A laboratory facility for studying pullout behaviour of buried pipelines

Parththeeban Murugathasan, Ashutosh Sutra Dhar, & Bipul Chandra Hawlader
Department of Civil Engineering – Memorial University of Newfoundland, St. John's, NL, Canada

ABSTRACT
The effect of ground movements on the performance of buried pipelines is an important consideration for pipeline integrity assessment. The experimental and analytical studies conducted in the past identified the important shearing mechanisms of soil around the pipe during relative ground movements. However, design methods for the assessment of pipes subjected to ground movements are not well developed, due to lack of quantitative data on the effects of soil shearing on the pullout force of the pipeline. The objective of the current study is to develop a laboratory test facility for pullout testing of buried pipelines to investigate pipe with different diameters and materials while simulating the ground conditions expected in the field. Finite-element modelling is used to assess the effects of the size of the test facility and rigidity of the boundary wall on the pullout behaviour. Based on the calculated effects, an optimum design of the test box is developed. The findings from this study suggest that a width of 10 times pipe diameter for the test cell is sufficient for axial pullout testing; however, the boundary wall stiffness should be designed to adequately minimize the wall deformations.

RÉSUMÉ
L'effet des mouvements du sol sur la performance des pipelines enfouis est un facteur important pour l'évaluation de l'intégrité des pipelines. Les études expérimentales et analytiques menées dans le passé ont identifié les importants mécanismes de cisaillement du sol autour de la conduite lors des mouvements relatifs du sol. Cependant, les méthodes de conception pour l'évaluation des tuyaux soumis aux mouvements du sol ne sont pas bien développées, en raison du manque de données quantitatives sur les effets du cisaillement du sol sur la force d'arrachement du pipeline. L'objectif de la présente étude est de mettre au point une installation d'essai en laboratoire pour les essais d'arrachement des pipelines enfouis afin d'étudier des tuyaux de diamètres et de matériaux différents tout en simulant les conditions du sol attendues sur le terrain. La modélisation par éléments finis est utilisée pour évaluer les effets de la taille de l'installation d'essai et de la rigidité de la paroi sur le comportement de retrait. Sur la base des effets calculés, une conception optimale de la boîte de test est développée. Les résultats de cette étude suggèrent qu'une largeur de 10 fois le diamètre du tuyau pour la cellule d'essai est suffisante pour les essais de retrait axial; cependant, la rigidité de la paroi limite doit être conçue pour minimiser de façon adéquate les déformations de la paroi.

1 INTRODUCTION

Buried pipelines have increasingly become the most popular transportation media of water and hydrocarbons, in recent years. Although buried pipelines are accepted as safe and feasible transporting media around the world, they face a major challenge when any ground movements occur due to landslides. The resulting relative ground movements generate external forces on pipelines in a longitudinal, transverse or oblique direction depending on pipe orientation against ground movements. Researchers employed laboratory pullout tests to investigate the ground loads on pipelines subjected to ground movements (e.g., Paulin et a. 1998, Wijewickreme et al. 2009, Daiyan et al. 2011). The main objective of this research is to develop a full-scale laboratory test facility which will be used to study the pullout behaviour of buried pipelines.

In the development of a test facility, the boundary wall effects are major constraints that can affect the test results considerably. Available experimental test data on pullout behaviour of buried pipelines are limited to particular pipe diameters/materials and often not comprehensive enough to address the effect of soil shearing during the pipe pullout. Numerical and analytical studies in this area still require more accurate data for validation/calibration purposes. For this reason, the focus of this study is to design a test facility which can be used to study pullout behaviour of pipe with different sizes up to the diameter of 100 mm.

This paper presents the results of finite-element analyses that have been conducted to examine the effect of test cell size and its wall rigidity while testing for pullout behaviour of buried pipelines. Numbers of finite-element models are analyzed to assess a suitable cell size and stiffness of cell wall to limit displacement of the side boundary walls due to soil pressure generated during backfilling of soil and pullout testing. Initial stresses of soil and shear-induced expansion of soil are simulated subsequently by considering gravity load and expanding the pipe boundary numerically.

2 REVIEW OF PREVIOUS STUDIES

Several full-scale experimental studies were conducted in the past to investigate pipe–soil interaction behaviour when the buried pipe is subjected to longitudinal or transverse movements. However, the number of laboratory tests conducted for modelling axial pullout behaviour of buried pipe is still limited. Paulin et al. (1998) developed a full-scale test facility which was constructed using concrete block walls. The test facility was adjustable to two different test bed configurations with dimensions of 1.4 m (width) x 3 m (height) x 3 m (length) and 1.4 m (width) x 0.63 m (height) x 3 m (length) for lateral and axial tests, respectively, to study force–displacement behaviour of pipeline buried in sand and clay soils. Soil movements and vertical deformation profiles of the test bed during the pipe movement were monitored. The axial pullout tests conducted in clay soil showed that the displacement required to mobilize maximum resistance was much less than the suggested values in ASCE (1984). The comparison of the back-calculated adhesion factor using the test results showed that the adhesion values are over-predicted in the existing design codes. Alam and Allouche (2010) used a 1.83 m (width) x 1.83 m (height) x 3.66 m (length) steel soil chamber with a 0.6 m high lid on top to assess the friction coefficient of the pipe-soil interface when the pipe is axially displaced. Axial tensile load tests on PVC pipes with an internal diameter of 203.2 mm were conducted for a range of different soil types. The inner walls of the chamber were covered by three layers of polythene sheets with lubricant applied in between the layers to reduce the wall friction. Elongation of the pipe, rigid body movement of the pipe, applied load and earth pressures around the pipe were measured during the axial pulling of the pipe. The earth pressure measurement showed a sudden drop at the crown of the pipe. The measured earth pressure close to the pipe near the springline showed an increase while the measurements at 450 mm away from the pipe showed fairly constant earth pressures during the movement of the pipe. The effects of boundary conditions were not assessed exclusively in detail in this study. Wang and Yang (2016) conducted full-scale testing on 172.3 mm and 223.1 mm diameter steel pipes buried in soft clay using a 1.4 m (width) x 1.0 m (height) x 1.5 m (length) test chamber in order to determine the axial friction coefficient (adhesion factor) of the pipe-soil interface. The boundary effect on the adhesion factor was reported to be negligible for the tests in the test chamber. Wijewickreme et al. (2009) performed full-scale tests to investigate the axial pipe-soil interaction of buried pipelines which were subjected to an axial pullout force. They examined the variation of normal soil stresses on the pipe surface to investigate the influence of dilation of sand due to shearing near the pipe-soil interface. The test facility was made of a timber frame with the dimensions of 2.5 m (width) x 2.5 m (height) x 3.8 m to 5 m (length). The axial pullout tests were performed using a 457 mm diameter steel pipe buried in a loose/dense state of Fraser river sand at H/D (depth to diameter) ratios equal to 2.5 and 2.7. The computer program FLAC 2D, which was developed based on a two-dimensional (2-D) explicit finite difference method, was used to assess the effects of the boundary distance of the longer walls. It was reported that the soil stresses had no significant changes near the boundary walls during the pullout test. Further, it was observed that the length of the test chamber had no significant effect on pipe pullout behaviour based on the tests conducted with two different test chamber lengths. They applied radial expansions of 0.7 to 1 mm in the pipe-soil interface for their numerical simulation to simulate soil dilation during shearing when the pipe is pulled. Karimian (2006) reported that only 1.2 to 2.8 mm of sand thickness is sheared during pipe pullout based on their tests conducted on sand-blasted steel pipes and polyethylene pipes buried in Fraser river sand.

Several full-scale lateral pullout tests were also performed to investigate the force–displacement behaviour of buried pipelines. Trautmann et al. (1985) tested lateral and uplift behaviour of buried pipe in dry Cornell filter sand to study the force–displacement relationship of different soil densities using various H/D ratios. 1.2 m (width) x 1.2 m (height) x 2.3 m (length) and 1.22 m (width) x 1.52 m (height) x 2.29 m (length) test boxes made of plywood were used for lateral and uplift tests, respectively. The chamber walls were further stiffened using lumber ribs to reduce the deflection of the side walls. The lateral tests were conducted using 102 mm and 324 mm diameter steel pipes and the uplift tests used 102 mm diameter steel pipes. Almahakeri et al. (2016) used a full-scale test facility which was surrounded by retaining walls with the inner dimension of 2 m (width) x 2 m (height) x 3.01 m (length) to investigate the bending behaviour of glass-fiber reinforced polymer (GFRP) pipes when subjected to lateral movements. They used 102 mm diameter steel and GFRP pipes with 3 different depth to diameter ratios to study the problem. The force–displacement data, deflection of pipe, strain on the pipe's outer surface and soil surface deformations were measured. Robert et al. (2016b) investigated the effects of unsaturated states of soils on pipe–soil interaction based on two different sands with laterally loaded pipe. The tests were conducted in Chiba sand and Cornell sand using two different test facilities and different laboratories. A 3.0 m (width) x 2.03 m (height) x 2.02 m (length) tank with a steel frame was used to test a 114.6 mm diameter steel pipe buried in Chiba sand at H/D = 6, and a 2.4 m (width) x 1.8 m (height) x 2.4 m (length) steel frame test box was used for the Cornell sand test. Pipe displacements in the horizontal and vertical directions and the earth pressure variations were measured during the test. Wang et al. (2017) investigated soil–nail interaction during pressure grouting using a steel soil chamber which had an internal dimension of 0.6 m (width) x 0.73 m (height) x 1 m (length). The side walls of the tank were made using a 10 mm thick steel plate with square steel stiffeners. A lubricant was applied between a flexible plastic sheet and stainless steel wall to reduce the friction of the tank wall. Applied force, resulted displacement and earth pressures around the nail were measured during the tests. The applied force was measured using a reaction frame with a hollow jack and a load cell when the nail was pulled with a controlled displacement rate. Robert et al. (2016a) used another 3.2 m (width) x 2.3 m (height) x 10.5 m (length) test box made of a steel frame and tested a 400 mm diameter HDPE pipe buried in glaciofluvial sand (Cornell sand) at 1.12 m depth to investigate the pipeline behaviour subjected to fault movement. The test box was split into two units in a way that enabled each unit to slide relatively at an angle of 65°.

In addition, centrifuge tests have been reported on the transverse or oblique movement of buried pipes (Ha et al. 2008; Daiyan et al. 2011; Dickin 1994). Also, numerical studies were performed on pipe-soil interaction (Phillips et al. 2004; Yimsiri et al. 2004; Pike and Kenny 2012; Almahakeri et al. 2016) with pipe subjected to different modes of movements.

3 DESIGN OF TEST CELL

A test cell with dimensions of 2 m (width) x 1.5 m (height) x 4 m (length) is first considered. These dimensions provide a width of 20 times the pipe diameter and a height of 15 times the pipe diameter for a 100 mm diameter pipe. The schematic drawing of the cross-section of the cell is shown in Figure 1. A pipe diameter of 100 mm buried at the H/D ratio of 6 is investigated for the effects of the test cell boundaries during pullout tests. The side wall distance and bedding distance are 10D and 6D, respectively, in the first model. However, different wall distances are considered to assess the boundary effects and the results are discussed later in this paper. The overall size of the cell is optimized to make the laboratory testing more convenient while ensuring sufficient boundary distances.

Type A36 steel is selected for the test cell, which is a readily available material. The thickness of the test cell wall is selected as 6 mm and is kept unchanged in the design to maintain a reasonable overall test cell weight. The rigidity of the boundary walls is increased by adding stiffeners to the wall, instead of changing the wall thickness and material. The steel plates are stiffened by adding more longitudinal and transverse stiffeners outside of the cell wall.

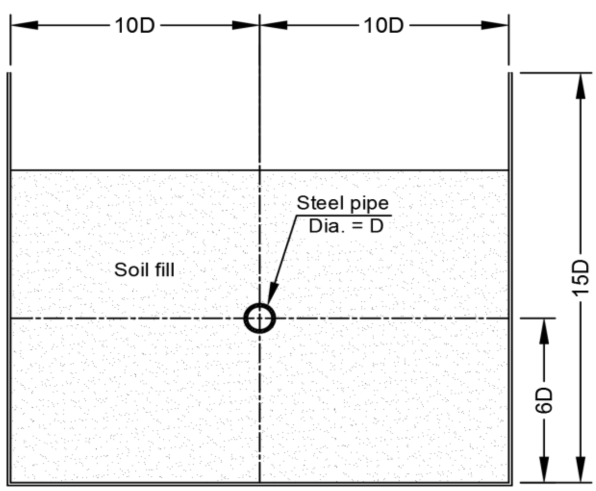

Figure 1. Schematic drawing of proposed test cell cross-section.

In addition to adequate cell size and wall rigidity requirements, some special features are incorporated into the test chamber to make the test chamber more versatile. Polycarbonate sheet (Lexan) window panels are used in the chamber wall to facilitate observations inside the chamber (30 cm wide and 130 cm deep panels). Circular openings are considered in the model on the front and back walls, enabling running a longer pipe through the chamber or fixing a hydraulic actuator to the pipe. Lubricated polyethylene sheets are used to reduce the cell-wall interface friction. Tognon et al. (1999) obtained the cell-soil interface friction angle of less than 5° using lubricated polymer sheets.

4 NUMERICAL MODELLING

4.1 Modelling Approach

The numerical analysis is conducted to investigate the appropriate boundary distances and wall rigidity of the test facility which is to be developed for axial pullout testing of buried pipelines. The numerical modelling is carried out using the commercially available finite-element software package Abaqus/Explicit. The large deformation of the soil and test cell wall due to the gravity load (soil fill) and the contact definitions between two deformable bodies demonstrate the necessity of using explicit finite-element code for this analysis. 2-D plane strain analysis is first carried out to assess the effect of boundary wall distance and wall friction on the pipe-soil interface behaviour. However, actual cell wall rigidity and boundary restraints could not be simulated properly in the 2-D model. Therefore, a three-dimensional (3-D) continuum model is developed at the same scale as the proposed experimental facility of pullout testing to investigate the effect of boundary wall rigidity on the longitudinal pipe movements. In the 2-D model, the soil and pipe are modelled using a four-noded linear quadrilateral element (CPE4R). The tank wall is modelled using the beam element (B21) which is a two-noded linear beam element in a plane. The typical finite-element mesh used in the 2-D analyses is shown in Figure 2.

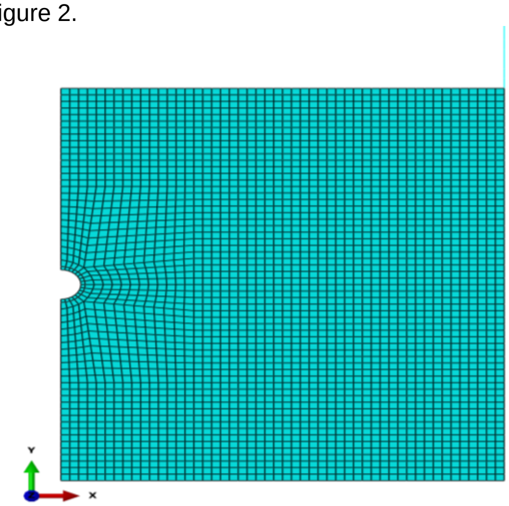

Figure 2. Typical finite-element mesh of soil, test cell and pipe used in 2-D model

In the 3-D model, the soil is modelled as continuum material using an eight-noded linear brick element (C3D8R). The cell wall and pipe are modelled using four-noded 3-D doubly curved shell elements (S4R). The typical finite-element mesh used in the 3-D analyses is shown in Figure 3. Suitability of the beam element and shell element is first assessed to select an effective element type to model the stiffeners. The use of shell elements with small mesh size has shown similar bending stiffness as do beam elements. Furthermore, avoiding the constraints between the beam and shell elements reduces the computational time significantly. Thus, the shell element (S4R) is employed for the stiffeners. The use of hourglass controlled elements (C3D8R, CPE4R & S4R) reduced the effects of hourglass modes in the results. Even though these element types are 1st order elements, as these are reduced integration elements, shear locking of elements is automatically avoided in the model response.

Mesh convergence analysis and element quality assessment are conducted separately to make sure that analysis results are independent of the mesh size and mesh quality for each model. A structured mesh has been generated for soil, pipe and cell with denser mesh near the pipe.

4.2 Boundary Conditions and Loadings

The pipe-soil interface and cell-soil interface are simulated using the built-in surface to surface contact approach available in Abaqus. In this approach, the friction coefficient is used to define the tangential behaviour (penalty type), and hard contact with separation after contact definition is used for normal behaviour between the surfaces. In this method, if the shear stress on the contact interface exceeds the critical shear stress (friction coefficient times normal stress), sliding occurs.

In addition to the nonlinear contact boundary conditions, the bottom face of the test tank is restrained for rotation and displacement in x, y and z directions. The vertical faces of the tank are not restrained in any direction; rather, walls are allowed to deform based on their flexural rigidity. Due to symmetrical geometry and loading conditions, only one-fourth and half of the physical model is created for the 3-D and 2-D analysis, respectively. Appropriate symmetric boundary conditions on the symmetric planes are employed.

The finite-element analysis is conducted in two main steps. The first step is to apply the gravity load that accounts for the effects of soil weight and creates the initial stresses on the soil. Besides developing initial soil stress, this step is quite important to assess the boundary wall deformations and corresponding changes in the soil stresses. The coefficient of lateral earth pressure under this condition is examined and is found to be close to the K_0 condition calculated using the elastic theory ($\nu/(1-\nu)$). In the second step, the pipe is enlarged by 1 mm (Wijewickreme et al. 2009) to mimic the effect of the shear-induced expansion of soil in the pipe-soil interface during the pullout.

4.3 Material Model and Parameters

The built-in Mohr–Coulomb model in Abaqus is used to model the soil. The Mohr–Coulomb model requires the following input parameters: Young's Modulus (E), Poisson's ratio (ν), the angle of internal friction (ϕ'), dilation angle (ψ_m) and unit weight of soil (γ). Good representative typical values of soil parameters are chosen for this analysis. A dilation angle of 5° is estimated by considering a peak friction angle of 35° and the critical state friction angle of 31°, based upon the relationship proposed by Bolton (1986). As the steel stresses are to be limited to the elastic region, only the elastic properties of steel are employed, and the plastic behaviour of steel is not modelled. The test cell and pipe are assigned with the same steel properties. The parameters used in the FE model are summarized in Table 1.

The friction coefficient (μ=tan (ϕ_μ)) is estimated in terms of interface friction angle (ϕ_μ). The interface friction angle, ϕ_μ, depends on the interface characteristics and the degree of relative movement between the two surfaces. A constant value of, μ = 0.3 is employed for the pipe-soil interface in this study. However, different friction coefficient values are used for the cell-soil interface to assess its effects on the soil response.

Table 1. Parameters used in FE analyses.

Parameter	Value
E_{soil} (MPa)	10
ν_{soil}	0.25
ϕ' (°)	35
ψ_m (°)	5
Density of soil, ρ_{soil} (kg/m^3)	1700
Cohesion[a], c' (kN/m^2)	0.1
E_{steel} (GPa)	200
ν_{steel}	0.3
Yield strength, σ_y (MPa)	250
Density of steel, ρ_{steel} (kg/m^3)	7850

[a]A small value of cohesion is assumed to model the Mohr–Coulomb model in Abaqus for numerical stability.

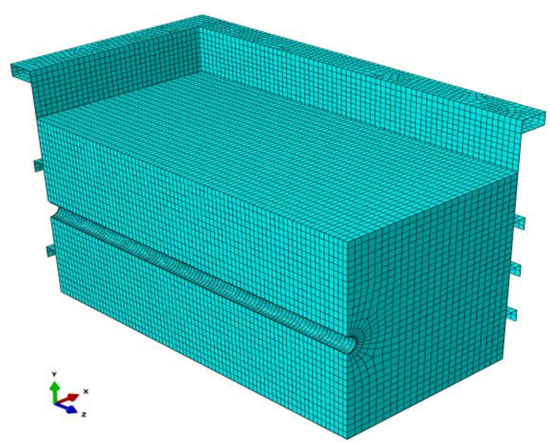

Figure 3. Typical finite-element mesh of soil, test cell and pipe used in 3-D model

5 RESULTS AND DISCUSSION

5.1 Preliminary Analyses

Several different wall thicknesses of the test cell are considered to investigate the effect of boundary wall rigidity on the initial soil stress development in the test cell and on the dilation (expansion of dense soil during axial pipe movement) using the 2-D plane strain analysis. Self-weights of the soil (γh) and the pipe are used to develop initial stresses in the soil domain. The additional surcharge load could be simulated by considering a higher fill of soil above the pipe but it is not exclusively considered in this study; rather, a constant H/D ratio is employed to study the boundary effect. The coefficient of lateral earth pressure at-rest (K_0) is not directly employed in the model. Therefore, the lateral earth stresses expected in the field should be developed by limiting the outward deformation of the cell wall. In order to achieve this, the cell wall should be sufficiently rigid. Ultimately, a steel plate having a thickness of 100 mm shows more rigid behaviour with approximately zero lateral deformation of the wall and gives a reasonable initial vertical and lateral soil stress profile, as expected in the field. A cell-soil friction angle of 5° is employed in this model. The effect of cell-soil interface friction angle on the initial soil stress development and on the simulation of soil dilation at the pipe-soil interface is studied separately using the 2-D model with the dimensions of 2 m (width) x 1.5 m (height). Figure 4 shows the variation of calculated vertical soil stresses near the boundary wall with depths for different cell-soil interface friction angles of 1°, 5°, 10° and 15°. The developed vertical soil stresses decrease with depth when the cell-soil interface friction angle increases due to the shear stresses developed along the wall. However, it is also noted that initial vertical and horizontal stresses near the pipe are not much affected by the wall friction angle when the wall is rigid and far enough from the pipe. Figure 5 shows the calculated vertical soil stresses near the pipe (0.2 m away from pipe center) with depth (between 0.3 m and 0.9 m soil depth) for cell-soil interface friction angles of 1° and 15° during the dilation simulation of the pipe pullout step. It clearly shows that the effect is insignificant at mid depth although a small variation of the calculated vertical stress is observed at greater soil depth. The effect of friction angle is found to be significant if the cell wall is close to the pipe.

5.2 Effect of Wall Distance and Wall Rigidity on the Soil Response

The results of the 2-D and 3-D models are used to examine the effects of wall distance and wall rigidity during the gravity step and during the simulation of soil dilation with the pipe pullout step. The cell-soil interface friction angle of 5° is used. The 3-D models are developed with the dimensions of a 2 m (width) x 1.5 m (height) x 4 m (length) and 6 mm thick wall, but with a different configuration of stiffeners until the wall deformations are controlled. 150 mm x 75 mm x 10 mm channel sections are used for horizontal stiffeners at the top of the cell. 75 mm x 75 mm x 10 mm angle sections are used to model all other stiffeners. Vertical stiffeners are used at approximately 0.5 m intervals. This facilitates the side wall displacement of the test cell to be within 1 mm after the gravity step and after the simulation of soil dilation. The results are shown in Figures 6 and 7, respectively.

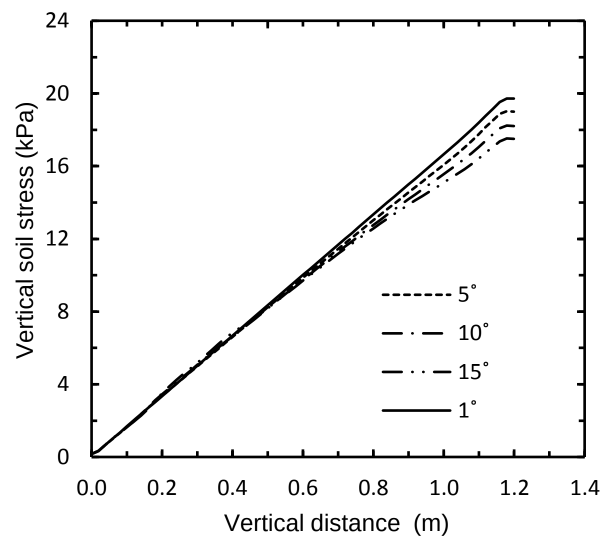

Figure 4. Vertical stresses with soil depth, 0.2 m away from the cell wall (initial loading).

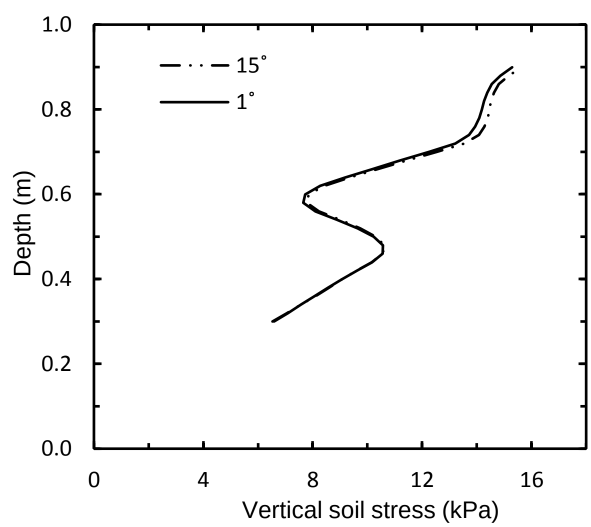

Figure 5. Vertical stresses with soil depth, 0.2 m away from the pipe centre during expansion.

A maximum horizontal displacement of 0.27 mm occurs on the lateral walls at the end of the gravity step (Figure 6). Subsequently, the wall displacement has increased only by 0.29 mm when the pipe is numerically expanded by 1 mm in the second step (Figure 7). The initial vertical and horizontal soil stresses are developed as expected; however, they are not exactly same as the results of the 2-D model, due to comparably less wall rigidity in the 3-D model, as discussed below. Since the increase in wall deformation is negligible in the second step, it is assumed that the soil dilation around the pipe would not be significantly influenced by the boundary of the cell.

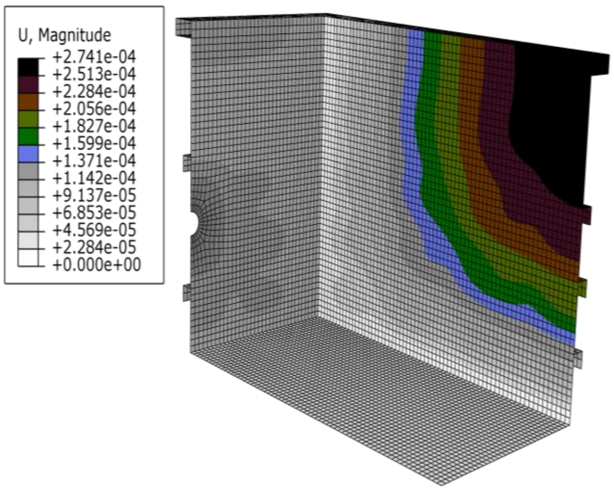

Figure 6. Deformation of test cell after gravity step.

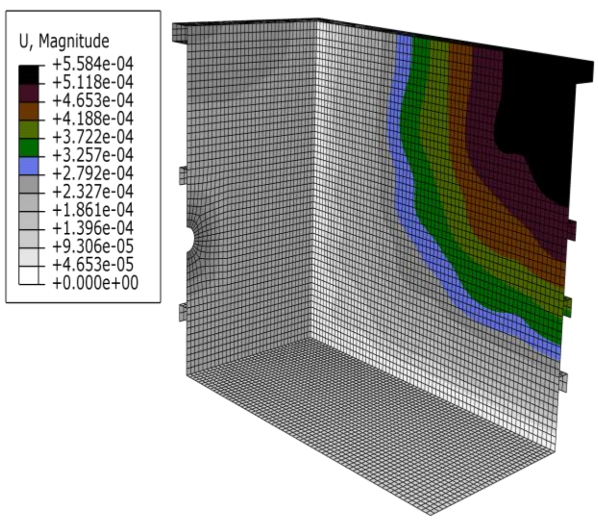

Figure 7. Deformation of test cell after simulation of dilation during the pullout.

The vertical and horizontal soil stresses at the springline level are examined to investigate the boundary effect on the pipe-soil response during the simulation. The results in Figure 8 show the variation of calculated horizontal stresses along the springline level at the end of the initial soil stress development step and after 1 mm expansion of the pipe for both 2-D and 3-D models. Both 2-D and 3-D models generate very close soil stresses in the initial gravity step. The horizontal soil stresses are increased significantly around the pipe in the second step and decrease towards the boundary wall. However, the increase in horizontal soil stresses in the 3-D model is less than the stress developed in the 2-D model. This difference could be due to low wall rigidly in the 3-D model. Moreover, it is noted that the soil stress change near the cell wall is only about 7.5% of the soil stress change near the pipe (i.e. stress increase near the pipe is 27 kPa, whereas the increase near the cell wall is 2 kPa, based on the 3-D model).

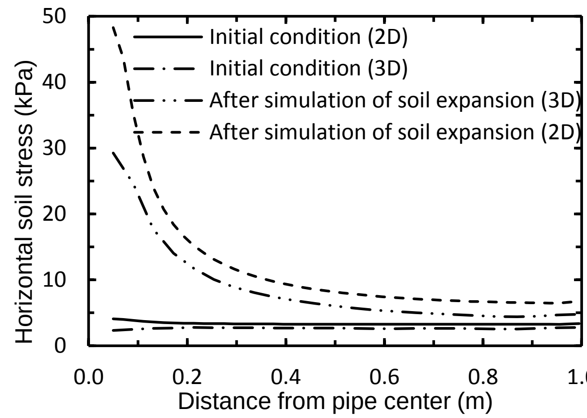

Figure 8. Horizontal soil stresses at springline level from pipe centre to cell wall.

Figure 9 shows the distribution of vertical soil stresses along the springline level for both 2-D and 3-D models at the end of two loading steps. Both models show a similar soil stress distribution in both steps. However, the 2-D model shows a high vertical soil stress immediately next to the pipe when the pipe is expanded, while the 3-D model shows a lower vertical stress. The soil movements in lateral and longitudinal directions may be the cause of lower stress in the 3-D model. The change in vertical soil stress decreases with the distance and the stress reaches very close to the initial condition towards the boundary wall. Based on the 3-D model results, it is noted that the significant soil stress changes occur within 0.7 m distance from the pipe centre when the dilation of the soil is simulated by 1 mm of expansion. In addition, several two-dimensional models with different wall distances are considered to examine the side wall effect on the soil response during the simulation of the soil dilation step. The outcomes demonstrate that a distance of 1 m is good enough to reduce the boundary effects. Therefore, a 2 m width of the test cell is adequate for pipe pullout tests with pipe diameters of up to 100 mm.

6 SUMMARY

In this study, a series of finite-element models is employed to develop an optimum test cell size with wall stiffeners for axial pullout testing of buried pipes while developing reasonably similar soil stresses expected in the field. An initial cell dimension of 2 m (width) x 1.5 m (height) x 4 m (length) is used as a base size of the test cell and subsequently, the effects of wall distances and wall stiffeners are studied by changing the width and the stiffener configurations. The analyses are conducted at the H/D ratio of 6 using a pipe diameter of 100 mm. The simple Mohr–Coulomb model is employed to simulate the soil behaviour. The effect of side wall distance, wall friction and wall rigidity are investigated using both 2-D and 3-D finite-element analyses. The effect of different H/D ratios is not considered in this investigation; rather, a constant H/D ratio is used in all the models. The soil shearing in the pipe-soil interface due to pipe pullout is not directly simulated; instead, it is imitated by expanding the pipe by 1 mm, based upon the values reported in the literature.

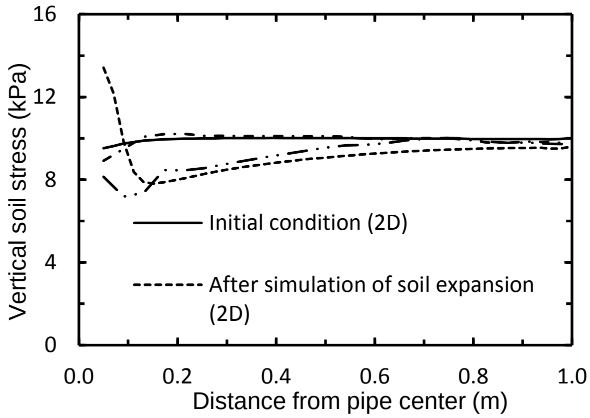

Figure 9. Vertical soil stresses at springline level from pipe centre to the cell wall.

The wall rigidity of the cell wall should be adequately designed to control the lateral deformation; otherwise, the resulting movement of soil in the lateral direction could affect the stress distribution in the soil. Higher wall rigidity could be efficiently achieved by adding more stiffeners to the thinner wall instead of increasing the wall thickness. The side wall distance is another key parameter which should be decided in such a way that the effect due to pipe-soil interface response does not reach the side wall during the pulling operation. This study suggests that the wall distance of 10D (10 times pipe diameter) is sufficient to eliminate the boundary effects; however, it depends on the amount of sand dilation occurring in the pipe-soil interface. The cell-soil interface friction angle shows a moderate effect on the soil response unless it is limited to lower values. A lower interface friction angle could be achieved by covering the cell inner face with lubricated polyethylene sheets.

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