement. However, for the far-branch pipe, the axial force gradually mobilizes over the pipe length.

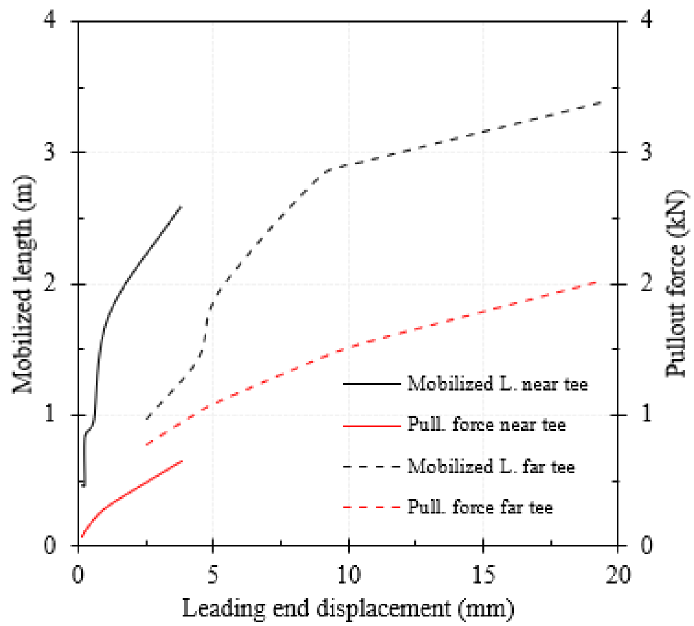


Figure 4-10: Axial force mobilization length and the corresponding pullout force for tests in loose sand

4.3.3 Tapping Tee and Branch Pipe Contribution

As discussed earlier, the soil resistance for the branched pipe can be separated into the frictional resistance to the axial movement of the pipe, the anchoring resistance of the tee-joint, and the resistance due to the branch pipe. To examine the contribution of the tee-joint, the load-displacement response from Test 2 (Tee only test) is compared with the load-displacement response of a similar pipe without branch from Reza and Dhar (2021b) in Figure 4-11. The load-displacement responses for both pipes match with each other at lower leading end displacement, indicating no effect of the tee-joint and the branch. However, at the leading end displacements closer to the one causing trailing end movement, the tee-only pipe shows a larger pulling resistance while the pullout resistance is reduced for the pipe without a branch. The higher resistance of the tee-only pipe has resulted from the anchoring effect of the tee-joint. The pullout resistance of around 3.25 kN was measured when the trailing end started to move, which is the contribution of axial frictional resistance of the pipe. Subtracting this from the total pullout force, the resistance due to the tee-joint is calculated to be 1.25 kN at the leading end displacement of 120 mm. The maximum lateral soil resistance calculated using Eq. 3-1 of Chapter 3 was also around 1.25 KN. The maximum lateral resistance of the tee-joint (F_t) calculated using Eq. 3-1 is shown in the inset of Figure 4-11. The mobilization of the tapping tee resistance is assumed to occur at the relative displacement of 6 mm based on the ALA (2005) guidelines for lateral soil spring. However, mobilization of soil resistance at a larger displacement is expected for MDPE pipe. The soil resistance was also calculated using the Terzaghi bearing capacity equation that provided a resistance of 2.5 kN in dense sand, which is greater than the resistance from the tee-joint observed during the test. Note that the bearing capacity of the tee-joint may not be fully mobilized at the displacement of 120 mm during the test.

The branch pipe contribution to the soil resistance is identified in this study from the difference between the forces for the branched pipe and the pipe without the branch (tee only). Figure 4-12 shows the branch pipe contribution to the pullout resistance calculated from the difference between the pullout forces in Test 1 (near branch dense) and Test 2 (near branch dense tee-only). A fitted curve is plotted to estimate the branch pipe resistance (F_b) as a function of displacement (x), where x is the displacement of the tapping tee and the displacement of the pipe, as shown in Eq. 4-1.

$$F_b = 0.0331x - 0.0002x^2 \qquad [4\text{-}1]$$

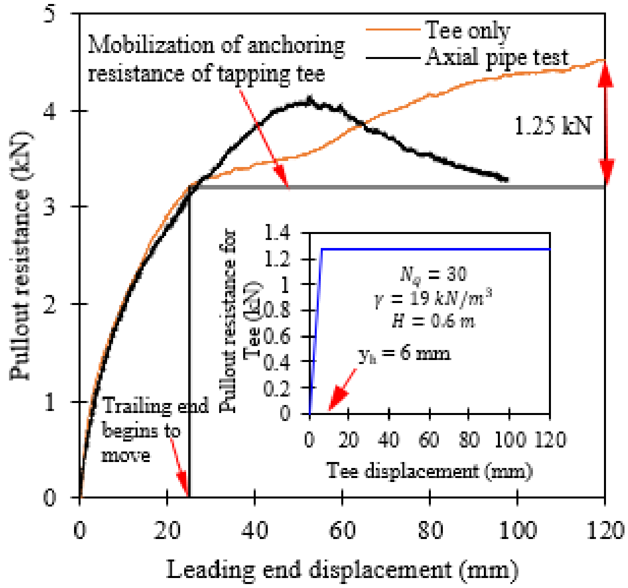


Figure 4-11: Anchoring resistance of tapping tee (dense sand)

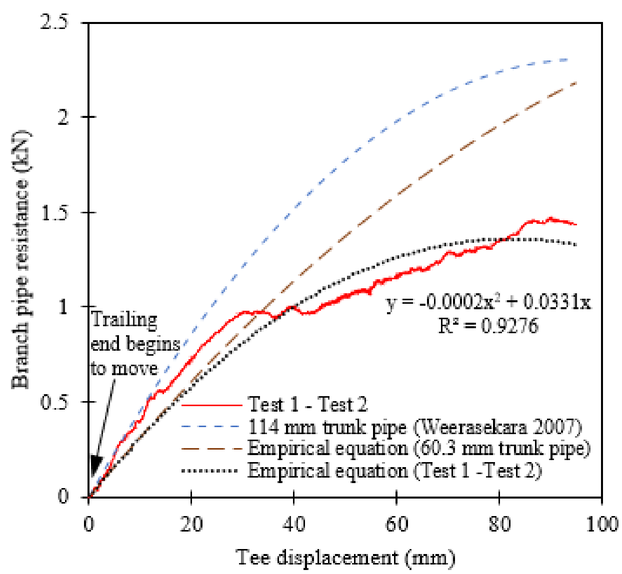


Figure 4-12: Contribution of the branch to soil resistance (dense sand test)

In Eq. 4-1, x is in mm and F_b in kN. Figure 4-12 includes the approximation obtained from the 60.3 mm pipes in this study and a similar empirical approximation ($F_b = 0.048x - 0.00025x^2$) derived from 114-mm pipes by Weeraserakara (2007). Weerasekara (2007) suggested the limiting value of the branch contribution (F_b) as ~ 2.5 kN as a 16-mm branch pipe would likely fail from yielding beyond this point. Identification of the tapping tee and the branch contribution to the soil resistance and the pipe-wall strain during axial ground movement would be useful for the assessment of branched pipe system subjected to ground movements.

Eq. 4-1 computes the branch pipe contribution as 1.3 kN for the far branch dense test. Adding this value to the maximum lateral resistance of the tee-joint (1.25 kN, as mentioned earlier), the total anchoring resistance for the test is calculated to be 2.55 kN. This value is compared with the force-displacement response measured in the test, as shown in Figure 4-13. The figure shows that the axial pipe frictional resistance contributes to 2.3 kN of the total pullout force considering the initiation of the trailing end displacement. The tee-joint and the branch combinedly contribute the rest of the pulling force, i.e., 2.3 kN, which is approximately equal to the one calculated from the soil-spring characteristics and the empirical approximation.

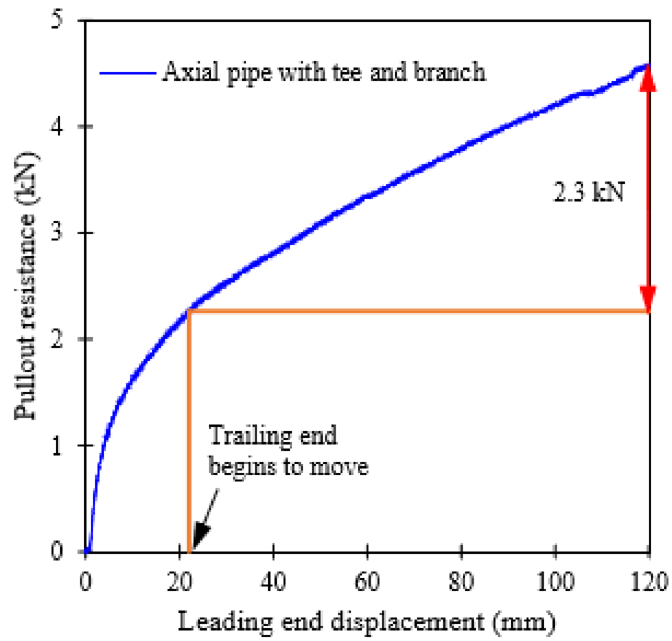


Figure 4-13: Combined contribution of the tee-joint and the branch to soil resistance (far branch dense sand test)

Similarly, the pullout resistance contributions of the tapping tee and the branch pipe in loose sand were estimated. Eq. 3-1 was used to calculate the lateral resistance of the tapping tee using the ASCE guideline, shown in Figure 4-14. This tapping tee resistance is compared with the result obtained from the test. In the far branch loose sand test (test 5), the frictional resistance due to the axial movement of the pipe was found 2.0 kN at 18.7 mm leading end displacement when the trailing end started to move (Figure 4-15). And the branch pipe contribution to the soil resistance was calculated 1.3 kN using Eq. 4-1. Thus, the anchoring resistance of the tee-joint was computed to be 1.2 kN, which is higher than the value calculated using the ASCE guideline. Moreover, Terzaghi bearing capacity equation estimated the soil resistance of 0.8 kN for the loose sand. Thus, the general bearing capacity equation estimates the lateral bearing capacity of the tee-joint lower than the experimental result for the case of the loose sand.

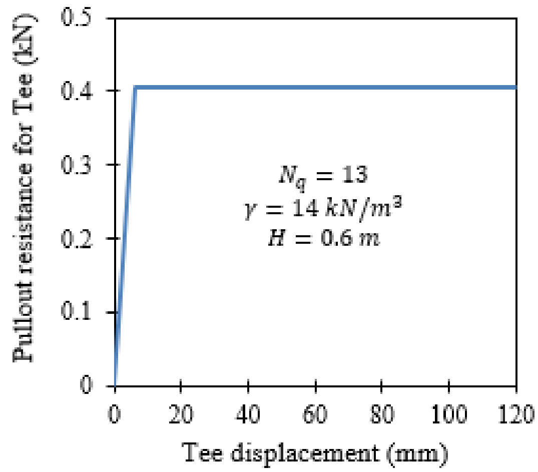


Figure 4-14: Anchoring resistance of tapping tee (loose sand)

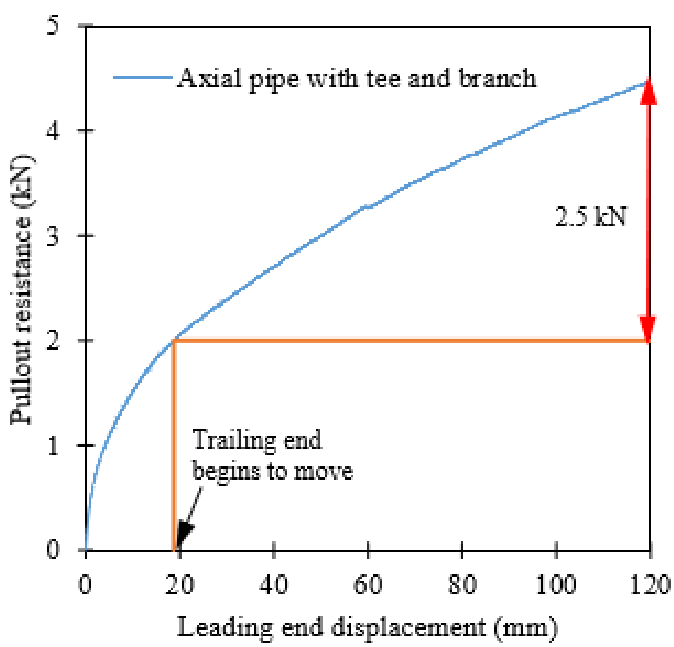


Figure 4-15: Combined contribution of the tee-joint and the branch to soil resistance (far branch loose sand test)

4.4 Summary

This chapter presents a study on the behavior of small diameter (42.2 mm) branched MDPE pipes under axial ground movement. Tests were conducted to identify the contribution of the tee-joint and the branch on the pipe responses in dense and loose sand. Pipe wall strains and lateral earth pressure in front of the tapping tee were measured during the tests to capture the mechanism of soil-pipe interaction. The main findings of the research are summarized below:

- The pullout force varies considerably with the position of the tee-joint within the test box with respect to the pipe pulling end. The axial force is higher for the pipe with a branch located closer to the pulling end due to the anchoring effect activating at a lower displacement. The pulling force is also higher for the pipes in dense sand than for the pipes in loose sand.
- Due to the anchoring effect, the pipe wall strain increases in front of the tee-joint. Since the anchor is on one side of the pipe (unsymmetric), bending strains develop on the pipe wall, causing a higher strain in the direction of the tee-joint. Pipe strain on the tee-joint is, however, negligible.
- The total pullout resistance is contributed by the frictional resistance along the pipe axis and the lateral resistance of the tee-joint and the branch pipe.
- The maximum tapping tee contribution to the total soil resistance may be estimated using the horizontal bearing capacity theory (ALA 2005, ASCE 1984).
- An empirical equation has been developed to approximate the contribution of the branch pipe in the pulling resistance.

CHAPTER 5 : Conclusions and Recommendations for Future Research

5.1 Overview

Medium density polyethylene (MDPE) pipes 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 can be increased by the presence of the lateral branches and the joints connecting the branch. The flexibility of the MDPE pipes coupled with the presence of branch connections can make the soil-pipeline interaction occurring at the joints during ground displacement very complex. This thesis conducts full-scale laboratory tests of 42.2-mm and 60.3-mm branched buried MDPE pipes with a tapping tee connection, subjected to axial ground movement to develop an understanding of the mechanism of load transfer in the pipes. The research investigates localized stress and strain concentration in the vicinity of the tapping tee due to the anchoring effects of the tee-joint and the branch. This chapter discusses the major conclusions drawn from this study and several recommendations for future research in this area.

5.2 Conclusions

The investigation of the pullout behavior of branched buried MDPE pipes leads to the following key findings.

- Measurement of soil stresses confirms that the test box used in this study can effectively investigate soil-pipe interaction without any treatment required to reduce sidewall friction. Soil vertical stress was not reduced due to the sidewall friction. The lateral earth pressure near the test box wall does not also considerably change during the pipe pullout.

- The presence of the pipe does not affect the vertical and horizontal soil stresses at a depth of 300 mm from the pipe springline, and these stresses can be estimated as geostatic stresses. On the contrary, the earth pressures near the pipe are significantly influenced due to the associated soil-pipe interaction.
- The stress normal to the pipe surface can be significantly higher than the corresponding geostatic stress even before the pullout starts due to the interaction between the pipe and the soil. The conventional design equations do not consider this high stress in the pulling force calculation.
- During pipe installation and soil placement, the coefficient of lateral earth pressure (calculated from the measured horizontal soil stress) near the tee-joint is higher than the coefficient of earth pressure at rest. This phenomenon indicates that the earth pressure is affected by the presence of the relatively rigid tapping tee.
- The axial ground movement further increases the normal stresses at the pipe-soil interface due to soil dilation. These increased stresses should be appropriately accounted for in the pipe wall stress calculation.
- The pullout force noticeably varies with the change in the tapping tee position with respect to the pipe pulling end and different soil densities during the tests. The mobilized soil pullout resistance is higher in the pipes with a branch connection near the pulling end than the far branch pipes.

- Anchoring effect of the tapping tee connection and the branch is comparatively lower in the pipes buried in loose sand than in dense sand.
- The strain is higher on the far branch pipe than the strain on the near branch pipe for the 60-mm diameter pipes. However, for the 42-mm diameter pipes, a higher strain is observed for the near branch pipe. Thus, the load-transfer mechanism for the 42-mm diameter pipe and 60-mm diameter pipe might be different.
- The anchoring resistance of the tee-joint causes strain nonuniformity between the top and the bottom of the pipe when the tapping tee entirely starts to contribute to the soil resistance.
- The tapping tee connection contributes to the axial force mobilization after the entire pipe length contributes to the frictional resistance at the pipe-soil interface. Soil axial pullout resistance initially mobilizes along the total pipe length, and the pipe length beyond the tee-joint also mobilizes before the tapping tee mobilization.
- The tapping tee movement significantly increases the lateral earth pressure in front of the tee-joint. ASCE (1984) and ALA (2005) guidelines can reasonably calculate the maximum lateral force on the tee. However, the guideline recommendation for the lateral displacement for maximum lateral resistance mobilization may not be applicable for the branched MDPE pipe.
- Soil reaction force on the tee-junction can induce a bending moment to the trunk pipe, causing very high strain on the pipe wall in front of the tee. Soil strain near the tapping tee also increases considerably due to this bending mechanism during the axial ground movement.

- The estimated tapping tee contribution to the total pullout resistance obtained from the tee-only test matches well with the ASCE (1984) guideline for lateral bearing capacity of pipes or anchor plates.
- The study proposed empirical equations to estimate the branch pipe contribution to soil resistance as a function of the tapping tee movement, where the branch pipe is connected. The branch pipe contribution was also separated experimentally, conducting a full-scale test with a complete branched pipe system and another pipe test with a tapping tee only having the branch cut down.

5.3 Recommendations for Future Research

Future research related to the current study can be conducted in the following areas.

- Only limited tests were conducted to understand the load-transfer mechanism for branched pipes when subjected to ground movement. The study revealed that the load-transfer mechanism is very complex for the branch pipes. Test results were used to separate the contribution of the pipe, joint, and branch on the pulling forces. However, additional tests are recommended to explore this further to develop design guidelines for the branched pipe subjected to ground movement.
- Full-scale laboratory tests of branched MDPE pipes with internal gas pressure are recommended to examine the effects. These tests will furthermore simulate the field condition of the gas distribution pipe.

- MDPE branched pipes with different types of connections than the pipes tested in this study are also currently used in the industry. Full-scale testing can be conducted with these pipes of different configurations.
- Three-dimensional numerical analysis of a branched pipe system could be challenging considering the computational time and cost required to analyze such a complex system. However, future research can be pursued initially in this regard to analyze a comparatively simpler system numerically.

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