

# Investigations of pipe installation using directional drilling

Moore, I.D.<sup>1</sup>, Allouche, E.N.<sup>2</sup>, Baumert, M.<sup>2</sup>

<sup>1</sup>GeoEngineering Centre at Queen's – RMC, Queen's University, Kingston, Canada

<sup>2</sup>Trenchless Technology Center, Louisiana Tech, LA, USA

## Abstract

A concerted research effort has been underway since 2002 to investigate the performance of steel, HDPE, and PVC pipes installed using directional drilling. In particular, the axial forces needed to pull the pipe into place, the magnitude and impact of mud pressures during drilling operations, and the performance of pipe under those loads has been studied. This paper summarizes the outcome and progress of various graduate research projects supported by a collaborative research grant.

First, load cells were developed to measure axial pulling forces. Measurements of pulling force for HDPE, PVC and steel pipes have been used to examine existing design equations and propose a new approach for estimating pulling force.

Second, mud pressures have been measured in the field, and factors influencing those mud pressures evaluated. The 'resistance' side of the mud pressure problem has also been investigated, with design equations developed to quantify the mud pressures that lead to tensile fracture of the soil around the borehole, and others to quantify the ground resistance to 'blowout' (mud release following mobilization of the shear strength of the overlying soil).

Finally, the time dependent response of HDPE is being measured and modeled so that long term axial stresses can be estimated over the service life of the installed pipe.

## Introduction to strategic research project

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Horizontal Directional Drilling (HDD) is now widely used in practice internationally. The propagation of equipment and contractor expertise in the 1990's was accompanied by research work on this technology. In particular, strategic research grant funding from the federal Canadian granting council NSERC has permitted a team of 16 faculty members and graduate students to undertake an integrated, coordinated research effort to investigate various factors influencing the success of 'pulled in place' installation (covering both directional drilling and pipe bursting). Figure 1 summarizes the seven graduate student projects that have been focused on the study of different aspects of directional drilling. This article outlines the work undertaken to measure the pulling forces that develop (Baumert, 2003; El Chazli, 2005), the response of the pipe to those pulling forces both during and after installation (work by Chehab and Cholewa), the drilling mud pressures that develop (Baumert, 2003), and mud loss due to blowout or tensile fracture of the soil (Kennedy, 2004 and work underway by Xia and Elwood).

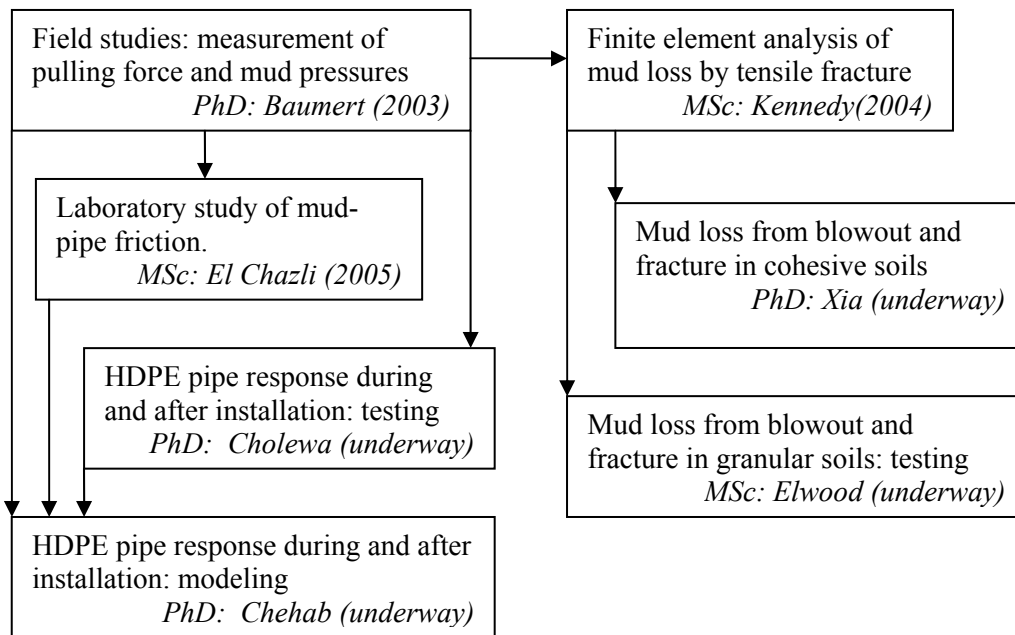


Figure 1. Graduate research projects on Horizontal Directional Drilling

### Field monitoring of pulling force and mud pressure

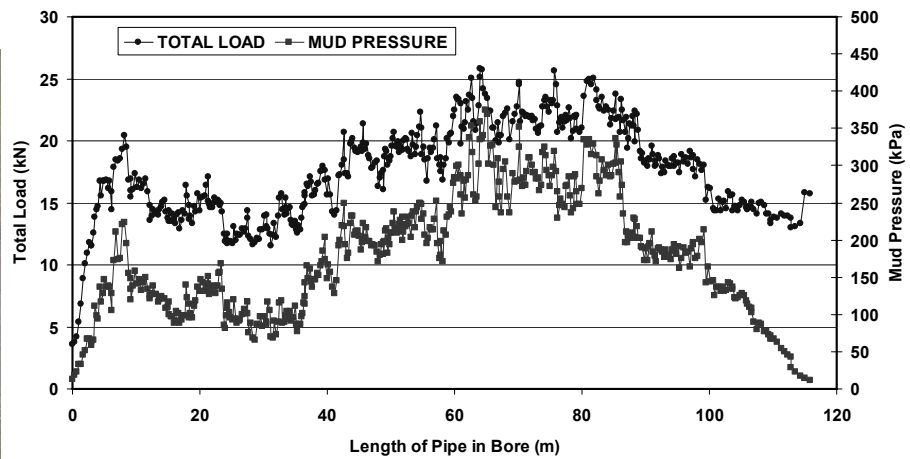
Two aspects of installation practice that have not been fully understood and which still cause problems in the field are 1. the estimation of expected pulling forces so that installation equipment can be reliably chosen, and 2. the prevention or control of mud loss as a result of soil failure around the borehole.

The first key element of the project was the development and use of load monitoring cells to record axial force histories for loads applied to pipes during pullback operations (when the pipe is inserted into the prepared borehole). Three load cells were developed by Baumert and Allouche (2003), Figure 2a, and these were used to monitor the installation of HDPE (high density polyethylene), PVC (polyvinyl chloride) and steel pipes, Baumert et al. (2004). Figure 2b shows a typical pulling force record measured by a load cell placed between the end of the drill string and the new pipe being pulled into place. Also shown are measurements of mud pressures at that location.

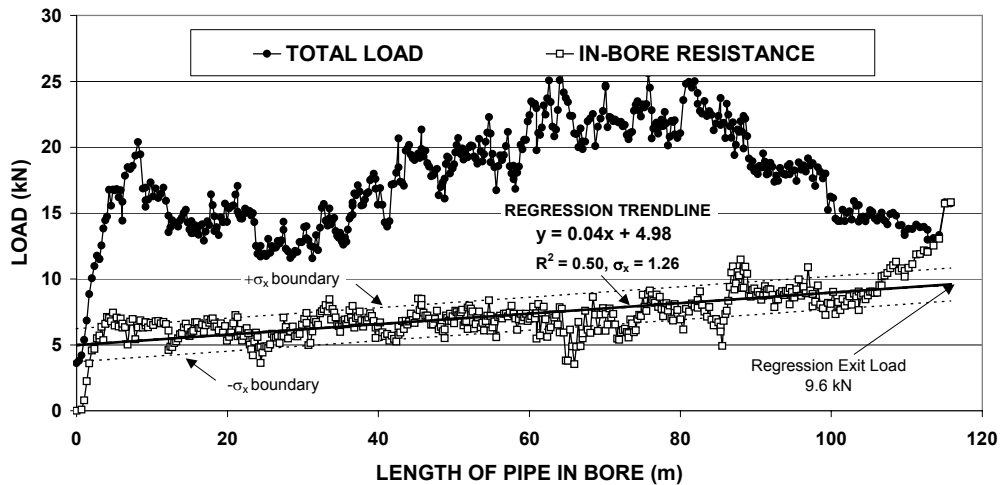
The effect of pressurized drilling mud on borehole stability, efficient removal of cuttings (during both pilot borehole drilling, and reaming), and the pulling forces needed to install the new pipe has also been explored, Baumert et al (2004). In particular, the mud pressures contribute to the pulling forces measured by the load cell. Figure 2c shows the measurements of total pulling force, as well as the force calculated as acting on the end of the new pipe (after the effect of mud pressures on the auger has been removed). Baumert et al. (2005) have explored the relationship between borehole geometry, mud characteristics, and the mobilized mud pressures using information collected from the oil and gas drilling communities.



a. Load cells



b. Record of pulling forces and mud pressures



c. Pulling force after accounting for the effect of mud pressure.

Figure 2. Equipment and field data after Baumert and Allouche (2002), Baumert et al. (2004).

Table 1. In-bore pipe resistance (200-300 mm OD)

Construction effort	Soil Type			
	Gravelly	Sandy	Silty	Clayey
High				
Medium	0.4 to 1.2 kN/m	0.4 kN/m		0.26±.03 <sup>+</sup> kN/m
Low				

\*Proposed framework only – values shown based on data collected to date

<sup>+</sup> Based on 12 installations in Silty clay

The established pulling force equations have been found to provide poor quality estimates of actual pulling forces, Baumert and Allouche (2002). Therefore, the pulling force data collected by Baumert (2003) has been used to propose a new approach for estimating pulling forces, Baumert et al (2004). This employs a new system reflecting three installation quality classifications:

- 1) high level, where effort is made to ensure a clean, stable bore, minimizing the solids remaining in the bore (usually arising with high cost projects or where the absence of a high level of construction effort may lead to pull loads that exceed rig capacity).
- 2) medium level, where effort is made to ensure an economic bore; this permits the contractor to reduce drilling and back reaming times, and the volume of drilling mud (it typically occurs where there is little risk of exceeding rig capacity or of causing surface heave above the borepath).

- 3) low level, where the focus is minimization of drilling and back reaming times and the volume of drilling mud. High solids content in the bore and high installation load levels per unit length of pipe installed are then considered acceptable. Little effort is made to minimize the risk of surface heave (this is generally used for shorter installations and should be limited to green-field conditions).

Table 1 provides typical values of force per unit length for installations in soils classified as: gravels, sands, silty soils, and clayey soils. Further values should be provided as additional projects are instrumented.

### Limiting mud pressures

Drilling mud plays a key role during the drilling process to return cuttings to the ground surface, stabilize the borehole, and lubricate the pipe being pulled into place. Unfortunately, the pressurized mud will lead to expansion of the borehole, and if the strength of the neighboring soil is exceeded, the mud-loss can occur. Both economic and environmental consequences then result. This is not just the cost of drilling fluid since environmental costs need to be considered.

Kennedy et al. (2004, 2006a) recognized that there are two possible mechanisms of ground failure can result in mud loss from a borehole:

- I. shear failure (or blowout), Figure 3a; and
- II. tensile fracture, Figure 3b.

The terms 'hydrofracture' or 'frac-out' are generally used to describe either of these possibilities.

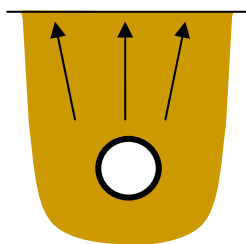
Kennedy et al. (2004, 2006a) used finite element analysis to examine the conditions leading to tensile fracture in a cohesive elastic-plastic soil. The limiting mud pressure causing fracture initiation  $P_{frac}$  is estimated by considering how the tangential stress in the soil at the crown or springline of the borehole reduces down to zero from the initial compressive stress of  $P_0$  (making the conservative assumption that the tensile strength of the soil is zero):

$$P_{frac}/P_0 = (3K_0 - 1) \text{ for } K_0 < 1,$$

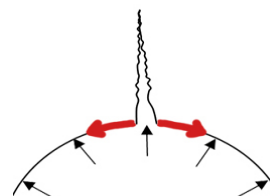
$$P_{frac}/P_0 = (3 - K_0) \text{ for } K_0 > 1$$

provided the fracture pressure is less than twice the undrained cohesion of the soil ( $P_{frac} < 2 C_u$ ). They concluded that the initiation of a tensile fracture occurs at the crown of the borehole where  $K_0 < 1$ , and at the springline where  $K_0 > 1$ .

Xia and Moore (2006) reported on a new approach to estimate the soil resistance to blowout, providing allowable mud pressure considering growth of maximum plastic radius with increasing borehole pressure. The new approach extends the use of purely axisymmetric analysis (e.g. Arends, 2003) to include explicit consideration of coefficient of lateral earth pressure. They made comparisons between estimations of the size of the plastic zone surrounding the borehole (where shear failure has occurred) using their new approach, the so-called 'Delft equation' of Arends (2003), and finite element calculations, demonstrating that their new closed form solution provides better estimates of plastic radius.



a. Shear failure - blowout



b. Tensile failure - hydraulic fracturing

Figure 3. Two mechanisms of soil failure leading to mud loss.

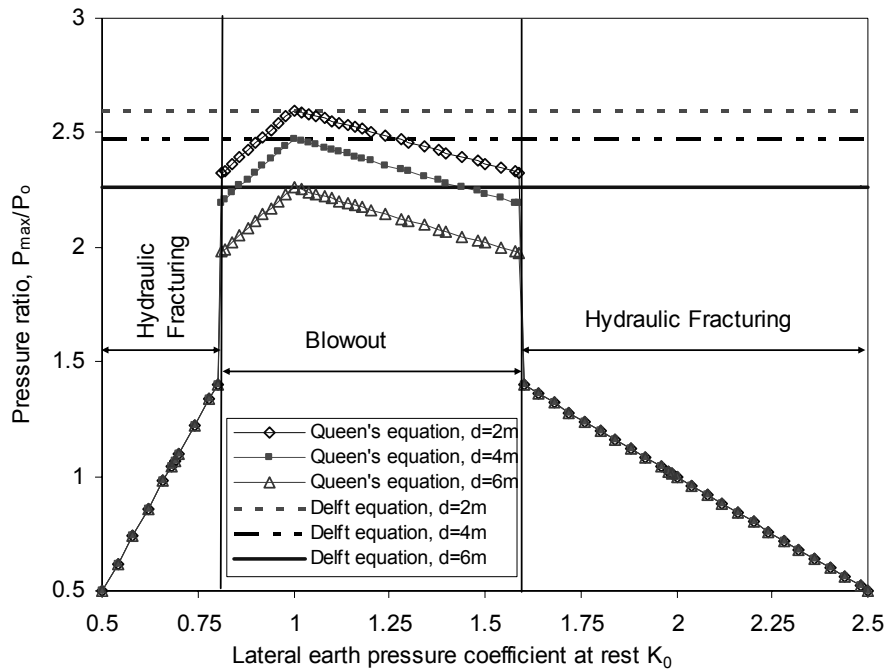


Figure 4 Relationship between pressure ratio (applied mud pressure to initial overburden pressure) and lateral earth pressure coefficient  $K_0$  (overconsolidated clay,  $C_u/P_0=0.7$ ).

Maximum mud pressure to prevent mud loss due to tensile fracture can be estimated using the procedure described by Kennedy et al. (2004). However, if shear failure develops in the vicinity of the borehole, blowout is the likely failure mechanism and the dependence of the maximum mud pressure on  $K_0$  can be estimated using the Xia and Moore (2006) solution.

Kennedy et al. (2006) developed the following criteria for judging whether hydraulic fracturing or blowout is critical for a given coefficient of lateral earth pressure at rest,  $K_0$ :

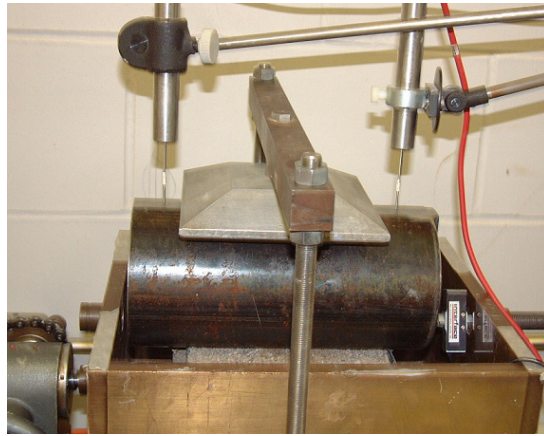
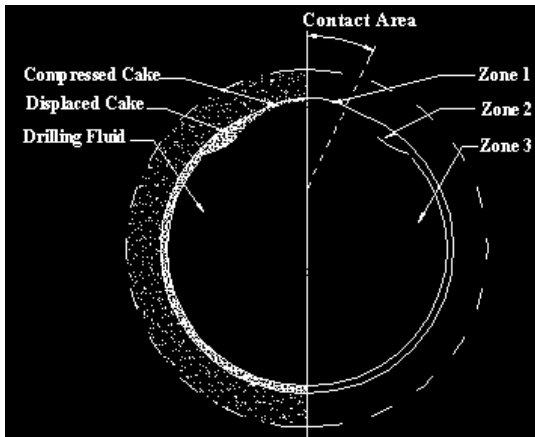
$$F_1(K_0, P_0, C_u) = 0.5(3K_0 - 1)P_0 - C_u \quad \text{for } K_0 < 1$$

$$F_2(K_0, P_0, C_u) = 0.5(3 - K_0)P_0 - C_u \quad \text{for } K_0 > 1$$

The sign of  $F$  depends on shear strength ( $C_u$ ), borehole depth ( $P_0$ ), and coefficient of lateral earth pressure,  $K_0$ . If function  $F$  is positive, blowout is expected, whereas if negative, tensile fracturing is expected.

Various values of cohesive strength and the coefficient of lateral earth pressure were used by Xia and Moore (2006) to investigate conditions that produce tensile fracture and blowout. For example, Figure 4 shows results for  $C_u/P_0=0.7$  (a possible strength condition for an overconsolidated clay). Maximum mud pressure values relative to initial vertical stress  $P_0$  are given for a range of  $K_0$  values. Tensile fracture is expected in these heavily overconsolidated clays where  $K_0 > 1.8$ . Blowout is expected at somewhat higher mud pressures when  $K_0 < 1.8$ . Other similar calculations reveal that blowout is most likely in normally consolidated and lightly overconsolidated clays.

Kennedy et al. (2006b) conducted a finite element study examining fracture initiation in the filtercakes that develop when drilling in sand. This work illustrates the likely significance of the filtercake cohesive, the initial stress conditions, and the friction angle of the sand. Physical tests are needed to understand how fracture initiates and propagates through the soil to the ground surface.



a. Pipe-mud-borehole system and regions of contact b. Pipe-soil friction tests  
Figure 5 Investigation of pipe friction through borehole, El Chazli (2005).

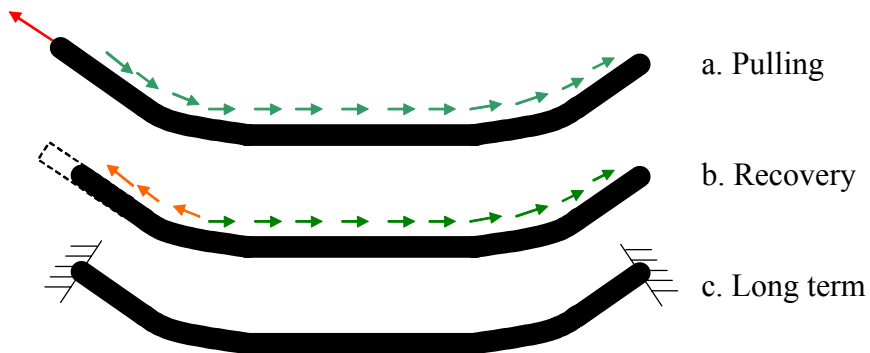
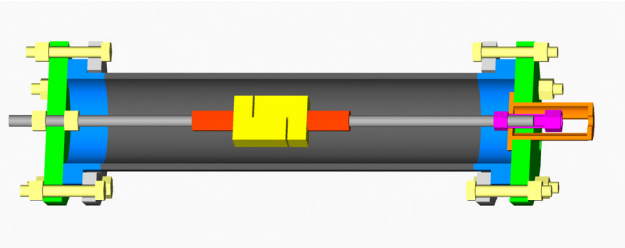
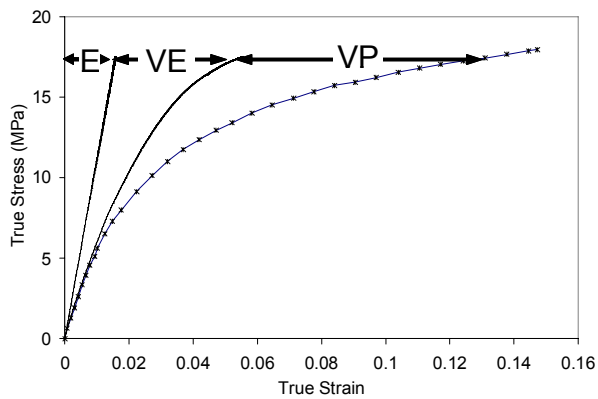


Figure 6 Schematic of load path for HDPE pipe at end of and following installation.

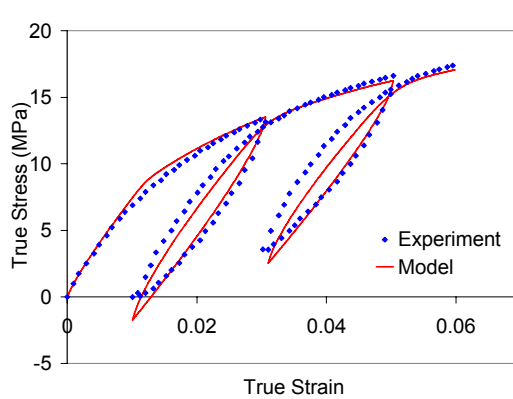


a. Laboratory test specimen b. Internal pipe restraint

Figure 7 Testing of HDPE pipes to simulate installation (see also Cholewa et al., 2006).



a. Different components of strain



b. Model performance for cyclic loading

Fig. 8 Modeling of HDPE to capture strain reversal, Chehab and Moore (2006).

### **Pipe response during pullback**

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El Chazli et al. (2005) examine the interaction of pipes sliding within the borehole, Figure 5a, and developed filtercake surfaces in the laboratory to facilitate measurements of pipe-filtercake friction, Figure 5b. Friction factors of from 0.2 to 0.5 were measured between steel and PVC pipes and the filtercake. They conclude that time-dependant behaviour (rheology) of drilling mud is a major factor affecting interface behavior, and that the interface behavior may, in part, account for the high variability observed in measured pull-loads.

Figure 6 represents three different stages of HDPE pipe response during installation. In the top illustration, the end of the installation process is being approached, with a large axial tension from the drill string applied to the end of the pipe, so that it moves through the ground. The pulling force from the drill rig is resisted by shear stresses that act on the external surface of the pipe. These actions result in increases in length of the pipe (tensile axial strains).

After the pipe has been pulled right through the borehole, it is left without end restraint for some period of time. As a result, the pipe begins to return to its original length. The axial contraction (strain recovery) that results will lead to shear stresses between the exterior of the pipe and the surrounding soil.

Finally, the ends of the pipe are attached to the fixtures that the pipe is intended to connect. From this point, the length stays constant and the resistance imposed to prevent any additional axial contraction leads to tensile axial stresses in the pipe.

These have been investigated in detail by Cholewa et al. (2006). Test fixtures have been developed to permit application of the load histories like those measured in the field, Figure 7a, and an internal restraint system and load cell permits long term measurements of axial stress history, Figure 7b.

Current HDPE pipe selection for use in directional drilling projects is based on the specification of pipe wall thickness to ensure that the maximum pulling force is less than some fraction of the ultimate axial load capacity of the pipe (e.g. 30%). The complex loading history discussed in the previous section and the axial tensions that are expected to be acting over the life of the pipeline lead to questions regarding the effect of those long term axial tensions on pipe durability. Furthermore, the loads measured where the pipe is attached to the drill string are not representative of the loads acting along the rest of the pipe during installation, since there are different shear stress regions, with shear direction dependent on the direction of mud flow, and/or the direction of pipe wall movement relative to the surrounding borehole.

Chehab and Moore (2006) describe the adaptation of the procedures of Moore and Hu (1996) and Zhang and Moore (1997ab) to develop new viscoelastic-viscoplastic constitutive models for estimating the cyclic response of the pipe materials, and the tensile stress history of the pipe during and after installation. Figure 8a shows the three components of the response: elastic ('E'), viscoelastic ('VE') and viscoplastic ('VP'), and the ability of the model to capture the cyclic response of the HDPE is demonstrated in Figure 8. The model performance will be assessed further using laboratory data obtained by Cholewa, and a one dimensional analysis developed to capture the complexities of pipe-soil interaction and the dependence on axial force on time and location.

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