Strain-Based Mechanical Failure Analysis of Buried Steel Pipeline Subjected to Landslide Displacement Using Finite Element Method

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STRAIN-BASED MECHANICAL FAILURE ANALYSIS OF BURIED STEEL PIPELINE SUBJECTED TO LANDSLIDE DISPLACEMENT USING FINITE ELEMENT METHOD

BY

SEAN GOODLUCK MAMUZO EDEKI

A thesis submitted in partial fulfillment of the requirements for the Master of Science Major in Mechanical Engineering South Dakota State University 2020
This thesis is approved as a creditable and independent investigation by a candidate for the master’s degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Advisor Date

Kurt Bassett
Department Head Date

Dean, Graduate School Date
This thesis is dedicated to my parents. My dad, Late Isaac Skido Edeki, and my mom

Lucy Victoria Edeki.
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ABSTRACT

STRAIN-BASED MECHANICAL FAILURE ANALYSIS OF BURIED STEEL PIPELINE SUBJECTED TO LANDSLIDE DISPLACEMENT USING FINITE ELEMENT METHOD

SEAN GOODLUCK MAMUZO EDEKI

2020

Landslide displacement is one of the major threats to the structural integrity of buried oil and natural gas pipelines that are often located far from major markets with terrains prone to permanent ground deformations. These pipelines can experience large longitudinal strains and circumferential deformation resulting from the differential ground movements thereby potentially impacting pipeline safety by adversely affecting structural capacity and leak tight integrity.

In order to proffer theoretical basis for the design, safety evaluation and maintenance of pipelines, the failure analysis and mechanical behavior of buried API X65 steel pipeline perpendicularly crossing landslide area was investigated with the Finite Element Method (FEM), considering soil – pipeline interaction using the strain-based approach in this thesis. The soil – pipe interaction system was rigorously modeled through finite elements using the ANSYS Parametric Design Language (APDL) Mechanical Finite Element (FE) software, which accounts for large strains, displacement, non-linear material behavior and special conditions of contact and friction on the soil – pipe interface.

Various diameter – thickness ratios (D/t-96 and D/t-72) pipeline models was used. This thesis focuses on the influence of various soil and pipeline parameters on the structural response of the pipeline, with particular emphasis on identifying pipeline failure.
(excessive longitudinal strains). The influence of soil strength and stiffness, and internal pressure on the structural response was also examined. Furthermore, a comparison of the conventional stress-based design approach versus strain-based approach was made.

The results show that there are two high strain areas on the buried pipeline sections where the bending deformations are bigger. The maximum strains on the pipeline were mostly tensile at the maximum soil displacement of 0.5 m in the deformation process. The compressive strains resulted in local buckling of the pipeline. Buried pipeline in the landslide bed with hard soil (non-cohesive) is more prone to failure. The biggest deformations appear on the pipeline sections that are on either side of the interface between the sliding soil and the stable surrounding soil at around 20 m and 16 m, respectively. The maximum displacement of the pipeline is smaller than the landslide displacement due to soil-pipe interaction. Bending deformations and tensile strain of the pipeline increase with landslide displacement increase. An increase in the soil’s elastic modulus, cohesion (changing the soil from cohesive to non-cohesive) and diameter-thickness (D/t) ratio of the pipeline resulted in increased bending deformation and tensile strain of the pipeline. Comparing stress-based to strain-based analysis of the pipeline showed that the stress-based approach is more conservative and attained the yield limit over two times earlier in the deformation process when compared to the strain-based approach which maximizes the plastic and ductile properties of steel pipes under landslide displacement. The strain limit of $\varepsilon_{x,\text{max}} \leq 2\%$ is in the strain-based approach in accordance with the strain-based design codes of DNV-OS-F101 (2000), CZA-Z662-07 and ASCE (2005). The results are presented in diagrams, tables, and plot curves form.
CHAPTER ONE: INTRODUCTION

Buried oil and natural gas steel pipelines suffer damages as a result of permanent ground deformations or ground movements. These damages may severely affect civil lifeline structures since it may cause economic losses, fires, environmental pollution and disable lifeline networks. Subsequently, the landslide analysis and behavior of buried steel pipelines have been investigated by many researchers. Most of the studies mainly deal with the numerical modelling of buried pipelines, soil-pipeline interaction, and earthquake induced pipeline stress. The landslide response analysis of buried steel pipelines is somewhat complex because it considers the 3D dynamic analysis of the soil-pipeline interaction under multipoint landslide excitation. Which makes a rigorous analysis impossible. For this reason, it is necessary to adopt elaborate and state-of-the-art means to estimate failure aspects of buried pipeline. Finite Element Methods (FEM) are very helpful for executing such rigorous analysis for the response of buried steel pipelines under landslide actions.

The investigation of geotechnical problems with the use of FEM has been widely used for many years. Linear and nonlinear problems such as deformation between the buried steel pipeline and soil is highly amenable to solution by FEM. For this reason, the ANSYS Mechanical APDL FE software was chosen in order to carry out the mechanical failure analysis. The strain-based approach for the pipeline design analysis was chosen over the traditional stress-based limit criteria analysis methods presented in various codes because the stress-based criteria may be inapposite to modern steels especially for displacement-controlled loads such as ground displacement. Strain and stress limits are compared in this analysis based on various codes and recommendations.
1.1 Overview of Steel Pipeline

Pipeline are the primary means of transportation for oil and natural gas, and have lifespan stretching over several decades. Generally, pipelines are buried underground for safety, economic, aesthetic, and environmental reasons and the construction technique used for installation either involves conventional trenching and backfilling or non-trench methods e.g. micro-tunneling. Inevitably, these pipelines traverse hills, rivers, mountains, plateaus, manmade obstacles, and natural geological topographic areas. Pipelines are usually designed based on operating pressure and flow requirements. For underground pipelines, additional requirements for design such as maximum and minimum cover depth, trench geometry and backfill properties are put into consideration. Along specific routes accessed by pipelines, they may experience long term and large-scale ground movement due to accumulated soil deformation such as subsidence, fault movement, frost heave, landslide movement etc. It has been a safety concern on how permanent ground deformation such as fault movement and landslides can affect buried pipelines facilities, and this has aroused wide attention in recent years. These failure scenarios affect buried pipelines by subjecting it to excessive plastic deformation associated with additional axial, shear and bending loads. And the high stress-strain on the pipeline will then lead to local plastic collapse or local buckling at the critical location hereby causing fluid content in the pipeline to spill out resulting in hazardous pollution.

The importance of oil and natural gas as energy resources has been important for over 100 years. Continuous growth in the demand of energy is estimated to increase total world natural gas consumption from 100 trillion ft\(^3\) in 2004 to 128 trillion ft\(^3\) in 2015 and will rise to 163 trillion ft\(^3\) in 2030. And large oil and natural gas reserves are often located
far from major markets. Hence, products recovered from these reserves must be transported through pipelines over long distances, sometimes hundreds of miles to refineries, ports, and distribution hubs.

Fig. 1.0: Photo of a buried steel natural gas pipeline under construction (credit: www.dailyenergyinsider.com)

Improving the long-distance pipeline transportation economics is a critical factor in determining whether oil and natural gas recovery from remote reserves is cost effective and safe with acceptable return in investment. Good engineering requires that economic designs should be provided at acceptable levels of safety, and this usually means predicting system performance for which little of no previous work or experience exists.

1.2 Why pipelines are buried

Pipelines are buried mostly for these categories of reasons: safety, economic and environmental. And below is a list of reasons under each category.

- Surface use of pipeline corridor or right of way (ROW)
• Protection from intentional or accidental damage
• Protection against expansion and contraction from ambient temperature changes and radiant energy gains and losses
• Minimizes variations of ambient temperature and the resultant effects on the fluid viscosity in the pipeline
• Provision of restraints longitudinally along the length of the pipeline
• Areas where regulations restrict above ground installations

1.3 Ground conditions

Determining the ground (soil) properties is necessary for studying the soil-pipeline interaction when considering the design of the buried pipeline. According to past researches, there is considerable difference in the failure aspects of a buried steel pipeline and the soil-pipeline interaction depending on the soil properties. Thorley & Atkinson (1994) stated that ideally, the ground conditions (soil properties) of the area where a steel pipeline will be buried should be assessed in order to estimate the behavior of both soil and pipeline structure before commencing detailed design.

To represent soil in this research, two groups will be explored: cohesive (silty clay) and non-cohesive (Loess) soils. Non-cohesive soil is also called frictional or drained soil, and cohesive soil is classified as undrained soil. These two groups of soils have different properties and can cause different failure modes in buried steel pipelines. Since these different groups of soil have different outcomes on the analysis and mechanical behavior of buried steel pipeline and soil-pipeline interaction, both will be used in this research for comparison for better analysis.
1.4 Stress-based vs strain-based pipeline design analysis approach

1.4.1 Stress-based design analysis approach

The conventional stress-based approach for pipeline mechanical behavior analysis for design may be insufficient for displacement controlled or partly displacement-controlled load scenarios such as pipeline deformations due to landslides actions. It focuses on load-controlled or stress-controlled events where the objective is to ensure that the pipeline is designed to prevent yielding. In a load-controlled event, the magnitude of the load is analyzed completely independently from the deformation or displacement of the structure. Design analysis rules for pipelines typically concentrate on limiting internal pressure to a specified percentage of specific minimum yield stress (SMYS) of the material. Stress-based design is limited to purely elastic behavior in a material where stress is directly proportional to strain consistent with the principle of Hooke’s law:

\[ \sigma = E\varepsilon \]

The design margin, or factor of safety, is the difference between the allowable stress and SMYS. The shape and properties of the plastic portion of the material response is not a consideration in stress-based design. Fig. 1.1(a) shows the stress-strain diagram with key parameters for the stress-based design analysis approach.
Basic design factors limit the circumferential stress to a maximum of 80% of SMYS, which is typically defined by the yield strength measured at 0.5% total strain for steel pipelines as shown in Fig. 1.0(b).

### 1.4.2 Strain-based design analysis approach

Strain-based analysis focuses on strain limits in conjunction with stress limits as opposed to only stress limits. Put another way, it is considered a limit-based design. The theory of strain is based on geometrical concepts of extensions and rotations. To relate the strain at a particular point to stress, material properties are required. The corresponding stress-strain relationship and coefficients can be used to analyze the deformation and displacement of the structure and predict the initiation of the inelastic, or plastic, response of materials. Strain-based approach covers both strain demand (applied strain) and strain capacity (strain limit). It also allows a more effective use of the pipeline’s axial and longitudinal strain capacity while maintaining the circumferential pressure containment capacity. This is accomplished by ensuring that materials have adequate strain capacity.
while mitigating strain demand whenever possible, to ensure an acceptable design or safety margin.

**Fig. 1.2: Strain-based design analysis approach**

The shape and associated properties of the steel pipeline’s plastic stress-strain response are central to the strain-based design approach. Fig. 1.2 shows the stress-strain diagram with key parameters for the strain-based design analysis approach.

The strain-based design approach was developed as a new technology for supplementing stress-based design for ensuring pipeline operational safety. X. K. Zhu & Brian N. Leis (2010) investigation shows that large axial strain can result in a pipeline failure at a critical tensile strain where the operating pressure might be less than its allowed value using conventional stress-based design. Consequently, the conventional stress-based design approach cannot be applied in cases where applied strain greatly exceeds the yield strain according to research by S. Igi and T. Sakimoto, (2010). The goal of this approach is to maintain pipeline service and integrity under large longitudinal plastic strains generally defined as greater than 0.5% [Y. Y. Wang et al (2011)] or longitudinal stress over the yield strength.
From a safety viewpoint, pipeline longitudinal strain can be allowed to exceed the specified yield strain under displacement load provided the pipeline can adequately meet the operating requirements without rupture. In such situations, it is possible to supplement the stress-based design method with the strain-based design approach method to satisfy stress, strain, and economic concerns [B. Liu et al (2008)]. According to W. Cimbali et al (2002), the fundamental criteria equation for strain-based design approach is the comparison of the applied strain, or strain demand ($\varepsilon_d$) to the permissible strain, or strain capacity ($\varepsilon_c$) based on the following relationship:

$$\varepsilon_d \leq \varepsilon_c$$

The capacity of deformation of pipelines subjected to strain-based mechanical behavior analysis is steered by some factors: loading (internal pressure), pipeline dimensions (diameter to thickness ratio), pipeline geometry (ovality) and pipeline material strength. Therefore, for the purpose of this research, strain-based design analysis approach was used to analyze the behavior of the buried pipeline.

### 1.5 Aim and Contribution

This thesis will present the use of the new strain-based approach with emphasis on the plastic strain capacity of steel pipelines, to evaluate the mechanical behavior of buried steel pipelines perpendicularly traversing areas prone to permanent ground deformations like landslides. This research results are intended to produce design and analysis methods that will help in making informed decisions for constructing, modifying/upgrade and maintenance of already existing pipelines for an anticipated 50-
year service life in landslide prone areas where they must be designed to accommodate large plastic strain to meet the increasing safety demands by assuring integrity and cost effectiveness.

### 1.6 Objectives

This thesis will focus on the analysis of the mechanical behavior of API X65 steel pipeline perpendicularly traversing an active landslide area by:

- Investigate the plastic deformation of X65 steel pipeline using the strain-based approach by performing a finite element (FE) analysis using the finite element software, ANSYS (Research Mechanical APDL) when subjected to lateral landslide displacement considering the effect of various scenarios:
  - Varying pipeline parameters: Diameter – wall thickness ratio (D/t), internal pressure
  - Varying soil parameters: Elastic modulus and cohesion values
  - Soil – pipeline interaction, and sliding /non-sliding soil interaction
- Investigate and compare the strain-based and conventional stress-based pipeline design analysis approach
CHAPTER TWO: LITERATURE REVIEW

2.1 Steel pipeline history

Not until early 1960s, steel pipelines used for pipeline construction have relatively low yield strengths. Types X52 and X56 steel pipeline with respective yield strengths of 358 MPa and 386 MPa were used almost exclusively. Then, around 1970, types X65 and X70 steel pipelines with respective yield strengths of 448 MPa and 483 MPa started to gain recognition but was not widely used because of the limitation in welding technology back then. Steel pipeline manufacturers started using thermomechanical treatment of steel to further improve the mechanical properties during the 1970s. Manufacturers, in the 1980s, started producing types X60 and X70 steel pipelines with respective yield strengths of 448 MPa and 483 MPa as the dominant steel type for use in the pipeline industry.

Due to the demand for higher operating pressures in excess of 10 MPa, and to achieve desired higher throughputs around the year 2000, steel manufacturers started producing type X80 steel pipelines with yield strength of 552 MPa. The X80 steel pipeline is produced using thermomechanical processing techniques and was set to become the next dominant steel pipeline for new pipeline construction. Several prominent pipelines have been constructed using the X80 steel pipelines, this includes over 1,000 miles of the Cheyenne Plains natural gas pipeline constructed in 2005. The development for suitable processing techniques for the manufacture of types X100 and X120 steel pipelines with respective yield strengths of 689 MPa and 827 MPa are also in progress. These high strength steel pipelines have been recommended for the of the anticipated arctic pipelines as a result of improved overall transport efficiency and construction cost.
savings. Currently, manufacturing techniques for types X100 and X120 steel pipelines produces pipelines with insufficient toughness and poor welding ability. So, until manufacturing technology advancements have been made that will produce type X100 and X120 steel pipelines more reliable for construction in the pipeline industry, type X65 to type X80 will continue to be used universally for new pipeline construction.

2.2 Overview of landslides (soil movements)

A landslide is a downslope movement of soil or rock, or both, which occur on the surface of rupture – either curved (rotational slide) or planar (translational slide) rupture. The material often moves as a coherent or semi coherent mass with minimal internal deformation. It is pertinent to note that in some landslide cases, landslides may involve other types of movements either at the inception of failure or later, that is if the properties change as the displaced material moves downslope.

Landslides can be classified into different types based on the type of movement and the type of material involved. The material in a landslide mass is either rock or soil (or both), as stated earlier. The latter which is described as earth if mainly composed of sand-sized or finer particles, and debris if composed of coarser fragments. Also, the type of movement describes the internal mechanics of how the landslide mass is displaced: topple, fall, spread, slide or flow. For the purpose of this research thesis, the material of the landslide is ‘soil’ and the type of soil movement is ‘slide’.

There are two (2) main types of soil slides: rotational and translational.
2.2.1 Rotational Landslides

A landslide on which the surface of rupture is curved upward (spoon-shaped) and the slide movement is rotational about an axis that is parallel to the contour of the slope. The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump. Schematic and pictorial examples of a rotational landslide are shown in Fig. 2.1 below.

![Fig. 2.1: (a) Schematic depiction of a rotational landslide (b) Photograph of a rotational landslide which occurred in New Zealand. The green curve at center left is the scarp (the area where the ground has failed). The hummocky ground at bottom right (in shadow) is the toe of the landslide (red line). This is called a rotational landslide as the earth has moved from left to right on a curved sliding surface. The direction and axis of rotation are also depicted. (Reference: The Landslide Handbook – A Guide to Understanding Landslides. By Lyn M. Highland and Peter Bobrowsky)]
2.2.2 Translational Landslides

The mass in a translational landslide moves out, or down and outward, along a relatively planar surface with little rotational movement or backward tilting. This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil. Schematic and pictorial examples of a translational landslide are shown in Fig. 2.2 below.

![Fig. 2.2: (a) Schematic of a translational landslide (b) A translational landslide that occurred in 2001 in the Beatton River Valley, British Columbia, Canada. (Reference: The Landslide Handbook – A Guide to Understanding Landslides. By Lyn M. Highland and Peter Bobrowsky)](image)

Pipeline would be exposed to either longitudinal or transverse soil movements depending on the pipeline orientation with respect to the direction of soil movement. For longitudinal landslide, the soil movement is parallel to the pipeline axis, while for
transverse landslide, the soil movement is perpendicular to the axis of the pipeline. For the purpose of this research thesis, the translational landslide scenario was used. Also, the pipeline axis is perpendicular to the landslide direction.

2.3 Studies on pipelines subjected to soil movements

In the past, the design of pipelines located in landslide prone areas was done based on the distress exerted on it by drag forces caused when the soil slides on the pipeline, using structural models shown in Fig. 2.3 (Georgiadis, 1991). Which means that the assessment of the load exerted on the pipeline by the landslide was most important. The impact force as landslide flows around a pipeline can be categorized into two, broadly based on a solid mechanics approach where the loading is a function primarily the shear strength of the soil and velocity of flow [Towhata and Al-Hussaini (1988); Schapery & Dunlap (1978); Georgiadis (1991); Marti (1976)] or a fluid mechanics approach focusing directly on the on the yield stress and viscosity of the flowing debris and drag coefficients resulting from it (Bruschi, et al (2006); Pazwash and Robertson, (1973)]. Review of recent work and results of more sophisticated experiments and numerical analysis are done by likes of Zakeri et al (2008, 2009) and Zakeri (2009). However, due to the increased computational capabilities, a more integrated approach is followed in the design of pipelines subjected to landslide induced forces, which accounts simultaneously for the soil-pipeline interaction response.
Fig. 2.3: A representative simplified structural model used in the past in designing buried pipelines subjected to landslide actions by estimating the drag forces induced by the landslide (Georgiadis et al. 1991)

Currently, the finite element method (FEM) and the analytical methods are the two kinds of approaches widely used in analyzing the behavior of pipeline subjected to landslides.

2.4 Studies using Finite Element Methods (FEM)

Gantes et al (2008) proposed a method to evaluate the effect of downslope ground movement on buried pipelines based on the finite element method: The modelling of the pipeline was done with shell or beam elements and appropriate discrete springs in orthogonal directions was used to model the soil. On the other hand, Cocchetti et al (2009a, 2009b) recognized the coupling in the different loading components and introduced using macro elements to reproduce the soil-pipeline interaction. And this accounts for all interaction in the vertical, horizontal, and axial soil reactions. Zhu and Randolph (2010) established a numerical approach primarily based on the finite element method but using remeshing. They use this to simulate large flow deformation of debris from a landslide and quantifying the displacements and load the pipeline is subjected to while embedded in the seabed. In their analysis, a simple 2D elastic perfectly plastic soil model with plane strain conditions was employed. Liu et al (2010) performed the failure
analysis of a natural gas buried X65 steel pipeline under deflection load by establishing a 3D finite element model of the soil and pipeline. For the analysis, the pipeline is assumed to be loaded in a parabolic deflection displacement along the axial direction. Zheng et al (2012) using 3d finite element modelling, investigated the response of a buried X65 pipeline due to non-uniform deflection of landslide process. The surrounding soil and the pipeline were modelled using solid elements with the behavior of the former assumed to be linear elastic (Fig. 2.4). A quartic polynomial displacement was applied to the soil of a landslide field where the pipeline was laid at the toe of the landslide. They investigated the effect of internal pressure, surrounding soil, landslide width and pipeline geometry, the found that the pipeline diameter to thickness ratio (D/t) and the width of the landslide had greater effect on the limited deflection displacement of the pipeline as compared with the effect of internal pressure under normal operation.
Jafarzadeh et al (2012) analyzed numerically using 3D finite elements, the behavior of 24” diameter buried pipeline in a cemented slope agitated by dynamic loading of earthquake in North Tehran. Yuan et al (2014) developed two alternative methods for the analysis of the behavior of pipelines under landslides loading: first was a refined analytical method that adopts a better assumption of tension at the sliding area, while the second was using a vector form intrinsic FE method that can address asymmetric conditions and model the dynamic process. Han et al (2012) investigated the behavior of buried pipelines that are subjected to landslide by representing the soil-pipeline interaction with two contact elements; horizontal, vertical and elastoplastic springs according to ASCE guidelines were used for the region outside the landslide, while the pipeline inside the landslide, the soil-pipeline interaction was modelled using soil-pipeline interaction elements which has only one degree of freedom of displacements on nodes. Chen et al (2014) using 1-D finite element modelling, investigated the stress
analysis of an X80 steel buried gas pipeline subjected to longitudinal and traverse landslide movements. Their results concluded that pipelines longitudinally traversing a landslide area has more stress concentration on the pipeline and therefore detrimental to it as compared to when it is laterally traversing. Wu et al (2014) made comparison using 3D numerical analysis the response of buried pipeline crossing the leading and the trailing edge of a landslide. In their investigation, an X70 steel pipeline was modelled with FLAC software with parameters: diameter is 1.016 m and internal pressure of 5 MPa. Li et al (2016) established a 3D model for predicting landslide hazards to gas transmission pipelines using strength reduction method for the landslide triggering. Fred et al (2016) established a 3D soil-pipeline interaction model using a discrete element method (DEM). They validated the model by comparing with medium scale physical soil-pipeline interaction.

![Fig. 2.5: Deformed mesh of the numerical model used for the simulation of a gas pipeline response subjected to Baishiping landslide, China (Wu et al. 2014)](image-url)
2.5 Studies using Analytical Solutions

Zhang et al (2015) proposed an elastoplastic semi-analytical method to deal with the plastic mechanical behavior of buried pipelines subjected to landslide based on the plane stress condition with consideration to temperature variation and internal pressure. They verified their proposed model by comparing the results they obtained with finite element analysis. Yuan et al (2012a, 2012b): by assuming that the axial force of the pipelines as a constant, they proposed an analytical model to estimate the failure of surface of buried steel pipelines (Fig. 2.5).

Fig. 2.6: Sketch that describes (a) response surface pipeline in deep-water under landslide impact (b) the pipeline divided into four segments according to various loading conditions (Yuan et al. 2012)
Randolph et al (2010): in order to evaluate the response to deformation of a pipeline when encountering landslide, they established a simple analytical model, initially for landslides acting perpendicular to the pipeline. They later extended to landslides impacting the pipeline at an angle. O’Rourke et al (1995) and Liu & O’Rourke (1997) came up with a simplified analytical approach for the estimation of peak axial strains developed in a pipeline that is subjected to permanent ground displacement longitudinally and transversely. Parker et al (2008) assumed a parabolic shape for the deformed pipeline, developed a closed form solution by modelling the pipeline as an elastic cable, the soil as a rigid plastic resistance and the landslide area as a distributed load.

2.6 Experimental studies

Experimental investigations to investigate how buried pipelines respond to landslide induced actions have also been carried out. Kefang et al (2011) investigated experimentally, how a 219 mm diameter buried pipeline was affected by a laterally traversing landslide by means of a full-scale landslide model. The landslide was induced excavating the front edge and posterior edge water injection. The results obtained showed that the key factors to affect pipeline landslide stability were the free-face conditions of side slope front edges and underground water. Feng et al (2015) conducted a large-scale field test at Chengdu University of Technology (Fig 2.6) to investigate the response of a gas pipeline crossing a landslide. The pipeline, 32 m long, has its ends at least 10 m outside the landslide area (boundary). It has a diameter of 325 mm and wall thickness of 8 mm. The pipeline has internal pressure of 2.5 MPa and was buried at a depth of 1.5 m
in a trench that is perpendicular to the landslide area. The test was carried out in six stages:

1. Preliminary observation and measuring
2. Observation and measuring of the first excavation of the retaining wall (1\textsuperscript{st} excavation)
3. Complete removal of the retaining wall (2\textsuperscript{nd} excavation)
4. Infiltration of water in the back scarp to promote sliding
5. Excavation of the collapse material (3\textsuperscript{rd} excavation), which hindered the development of the landslide
6. Complete removal of the collapsed free face material (4\textsuperscript{th} excavation)

It was observed that the stresses in the pipeline changed with respect to the landslide displacement which can be described with an exponential function. Both sides of the landslide border and the central part of the landslide were the areas on the pipeline where the most critical stresses were concentrated.
Fig. 2.7: Large-scale field test of buried pipeline subjected to landslide induced actions (a) plan view of the landslide and pipeline model (b) Geological cross section of the landslide model (c) photo of the landslide and pipeline model after the experiment (Feng et al. 2012)

2.7 Design codes provisions for general and strain-based design analysis approach for buried pipelines

Several codes provisions that apply to strain-based design analysis of pipelines can be placed in three general categories:

- Codes that provide a comprehensive overall pipeline standard that includes requirements both for stress and strain-based designs e.g. “DNV-OS-F101, Submarine pipeline Systems (2000)”, and “CSA Z662-07, Oil and Gas pipeline Systems, Canadian Standards Associations (2007)”

- Codes that specifically allow strain-based design but do not provide extensive provisions related to strain-based design e.g. “ASME B31.8, Gas Transmission and Distribution Piping Systems, American Society of Mechanical Engineers (1995)”, and “API 1104, Welding of pipelines and Related Facilities, American Petroleum Institute”.

• American society of Civil Engineers (2005)

A general idea of the types of provisions that allow strain-based design approach can be gained from the provision designated section A842.23 in ASME B31.8, Gas Transmission and Distribution Piping Systems, American Society of Mechanical Engineers (1995) as follows:

“In situations where the pipeline experiences a predictable noncyclic displacement of its support (e.g., fault movement along the pipeline route or differential subsidence along the line) or pipeline sag before support contact, the longitudinal and combined stress limits need not be used as a criterion for safety against excessive yielding, so long as the consequences of yielding are not detrimental to the integrity of the pipeline. The permissible maximum longitudinal strain depends upon the ductility of the material, any previously experienced plastic strain, and the buckling behavior of the pipeline. Where plastic strains are anticipated, the pipeline eccentricity, pipeline out-of-roundness, and the ability of the weld to undergo such strains without detrimental effect should be considered. Similarly, the same criteria may be applied to the pipeline during construction (e.g., pull-tube or bending shoe risers).”
Regulatory codes for further study of the history and growth of strain-based design analysis approach in codes and standards would include the British Standard BS 8010 Part 3, the Dutch standard NEN 3650 Requirements for steel pipeline transportation systems (1992) that allows strain-based design both for construction and operation with a distinction given between alternating plasticity and ratcheting, and the previous editions to DNV 2000. These editions are DNV Rules for Submarine pipeline Systems (Dec. 1996) and DNV Rules for Submarine pipeline Systems (1981 with corrections from 1982). The 1996 edition had extensive discussion of strain-based design approach that was updated for the 2000 edition.

As earlier highlighted, the strain-based design criteria are based on limit state design and displacement control load. If the safe operation can be ensured under displacement load, the pipeline strain is allowed to be more than the specified yield strain. Table 2.1 shows the limits for tensile strain criteria on strain-based as compared by various governing codes.

Table 2.1: Pipeline tensile limit criteria for various design codes

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Tensile Limit/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSA-Z662-07 App.C</td>
<td>2.5&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>DNV-OS-F101 (2000)</td>
<td>Accumulated Plastic Strain ≥2.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>ASCE (2005)</td>
<td>2.0&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Applies to installation and/or infrequent loads of subsea pipelines.
<sup>b</sup> Installation and materials for different circumstances need to meet additional requirements.
<sup>c</sup> Longitudinal strain from ground movement due to earthquake, landslide, or mine subsidence.

A key factor in determining the tensile strain limit is the yield strength to tensile strength (Y/T) ratio. For the base material, whose accumulated plastic strain may be more than 2%, DNV-OS-F101 (2000) recommends that Y/T is a lower level: 0.85. For the base
materials, whose minimum yield stress are 415 MPa or more, it recommends that the $Y/T$ in transverse is 0.92. For base materials less than 415 MPa, DNV-OS-F101 (2000) recommends 0.90. The tensile strain limit may decrease with the increase of $Y/T$, just as shown in Fig. 2.7 below.

![Comparison of tensile strain limit](image)

**Fig. 2.8: Comparison of tensile strain limit**

For compression strain limit, it may be estimated by using the following empirical formula in CZA Z662 code:

$$
\varepsilon_{c}^{\text{crit}} = 0.5 \frac{t}{D} - 0.0025 + 3000 \left( \frac{(P_i - P_e)D}{2tE_s} \right)^2
$$

Where:

- $\varepsilon_{c}^{\text{crit}}$ = ultimate compressive strain capacity of the pipeline wall
- $t$ = pipeline wall thickness
- $D$ = outer diameter of the pipeline
- $P_i$ = maximum internal design pressure
- $P_e$ = minimum external hydrostatic pressure
- $E_s$ = elastic modulus of steel pipeline
CHAPTER THREE: METHODOLOGIES & RELEVANT THEORIES

This chapter covers some of the basic theoretical concepts that are encountered in the course of the subsequent chapters.

3.1 Strain-based analysis method theories

3.1.1 True stress and strain equations

When pipelines experience large strains and displacements, particularly in the plastic region, the material behavior is no longer linearly elastic and therefore stresses cannot be accurately anticipated. This problem is compounded when material properties vary in anisotropic materials. A limit-load analysis incorporating elastic-plastic stress analysis and equivalent strains is required providing a more accurate assessment of the protection against plastic collapse.

Usually, engineering stress is calculated based on the undeformed cross-sectional area. For small-scale yielding, this is generally accurate enough within the scatter of the material properties. However, for extensive yielding, the assumption of the cross-sectional area remaining relatively constant ceases to be accurate. As the strain becomes large and the cross-sectional area decreases, the true stress can be much larger than the engineering stress because of the reduction of cross-sectional area. True stress is calculated using the applied load to the instantaneous cross-sectional area. True stress is related to the engineering stress assuming constant specimen volume as shown below.

\[ A \cdot l = A_i \cdot l_i \]

Where \( A_i \) and \( l_i \) are the initial area and initial length, respectively.

Now, showing that the true stress, \( \sigma_t \) is related to the engineering stress, \( \sigma_E \) and engineering strain, \( \varepsilon_E \), we have:
\[
\bar{\sigma} = \frac{P}{A} = \frac{P}{A_i} \cdot \frac{l}{l_i} = \sigma_E(1 + \varepsilon_E)
\]

True strain, \(\varepsilon_T\) is the sum of all the instantaneous engineering strains.

\[
\bar{\varepsilon} = \sum \frac{\Delta l}{l}
\]

True strain, \(\varepsilon_T\) can be related to the engineering strain, \(\varepsilon_E\) by:

\[
\bar{\varepsilon} = \int_{l_i}^{l_f} \frac{dl}{l} = \ln \frac{l_f}{l_i}
\]

Where \(l_f = l_i + \Delta l\) is the final length.

And,

\[
\varepsilon_E = \frac{\Delta l}{l_i}
\]

Therefore, true strain, \(\varepsilon_T\) will be:

\[
\bar{\varepsilon} = \ln \frac{l_f}{l_i} = \ln \frac{l_i + \Delta l}{l_i} = \ln \left(1 + \frac{\Delta l}{l_i}\right) = \ln(1 + \varepsilon_E)
\]

### 3.1.2 True stress-strain curves

Strain capacity is gotten from the stress-strain curve of the steel pipeline, which is typically obtained from the uniaxial tensile test. Therefore, the mathematical equations used to represent the stress-strain curves need to be designed to capture the actual shape of the curves in real materials. Since changes in microstructure can alter the S-N curve and TMCP (thermo-mechanical control process) material properties vary with direction, one mathematical equation representing a group of materials or all axes might be unable to uniquely determine the full stress-strain curve using material parameters such as yield strength, ultimate strength, and uniform elongation.
The Ramberg-Osgood equation was established to define the nonlinear relationship to characterize the elastic and plastic portions of the stress-strain curve as early as 1943 [W. Ramberg and W. R. Osgood (1943)]. Before yielding, the relationship takes the form of Hooke’s law. Beyond yielding, the strain is the sum of both the elastic and plastic strain as shown below:

\[
\bar{\varepsilon} = \bar{\varepsilon}_e + \bar{\varepsilon}_p
\]

Where

\[
\bar{\varepsilon}_e = \frac{\sigma}{E}
\]

And

\[
\bar{\varepsilon}_p = K \left(\frac{\sigma}{E}\right)^n
\]

The Ramberg-Osgood equation for the simple form of strain is:

\[
\bar{\varepsilon} = \frac{\sigma}{E} + K \left(\frac{\sigma}{E}\right)^n
\]

### 3.1.3 Ramberg-Osgood vs. CSA Stress-Strain Curve Equations

Two widely used stress-strain curve equations, i.e., the Ramberg-Osgood and the CSA Z662 equations are examined in this section. Both equations create smooth stress-strain curves (i.e., the round-house shape). The Ramberg-Osgood equation shows the relationship between the true stress (\(\bar{\sigma}\)) and true strain (\(\bar{\varepsilon}\)) as shown below:

\[
\bar{\varepsilon} = \frac{\bar{\sigma}}{E} + 0.002 \left(\frac{\bar{\sigma}}{\sigma_0}\right)^m
\]

where \(E\), \(\sigma_0\) and \(m\) are the young’s modulus, reference stress, strain hardening exponent respectively of the equation. The reference stress, \(\sigma_0\) is the true stress by definition, and it is corresponding to a plastic strain of 0.2%, and therefore is usually very close to the
yield strength (YS) at 0.5% strain. The engineering stress-strain curve calculated from the Ramberg-Osgood equation usually consists of a natural peak, i.e., ultimate tensile strength (UTS) and uniform elongation (UEL). By calibrating $\sigma_0$ and $n$, the Ramberg-Osgood equation can generate a stress-strain curve for given yield strength and ultimate tensile strength. The uniform elongation, however, is an outcome of the equation and cannot be independently varied.

In contrast to the Ramberg-Osgood equation, the equation given in CSA Z662 (2011) defines the relationship between the engineering stress ($\sigma$) and engineering strain ($\varepsilon$) in the equation below:

$$\varepsilon = \frac{\sigma}{E} + \left(0.005 - \frac{\sigma_y}{E}\right)\left(\frac{\sigma}{\sigma_y}\right)^n$$

Where $\sigma_y$ is the yield strength at 0.5% strain and $n$ is the strain hardening exponent of the CSA equation. It is pertinent to note that for any given set of yield strength, ultimate tensile strength, and uniform elongation, a unique strain hardening exponent, $n$ can be determined by the equation below:

$$n = \ln \left(\frac{UEL - UTS}{0.005 - \frac{YS}{E}}\right) \div \ln \left(\frac{1}{Y/T}\right)$$

As shown above, CSA equation can uniquely determine a full stress-strain curve which satisfies the YS, UTS (or Y/T ratio), and UEL exactly.

### 3.1.4 Von Mises Failure Criterion

The von Mises Criterion (1931) gives another reasonable estimation of failure. It is also known as the maximum distortion energy criterion, octahedral shear stress theory,
or Maxwell-Huber-Hencky-Von Mises theory. This theory is often used to estimate the yield of ductile materials. Distribution of von Mises stress over the tensile and/or compressive regimes can also be used as criteria to understand the failure mechanisms. It states that failure occurs when the energy of distortion reaches the same energy for yielding/failure ($\sigma_y$) in uniaxial tension. It is expressed mathematically as:

$$\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \leq \sigma_y^2$$

The above equation can be represented as a principal ellipse as shown in Fig. 3.1 below.

![Fig. 3.1: Shows a diagrammatic representation of the difference between Von Mises and maximum shear criterion (Credit: Pilkey, W. D., 1994)](image)

The maximum shear criterion represented in the illustration above by the dashed line, is a more conservative theory than the Von Mises criterion because it lies within the Von Mises ellipse. In addition to bounding the principal stress to prevent ductile failure, the Von Mises criterion also gives a reasonable estimation of fatigue failure, especially in cases of repeated tensile and tensile – shear loading.
3.2 Theories Relevant to Modelling using ANSYS FE Software

The following section gives brief descriptions of some of the common aspects that are involved as part of the modelling using the ANSYS software.

3.2.1 Rate-Independent Plasticity

Plasticity is used to model materials subjected to loading beyond their elastic limit. In other words, rate-dependent plasticity is characterized by the irreversible straining that occurs in a material once a certain level of stress is reached. The plastic strains are assumed to develop instantaneously, that is, independent of time. Metals and other materials such as soils tend to have an initial elastic region in which the deformation is directly proportional to the load, but beyond the elastic limit, a non-recoverable plastic strain develops. Fig. 3.2 below shows a typical plastic behavior of material in uniaxial compression. The strain can be decomposed into a recoverable elastic strain, $\varepsilon_e$ and an inelastic strain or plastic strain, $\varepsilon_p$. The stress at the initial yield point is $\sigma_0$. For strain hardening materials, the yield stress increases with increasing plastic deformation to a value of $\sigma_y$.

![Fig. 3.2: Shows a stress-strain curve of a typical plastic behavior of steel in uniaxial compression (credit: https://en.wikipedia.org/wiki/Flow_plasticity_theory#Flow_rule_2. Accessed March 3, 2020)](image)
Removing the load recovers the elastic portion of the total strain, and if the load is completely removed, a permanent deformation due to the plastic strain remains in the material. Evolution of the plastic strain depends on the load history such as temperature, stress, and strain rate, as well as internal variables such as yield strength, back stress, and damage.

3.2.2 Plasticity Theory

Plasticity theory provides a mathematical relationship that characterizes the elastoplastic response of materials. The constitutive models for this behavior start with a decomposition of the total strain into elastic and plastic parts and separate constitutive models are used for each. There are three ingredients in the rate-independent plasticity theory namely: yield criterion, flow rule and hardening rule. But for the purpose of this research, we would only be discussing only two of the theories (yield criterion and flow rule) used for the model of the soil.

3.3 Soil Modeling Methodologies as Related to Plasticity

(a) Yield criterion: This defines the material state at the transition from elastic to elastic-plastic behavior. In other words, it determines the stress level at which yielding is initiated. For multi-component stresses, this is represented as a function of the individual components, \( f(\{\sigma\}) \), which can be interpreted as an equivalent stress, \( \sigma_e \) (also known as Von Mises effective stress):

\[
\sigma_e = f(\{\sigma\})
\]

Where:

\[ \{\sigma\} = \text{stress vector} \]

When the equivalent stress is equal to a material yield strength, \( \sigma_y \),
\[ f(\sigma) = \sigma_y \]

And the material will develop plastic strains. If equivalent stress, \( \sigma_e \) is less than yield stress, \( \sigma_y \), the material is elastic, and the stresses will develop according to the elastic stress-strain relations. It is pertinent to note that the equivalent stress, \( \sigma_e \), can never exceed the material yield strength since in that case, plastic strains would develop instantaneously thereby reducing the stress for the material to yield.

(b) Flow rule: The flow rule is the determinant of the direction of plastic straining and is represented by the equation below:

\[
\{d\varepsilon^{pl}\} = \lambda \left( \frac{\partial Q}{\partial \sigma} \right)
\]

Where:

\( \lambda \) = Plastic multiplier (determines the amount of plastic straining)

\( Q \) = Plastic potential (determines the direction of plastic straining)

If \( Q \) is the yield function (as is normally assumed), the is termed associated flow rule, and the plastic strains occur in a direction normal to the yield surface as shown in Fig. 3.3 below:

![Fig. 3.3: Plastic strain flow rule (ANSYS Mechanical APDL, 2013 R2 Theory Reference)](image-url)
If the plastic potential is not proportional to the yield surface, the model has a non-associated flow rule, which is typically used to model soils and granular materials that plastically deform due to internal frictional sliding. For non-associated flow rules, the plastic strain increment is not in the same direction as the stress increment.

### 3.3.1 The Drucker-Prager Plasticity Model

The difference between the typical metal plasticity model and the Drucker-Prager plasticity model is its dependence on hydrostatic pressure. For metal plasticity (assuming Mises or similar yield surface), only the deviatoric stress is assumed to cause yielding, that is if we plot the yield surface in principal stress space, this results in a cylinder whose axis is the hydrostatic pressure line, indicating that yielding is independent of the hydrostatic stress state. On the other hand, the Drucker – Prager plasticity model has a term that is dependent on the hydrostatic pressure. For a linear yield surface, i.e. the linear shape when plotted in the plane of effective stress versus hydrostatic pressure, this means that if there is some hydrostatic tension, the yield strength would be smaller. In compression, an increase in hydrostatic pressure produces an increase in the yield strength. Also, because volumetric strain is associated with hydrostatic pressure, volumetric expansion of the material due to yielding is accounted for. When the yield surface is plotted in principal stress space, it would look like a cone as shown in Fig 3.4 below. No hardening would be assumed, some material behavior us elastic-perfectly plastic.
The equivalent stress, $\sigma_e$, can be represented by the equation below:

$$\sigma_e = 3\beta \sigma_m + \left[\frac{1}{2} \{s\}^T [M] \{s\}\right]^\frac{1}{2}$$

Where:

$\sigma_m = \text{hydrostatic pressure}$

$\{s\} = \text{deviatoric stress}$

$\beta = \text{material constant}$

The material constant, $\beta$, is defined as:

$$\beta = \frac{2\sin\phi}{\sqrt{3(3 - \sin\phi)}}$$

Where:

$\phi = \text{angle of friction}$

The material yield parameter (yield stress), $\sigma_y$, is defined as:

$$\sigma_y = \frac{6\cos\phi}{\sqrt{3(3 - \sin\phi)}}$$
Where:

\[ c = \text{cohesion value} \]

The Drucker-Prager yield criterion can then be represented in the equation below:

\[
F = 3\beta \sigma_m + \left[ \frac{1}{2} \{s\}^T [M] \{s\} \right]^{\frac{1}{2}} - \sigma_y = 0
\]

The two main characteristics that result is:

(a) The yield strength changes depending on the hydrostatic stress state

(b) Some inelastic volumetric strain can occur, as defined by the flow potential

And as a result of that, the Drucker-Prager plasticity model is used for geomechanics where the importance of hydrostatic independence and inelastic volume strain are paramount.

The ANSYS Mechanical APDL FE software support the use of three Drucker-Prager plasticity models namely:

- Classic Drucker-Prager (CDP)
- Extended Drucker-Prager (EDP)
- Extended Drucker-Prager Cap (EDP Cap)

For the purpose of the research, only the extended Drucker-Prager (EDP) was used and would be discussed.

3.3.2 The Extended Drucker-Prager (EDP) Plasticity Model

This is an extension of the classic Drucker-Prager yield criterion, and commonly used for geomaterials with internal cohesion and friction. But here, the yield surface and the flow potential can be taken as linear, hyperbolic, and power law independently, and thus results in either an associated or non-associated flow rule. Also, the yield functions can also be combined with an isotropic or kinematic hardening rule to evolve the yield
stress during plastic deformation. And that addresses some of the shortcomings of the classic Drucker-Prager (CDP) plasticity model. The EDP plasticity model is defined via three yield criteria forms and corresponding plastic flow potentials.

The EDP yield criteria include the three following forms:

(a) Linear form

(b) Power law form

(c) Hyperbolic form

The EDP plastic flow potentials correspond in form to each of the yield criteria forms. Which are the Linear, power law and the hyperbolic form. However, the user-defined parameters for the flow potentials are independent of those for the yield criteria, and any potential can be combined with any yield criterion.

For the purpose of the research, only the EDP linear yield criteria form with the corresponding linear plastic flow potential form were used and would be discussed.

3.3.3 The Extended Drucker-Prager (EDP) Linear Form

A brief explanation of the Linear form of the yield criteria and plastic flow potentials with the ANSYS FE software input commands are explained below.

3.3.4 EDP Linear Yield Criterion Form

EDP linear yield criterion form is given by:

\[ f(\sigma, \sigma_y) = \sigma_e + \alpha \frac{1}{3} tr(\sigma) - \sigma_y = 0 \]

OR

\[ F = q + \alpha \sigma_m - \sigma_y (\dot{\varepsilon}_{pl}) = 0 \]

Where:

\( \alpha = \) pressure sensitivity
\( \sigma_y = \) uniaxial yield stress

The parameters, \( \alpha \) and \( \sigma_y \) above are user-defined.

Initializing the EDP linear yield criterion ANSYS FE software is done by inputting “TB,EDP,,,LYFUN” function and entering the user-defined constants parameters C1 and C2 by inputting “TBDATA,,,,”. Table 3.1 shows the constants.

**Table 3.1: User-defined constants parameters for EDP linear yield criterion**

<table>
<thead>
<tr>
<th>Constant</th>
<th>Meaning</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>( \alpha )</td>
<td>Pressure sensitivity</td>
</tr>
<tr>
<td>C2</td>
<td>( \sigma_y )</td>
<td>Uniaxial yield stress</td>
</tr>
</tbody>
</table>

The constants parameters C1 (\( \alpha \)) and C2 (\( \sigma_y \)) for the EDP linear yield criterion are given below.

Constant C1, pressure sensitivity (\( \alpha \)) is given by the equation below:

\[
\alpha = \frac{6 \sin \theta}{(3 - \sin \theta)}
\]

Where:

\( \theta = \) Angle of friction

Constant C2, uniaxial yield stress (\( \sigma_y \)) is the yield strength of soil used.

**3.3.5 EDP Linear Plastic flow potential form**

EDP Power Law Plastic flow potential form is given by:

\[
Q(\sigma,\sigma_y) = \sigma_e + \bar{\alpha} \frac{1}{3} tr(\sigma)
\]

Where:

\( \bar{\alpha} = \) flow potential pressure sensitivity
OR

\[ Q = q + \alpha \sigma_m - \sigma_y (\dot{\varepsilon}_{pl}) \]

Where \( \dot{\varepsilon}_{pl} \) is the plastic strain and is defined as:

\[ \dot{\varepsilon}_{pl} = \lambda \frac{\partial Q}{\partial \sigma} \]

Where:

\( \lambda \) = plastic multiplier

Initializing the EDP linear plastic flow potential in ANSYS FE software is done by inputting “TB,EDP,,,LFPOT” function and entering the user-defined constant parameter C1 by inputting “TBDATA,,”. Table 3.2 shows the constant.

**Table 3.2: User-defined constant parameter for EDP linear plastic flow potential**

<table>
<thead>
<tr>
<th>Constant</th>
<th>Meaning</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>( \bar{\alpha} )</td>
<td>Pressure sensitivity</td>
</tr>
</tbody>
</table>

The constants parameters C1 (\( \bar{\alpha} \)) for the EDP plastic flow potential is given below.

Constant C1, pressure sensitivity (\( \alpha \)) is given by the equation below:

\[ \bar{\alpha} = \frac{6 \sin \varphi}{(3 - \sin \varphi)} \]

Where:

\( \varphi \) = Dilatancy angle

When the flow potential is the same as the yield function, the plastic flow rule is associated, and that results in a symmetric stiffness matrix. When the flow potential is different from the yield function, the plastic flow rule is non-associated, and this results
in an asymmetric material stiffness matrix. By default, the asymmetric stiffness matrix will be symmetrized.

Calculations for the EDP constants parameters are shown in APPENDIX C.

### 3.3.6 Bilinear Isotropic Hardening

This is usually described by a bilinear effective stress versus effective strain curve. The elastic modulus, $E$ of the material is the initial slope of the curve. Beyond the user-specified initial yield stress, $\sigma_y$ plastic strain develops, and stress-versus-total-strain continues along a line with slope defined by user-specified tangent modulus, $E_T$. It should be noted that the tangent modulus cannot be less than zero or greater than the elastic modulus of the material. The material in this case is the steel pipe.

Initializing the Bilinear isotropic Hardening command in ANSYS FE software is done through the $MP$ commands. The material table is defined by the “TB,BISO” command, and the user-defined constants with “TBDATA” command. The user-defined constants parameters $C1$ and $C2$ are shown in Table 3.3 below.

**Table 3.3: User-defined constant parameters for Bilinear isotropic Hardening**

<table>
<thead>
<tr>
<th>Constant</th>
<th>Meaning</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C1$</td>
<td>$\sigma_y$</td>
<td>Yield stress</td>
</tr>
<tr>
<td>$C2$</td>
<td>$E_T$</td>
<td>Tangent modulus</td>
</tr>
</tbody>
</table>

The constants parameters $C1$ ($\sigma_y$) and $C2$ ($E_T$) for Bilinear isotropic Hardening are given below.

Constant $C1$ is the uniaxial yield stress ($\sigma_y$) of the steel pipeline.

Constant $C2$ is the tangent modulus ($E_T$) given by the equation below:

$$ E_T = \frac{\sigma_u - \sigma_y}{\varepsilon_u - \varepsilon_y} $$
Where:

\[ \sigma_u = \text{Ultimate tensile stress} \]
\[ \sigma_y = \text{Uniaxial yield stress} \]
\[ \varepsilon_u = \text{Ultimate strain} \]
\[ \varepsilon_y = \text{Yield strain} \]

3.4 **Soil-Pipeline Interaction and Contact Friction Theory & Methodology**

When there is soil movement around a perpendicularly buried pipeline, the soil will exert load on the pipeline as a result of the displacement. The pipeline usually will slow the landslide down. And that is happens as a result of the contact and friction between the pipeline and the soil. In the fundamental Coulomb friction model, two surfaces in contact can carry shear stress. When the equivalent shear stress is less than a limit frictional stress \( \tau_{lim} \), there will be no motion between the two surfaces. This is called sticking. The Coulomb friction model definition is show by the relation below:

\[ \tau_{lim} = \mu P + b \]

Where:

\[ P = \text{contact normal pressure} \]
\[ \mu = \text{friction coefficient} \]
\[ b = \text{contact cohesion} \]

Once the equivalent frictional stress exceeds the limit frictional stress \( \tau_{lim} \), the contact and target surfaces (defined by CONTA174 and TARGE170 elements in this research and discussed in detail the next chapter) will slide relative to each other. This is known as sliding. The sticking/sliding calculations determine when a point transitions from sticking
to sliding or vice versa. The contact cohesion provides sliding resistance even with zero normal pressure.

Contact friction is a material property used with the chosen contact element of CONTA174. It may be specified either through the coefficient of friction (µ) for isotropic or orthotropic friction models or as a user specified friction property.

(a) **Isotropic friction**: This model uses a single coefficient of friction (µ), based on the assumption of the uniform stick-slip behavior in all directions. It is applicable to both 2-D and 3-D contacts surfaces, and all contact elements. The single coefficient of friction, \( MU \), using either \( TB \) command input or the \( MP \) command.

(b) **Orthotropic friction**: This model specifies two different coefficients of friction to model different stick-slip behavior in different directions. This is applicable only to 3-D contact surfaces. The two coefficients of friction are defined in two orthogonal sliding directions also known as the principal directions.

### 3.5 Geometric Features of the Model Set-up

The pipeline is placed perpendicularly to the sliding direction of the landslide and parallel to the slope crest. Therefore, the mobilization of the soil mass will occur perpendicularly to the pipeline axis. The soil and pipeline model were set up assuming the landslide is semi-infinite in space and the pipeline is infinite in the axial direction, and on the basis of a typical landslide. The total length of the of the whole model in the \( z \) – direction is 140 m, the total width of the landslide in the \( x \) – direction is 30 m, height of the model in the \( y \) – direction is 22.3 m, width of the landslide soil is 40 m, and the buried depth of the pipeline is 2 m. The model is defined in a 3-D space by its cartesian coordinates \( x, y \) and \( z \) and the bottom face of the model is in the \( xz \) plane and the side
faces of the model (right and left sides) are normal to the $xz$ plane. The pipeline runs across the entire length of the model in the $z$ – direction. A graphical representation of the model is shown in Fig. 3.5 below.

Fig. 3.5: Illustration of the soil and pipeline model setup

3.5.1 Pipeline Model Dimensions

In all cases considered in this thesis the outer diameter of the pipeline, $D_o$ is 914.4 mm (0.9144 m or 36 inches), whereas different pipeline wall thickness, $t$ of 12.7 mm (0.0127 m or 0.5 inches) and 9.53 mm (0.00953 or 0.375 inches) was used, so that different pipeline diameter to wall thickness ratio, $D_o/t$ (also known as Standard Dimension Ratio) values is covered. And this value can be obtained by the equation below:

$$SDR = \frac{D_o}{t}$$

Where:

$D_o = \text{pipeline outer diameter}$

$t = \text{pipeline wall thickness}$
This $D_o/t$ values used in this research are typical for onshore oil, natural gas, and water pipelines applications.

![Pipeline model with dimensions](image)

**Fig. 3.6: Pipeline model with dimensions**

Please refer to APPENDIX C for calculations for the $D_o/t$ values of the pipelines.

### 3.5.2 Pipeline Maximum Operating Pressure ($p_{\text{max}}$)

This is the maximum pressure by design, that the pipeline can be subjected to. It can be deduced from the expression below:

$$p_{\text{max}} = 0.72 \times 2\sigma_y \frac{t}{D_o}$$

Where:

- $0.72 =$ safety (reduction) factor constant (*ASME guideline, 2007*)
- $\sigma_y =$ pipeline yield strength
- $t =$ pipeline wall thickness
- $D_o =$ pipeline outer diameter

In this research, the two pipelines analyzed has different $p_{\text{max}}$ values. Please refer to APPENDIX C for calculations.
In order to improve the computational accuracy and ease of numerical analysis of the soil-pipeline model, half of the whole model was established for the symmetry of structure and loads. Fig. 3.7 below shows the dimensions of half of the whole model that was numerically analyzed.

*Fig. 3.7: Illustration of half of whole model (pipeline and soil) with dimensions for symmetrical analysis*
CHAPTER FOUR: FINITE ELEMENT METHOD (FEM) ANALYSIS

In finite element method, the actual continuum or body of solid is represented by a collection of subdivisions called finite elements. These elements are interconnected at specified joints called nodes or nodal points. The nodes are usually placed on the boundaries where adjacent elements are considered to be connected. It is necessary to assume that the variation of field variable inside a finite element can be approximated by a simple function because the actual variation of the field variable, such as displacement, stress, strain, pressure or velocity, inside a continuum is unknown. These approximated functions, which are also called interpolation models, are characterized as the values of the field variables at the nodes. When field equations, such as equilibrium equations, for the whole continuum are created, the new unknowns become the nodal values of the field variables. However, the nodal values of the field variable can become known values by solving the field equations, which are generally composed of matrix equations. Once these are known, the field variable throughout the assemblage of elements is clarified by the approximated functions. This synchronized step-by-step process is always followed for the solution of a general continuum problem by the finite element.

4.1 Numerical Simulation Modeling

In this research, the 3-D nonlinear finite element analysis was carried out using the ANSYS Mechanical Parametric Design Language (APDL) Academic Research, release 19.0 finite element analysis software. Every command used to build and numerically analyze the model was written with a script language and read into the ANSYS software. The script language was adjusted in terms of defined parameters for each model created. The aspects of the model such as geometry, material properties,
mesh size, contact and displacement conditions are defined as parameters were created at the beginning of the input script language file. The nonlinear material behavior of the steel pipeline and surrounding soil, the soil-steel pipeline interaction, as well as the distortion of the pipeline cross section and the deformation of the surrounding soil are modeled in a rigorous manner, so that the pipeline performance criteria are evaluated with a high-level accuracy.

In order to perform this analysis for the buried X65 steel pipeline for this research, the following assumptions were made:

(a) Property of soil is elastic-plastic characterized by Mohr Coulomb theory

(b) Steel pipeline is elastic perfectly plastic and isotropic

(c) Soil-pipeline interface contact property is finite sliding, and perfect without defects

(d) The welding between steel pipeline segments or joints are neglected

(e) Pipeline line is infinite in the axial (longitudinal) direction

(f) Overall temperature of the pipeline and soil is negligible

It is important to note that there are limitations in the above assumptions; it is difficult to show actual pipeline performance by disregarding welded joints between pipeline segments, application of fully bonded contact area between pipeline and soil, and adaptation of simplified material properties of both soil and pipeline. This is because these assumptions do not reflect actual pipeline performance. However, these assumptions make the analysis less complex because typical pipeline performance can be analyzed by disregarding ignorable small effects on pipeline performance.
In modeling the soil-pipeline interaction, some aspects, mentioned below, were considered.

- The mechanical behavior of the steel pipeline
- The interaction between the soil and the buried pipeline
- The behavior of the soil surrounding the pipeline
- The orientation and geometry of the pipeline
- The appropriate elements for modeling the steel pipeline, the soil, and the soil-pipeline interaction.

4.2 Pipeline Modeling

The steel pipeline in this research cuts perpendicularly across the whole soil and the landslide area. The 3-D pipeline was modeled using command reference CVL4. CYL4 is a command reference that defines a circular area or cylindrical volume anywhere on the working plane. It considers the inner and outer radii of the circle of the cylinder, and this was used to represent the different thickness of pipelines in this thesis. From the working plane, makes a perpendicular distance representing the depth of the cylinder (length of pipeline). The mechanical properties of the steel pipeline used for the numerical analysis are shown in Table 4.1 below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Outer Diameter, Do (m)</th>
<th>Thickness (m)</th>
<th>Diameter-Thickness ratio</th>
<th>Elastic Modulus, E (Pa)</th>
<th>Yield Strength (Pa)</th>
<th>Tensile Strength (Pa)</th>
<th>Poisson’s Ratio</th>
<th>Density (Kg/m^3)</th>
<th>Pipe Buried Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>API X65 Steel Pipe</td>
<td>0.9144</td>
<td>0.00953</td>
<td>96</td>
<td>2.10E+11</td>
<td>4.48E+08</td>
<td>5.35E+08</td>
<td>0.3</td>
<td>7800</td>
<td>2</td>
</tr>
<tr>
<td>API X65 Steel Pipe</td>
<td>0.9144</td>
<td>0.0127</td>
<td>72</td>
<td>2.10E+11</td>
<td>4.50E+08</td>
<td>5.31E+08</td>
<td>0.3</td>
<td>7800</td>
<td>2</td>
</tr>
</tbody>
</table>
4.3 Soil Modeling

Two types of soils were used in modeling the soil in this research to investigate how the pipeline behaves in each type and how it affects its mechanical behavior. The soil types are cohesive (silty clay) and non-cohesive (Loess). The sliding soil and the stable surrounding soil are assumed to be the same type of soil at each given time. It was modeled with a SOLID186 element. SOLID186 is a higher order 3-D 20-node tetrahedral solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. Its element supports plasticity, hyper-elasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper-elastic materials, and well suited to modeling irregular meshes. It can be in a tetrahedral-shaped element and a pyramid-shaped element as shown in Fig. 4.1 below. The tetrahedral option with mid-side nodes was used in this research.

![Fig. 4.1: SOLID186 element structural tetrahedral and pyramid solid geometry](image)
The mechanical behavior of the soil material is described, as earlier discussed, through the Mohr-Coulomb constitutive model. The whole soil model (landslide and surrounding soil) was created by creation of the dimensional geometry with respect to the cartesian coordinates and the VDRAG command was used to extend the specified length in the z-direction to create the volume. The mechanical properties of the soils are shown in Table 4.2 below.

Table 4.2: Physical and mechanical parameters of soils

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Elastic Modulus, E (Pa)</th>
<th>Cohesion, c (Kpa)</th>
<th>Friction Angle, $\phi$ (*)</th>
<th>Poisson’s Ratio</th>
<th>Dilation Angle, $\phi$ (*)</th>
<th>Density (kg/m$^3$)</th>
<th>Friction Coefficient, $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesive (Silty Clay)</td>
<td>2.00E+7</td>
<td>15</td>
<td>15</td>
<td>0.3</td>
<td>0</td>
<td>1700</td>
<td>0.3</td>
</tr>
<tr>
<td>Non-cohesive (Loess)</td>
<td>3.30E+7</td>
<td>25.6</td>
<td>11.7</td>
<td>0.44</td>
<td>0</td>
<td>1400</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4.4 Soil-pipeline Contact Modeling

The interface between the outer surface of the pipeline and the surrounding soil and the sliding landslide soil with the stable surrounding soil were simulated by a contact algorithm. This allows separation of the pipeline and the soil, and accounts for interface friction through a friction coefficient, $\mu$. The soil-pipeline contact mechanism and the contact elements used in ANSY FE software for this research to model the soil-pipeline interaction are briefly discussed below. The discretization method of surface to surface used in contact pair can get more accurate contact stress and reduce the penetration behavior between surfaces.
4.4.1 CONTA174 Element Description

It is a 3-D 8-Node Surface-to-Surface Contact. CONTA174 is used to represent contact and sliding between 3-D “target” surfaces and a deformable surface, defined by the element. The element is applicable to 3-D structural and coupled field contact analysis. Contact occurs when the element surface penetrates one of the target segment elements on a specified target surface. This element also allows separation of bonded contact to simulate interface delamination.

![Fig. 4.2: Soil-pipe contact element, CONTA174 Geometry](image)

It supports isotropic and orthotropic Coulomb friction. For this analysis, an isotropic Coulomb friction is assumed by assigning a single coefficient of friction. The 3-D contact surface elements, CONTAC174, are associated with the 3-D target segment elements, TARGE170 via a shared real constant set. ANSYS looks for contact only between surfaces with the same real constant set. For either rigid-flexible or flexible-flexible contact, one of the deformable surfaces must be represented by a contact surface. In this research it is used for the soil-pipeline interaction.

4.4.2 TARGE170 Element Description

This element is used to represent various 3-D “target” surfaces for the associated contact elements. The contact elements themselves overlay the solid elements describing...
the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. This target surface is discretized by a set of target segments elements and is paired with its associated contact surface via a shared real constant set.

![Image](image.png)

**Fig. 4.3: Soil contact element, TARGE170 Geometry**

The target surface can either be deformable or rigid. As shown in Fig. 4.3 above, for modelling rigid-flexible contact, the rigid surface must be represented by a target surface. For flexible-flexible contact, one of the deformable surfaces must be overlain by a target surface. Each target surface can be associated with only one contact surface, and vice-versa. However, several contact elements could make up the contact surface and thus come in contact with the same target surface.

### 4.5 Model Volume Meshing for FE Analysis

For FE analysis, it is very important to determine the type, shape, and number of elements in order to obtain a more accurate results based on the available computational capacity of the system being used. The system used for the analysis has the following computational information:

- System Operating System(OS): Windows 10 Pro/64-bit OS, x64 based processor
• Processing unit: Intel Core i7 vPro Central Processing Unit (CPU). With two processors of 2.80GHz each
• Memory: 12.0 GB RAM
Discretization was carried out by using a free mesh on the entire model. A free mesh has no element shape restrictions and also no specified pattern applied to it. But the meshing used in this research is the 3-D tetrahedral elements interconnected by nodes, with different element sizes for the surrounding soil, landslide soil and the pipeline. Element size ranges from 1 to 10, 1 being the finest and 10 being more course. The element size of 8 was used for the surrounding stable soil. The element sizes of 2 and 1 were used for the landslide soil and the pipeline, respectively. The main reason for finer element sizes for the landslide soil and especially the pipeline is to ensure sufficient computational accuracy in the area of interest while also limiting computational time. The meshing process was carried out with the following command references in the ANSYS FE software.

• ESIZE – to specify the default number of line divisions
• SMRTSIZE – specify the overall element size level for meshing
• VMESH – generates nodes and volumes elements within volumes, i.e. specifies which volume to be meshed

Fig. 4.4 below shows the meshed model used for this research.
4.6 Boundary Conditions (BC)

In the 3-D FE model, boundary constraints were imposed bottom surface (area) of the whole model and on both ends circular joints or circumferential surfaces of the pipeline to simulate the effects of infinite extension of the pipeline on the studied pipeline section. The base of the model was constrained from vertical and horizontal displacements i.e. $x$ and $y$ directions. The fixed constraints were imposed on areas outside the landslide soil area so as to limit its movement and simulate the constraints and
supporting effects on the rest of the surround soil area. Both cases of boundary conditions are shown in Fig. 4.5 below.

![Fig. 4.5: Illustrations of boundary constraint for the FE model (a) sketch of the whole model showing BC for bottom surface of surrounding soil and ends of pipeline (b) BC of model of half of whole soil used for the simulation](image)

It should be noted that this boundary conditions were applied to all the models for the numerical analysis for this thesis

### 4.7 Landslide constraint and displacement

A controlled oblique displacement of 0.5 m was gradually imposed at the top area of the sliding soil in order to simulate the effects of soil movement on the pipeline as
shown in Fig. 4.6. i.e. the landslide direction was gotten from the resultant force from the values of the vertical and horizontal vectors, $u_x$ and $u_y$ which are 0.2498 and 0.43315 respectively and $u_z = 0$. It is noteworthy that since the volume of the landslide soil is larger than that of the pipeline, the integral movement of the landslide is not influenced by the pipeline when it is pushing and squeezing against the pipeline. and it is assumed that the speed of the landslide is consistent and the displacement load of soil mass sliding downwards is even distributed around the pipeline. Also, the vertical friction of the soil mass against the pipeline is neglected. The same displacement was applied to all the models for the numerical analysis for this thesis.
Fig. 4.6: Illustrations of landslide displacement constraint (a) a 2-D meshed model showing the landslide displacement and direction in the xy – plane (b) 3-D meshed model showing the landslide displacement

4.8 Simulation in ANSYS FE Software

Twelve models with varying parameters were created and analyzed for comparison during the course of this research. The parameters of each model are shown in Tables 5.1, 5.2, 5.3 and 5.4.

The Finite Element Analysis of the models were carried out in three major steps namely:

- Creating the 3-D model in the ANSYS FE software by applying the dimensions, creating the volumes, and determining material properties
- Meshing the model and application of boundary constraints and displacement
- Simulating the applied displacement, reading, and interpreting the results
The sub steps within the major steps mentioned above will be discussed later. ANSYS FE software solver is divided into three parts: the pre-solver, the mathematical engine, and the post-solver. The pre-solver formulates the mathematical model reading data from the pre-processor, the math engine calculates the solution, and the post-processing stage reads and interprets the results.

The sub-steps with the major three steps used in developing the script language to the ANSYS FE software are listed below.

**The Pre-processor Mode (/prep7)**

- Defining the element type for the soil (SOLID186)
- Defining the material properties of the soil: Young’s Modulus, density, and Poisson’s ratio
- Defining the plasticity preference and inputting parameters for the soil (Extended Drucker Prager Model)
- Defining the material properties of the steel pipeline: Young’s Modulus, density, Poisson’s ratio, and Bilinear Isotropic Hardening
- Defining the contact elements for soil-pipeline interaction
- Defining the friction coefficient of the contact elements
- Creation of the surrounding soil geometry
- Defining the pipeline element
- Creation of the pipeline geometry
- Creation of the landslide soil geometry
- Determining the contacts sliding surfaces between soil-soil and soil-pipeline
- Selecting respective volumes for meshing, defining element size and meshing volume

**Solution Mode (/solution)**

- Applying boundary conditions
- Applying pressure to the respective areas of the pipeline
- Determining time steps and total time
- Applying displacement at the respective elements, lines, areas and/or volumes of the soil
- Solving the problem in solver

**Post-processor command (/post)**

- Reviewing, interpreting, and analyzing results
- Values for Von Mises stress, displacement vector, displacement of the nodes

All script language written to ANSYS Mechanical APDL for all models with varying parameters following the steps above are contained in Appendix A of this thesis.
CHAPTER FIVE: RESULTS OF FE NUMERICAL ANALYSIS

For each scenarios and models to be numerically evaluated, the nodal results for the pipeline displacement, Von Mises plastic strain and Von Mises stress were gotten for each scenario i.e. varying the diameter to thickness ratio of the pipeline, the soil type and its parameters, and depicted in various models by applying different internal pressure in the pipeline. The local coordinate system data was used to analyze the pipeline behavior precisely and rigorously in the landslide area. The size of the outer diameter of the pipeline, landslide displacement, the dimensions of the landslide and the surrounding soil remains the same for all scenarios and individual models.

5.1 ANSYS FE Simulation Results

Under the landslide displacement, change process of stress and strain leading to deformation of the pipeline is shown in the subsequent sections for different parameters of the soil and pipeline, as well as applied internal pressure for different scenarios. The blue band indicates the minimum value, and the red band indicates the maximum value for a particular plot. The value of results (deflection, Von Mises plastic strain and the Von Mises stress) varies from minimum to maximum through a variety of intermediate color codes (light blue, green, yellow, and amber).

5.1.1 Nodal Results

Results from the ANSYS FE software solver output for Scenario 1 are shown below.

Table 5.1: Scenario 1 Soil and pipe parameters

<table>
<thead>
<tr>
<th>Pipe Diameter - Thickness Ratio (D/t)</th>
<th>Soil Type</th>
<th>Pipe Maximum Design Pressure, p_{max} (Pa)</th>
<th>Model 1 Applied Pressure, p</th>
<th>Model 2 Applied Pressure, p</th>
<th>Model 3 Applied Pressure, p</th>
<th>Landslide Displacement, d (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>Cohesive Soil (Silty clay)</td>
<td>7.00E+06</td>
<td>p = 0</td>
<td>p = 56% p_{max}</td>
<td>p = p_{max}</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Pipeline displacement for Scenario 1

**Fig. 5.1:** (a) Scenario 1 displaced pipe representation (b) Model 1: Pipeline displacement when internal pressure, $p = 0$, (c) Model 2: when $p = 56\%p_{\text{max}}$ (d) Model 3: when $p = p_{\text{max}}$
**Von Mises Plastic Strain for Scenario 1**

**Fig. 5.2:** Scenario 1 Von Mises Plastic Strain (a) Model 1: when internal pressure, $p = 0$, (b) Model 2: when $p = 56\%p_{\text{max}}$ and (c) Model 3: when $p = p_{\text{max}}$
Fig. 5.3: Scenario 1 Von Mises Stress (a) Model 1: when internal pressure, $p = 0$, (b) Model 2: when $p = 56\% p_{\text{max}}$ and (c) Model 3: when $p = p_{\text{max}}$
Please refer to Appendix B for nodal plot results for Scenario 2, 3 and 4 depicting models 4 through 12 showing pipeline displacement, Von Mises plastic strain and Von Mises stress for respective internal pressure, $p$ values of $p = 0$, $p = 56\% p_{\text{max}}$ and $p = p_{\text{max}}$ in Fig. B5.4 through to Fig. B5.12. The corresponding soil and pipe parameters for Scenario 2, 3 and 4 are shown in Table 5.2 through Table 5.4 below.

**Table 5.2: Scenario 2 soil and pipe parameters**

<table>
<thead>
<tr>
<th>Pipe Diameter-Thickness Ratio \noalign{\smallskip} (D/t)</th>
<th>Soil Type \noalign{\smallskip}</th>
<th>Pipe Maximum Design Pressure, $p_{\text{max}}$ (Pa)</th>
<th>Model 4 \noalign{\smallskip}</th>
<th>Model 5 \noalign{\smallskip}</th>
<th>Model 6 \noalign{\smallskip}</th>
<th>Landslide Displacement, $d$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>Non-cohesive Soil (Loess)</td>
<td>7.00E+06</td>
<td>$p = 0$</td>
<td>$p = 56% p_{\text{max}}$</td>
<td>$p = p_{\text{max}}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 5.3: Scenario 3 soil and pipe parameters**

<table>
<thead>
<tr>
<th>Pipe Diameter-Thickness Ratio \noalign{\smallskip} (D/t)</th>
<th>Soil Type \noalign{\smallskip}</th>
<th>Pipe Maximum Design Pressure, $p_{\text{max}}$ (Pa)</th>
<th>Model 7 \noalign{\smallskip}</th>
<th>Model 8 \noalign{\smallskip}</th>
<th>Model 9 \noalign{\smallskip}</th>
<th>Landslide Displacement, $d$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>Cohesive Soil (Silty clay)</td>
<td>9.00E+06</td>
<td>$p = 0$</td>
<td>$p = 56% p_{\text{max}}$</td>
<td>$p = p_{\text{max}}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 5.4: Scenario 4 soil and pipe parameters**

<table>
<thead>
<tr>
<th>Pipe Diameter-Thickness Ratio \noalign{\smallskip} (D/t)</th>
<th>Soil Type \noalign{\smallskip}</th>
<th>Pipe Maximum Design Pressure, $p_{\text{max}}$ (Pa)</th>
<th>Model 10 \noalign{\smallskip}</th>
<th>Model 11 \noalign{\smallskip}</th>
<th>Model 12 \noalign{\smallskip}</th>
<th>Landslide Displacement, $d$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>Non-cohesive Soil (Loess)</td>
<td>9.00E+06</td>
<td>$p = 0$</td>
<td>$p = 56% p_{\text{max}}$</td>
<td>$p = p_{\text{max}}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### 5.2 Result and Discussions

The mechanics of the pipeline response to the landslide represented schematically in Fig. 5.13 below. The length of region A pointed as $l_B$ is a characteristic of the soil-pipeline interaction. It is divided into two, namely $l_{b,2}$ which lies within the stable surrounding soil, and $l_{b,1}$ which lies within the moving landslide soil. $d_{s,2}$ and $d_{s,1}$
represents displacement of the landslide and the reaction force by the stable surrounding soil, respectively.

Fig. 5.13: Illustration of the displacement mechanisms along the pipeline axis

With the increasing landslide displacement, bending deformation (tensile and compressive strains) was observed on the pipeline on both sides of the interface between the landslide and the stable surrounding soil as shown in Fig. 5.13.

The results obtained from the plots are in the local coordinate system (LCS). The results compared the two pipelines with diameter to thickness ratios in different scenarios [different soil type: Cohesive (Silty clay) and non-cohesive (Loess) and varying internal pressure]. The values of the maximum displacement, Von Mises plastic strain and the Von Mises stress were compared and analyzed.

5.2.1 Buckling of non-pressurized pipeline

Buckling of the buried non-pressurized pipeline was observed in all scenarios as a result of the landslide displacement. Under small displacement of the landslide, there are two plastic area on either side of the landslide soil and stable surrounding soil interface (20 m of pipe distance). Buckling appears on the interface between the sliding soil and
the stable surrounding soil with the increasing landslide displacement firstly. The buckling mode of non-pressurized pipeline is collapse. The shape of the pipeline deformation becomes from S-shape to Z-shape after the collapse occur. The local collapse is more catastrophic with the landslide displacement.

5.2.2 Buckling of pressurized pipeline

With the increasing of the landslide displacement with pressure, \( p = 56\% \rho_{\text{max}} \) and \( p = \rho_{\text{max}} \) for all scenarios of the pipeline, buckling deformation appears. At first, plastic strains appear with no buckling deformation, but subsequently as the landslide displacement increases, buckling starts showing on either side of the interface between the landsliding soil and the stable surrounding soil as shown in the figures below. Buckling appears at the interface (20 m pipe distance) lastly. More buckling deformation was observed in scenario 2 and scenario 4, i.e. when the pipeline is buried in non-cohesive (Loess) soil. The bending moment increases with the increase of the landslide displacement. For the pipeline buckling as shown in Fig. 5.15 (b), the strain of the lower part is tension, while it is mainly compression strain in the upper part. The wrinkling amplitude increases with the increase in landslide displacement. Internal pressure in the pipeline increases resistance to local buckling because the tensile hoop stress helps the pipe resist the diametrical changes that occur locally at the buckle.

5.2.3 Pipeline Axial Plastic Strain

Fig. 5.14 and Fig. 5.15 shows the axial plastic strain distribution of the bending outside of the pipeline in scenario 1 to scenario 4. From the curves, the most dangerous place is in the landslide bed (20 m distance of the pipeline), the interface between the sliding soil and the stable surrounding soil. It is shown that the most strain in the pipeline
occur in this area. The maximum Von Mises plastic strain in the pipeline when buried in the non-cohesive (Loess) soil in scenario 2 and 4 is about 1.7 times than it is when buried in cohesive (Silty clay) soil. This shows that the buried pipeline is prone to failure in the landslide bed with hard soil.

**Fig. 5.14:** Axial Von Mises Plastic strain distribution along pipeline length (a) Scenario 1 (b) Scenario 2

It was observed that overall, the maximum plastic strains in the pipeline was observed when pressure, $p = 0$ and $p = p_{\text{max}}$. The high strain in the pipeline when $p = 0$ is
due to the fact that there is no counteracting hoop stress as a result of the absence of internal pressure on the internal wall of the pipeline, leading to ease of collapsing of the pipe. When $p = p_{\text{max}}$, the plastic strain was high due to excessive internal pressure, thereby encouraging deformation with the landslide displacement.

![Scenario 3 (D/t-72, Cohesive Soil) Von Mises Plastic Strain Curve](image1)

![Scenario 4 (D/t-72, Non-cohesive Soil) Von Mises Plastic Strain Curve](image2)

**Fig. 5.15:** Axial Von Mises Plastic strain distribution along pipeline length (a) Scenario 3 (b) Scenario 4

Fig. 5.16 shows the Von Mises plastic strain distribution in the pipeline under different pipe displacement. Fig. 5.16 (a) represents scenario 1 (D/t-96 pipeline buried in cohesive soil) when pressure, $p = 0$ (model 1), the deformation in the pipeline as a result
of landslide displacement reaches the plastic strain limit of 2% (0.02) when the pipe axial displacement is 0.1 m. When the pressure, \( p = 56\% p_{\text{max}} \) (model 2), plastic strain limit of the pipe was attained at 0.39 m pipe displacement, and when \( p = p_{\text{max}} \) (model 3), the plastic strain limit was attained at 0.395 m pipe displacement. In scenario 2 (D/t-96 pipeline buried in non-cohesive soil) as shown in Fig. 5.16 (b), when pressure, \( p = 0 \) (Model 4), the plastic strain limit of 2% (0.02) was reached when the pipe axial displacement is 0.065 m. When the pressure, \( p = 56\% p_{\text{max}} \) (model 5), plastic strain limit of the pipe was attained at 0.12 m pipe displacement, and when \( p = p_{\text{max}} \) (Model 6), the plastic strain limit was attained at 0.14 m pipe displacement.

Fig. 5.16: Pipeline Axial Von Mises Plastic strain distribution vs displacement curve (a) Scenario 1 (b) Scenario 2

Fig. 5.17 (a) represents scenario 3 (D/t-72 pipeline buried in cohesive soil) when pressure, \( p = 0 \) (model 7), the deformation in the pipeline as a result of landslide displacement reaches the plastic strain limit of 2% (0.02) when the pipe axial displacement is 0.13 m. When the pressure, \( p = 56\% p_{\text{max}} \) (model 8), the plastic strain in the pipe didn’t get to the limit criteria. It is 0.016. And when \( p = p_{\text{max}} \) (model 9), the plastic strain limit was attained at 0.37 m pipe displacement. In scenario 4 (D/t-72
pipeline buried in non-cohesive soil) as shown in Fig. 5.18 (b), when pressure, \( p = 0 \) (Model 10), the plastic strain limit of 2% (0.02) was reached when the pipe axial displacement is 0.09 m. When the pressure, \( p = 56\% p_{\text{max}} \) (model 11), plastic strain limit of the pipe was attained at 0.165 m pipe displacement, and when \( p = p_{\text{max}} \) (Model 12), the plastic strain limit was attained at 0.17 m pipe displacement.

![Fig. 5.17: Pipeline Axial Von Mises Plastic strain distribution vs displacement curve (a) Scenario 3 (b) Scenario 4](image)

In all scenarios, the accumulated plastic strain in the pipeline at the maximum landslide displacement of 0.5 m, exceeded the limit criteria of 2% (0.02), except in scenario 3 when the pressure is 56%\( p_{\text{max}} \) which is around 2% as shown in Fig. 5.17 (a). This means that at 0.5 m axial pipeline displacement, both Engineering Critical Assessment (ECA) and other additional requirements of materials are needed [DNV-OS-F101 (2007)].

### 5.2.4 Pipeline Von Mises Axial Stress

The stress distribution in the pipeline for all scenarios and individual models are similar as shown in Fig. 5.18 and 5.19. In all the scenarios, there are two plastic
deformations. The distance between the plastic deformation locations in the sliding soil and the middle part of the pipeline is smaller when the pipeline is buried in non-cohesive (loess) soil as shown in Fig. 5.19 (a) and (b). This invariably means that when buried in the non-cohesive soil, the dangerous section of the pipeline is closer to the middle part. In all scenarios, when the pressure, $p = 0$, there is only one plastic deformation of the pipeline, and it is in the sliding soil.

Stress increases with the increase in landslide displacement. The two plastic deformation parts appear on the middle part and the section in the landslide bed zone. The highest spike of stress in the pipeline occurred when there is no pressure in the pipeline for all scenarios. Also, the stress in the pipe exceeded the yield limit at the landslide displacement of 0.5 m in all scenarios.
**Fig. 5.18:** Axial Von Mises stress distribution along pipeline length (a) Scenario 1 (b) Scenario 2
Fig. 5.19: Axial Von Mises stress distribution along pipeline length (a) Scenario 3 (b) Scenario 4

Fig. 5.20 shows the Von Mises stress distribution in the pipeline under different pipe displacement. Fig. 5.20 (a) represents scenario 1 (D/t-96 pipeline buried in cohesive soil) when pressure, \( p = 0 \) (model 1), the deformation in the pipeline as a result of landslide displacement reaches the yield strength of 448 MPa when the pipe axial displacement is 0.065 m. When the pressure, \( p = 56\% p_{\text{max}} \) (model 2), the yield strength of the pipe was attained at 0.06 m pipe displacement, and when \( p = p_{\text{max}} \) (model 3), the yield strength was attained at 0.14 m pipe displacement. In scenario 2 (D/t-96 pipeline buried in non-cohesive soil) as shown in Fig. 5.20 (b), when pressure, \( p = 0 \) (Model 4), the yield strength of the pipe was reached when the pipe axial displacement is 0.41 m. When the pressure, \( p = 56\% p_{\text{max}} \) (model 5), yield strength of the pipe was attained at 0.035 m pipe displacement, and when \( p = p_{\text{max}} \) (Model 6), the yield strength was attained at 0.095 m pipe displacement.
Fig. 5.20: Pipeline Axial Von Mises Stress distribution vs displacement curve (a) Scenario 1 (b) Scenario 2

Fig. 5.21 (a) represents scenario 3 (D/t-72 pipeline buried in cohesive soil) when pressure, $p = 0$ (model 7), the deformation in the pipeline as a result of landslide displacement reaches the yield strength of 450 MPa when the pipe axial displacement is 0.32 m. When the pressure, $p = 56\% p_{\text{max}}$ (model 8), the yield strength of 450 MPa was attained when the pipe axial displacement is 0.06 m. And when $p = p_{\text{max}}$ (model 9), the yield strength was attained at 0.3 m pipe displacement. In scenario 4 (D/t-72 pipeline buried in non-cohesive soil) as shown in Fig. 5.21 (b), when pressure, $p = 0$ (Model 10), the pipe yield strength of 450 MPa was reached when the pipe axial displacement is 0.055 m. When the pressure, $p = 56\% p_{\text{max}}$ (model 11), pipe yield strength was attained at 0.11 m pipe displacement, and when $p = p_{\text{max}}$ (Model 12), the pipe yield strength was attained at 0.12 m pipe displacement.
Fig. 5.21: Pipeline Axial Von Mises Stress distribution vs displacement curve (a) Scenario 3 (b) Scenario 3

In all scenarios, both the D/t-96 and D/t-72 pipelines exceeded the yield strength at the maximum landslide displacement of 0.5 m. But it was observed that by the gradual displacement of the pipeline as a result of the landslide action, the yield strength of the pipe was first attained in all scenarios when there is pressure in the pipeline before the accumulated plastic strain limit was reached except in in two cases when the pipeline was not pressurized.

5.2.5 Pipeline Displacement

Fig. 5.22 shows the pipeline displacement comparison data for scenario 1 through 4 with different pressure values and subjected to a maximum of 0.5 m landslide displacement. The maximum pipeline displacement in all models occurred at the mid-section of the pipeline in the sliding soil (l_{b1} region). The differences were small but less than the landslide displacement, which results from the soil-pipe interaction since the pipeline tend to act as resistance to the movement of the landslide. The pipeline displacement along with the displacement of the landslide with a non-linear rule, therefore the soil-pipe interaction is critical and should be considered for the mechanical
analysis of buried pipeline. The maximum pipeline displacement observed in all models was observed when pressure, $p = 0$, followed by when pressure, $p = p_{max}$.

(a)

Scenario 1 (D/t-96, Cohesive Soil) Pipe Displacement Curve

(b)

Scenario 2 (D/t-96, Non-cohesive Soil) Pipe Displacement Curve

<table>
<thead>
<tr>
<th>Applied pressure (Pa)</th>
<th>Maximum Pipe Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1: $p = 0$</td>
<td>0.4602</td>
</tr>
<tr>
<td>Model 2: $p = 0.56p_{max}$</td>
<td>0.4541</td>
</tr>
<tr>
<td>Model 3: $p = p_{max}$</td>
<td>0.4580</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Applied pressure (Pa)</th>
<th>Maximum Pipe Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 4: $p = 0$</td>
<td>0.4877</td>
</tr>
<tr>
<td>Model 5: $p = 0.56p_{max}$</td>
<td>0.4641</td>
</tr>
<tr>
<td>Model 6: $p = p_{max}$</td>
<td>0.4675</td>
</tr>
</tbody>
</table>
Fig. 5.22: Pipeline displacement vs Pipeline distance curve (a) Scenario 1 (b) Scenario 2 (c) Scenario 3 (d) Scenario 4
The least pipeline displacement in all models was observed when pressure is $56\%p_{\text{max}}$.

The displacement in the thicker pipeline (D/t-72) in scenario 3 and 4 as shown in Fig. 5.22 (c) and (d) was less compared to that of the thinner pipeline in Scenario 1 and 2 as shown in Fig. 5.22 (a) and (b). Also, the highest pipeline displacements was observed when the pipeline is buried in the non-cohesive (Leoss) soil.

### 5.3 Influence of pipeline Parameters

#### 5.3.1 Diameter – Thickness Ratio (D/t)

The smaller the diameter-thickness ratio, the stronger the bending stiffness is. As shown in all models in this research, the displacement curve for a displacement of 0.5 m with two pipelines of different D/t values were analyzed. Displacement and bending deformation of the pipeline decrease when the D/t value decreases. And the displacement changes of the pipeline at the interface of the sliding soil and the surrounding soil were small. Axial plastic strain increases with the increase in D/t value. So thin walled pipelines are prone to failure when subjected to landslide movements. Likewise, the stress in the pipeline increase with the increase of the D/t value. Though analyzing the models through stress, all the model failed since they all exceeded the yield strength, but the axial stress values of the thicker pipeline (D/t-72) are significantly lower than the thinner pipeline (D/t-96).

#### 5.3.2 Internal Pressure

It was observed that when pressure $p = 0$, it deformed the highest, when $p = 0.56p_{\text{max}}$, the deformation on the pipeline decreased significantly, and when the pressure was at $p_{\text{max}}$ the deformation rose again but not as high as when $p = 0$. The highest deformations occurred in the $l_{b,s}$ (stable surrounding soil) region and also in the interface
between the sliding soil and the stable surrounding soil. Though the pipeline deformation was significant with the increase in pressure, but the stiffness caused in the internal wall of the pipeline was observed to decrease slightly the deformation when the pressure is around the normal operation pressure of $56\% p_{\text{max}}$. Under the joint action of landslide displacement and internal pressure, the pipeline mechanics is affected mostly when the pressure is at $p_{\text{max}}$. Therefore, pipelines with higher operating pressures are more dangerous when it comes to operational safety.

### 5.4 Influence of Soil Parameters

The two types of soils used for the analysis in this research are Silty clay (cohesive) and Loess (non-cohesive). The loess soil has a higher elastic modulus and cohesion values than the silty clay soil as shown in Table 4. This greatly affect the soil-pipeline interaction.

#### 5.4.1 Soil’s Elastic Modulus

With the displacement of the landslide in all models, the bending deformation of the pipeline significantly increased with the models that were buried in the non-cohesive (loess) soil, i.e. with higher elastic modulus. Since it is a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression.

#### 5.4.2 Soil’s Cohesion

Also, the non-cohesive (Loess) soil has higher cohesion value and caused higher deformation in the pipeline. This is because deformation of the landslide soil with higher cohesion is small under the action of the buried pipeline. Curvature radius decreases with the increase in the soil’s cohesion in the bending deformation locations.
In summary, as a result of burying the pipelines in two different soils with different elastic modulus and cohesion value the maximum Von Mises plastic strain increased in the D/t-96 pipeline, from 0.09 (9%) to 0.15 (15%) when the pressure $p = 0$, 0.07 (7%) to 0.23 (23%) when the pressure $p = 56\% p_{\text{max}}$, and 0.11 (11%) to 0.16 (16%) when $p = p_{\text{max}}$. Also, the maximum Von Mises stress in the pipeline increased from 460.3 MPa to 525.7 MPa when $p = 0$, and 456.6 MPa to 458.7 MPa when $p = p_{\text{max}}$ in the D/t-72 pipeline as shown in Table 5.5 and 5.6. The maximum axial tensile plastic strains was observed to occur in the pipeline in the $l_{b,s}$ region, and appears to be bending outside, and it is much bigger than the maximum compressive strain which resulted in local buckling that is on the inside. Therefore, excessive tensile plastic strain is the main reason for pipeline failure in displacement-controlled scenario.

**Table 5.5:** Maximum axial Von Mises plastic strain values and location in the pipelines

<table>
<thead>
<tr>
<th>Scenario 1 (D/t-96, Cohesive Soil)</th>
<th>Scenario 2 (D/t-96, Non-cohesive Soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied pressure (Pa)</td>
<td>Max Von Mises Plastic Strain</td>
</tr>
<tr>
<td>Model 1  $p = 0$</td>
<td>0.09</td>
</tr>
<tr>
<td>Model 2  $p = 56% p_{\text{max}}$</td>
<td>0.07</td>
</tr>
<tr>
<td>Model 3  $p = p_{\text{max}}$</td>
<td>0.11</td>
</tr>
<tr>
<td>Model 4  $p = 0$</td>
<td>0.15</td>
</tr>
<tr>
<td>Model 5  $p = 56% p_{\text{max}}$</td>
<td>0.23</td>
</tr>
<tr>
<td>Model 6  $p = p_{\text{max}}$</td>
<td>0.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 3 (D/t-72, Cohesive Soil)</th>
<th>Scenario 4 (D/t-72, Non-cohesive Soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied pressure (Pa)</td>
<td>Max Von Mises Plastic Strain</td>
</tr>
<tr>
<td>Model 7  $p = 0$</td>
<td>0.07</td>
</tr>
<tr>
<td>Model 8  $p = 56% p_{\text{max}}$</td>
<td>0.02</td>
</tr>
<tr>
<td>Model 9  $p = p_{\text{max}}$</td>
<td>0.07</td>
</tr>
<tr>
<td>Model 10 $p = 0$</td>
<td>0.13</td>
</tr>
<tr>
<td>Model 11 $p = 56% p_{\text{max}}$</td>
<td>0.08</td>
</tr>
<tr>
<td>Model 12 $p = p_{\text{max}}$</td>
<td>0.06</td>
</tr>
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</table>
Table 5.6: Maximum axial Von Mises plastic stress values and location in the pipelines

<table>
<thead>
<tr>
<th>Scenario 1 (D/t-96, Cohesive Soil)</th>
<th>Scenario 2 (D/t-96, Non-cohesive Soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending Deformation Region and (Ls)</strong></td>
<td><strong>Bending Deformation Region and (Ls)</strong></td>
</tr>
<tr>
<td><strong>Applied pressure (Pa)</strong></td>
<td><strong>Max Von Mises Stress (Mpa)</strong></td>
</tr>
<tr>
<td>Model 1</td>
<td>$p = 0$</td>
</tr>
<tr>
<td>Model 2</td>
<td>$p = 56% p_{\text{max}}$</td>
</tr>
<tr>
<td>Model 3</td>
<td>$p = p_{\text{max}}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 3 (D/t-72, Cohesive Soil)</th>
<th>Scenario 4 (D/t-72, Non-cohesive Soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending Deformation Region and (Ls)</strong></td>
<td><strong>Bending Deformation Region and (Ls)</strong></td>
</tr>
<tr>
<td><strong>Applied pressure (Pa)</strong></td>
<td><strong>Max Von Mises Stress (Mpa)</strong></td>
</tr>
<tr>
<td>Model 7</td>
<td>$p = 0$</td>
</tr>
<tr>
<td>Model 8</td>
<td>$p = 56% p_{\text{max}}$</td>
</tr>
<tr>
<td>Model 9</td>
<td>$p = p_{\text{max}}$</td>
</tr>
</tbody>
</table>

In scenario 1 and 2, on average, the D/t-96 pipeline buried in cohesive (silty clay) and non-cohesive (loess) soil respectively, attained the plastic strain limit of 2% (0.002) 2.5 times and 1.3 times later than when it attained the stress limit of 445 MPa. In scenario 3 and 4, on average, the D/t-72 pipeline buried in cohesive (silty clay) and non-cohesive (loess) soil respectively, attained the plastic strain limit of 2% 0.9 times and 1.5 times later than when it attained the stress limit of 450 MPa.
CHAPTER SIX: SUMMARY AND CONCLUSION

Using the advanced and high computational capabilities of finite element simulation tools, the mechanical behavior of buried X65 steel pipeline crossing active landslide was investigated rigorously. The pipeline is assumed to be horizontal and perpendicular to the landslide direction, an idealized case, which allows for the investigation of several soil and pipeline parameters on pipeline deformation, strain, and stress capacity. The effects of various soil conditions, cohesive (silty clay) and non-cohesive (Loess), expressed through varying values of stiffness parameters (soil cohesion, $c$, and elastic modulus, $E$) on the structural response of the pipeline were analyzed, with emphasis on pipeline wall failure. The summarized conclusions were made after the analysis:

1) Pipeline displacement, bending deformation and the axial plastic strain in the pipeline decrease with the decrease in diameter-thickness ratio ($D/t$).

2) The pipeline buckled when non-pressurized, and the buckling mode is collapse under the landslide displacement. But wrinkling appears on the buried pipeline when the internal pressure is $56\%p_{\text{max}}$. For pressurized pipeline, when buried in non-cohesive (loess) soil, there are three buckling locations (on either sides of the interface between sliding and non-sliding soil, and the interface), as opposed to buckling on only two locations (on either sides of the interface) when buried in cohesive (silty clay) soil. Plastic strain increases increase with the increase in landslide displacement. Internal pressure is the most important factor that affects the buckling pattern.
3) With the decrease in diameter-thickness ratio (D/t), the buckling location decreases i.e. thick-walled pipelines can be laid in areas with landslide movements.

4) The tensile plastic strain on the pipeline is much greater than the compressive strain in the deformation process, therefore the accumulative tensile plastic strain limit was used as the failure criteria. The bending deformation and tensile strain of the pipeline increase with the increase in the displacement of the landslide. Also, the maximum displacement of the pipeline is less than that of the sliding soil as a result of soil-pipeline interaction which stem from the pipeline acting as resistance the landslide displacement.

5) The internal pressure can prove favorable or detrimental. It is favorable because at moderate operational pressure, it has a stabilizing effect on the pipeline’s internal wall i.e. counterbalancing the inward collapse of the pipe wall when under bending deformation. On the other hand, it is detrimental because it provokes severe hoop stress with its increment. So as the pressure increases the deformation also increases in the pipeline. But the axial tensile strain increases with a small change rate, which is due to early yielding of the steel pipe.

6) Bending deformation and the maximum tensile strain in both the D/t-96 and D/t-72 pipelines increases when buried in the non-cohesive (Loess) soil. i.e. increasing the elastic modulus and the cohesion values of the soil which increases its stiffness.
7) The highest deformation of both D/t-96 and D/t-72 pipelines, when buried in cohesive and non-cohesive soil was observed when there was no pressure in the pipeline leading to pipeline collapse.

8) Comparing the Von Mises plastic strain and the Von Mises stress, on average, the D/t-96 pipeline when buried in cohesive (silty clay) soil attained the plastic strain limit of 2% 2.5 times later than when it attained the stress limit of 445 MPa in scenario 1.

9) In accordance with the strain-based failure criterion, the accumulated plastic strain limit of the steel pipeline ($\varepsilon_{x,max} \leq 2.0\%$) in each scenario was attained later in the pipeline displacement process indicating that the stress-based failure criterion is more conservative than its strain-based counterpart when analyzing displacement-controlled failure analysis of pipelines.

10) The methods used in the deformation evaluation, buckling mode and limit state analysis developed in this thesis can be used for safety assessment and prediction of buried pipeline crossing landslide prone areas. But experimental result comparison or data from real event is needed for verification of the finite element method and models used.

Conclusively, the strain-based design idea allows a pipeline plastic property to reach or even exceed the yield strain, which can sufficiently improve the bearing capacity of the pipeline. Compared with the stress-based idea, it takes advantage of security of plasticity and ductility properties of steel pipe and improving the transport capacity of the pipeline. This will provide references for design, route selection, construction and operation of pipelines subjected to landslide actions.
6.1 Design recommendations

1) Calibration and strengthening sections of pipelines where bending deformations are expected as a result of permanent ground deformations i.e. the section on both sides of the interface between the landslide soil and the stable surrounding soil, should be considered in future designs.

2) When pipelines routes pass through areas prone to landslide displacements, it is highly recommended that the pipelines be buried in cohesive soil since it is proven to cause less mechanical strain on the pipeline external wall.

3) A protective device with simple structure with convenient installation should be designed to wrap around the buried pipeline crossing landslide prone areas to prevent damage. The protective pipeline device and water in the annular space as shown in Fig. 5.24 can effectively protect oil and gas pipelines under permanent ground deformations.

6.2 Recommendations for future studies

1) More studies that investigate how different landslide geometries, i.e. its shape, width, and soil mass, can affect the pipeline response, is decisive in accessing the pipeline vulnerability. This will ultimately help in concluding on the worst-case scenario regarding pipeline design.

2) Most studies today were carried out on straight pipes, which in the real-life scenario is not the exact case. Studies to investigate the effect of landslide actions on bends and joints i.e. elbows, Tee’s and valve areas, which prove to be the most vulnerable parts of the pipeline and more susceptible to failure.
LITERATURE CITED

1) American Lifelines Alliance (ALA). Guidelines for the design of buried steel pipes, (2001)


5) CSA Z662 Oil and Gas Pipeline Systems, Canadian Standards Association (1999).


9) B. Liu et al., Tensile Strain Capacity of Pipelines for Strain-Based Design.  


13) American Society of Civil Engineers (ASCE). Guidelines for the Seismic Design of Oil and Gas Pipeline System. 2001. 68-76


22) SUZUKI Nobuhisa et al., Strain Capacity of High-Strength Line Pipes. JFE TECHNICAL REPORT, No. 12 (Oct. 2008)


APPENDIX A – ANSYS FE software Scripting language

Scripting language used in ANSYS Mechanical APDL Finite Element Software

A.1 Scripting language for Scenario 1

A.1.1 When pressure, \( p = 0 \) (Model 1)

/title,Sean Edeki's Thesis Model (D/\( t=96, p=0, d=0.5, \) Silty Clay)

/filename,3DModel

/units,bin

/prep7 !preprocessor

!Soil element

ET,1,SOLID186 !20-Node tetrahedral element

MSHAPE,1,3D

KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil

MP,EX,1,2e7 !Young's Modulus of Cohesive soil (Silty clay)(Pa)

MP,DENS,1,1700 !Soil density (kg/m^3)

MP,PRXY,1,0.3 !Poisson's ratio of cohesive soil (Silty clay)

!Extended Drucker-Prager Material Model Definition

TB,EDP,1,1,2,LYFUN !EDP Linear Yield Criterion

TBDATA,1,0.5665,2e7
TB,EDP,1,1,1,LFPOT !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800 !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.48e8,4.8e7

!Soil-pipe contact elements
ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3 !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation
k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
1,1,5 !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,,,5

!Steel Pipe element
CYL4,20,8.77,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
l,35,37

VDRAG,1,,,,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,0.4572,,20

VSBV,1,3                   !Volume Subtract

CYL4,20,8.77,0.44767,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1                   !Element Size
VMESH,2
SMRTSIZE,4
VMESH,4

TYPE,1
MAT,2
SMRTSIZE,2
ESIZE,1
VMESH,1

!Contacts
!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL
ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,,

ANTYPE,TRANS,NEW
NLGEOM,ON

!displacement constraint
ASEL,s,,,15  !Area of bottom of whole soil

NSLA,s,1

D,all,ALL,0

NSEL,all

ALLSEL,ALL

\[ k_\text{=}2 \]

!Displacement by landslide (0.5m)

ASEL,s,,,7

NSLA,s,1

D,all,ux,0.8663/k_  !in m

D,all,uy,-0.4996/k_

D,all,uz,0

NSEL,all

ALLSEL,ALL

!Pipe boundary constraint

ASEL,s,,,2

NSLA,s,1

D,all,ALL,0  !in m

NSEL,all

ALLSEL,ALL
!Pipe internal pressure

ASEL,s,,,12

NSLA,s,l

SF,all,PRES,0 !in Pa

NSEL,all

ALLSEL,ALL

ASEL,s,,,14

NSLA,s,l

SF,all,PRES,0 !in Pa

NSEL,all

ALLSEL,ALL

TIME,10 !total time for load step

OUTRES,all,-10/k_ !total steps for output

DELTIM,0.2,0.2,10 !del t, min del t, max del t (Time step size per load step)

KBC,0

SOLVE

Finish

A.1.2 When pressure, $p = 56\% p_{max}$ (Model 2)

/title,Sean Edeki's Thesis Model (D/t=96,p=56%Pmax,d=0.5,Silty Clay)
/filename,3DModel

/units,bin

/prep7    !preprocessor

!Soil element
ET,1,SOLID186   !10-Node tetrahedral element
MSHAPE,1,3D
KEYOPT,1,16,1   !Enable Stress State

!Material properties of whole soil
MP,EX,1,2e7     !Young's Modulus of Cohesive soil (Silty clay)(Pa)
MP,DENS,1,1700  !Soil density (kg/m^3)
MP,PRXY,1,0.3   !Poisson's ratio of cohesive soil (Silty clay)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN  !EDP Linear Yield Criterion
TBDATA,1,0.5665,2e7

TB,EDP,1,1,1,LFPOT  !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800 !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.48e8,4.8e7

!Soil-pipe contact elements
ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3 !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation
k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4
k,5,0,0,70

1,1,5 !Creating line between keypoints 1 and 5
VDRAG,all,,,,,5

!Steel Pipe element
CYL4,20,8.77,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3
k,37,30,1,20
l,35,37
VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,0.4572,,20
VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.44767,,0.4572,,70
!Meshing

TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,4
VMESH,4

TYPE,1
MAT,2
SMRTSIZE,2
ESIZE,1
VMESH,1

!Contacts

!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,

ANTYPE,TRANS,NEW
NLGEOM,ON

!displacement constraint
ASEL,s,,,15 !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_ = 2

!Displacement by landslide (0.5m)
ASEL,s,,,7
NSLA,s,1
D,all,ux,0.8663/k_           !in m
D,all,uy,-0.4996/k_
D,all,uz,0
NSEL,all
ALLSEL,ALL

!Pipe boundary constraint
ASEL,s,,,2
NSLA,s,1
D,all,ALL,0                   !in m
NSEL,all
ALLSEL,ALL

!Pipe internal pressure
ASEL,s,,,12
NSLA,s,1
SF,all,PRES,3920000           !in Pa (56% of Pmax); Pmax=7e6 Pa
A.1.3 When pressure, \( p = p_{\text{max}} \) (Model 3)
!Soil element
ET,1,SOLID186 !20-Node tetrahedral element
MSHAPE,1,3D
KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil
MP,EX,1,2e7 !Young's Modulus of Cohesive soil (Silty clay)(Pa)
MP,DENS,1,1700 !Soil density (kg/m^3)
MP,PRXY,1,0.3 !Poisson's ratio of cohesive soil (Silty clay)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN !EDP Linear Yield Criterion
TBDATA,1,0.5665,2e7

TB,EDP,1,1,1,LFPOT !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800 !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0

TBDATA,1,4.48e8,4.8e7

!Soil-pipe contact elements

ET,3,CONTA174

ET,4,TARGE170

KEYOPT,4,1,1

MP,MU,3,0.3                       !Contact elements friction coefficient

MP,MU,4,0.2

!Soil geometry creation

k,1,0,0,0

k,2,30,0,0

k,3,30,5,0

k,4,0,22.3,0

a,1,2,3,4

k,5,0,0,70

1,1,5                               !Creating line between keypoints 1 and 5

VDRAG,all,,,,,,5

!Steel Pipe element
!Steel pipe geometry creation

k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
1,35,37

VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP       !Volume Subtract

CYL4,20,8.77,,0.4572,,70
VSBV,1,2       !Volume Subtract

CYL4,20,8.77,0.44767,,0.4572,,70

!Meshing

TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1                   !Element Size
VMESH,2
SMRTSIZE,4
VMESH,4

TYPE,1
MAT,2
SMRTSIZE,2
ESIZE,1
VMESH,1

!Contacts
!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL
!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,

ANTYPE,TRANS,NEW
NLGEOM,ON

!displacement constraint
ASEL,s,,,15 !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_=2
!Displacement by landslide (0.5m)
ASEL,s,,,7
NSLA,s,1

D,all,ux,0.8663/k_               !in m

D,all,uy,-0.4996/k_

D,all,uz,0

NSEL,all

ALLSEL,ALL

!Pipe boundary constraint

ASEL,s,,,2

NSLA,s,1

D,all,ALL,0              !in m

NSEL,all

ALLSEL,ALL

!Pipe internal pressure

ASEL,s,,,12

NSLA,s,1

SF,all,PRES,7e6                   !in Pa (100% of Pmax); Pmax=7e6 Pa

NSEL,all

ALLSEL,ALL

ASEL,s,,,14

NSLA,s,1
SF,all,PRES,7e6               !in Pa (100% of Pmax); Pmax=7e6 Pa
NSEL,all
ALLSEL,ALL

TIME,10                   !total time for load step
OUTRES,all,-10/k_          !total steps for output
DELTIM,0.2,0.2,10          !del t, min del t, max del t (Time step size per load step)

KBC,0
SOLVE
finish

A.2   Scripting language for Scenario 2

A.2.1   When pressure, \( p = 0 \) (Model 4)

/title,Sean Edeki's Thesis Model (D/t=96,p=0,d=0.5,Loess)
/filename,3DModel
/units,bin

/prep7                         !preprocessor

!Soil element
ET,1,SOLID186                 !20-Node tetrahedral element
MSHAPE,1,3D
KEYOPT,1,16,1  !Enable Stress State

!Material properties of whole soil
MP,EX,1,3.3e7  !Young's Modulus of Non-cohesive soil (Loess)(Pa)
MP,DENS,1,1400  !Soil density (kg/m^3)
MP,PRXY,1,0.44  !Poisson's ratio of Non-cohesive soil (Loess)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN  !EDP Linear Yield Criterion
TBDATA,1,1.0096,2.8e7

TB,EDP,1,1,1,LFPOT  !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11  !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800  !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3  !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.48e8,4.8e7
!Soil-pipe contact elements

ET,3,CONTA174

ET,4,TARGE170

KEYOPT,4,1,1

MP,MU,3,0.3                       !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation

k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70

1,1,5                           !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,5

!Steel Pipe element

CYL4,20,8.77,,,0.4572,,70

VSBV,1,2
!Steel pipe geometry creation

k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
l,35,37

VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,,0.4572,,20
VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.44767,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,4
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,2
VMESH,1

!Contacts
!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL
ASEL, s,, 19
NSLA, s, 1
TYPE, 3
MAT, 4
REAL, 4
ESURF
ALLSEL, ALL

!Surface 4
ASEL, s,, 3
NSLA, s, 1
TYPE, 4
MAT, 4
REAL, 4
ESURF
ALLSEL, ALL

ASEL, s,, 11
NSLA, s, 1
TYPE, 4
MAT, 4
REAL, 4
ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,,

ANTYPE, TRANS, new
NLGEOM,ON

!displacement constraint
ASEL,s,,,15 !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_=2
!Displacement by landslide (0.5m)
ASEL,s,,,7
NSLA,s,1
D,all,ux,0.8663/k_ !in m
D, all, uy, -0.4996/k

D, all, uz, 0

NSEL, all

ALLSEL, ALL

! Pipe boundary constraint

ASEL, s, , , 2

NSLA, s, 1

D, all, ALL, 0 ! in m

NSEL, all

ALLSEL, ALL

! Pipe internal pressure

ASEL, s, , , 12

NSLA, s, 1

SF, all, PRES, 0 ! in Pa

NSEL, all

ALLSEL, ALL

ASEL, s, , , 14

NSLA, s, 1

SF, all, PRES, 0 ! in Pa

NSEL, all
ALLSEL, ALL

TIME, 10                  !total time
OUTRES, all, -10/k_        !total steps for output
DELTIM, 0.2, 0.2, 10        !del t, min del t, max del t (Time step size per load step)

KBC, 0
SOLVE
Finish

A.2.2 When pressure, \( p = 56\%p_{\text{max}} \) (Model 5)
/title, Sean Edeki's Thesis Model (D/t=96, p=0.56p_{\text{max}}, d=0.5, Loess)
/filename, 3DModel
/units, bin

/prep7                     !preprocessor

!Soil element
ET, 1, SOLID186            !20-Node tetrahedral element
MSHAPE, 1, 3D
KEYOPT, 1, 16, 1           !Enable Stress State

!Material properties of whole soil
MP,EX,1,3.3e7  !Young's Modulus of Non-cohesive soil (Loess)(Pa)
MP,DENS,1,1400  !Soil density (kg/m^3)
MP,PRXY,1,0.44  !Poisson's ratio of Non-cohesive soil (Loess)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN  !EDP Linear Yield Criterion
TBDATA,1,1.0096,2.8e7

TB,EDP,1,1,1,LFPOT  !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11  !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800  !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3  !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.48e8,4.8e7

!Soil-pipe contact elements
ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3 !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation
k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
l,1,5 !Creating line between keypoints 1 and 5
VDRAG,all,,,,5

!Steel Pipe element
CYL4,20,8.77,,,0.4572,,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
l,35,37

VDRAG,1,,,,,,27

VSBV,3,1,SEPO,KEEP !Volume Subtract
CYL4,20,8.77,,,0.4572,,20
VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.44767,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,4
VMESH,4
TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,2
VMESH,1

!Contacts
!Surface 1
ASEL,s,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL
!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL
finish
/solution
NROPT, UNSYM,

ANTYPE, TRANS, new
NLGEOM, ON

!displacement constraint
ASEL, s,,15                      !Area of bottom of whole soil
NSLA, s, 1
D, all, ALL, 0
NSEL, all
ALLSEL, ALL

k_ = 2
!Displacement by landslide (0.5m)
ASEL, s,,7
NSLA, s, 1
D, all,ux, 0.8663/k_    !in m
D, all,uy, -0.4996/k_
D, all, uz, 0
NSEL, all
ALLSEL,ALL

!Pipe boundary constraint
ASEL,s,,,2
NSLA,s,1
D,all,ALL,0 !in m
NSEL,all
ALLSEL,ALL

!Pipe internal pressure
ASEL,s,,,12
NSLA,s,1
SF,all,PRES,3920000 !in Pa (56% of Pmax); Pmax=7e6 Pa
NSEL,all
ALLSEL,ALL

ASEL,s,,,14
NSLA,s,1
SF,all,PRES,3920000 !in Pa (56% of Pmax); Pmax=7e6 Pa
NSEL,all
ALLSEL,ALL

TIME,10 !total time
OUTRES, all, -10/k_ ! total steps for output
DELTIM, 0.2, 0.2, 10 ! del t, min del t, max del t

KBC, 0
SOLVE
Finish

A.2.3 When pressure, \( p = p_{\text{max}} \) (Model 6)
$title, Sean Edeki's Thesis Model (D/t=96, p=pmax, d=0.5, Loess)
$filename, 3DModel
$units, bin

/prep7 ! preprocessor

! Soil element
ET, 1, SOLID186 ! 20-Node tetrahedral element
MSHAPE, 1, 3D
KEYOPT, 1, 16, 1 ! Enable Stress State

! Material properties of whole soil
MP, EX, 1, 3.3e7 ! Young's Modulus of Non-cohesive soil (Loess)(Pa)
MP, DENS, 1, 1400 ! Soil density (kg/m^3)
MP,PRXY,1,0.44  !Poisson's ratio of Non-cohesive soil (Loess)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN  !EDP Linear Yield Criterion
TBDATA,1,1.0096,2.8e7

TB,EDP,1,1,1,LFPOT  !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11  !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800  !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3  !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.48e8,4.8e7

!Soil-pipe contact elements
ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3  !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation
k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
1,1,5                      !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,5

!Steel Pipe element
CYL4,20,8.77,,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3
VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,,0.4572,,20
VSBV,1,3 !Volume Subtract
CYL4,20,8.77,0.44767,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,4
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,2
VMESH,1

!Contacts
!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL
ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF

ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF

ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF

ALLSEL,ALL

finish

/solution
NROPT, UNSYM,,

ANTYPE, TRANS, new
NLGEOM, ON

!displacement constraint
ASEL, s,,15 !Area of bottom of whole soil
NSLA, s, 1
D, all, ALL, 0
NSEL, all
ALLSEL, ALL

k_ = 2
!Displacement by landslide (0.5m)
ASEL, s,,,7
NSLA, s, 1
D, all, ux, 0.8663/k_ !in m
D, all, uy, -0.4996/k_
D, all, uz, 0
NSEL, all
ALLSEL, ALL

!Pipe boundary contraint
ASEL,s,,,2
NSLA,s,l
D,all,ALL,0 !in m
NSEL,all
ALLSEL,ALL

!Pipe internal pressure
ASEL,s,,,12
NSLA,s,l
SF,all,PRES,7e6 !in Pa (p = pmax); Pmax=7e6 Pa
NSEL,all
ALLSEL,ALL

ASEL,s,,,14
NSLA,s,l
SF,all,PRES,7e6 !in Pa (p = pmax); Pmax=7e6 Pa
NSEL,all
ALLSEL,ALL

TIME,10 !total time
OUTRES,all,-10/k_ !total steps for output
DELTIM,0.2,0.2,10 !del t, min del t, max del t
KBC,0
SOLVE
finish

A.3 Scripting language for Scenario 3

A.3.1 When pressure, $p = 0$ (Model 7)

/title,Sean Edeki's Thesis Model (D/t=72,p=0,d=0.5,Silty Clay)
/filename,3DModel
/units,bin

/prep7 !preprocessor

!Soil element
ET,1,SOLID186 !20-Node tetrahedral element
MSHAPE,1,3D
KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil
MP,EX,1,2e7 !Young's Modulus of Cohesive soil (Silty clay)(Pa)
MP,DENS,1,1700 !Soil density (kg/m^3)
MP,PRXY,1,0.3 !Poisson's ratio of cohesive soil (Silty clay)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN        !EDP Linear Yield Criterion
TBDATA,1,0.5665,2e7

TB,EDP,1,1,1,LFPOT        !EDP Linear Plastic Flow Potential
TBDATA,1,0

Material properties of steel pipe

MP,EX,2,2.1e11        !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800        !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3         !Poisson's ratio of Steel pipe
MP,PRXY,2,0.3         !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.5e8,4.7e7

Soil-pipe contact elements

ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3           !Contact elements friction coefficient
MP,MU,4,0.2
!Soil geometry creation

k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
l,1,5                             !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,,,,5

!Steel Pipe element
CYL4,20,8.77,,,,,,,,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
l,35,37
VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,,0.4572,,20
VSBV,1,3 !Volume Subtract
CYL4,20,8.77,0.4445,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,2
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,1
VMESH,1
!Contacts

!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL
!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,,
ANTYPE, TRANS, new
NLGEOM, ON

!Boundary conditions
ASEL, s,, 15                      !Area of bottom of whole soil
NSLA, s, 1
D, all, ALL, 0
NSEL, all
ALLSEL, ALL

ASEL, s,, 2                     !End surface of pipe
NSLA, s, 1
D, all, ALL, 0
NSEL, all
ALLSEL, ALL

k_ = 2
!Displacement by landslide (0.5m)
ASEL, s,, 7
NSLA, s, 1
D, all, ux, 0.8663/k_          !in m
D, all, uy, -0.4996/k_
D, all, uz, 0
NSEL, all
ALLSEL, ALL

!Pipe internal pressure
ASEL, s,,, 12
NSLA, s, 1
SF, all, PRES, 0 !in Pa
NSEL, all
ALLSEL, ALL

ASEL, s,,, 14
NSLA, s, 1
SF, all, PRES, 0 !in Pa
NSEL, all
ALLSEL, ALL

TIME, 10 !total time
OUTRES, all, -10/k_ !total steps for output
DELTIM, 0.2, 0.2, 10 !del t, min del t, max del t

KBC, 0
SOLVE
finish
A.3.2 When pressure, $p = 56\% p_{\text{max}}$ (Model 8)

/title, Sean Edeki's Thesis Model (D/t=72, p=56\%p_{\text{max}}, d=0.5, Silty Clay)
/filname, 3DModel
/units, bin

/prep7

!Soil element
ET, 1, SOLID186 ! 20-Node tetrahedral element
MSHAPE, 1, 3D
KEYOPT, 1, 16, 1 ! Enable Stress State

! Material properties of whole soil
MP, EX, 1, 2e7 ! Young's Modulus of Cohesive soil (Silty clay)(Pa)
MP, DENS, 1, 1700 ! Soil density (kg/m^3)
MP, PRXY, 1, 0.3 ! Poisson's ratio of cohesive soil (Silty clay)

! Extended Drucker-Prager Material Model Definition
TB, EDP, 1, 1, 2, LYFUN ! EDP Linear Yield Criterion
TB DATA, 1, 0.5665, 2e7

TB, EDP, 1, 1, 1, LFPOT ! EDP Linear Plastic Flow Potential
TB DATA, 1, 0
!Material properties of steel pipe

MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800 !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.5e8,4.7e7

!Soil-pipe contact elements

ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3 !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation

k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70

l,1,5  !Creating line between keypoints 1 and 5

VDRAG,all,,,,,,5

!Steel Pipe element

CYL4,20,8.77,,,0.4572,,70

VSBV,1,2

!Steel pipe geometry creation

k,35,30,1,0

k,36,0,18.3,0

a,35,36,4,3

k,37,30,1,20

1,35,37

VDRAG,1,,,,,,27

VSBV,3,1,SEPO,,KEEP  !Volume Subtract

CYL4,20,8.77,,,0.4572,,20

VSBV,1,3  !Volume Subtract
CYL4,20,8.77,0.4445,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,2
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,1
VMESH,1

!Contacts
!Surface 1
ASEL,s,,6
NSLA,s,1
TYPE,3
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL
!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,,

ANTYPE, TRANS, new
NLGEOM,ON

!Boundary conditions
ASEL,s,,,15 !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

ASEL,s,,2  !End surface of pipe
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_=2
!Displacement by landslide (0.5m)
ASEL,s,,7
NSLA,s,1
D,all,ux,0.8663/k_  !in m
D,all,uy,-0.4996/k_
D,all,uz,0
NSEL,all
ALLSEL,ALL

!Pipe internal pressure
ASEL,s,,12
NSLA,s,1
A.3.3 When pressure, \( p = p_{\text{max}} \) (Model 9)

/title, Sean Edeki's Thesis Model (D/t=72, p=pmax, d=0.5, Silty Clay)
/filname, 3DModel
/units, bin
!preprocessor

!Soil element
ET,1,SOLID186 !20-Node tetrahedral element
MSHAPE,1,3D
KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil
MP,EX,1,2e7 !Young's Modulus of Cohesive soil (Silty clay)(Pa)
MP,DENS,1,1700 !Soil density (kg/m^3)
MP,PRXY,1,0.3 !Poisson's ratio of cohesive soil (Silty clay)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN !EDP Linear Yield Criterion
TBDATA,1,0.5665,2e7

TB,EDP,1,1,1,LFPOT !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800 !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.5e8,4.7e7

!Soil-pipe contact elements
ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3 !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation
k,1,0,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
1,1,5 !Creating line between keypoints 1 and 5
VDRAG,all,,,,5
!Steel Pipe element
CYL4,20,8.77,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
l,35,37

VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,0.4572,,20
VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.4445,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,2
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,1
VMESH,1

!Contacts
!Surface 1
ASEL,s,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL
ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL, ALL

!Surface 3
ASEL,s,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL, ALL

ASEL,s,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL, ALL

!Surface 3
ASEL,s,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,,

ANTYPE, TRANS, new
NLGEOM,ON

!Boundary conditions
ASEL,s,,15 !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

ASEL,s,,2 !End surface of pipe
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_=2

!Displacement by landslide (0.5m)
ASEL,s,,,7
NSLA,s,1
D,all,ux,0.8663/k_ !in m
D,all,uy,-0.4996/k_
D,all,uz,0
NSEL,all
ALLSEL,ALL

!Pipe internal pressure
ASEL,s,,,12
NSLA,s,1
SF,all,PRES,9e6 !in Pa (100% of Pmax); Pmax=9e6 Pa
NSEL,all
ALLSEL,ALL

ASEL,s,,,14
NSLA,s,1
SF,all,PRES,9e6           !in Pa (100% of Pmax); Pmax=9e6 Pa
NSEL,all
ALLSEL,ALL

TIME,10                  !total time
OUTRES,all,-10/k_        !total steps for output
DELTIM,0.2,0.2,10        !del t, min del t, max del t

KBC,0
SOLVE
finish

A.4 Scripting language for Scenario 4
A.4.1 When pressure, $p = 0$ (Model 10)
/title,Sean Edeki's Thesis Model (D/t=72,p=0,d=0.5,Loess)
/filename,3DModel
/units,bin

/prep7                  !preprocessor

!Soil element
ET,1,SOLID186          !10-Node tetrahedral element
MSHAPE,1,3D

KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil

MP,EX,1,3.3e7 !Young's Modulus of Non-cohesive soil (Loess)(Pa)

MP,DENS,1,1400 !Soil density (kg/m^3)

MP,PRXY,1,0.44 !Poisson's ratio of Non-cohesive soil (Loess)

!Extended Drucker-Prager Material Model Definition

TB,EDP,1,1,2,LYFUN !EDP Linear Yield Criterion

TBDATA,1,1,0.0096,2.8e7

TB,EDP,1,1,1,LFPOT !EDP Linear Plastic Flow Potential

TBDATA,1,0

!Material properties of steel pipe

MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)

MP,DENS,2,7800 !Steel pipe density (kg/m^3)

MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe

TB,BISO,2,1

TBTEMP,0

TBDATA,1,4.5e8,4.7e7
!Soil-pipe contact elements

ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3                       !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation

k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
l,1,5                            !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,,,5

!Steel Pipe element

CYL4,20,8.77,,,,,,,,,70
VSBV,1,2
!Steel pipe geometry creation

k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20
l,35,37

VDRAG,1,,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,,0.4572,,20
VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.4445,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,2
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,1
VMESH,1

!Contacts
!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL
ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF

ALLSEL,ALL

finish

/solution

NROPT,UNSYM,,

ANTYPE, TRANS, new

NLGEOM,ON

!Soil boundary constraint
ASEL,s,,,15 !Area of bottom of whole soil

NSLA,s,1

D,all,ALL,0

NSEL,all

ALLSEL,ALL

!Pipe boundary constraint !End surface of pipe
ASEL,s,,,2

NSLA,s,1

D,all,ALL,0

NSEL,all
ALLSEL,ALL

k_ = 2

!Displacement of landslide (0.5m)
ASEL,s,,7
NSLA,s,l
D,all,ux,0.8663/k_ !in m
D,all,uy,-0.4996/k_
D,all,uz,0
NSEL,all
ALLSEL,ALL

!Pipe internal pressure
ASEL,s,,12
NSLA,s,l
SF,all,PRES,0 !in Pa
NSEL,all
ALLSEL,ALL

ASEL,s,,14
NSLA,s,l
SF,all,PRES,0 !in Pa
NSEL,all
ALLSEL,ALL

TIME,10 !total time

OUTRES,all,-10/k_ !total steps for output

DELTIM,0.2,0.2,10 !del t, min del t, max del t

KBC,0

SOLVE

Finish

A.4.2 When pressure, \( p = 56\% p_{\text{max}} \) (Model 11)

/title,Sean Edeki's Thesis Model (D/t=72,p=0.56p_{\text{max}},d=0.5,Loess)

/filename,3DModel

/units,bin

/prep7 !preprocessor

!Soil element

ET,1,SOLID186 !20-Node tetrahedral element

MSHAPE,1,3D

KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil
MP,EX,1,3.3e7 !Young's Modulus of Non-cohesive soil (Loess)(Pa)
MP,DENS,1,1400 !Soil density (kg/m^3)
MP,PRXY,1,0.44 !Poisson's ratio of Non-cohesive soil (Loess)

!Extended Drucker-Prager Material Model Definition
TB,EDP,1,1,2,LYFUN !EDP Linear Yield Criterion
TBDATA,1,1.0096,2.8e7

TB,EDP,1,1,1,LFPOT !EDP Linear Plastic Flow Potential
TBDATA,1,0

!Material properties of steel pipe
MP,EX,2,2.1e11 !Young's Modulus of Steel pipe (Pa)
MP,DENS,2,7800 !Steel pipe density (kg/m^3)
MP,PRXY,2,0.3 !Poisson's ratio of Steel pipe
TB,BISO,2,1
TBTEMP,0
TBDATA,1,4.5e8,4.7e7

!Soil-pipe contact elements
ET,3,CONTA174
ET,4,TARGE170
KEYOPT,4,1,1

MP,MU,3,0.3 !Contact elements friction coefficient
MP,MU,4,0.2

!Soil geometry creation
k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4

k,5,0,0,70
l,1,5 !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,5

!Steel Pipe element
CYL4,20,8.77,,,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3

k,37,30,1,20

l,35,37

VDRAG,1,,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,0.4572,,20

VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.4445,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,3
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,1
VMESH,1

!Contacts
!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL
!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4

ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4

ESURF
ALLSEL,ALL

ASEL,s,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 4
ASEL,s,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL
finish
/solution
NROPT,UNSYM,,

ANTYPE, TRANS, new
NLGEOM,ON

!Soil boundary constraint
ASEL,s,,,15 !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

!Pipe boundary constraint !End surface of pipe
ASEL,s,,,2
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_ =2

!Displacement of landslide (0.5m)
ASEL,s,,,7

NSLA,s,l

D,all,ux,0.8663/k_  !in m

D,all,uy,-0.4996/k_

D,all,uz,0

NSEL,all

ALLSEL,ALL

!Pipe internal pressure

ASEL,s,,,12

NSLA,s,l

SF,all,PRES,5040000  !in Pa (56% of Pmax); Pmax=9e6 Pa

NSEL,all

ALLSEL,ALL

ASEL,s,,,14

NSLA,s,l

SF,all,PRES,5040000  !in Pa (56% of Pmax); Pmax=9e6 Pa

NSEL,all

ALLSEL,ALL

TIME,10  !total time

OUTRES,all,-10/k_  !total steps for output
DELTIM,0.2,0.2,10 !del t, min del t, max del t

KBC,0
SOLVE
Finish

A.4.3 When pressure, $p = p_{max}$ (Model 12)

/title, Sean Edeki's Thesis Model (D/t=72, p=pmax, d=0.5, Loess)
/filname, 3DModel
/units, bin

/prep7 !preprocessor

!Soil element
ET,1,SOLID186 !20-Node tetrahedral element
MSHAPE,1,3D
KEYOPT,1,16,1 !Enable Stress State

!Material properties of whole soil
MP,EX,1,3.3e7 !Young's Modulus of Non-cohesive soil (Loess)(Pa)
MP,DENS,1,1400 !Soil density (kg/m^3)
MP,PRXY,1,0.44 !Poisson's ratio of Non-cohesive soil (Loess)
!Extended Drucker-Prager Material Model Definition

TB,EDP,1,1,2,LYFUN 
!EDP Linear Yield Criterion

TBDATA,1,1.0096,2.8e7

TB,EDP,1,1,1,LFPOT 
!EDP Linear Plastic Flow Potential

TBDATA,1,0

!Material properties of steel pipe

MP,EX,2,2.1e11 
!Young's Modulus of Steel pipe (Pa)

MP,DENS,2,7800 
!Steel pipe density (kg/m^3)

MP,PRXY,2,0.3 
!Poisson's ratio of Steel pipe

TB,BISO,2,1

TBTEMP,0

TBDATA,1,4.5e8,4.7e7

!Soil-pipe contact elements

ET,3,CONTA174

ET,4,TARGE170

KEYOPT,4,1,1

MP,MU,3,0.3 
!Contact elements friction coefficient

MP,MU,4,0.2
!Soil geometry creation
k,1,0,0,0
k,2,30,0,0
k,3,30,5,0
k,4,0,22.3,0
a,1,2,3,4
k,5,0,0,70
l,1,5 !Creating line between keypoints 1 and 5
VDRAG,all,,,,,,5

!Steel Pipe element
CYL4,20,8.77,,,0.4572,,70
VSBV,1,2

!Steel pipe geometry creation
k,35,30,1,0
k,36,0,18.3,0
a,35,36,4,3
k,37,30,1,20
l,35,37
VDRAG,1,,,,,27

VSBV,3,1,SEPO,,KEEP !Volume Subtract
CYL4,20,8.77,,,0.4572,,20
VSBV,1,3 !Volume Subtract

CYL4,20,8.77,0.4445,,0.4572,,70

!Meshing
TYPE,1
MAT,1
SMRTSIZE,8
ESIZE,1 !Element Size
VMESH,2
SMRTSIZE,3
VMESH,4

TYPE,1
MAT,2
ESIZE,1
SMRTSIZE,1
VMESH,1
!Contacts

!Surface 1
ASEL,s,,,6
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,17
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 2
ASEL,s,,,10
NSLA,s,1
TYPE,3
MAT,3
REAL,3
ESURF
ALLSEL,ALL

ASEL,s,,,24
NSLA,s,1
TYPE,4
MAT,3
REAL,3
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,4
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,5
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

!Surface 3
ASEL,s,,,18
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,19
NSLA,s,1
TYPE,3
MAT,4
REAL,4
ESURF
ALLSEL,ALL
!Surface 4
ASEL,s,,,3
NSLA,s,1
TYPE,4
MAT,4
REAL,4
ESURF
ALLSEL,ALL

ASEL,s,,,11
NSLA,s,1
TYPE,4
MAT,4
REAL,4

ESURF
ALLSEL,ALL

finish
/solution
NROPT,UNSYM,,
ANTYPE, TRANS, new
NLGEOM,ON

!Soil boundary constraint
ASEL,s,,,15  !Area of bottom of whole soil
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

!Pipe boundary constraint  !End surface of pipe
ASEL,s,,,2
NSLA,s,1
D,all,ALL,0
NSEL,all
ALLSEL,ALL

k_ = 2
!Displacement of landslide (0.5m)
ASEL,s,,,7
NSLA,s,1
D,all,ux,0.8663/k_  !in m
D,all,uy,-0.4996/k_
D,all,uz,0
NSEL, all

ALLSEL, ALL

! Pipe internal pressure
ASEL, s,, 12

NSLA, s, 1
SF, all, PRES, 9e6 ! in Pa (p=max); Pmax=9e6 Pa

NSEL, all

ALLSEL, ALL

ASEL, s,, 14

NSLA, s, 1
SF, all, PRES, 9e6 ! in Pa (p=max); Pmax=9e6 Pa

NSEL, all

ALLSEL, ALL

TIME, 10 ! total time

OUTRES, all, -10/k_ ! total steps for output

DELTIM, 0.2, 0.2, 10 ! del t, min del t, max del t

KBC, 0

SOLVE

Finish
A.4 Scripting language for node selection

asel,s,,,3
asel,a,,,11
asel,a,,,12
asel,a,,,14

nsla,s,1 !select nodes from the area

NSEL,r,loc,z,10,30

NSEL,r,loc,x,20+0.002,20+0.003

NSEL,r,loc,y,8.77+0.4572-0.001,8.77+0.4572+0.001
APPENDIX B – Nodal Results

Results from the ANSYS FE software solver output for Scenario 2 showing when internal pressure, \( p = 0 \) (Model 4), \( p = 56\%p_{\text{max}} \) (Model 5) and \( p = p_{\text{max}} \) (Model 6) are shown below.

**Pipeline Displacement for Scenario 2**

![](image1)

(a)

![](image2)

(b)

![](image3)

(c)

*Fig. B5.4: Scenario 2 Pipeline displacement (a) Model 4: when internal pressure, \( p = 0 \) (b) Model 5: when \( p = 56\%p_{\text{max}} \) (c) Model 6: when \( p = p_{\text{max}} \)*
Von Mises Plastic Strain for Scenario 2

Fig. B5.5: Scenario 2 Von Mises Plastic Strain (a) Model 4: when internal pressure, $p = 0$, (b) Model 5: when $p = 56\% p_{max}$ (c) Model 6: when $p = p_{max}$
Von Mises Stress for Scenario 2

Fig. B5.6: Scenario 2 Von Mises Stress
(a) Model 4: when internal pressure, \( p = 0 \)
(b) Model 5: when \( p = 56\%p_{\text{max}} \)
(c) Model 6: when \( p = p_{\text{max}} \)
Results from the ANSYS FE software solver output for Scenario 3 showing when internal pressure, \( p = 0 \) (Model 7), \( p = 56\% p_{\text{max}} \) (Model 8) and \( p = p_{\text{max}} \) (Model 9) are shown below.

**Pipeline Displacement for Scenario 3**

*Fig. B5.7:* Scenario 3 Pipeline displacement (a) Model 7: when internal pressure, \( p = 0 \)  
(b) Model 8: when \( p = 56\% p_{\text{max}} \)  
(c) Model 9: when \( p = p_{\text{max}} \)
Von Mises Plastic Strain for Scenario 3

Fig. B5.8: Scenario 3 Von Mises Plastic Strain (a) Model 7: when internal pressure, $p = 0$, (b) Model 8: when $p = 56\%p_{\text{max}}$ (c) Model 9: when $p = p_{\text{max}}$
Fig. B5.9: Scenario 3 Von Mises Stress (a) Model 7: when internal pressure, $p = 0$, (b) Model 8: when $p = 56\% p_{\text{max}}$ (c) Model 9: when $p = p_{\text{max}}$
Results from the ANSYS FE software solver output for Scenario 4 showing when internal pressure, \( p = 0 \) (Model 10), \( p = 56\%p_{\text{max}} \) (Model 11) and \( p = p_{\text{max}} \) (Model 12) are shown below.

**Pipeline Displacement for Scenario 4**

![Pipeline Displacement for Scenario 4](image)

Fig. B5.10: Scenario 4 Pipeline displacement (a) Model 10: when internal pressure, \( p = 0 \) (b) Model 11: when \( p = 56\%p_{\text{max}} \) (c) Model 12: when \( p = p_{\text{max}} \)
Von Mises Plastic Strain for Scenario 4

Fig. B5.11: Scenario 4 Von Mises Plastic Strain (a) Model 10: when internal pressure, \( p = 0 \), (b) Model 11: when \( p = 56\%p_{\text{max}} \) (c) Model 12: when \( p = p_{\text{max}} \)
**Von Mises Stress for Scenario 4**

*Fig. B5.12: Scenario 4 Von Mises Stress (a) Model 10: when internal pressure, \( p = 0 \), (b) Model 11: when \( p = 0.56p_{\text{max}} \) (c) Model 12: when \( p = p_{\text{max}} \)*
APPENDIX C – Calculations for various parameters and constants

Calculations of various parameters and constants as related to this research.

C.1 Extended Drucker-Prager (EDP) Linear Form Calculations

C.1.1 For cohesive soil (Silty clay)

(a) EDP Linear Yield Criterion Form

Constant C1, pressure sensitivity ($\alpha$) is given by the equation below:

$$\alpha = \frac{6 \sin \theta}{(3 - \sin \theta)}$$

Where:

$\theta$ = Angle of friction = 15°

$$\alpha = \frac{6 \times \sin 15^\circ}{(3 - \sin 15^\circ)}$$

$$\alpha = \frac{1.5529}{(3 - 0.2588)}$$

$$\alpha = \frac{1.5529}{2.7412}$$

$$\alpha = 0.5665$$

Constant C2, uniaxial yield stress ($\sigma_y$) is the yield strength of soil used.

$$\sigma_y = 20 \text{ MPa}$$

(b) EDP Linear Plastic flow potential form

Constant C1, pressure sensitivity ($\alpha$) is given by the equation below:

$$\alpha = \frac{6 \sin \varphi}{(3 - \sin \varphi)}$$
Where:
\[ \phi = \text{Dilatancy angle} = 0 \]

\[
\begin{align*}
\bar{\alpha} &= \frac{6 \times \sin 0^\circ}{(3 - \sin 0^\circ)} \\
\bar{\alpha} &= \frac{0}{(3 - 0)} \\
\bar{\alpha} &= \frac{0}{3} \\
\bar{\alpha} &= 0
\end{align*}
\]

C.2  Pipe Diameter – Thickness Ratio Calculations

\[ SDR = \frac{D_o}{t} \]

Where:
\( D_o = \text{pipeline outer diameter} \)
\( t = \text{pipeline wall thickness} \)

C.2.1  For D/t-96 pipeline

\[ SDR = \frac{D_o}{t} \]

Where:
\( D_o = 914.4 \text{ mm (0.9144 m or 36 inches)} \)
\( t = 9.53 \text{ mm (0.00953 m or 0.375 inches)} \)

P.S: This parameter is usually calculated using the dimensions in inches
\[ SDR = \frac{D_o}{t} \]

\[ SDR = \frac{36}{0.375} \]

\[ SDR = 96 \]

C.2.2 For D/t-72 pipeline

\[ SDR = D_o / t \]

Where:

\[ D_o = 914.4 \text{ mm (0.9144 m or 36 inches)} \]

\[ t = 12.7 \text{ mm (0.0127 m or 0.5 inches)} \]

\[ SDR = \frac{36}{0.5} \]

\[ SDR = 72 \]

C.3 Determination of Maximum Design Operating Pressure (\( p_{max} \)) for the Pipelines

\[ p_{max} = 0.72 \times 2\sigma_y \frac{t}{D_o} \]

Where:

0.72 = safety (reduction) factor constant (ASME guideline, 2007)

\( \sigma_y \) = pipeline yield strength

\( t \) = pipeline wall thickness

\( D_o \) = pipeline outer diameter
C.3.1 For D/t-96 pipeline

\[ p_{\text{max}} = 0.72 \times 2\sigma_y \frac{t}{D_o} \]

Where:

\( 0.72 = \text{safety (reduction) factor constant (ASME guideline, 2007)} \)
\( \sigma_y = 450 \text{ MPa} \)
\( t = 9.53 \text{ mm} \)
\( D_o = 914.4 \text{ mm} \)

\[ p_{\text{max}} = 0.72 \left( 2 \times 450 \frac{9.53}{914.4} \right) \]

\[ p_{\text{max}} = 0.72 \times 9.38 \]

\( p_{\text{max}} = 6.8 \text{ MPa} \approx 7 \text{ MPa} \)

C.3.2 For D/t-72 pipeline

\[ p_{\text{max}} = 0.72 \times 2\sigma_y \frac{t}{D_o} \]

Where:

\( 0.72 = \text{safety (reduction) factor constant (ASME guideline, 2007)} \)
\( \sigma_y = 450 \text{ MPa} \)
\( t = 12.7 \text{ mm} \)
\( D_o = 914.4 \text{ mm} \)
\[ p_{\text{max}} = 0.72 \left( 2 \times 450 \frac{12.7}{914.4} \right) \]

\[ p_{\text{max}} = 0.72 \times (900 \times 0.0139) \]

\[ p_{\text{max}} = 0.72 \times 12.51 \]

\[ p_{\text{max}} = 9 \text{ MPa} \]