INVESTIGATION OF SOIL-PIPE FORCES AND THE RESULTANT STRESS ANALYSIS FOR UNDERGROUND PIPELINES

A thesis submitted in partial fulfilment of the requirements for the Degree of
Master of Technology
(Pipeline Engineering)

Submitted by:

Dan Jo Chacko
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College of Engineering Studies
University of Petroleum and Energy Studies
Dehradun
May, 2015

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BONAFIDE CERTIFICATE

This is to certify that the work contained in this thesis titled “Investigation of Soil-Pipe Forces and the Resultant Stress Analysis for Underground Pipelines” has been carried out by Dan Jo Chacko under my/our supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Pipelines are very important lifelines to modern society as they are used for the transport of energy and services. A good engineering design practice requires that environmental and economic factors need to be taken into consideration. This is often means that the overall design performance must be predicted beforehand. Analysing an underground pipeline is quite different from analysing basic piping. There are a number of unique characteristics of a pipeline like code requirements and techniques which are required for its analysis. Elements of analysis include pipe movement, anchorage force, soil friction, lateral soil force and soil-pipe interaction.

Pipelines can be buried in various environments with varying soil properties. As the soil properties differ, the stress on the pipeline varies. Based on soil information obtained from investigation along the pipeline route, geotechnical analyses are preformed to determine pipeline construction method. As the major segment of a pipeline is usually buried, soil-pipeline interaction analysis is the most important part of pipeline stress analysis. Before analysis, soil forces that are acting on the pipeline must be investigated.

In this paper, analytical and numerical solutions will be researched to determine the forces and the stresses in a buried pipeline. Application of stress analysis and comparing the soil pipe interaction allows one to assess the integrity of the pipeline. The purpose of this research is to aid in the selection of proper pipeline design and construction mode which will ensure pipeline integrity and minimize project costs. For the common case of buried pipelines built in backfilled trenches, stress analysis methods are employed to determine the necessary issues so as to determine the interaction with the native soil, that result in a significant increase or decrease in the force applied on the pipeline during ground movement. The described approach can be employed in project-specific analyses to determine soil pipe interaction, and thus avoid unnecessary excavation costs or mitigation measures.

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NOMENCLATURE

Ca	- Corrosion allowance
$SMYS$	- Specified minimum yield strength
LF	- Longitudinal Joint Factor
P	- Internal pressure, psi
D	- Diameter, in
t	- Nominal wall thickness of pipe, inch
l	- Length of a pipe section, inch
T_1	- Temperature that the time of installation, °F
T_2	- Maximum operating temperature, °F
α	- Linear coefficient of thermal expansion, inch/inch/°F
v	- Poisson's ratio (0.3 for steel)
S_h	- Hoop stress due to fluid pressure, psi
S_L	- Longitudinal stress in the pipe, psi
E	- Modulus of elasticity of pipe, psi
Δ	- Net free expansion, inch
f	- Axial friction force, lbs/in

μ	- Coefficient of friction between pipe and soil
γ	- Density of backfill soil, lbs/ft^3
H	- Depth of soil cover to top of pipe, ft.
W_p	- Weight of pipe and content, lbs/ft
U	- Ultimate soil resistance, lbs/ft
θ	- Angle pipe makes with soil during displacement
K	- Elastic constant, lbs. /inch
K_o	- Ccoefficient of lateral soil pressure
L	- Active length, inches
F	- Anchor force or expansion force, lbs
Q	- End resistance force, lbs.
β	- Constant $\sqrt{\frac{K}{4EI}}$
C	- Constant
I	- Moment of inertia
Z	- Section modulus, inches^3

CHAPTER 1

1. INTRODUCTION

One of the major factors that affect good engineering is that favorable economic designs are provided at an acceptable safety range. More often than not engineers are bound with the problem of predicting the performance of a system with little information and data.

Pipelines are one of the safest and most economical means of transporting hydrocarbons, gases, water and other fluids or slurries. Pipelines are usually buried to increase the economic feasibility of the oil and natural gas. These buried pipelines are subjected to a multiple external loads. As pipelines are a serious asset, they can cause serious economic and environmental consequences if they fail in any way.

The pipeline industry has been interested in predicting soil and pipe behavior when the pipeline is subjected to external loadings so as to minimize the risk of any accident, injury and material loss and also to prevent the damages that cause a great risk to the environment. Pipelines are generally designed on the basis of the, flow requirements and the operating pressure. For buried pipelines, additional design requirements are needed such as the maximum and minimum cover depth, the trench geometry and backfill properties. Owing to the highly nonlinear behavior of soil material, pipe-soil interface phenomena, and the possibility of pipe distortion, buried pipe-soil system has a relatively complex behavior.

Pipe soil interactions are usually used to investigate the various stresses created due to the pipeline operating parameters, external loads and soil properties. Soil pipe interaction gives a proper understanding of how the stresses are created and varies in the soil across the length of the pipeline.

To ensure a realistic and acceptable analysis it is important that any significant interaction process between the pipe and the soil is recognized and represented in the calculations. This is necessary for the identification, experimental investigation and theoretical modelling of the soil-pipe interaction under appropriate loading conditions leading to a gradual improvement of the modelling of buried pipelines.

This paper will investigate the various stresses that occur in a pipeline due with a major concern on how they vary with soil properties and soil types. The type of soil which is predetermined by the surveyor plays an important role in predetermining the stresses in the pipeline as all stresses will be calculated with regards to the surveyed soil. If at all the surveyed soil turns out to be incorrect, during the time of construction it will hinder great problems as re-engineering and re-planning of the project will be needed. Also the scope of the project gets hindered as there will be economic losses followed by time delays.

Soil types greatly hinder the stresses that are created with regards to soil pipe interaction, thus a proper investigation on how these variables varies due to different boundary conditions will be studied. A numerical analysis will be investigated on how these stresses changes with various soil types including hard rocks.

CHAPTER 2

2. LITERATURE REVIEW

One of the major however usually neglected problem in the pipeline industry is the soil and pipe interaction and its complexity. If at all a natural disaster involving ground movement such as an earthquake occurs, the nonlinear behavior of the soil further increases the complexity. This complexity is credited to the soil rather than the pipe. However in this thesis will not include external loadings.

2.1 Soil Model

When comparing other engineering materials such as steel and concrete, soil behavior is very difficult to predict. This is because soil is a multi-phase material consisting mainly solid particles, water and air (or sometimes oil and gas may be present). These make the components of soil very complex. The soil properties vary across the region to region across the field.

To describe the behavior of soil, many conceptual models have been developed. All of them are the simplifications of real soil behavior and concentrated on some particular aspect. Some of the models are relatively simple, but some of them are very complex. However, there is no unique model yet developed that is valid for all geologic materials under all loading and physical conditions, this is still true today (FaiNg, 1994).

The classification of soils (Indian Standard 1498, 1970)

a) **Clay**

An aggregate of microscopic and sub-microscopic particles derived from the chemical decomposition and disintegration of rock constituents. It is plastic within a moderate to wide range of water content.

b) Slit

It is a fine-grained soil with little or no plasticity. If shaken in the palm of the hand, a part of saturated inorganic silt expels enough water to make its surface appear glossy. If the pat is pressed or squeezed between the fingers, its surface again becomes dull.

c) Sand and gravel

Cohesion-less aggregates of angular, sub-angular, sub-rounded, rounded, flaky or flat fragments of more or less unaltered rocks or minerals. Particles from 0.06mm up to 2mm are referred to as sand, and those with a size greater than 2mm to 60mm as gravel

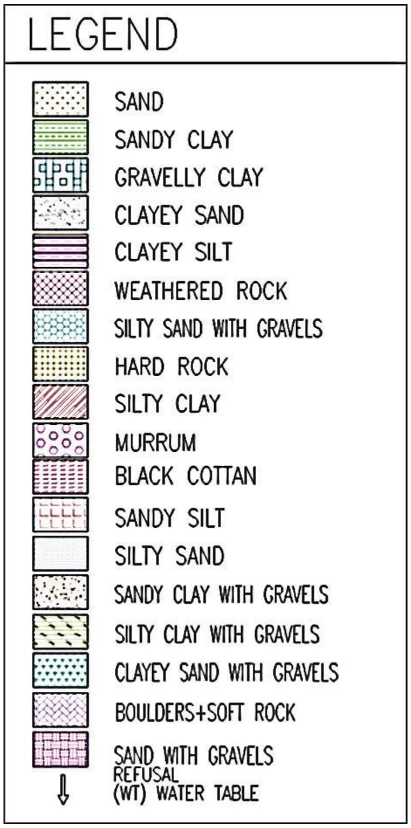

Figure 1: Various ground properties during for pipeline design and construction

2.2 Soil Spring models

A study was done on the Guidelines for Seismic Design of Buried Pipelines by Suresh R. Dash and Sudhir K. Jain in 2007. They analyzed a number of important pipelines and came out with a finite element model that best represents the non-linearity of the system. The models used to represent the soil pipe interaction are *Continuum model, Soil mesh finite element model and Beam on Nonlinear Winkler Foundation model*. In a continuum model a rigorous mathematical formulation is devised for a flexible pipe of finite length embedded in a semi-infinite soil medium and in a Soil mesh model the complicated nonlinearity of the system is modeled. Whereas in the Beam on Nonlinear Winkler Foundation (BNWF) model the soil is represented by independent springs lumped at discrete locations of the pipe. The BNWF model is extensively used in practice due to its simplicity, mathematical convenience and ability to incorporate nonlinearity. (Dash, 2007)

The pipe can either be modeled as a three dimensional shell element or as a two dimensional beam element depending on the pipeline geometry and loading condition as shown in figure1. The soil surrounding the pipe is modeled as nonlinear springs. Basically four types of springs are used to model the surrounding soil as:

i) Axial soil spring: Represents soil resistance over the pipe surface along its length.
ii) Lateral soil spring: Represents the lateral resistance of soil to the pipe movement.
iii) Vertical bearing spring: Represent the vertical resistance of soil at the bottom of the pipe.
iv) Vertical uplift spring: Represent the vertical resistance of the soil at the top of the pipe.

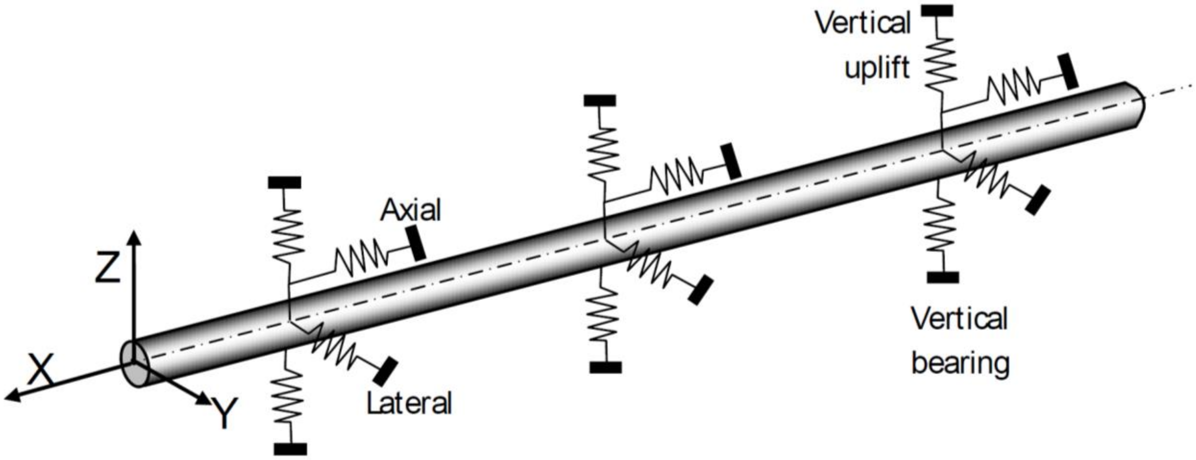

Figure 2: Soil-Pipe interaction of Beam on Nonlinear Winkler Foundation (BNWF) model

2.3 Soil- Pipe Interaction Modes

The stress which is observed in a pipe line is quite different from those stresses that are observed in a process piping or free standing pipe. Underground pipelines/buried pipelines experiences an interaction between the soil and the pipe.

Cases when an external load acts on a buried pipe, the actual magnitude and distribution of the soil pressure around the pipe is difficult to estimate accurately and is related to the depth of burial, geometry and plan of the site, pipe stiffness and mechanical properties of the soil. The complete definition of the soil-pipe system also requires specification of the load transfer conditions at the soil/pipe interface. Tangential load conditions may vary between non-slippage and full slippage but normally non-slippage until a prescribed stress is reached.

2.3.1 Diametric Deflection

The vertical load acting on a pipe is very much influenced by the arching action of the surrounding soil. For rigid pipes, the deformation of the pipe crown is generally very small when compared with the soil deformation on either side of the pipe. This differential settlement of the soil gives rise to the concentration of load on the pipe crown and this is called the negative arching effect of soil. The horizontal stresses caused by pipe deformation remain practically unchanged in this case. For flexible pipes, soil arches will be formed around the pipe due to the large downward deflection of the pipe crown, thus reducing the external load imposed on the pipe. This is called positive arching action. In addition to the downward deflection of the crown, the two sides of the pipe also deflect, in this case horizontally outwards. This will generate lateral passive resistance in the soil resulting in an increase of the horizontal stresses. (FaiNg, 1994)

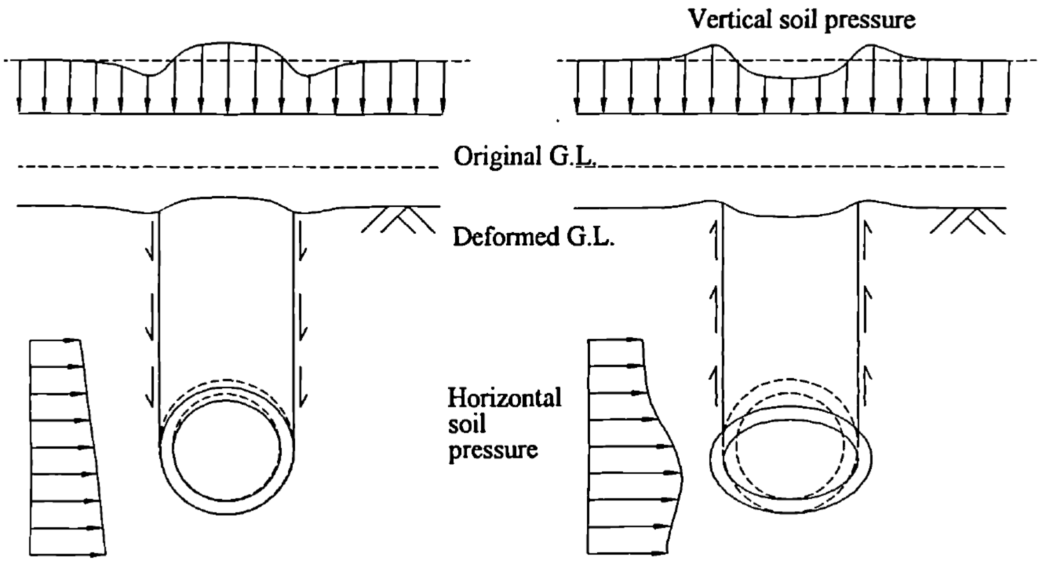

Figure 3: Load distribution and ground settlement profile-Negative/Positive arching effect.

2.3.2 Axial Soil-Pipe Interaction

The ground movement acting horizontally and parallel with the longitudinal axis of a pipe may create a soil pipe interaction if the axial stiffness of the pipeline permits it to resist the deformation of the ground. The relative soil/pipe movement is usually concentrated in a narrow annular zone where shear failure and slippage occurs at the soil/pipe interface. The relative movement decreases rapidly away from the pipe surface.

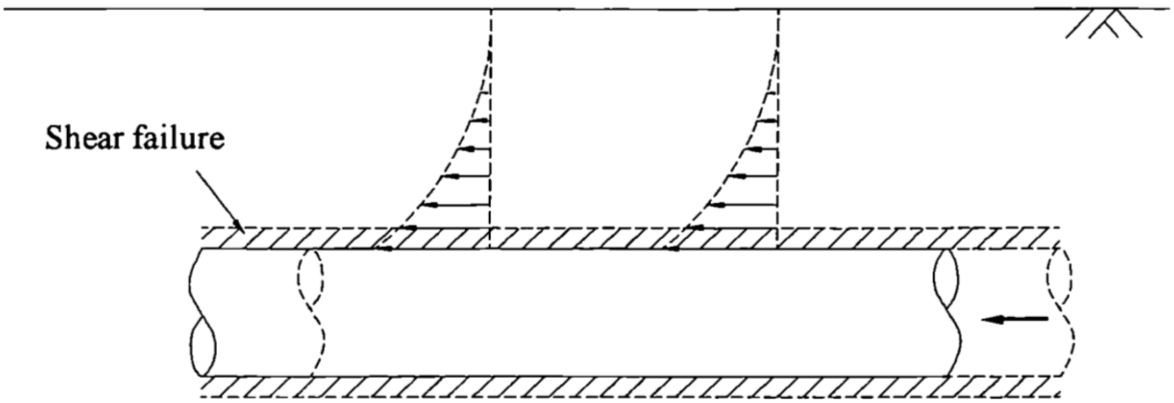

Figure 4: Resulting ground movement due to axial pipe movement

2.3.3 Longitudinal Bending

If a very flexible pipe passes through a soil displacement field, it will follow the ground displacement profile exactly. For a more rigid pipe, the bending stiffness of the pipe will provide a certain restraint to the pipe displacement which will be different to that of the soil. The loading along the pipe may vary according to the relative displacement between the soil and the pipe, reaching a maximum value where the soil adjacent to the pipe is brought to complete failure. The maximum restraint that can be offered by the soil may be influenced by the direction in which ground movement takes place (upward, downward and lateral movements).

The settlement of the soil past a pipe will enforce that the soil is loaded from the material above the pipe or the soil is moving downwards. Excessive relative movement between the soil and the pipe will produce tensile and shear failure in the overlying soil leading to the development of a soil wedge over the pipe rather than complete failure of the surrounding soil. (FaiNg, 1994)

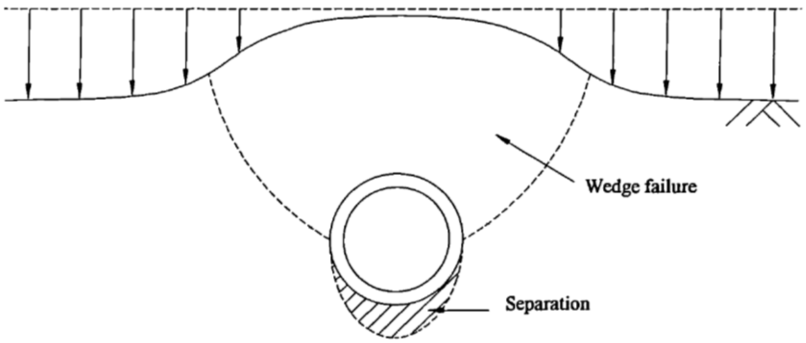

Figure 5: Ground behavior due to settlement around a stationary pipe

Conversely, if the soil is moving upward relative to the pipe, restraint will be provided by the passive resistance of the underlying soil. The soil resistance will increase with the displacement of the pipe reaching a maximum value when the surrounding soil has been brought to complete failure.

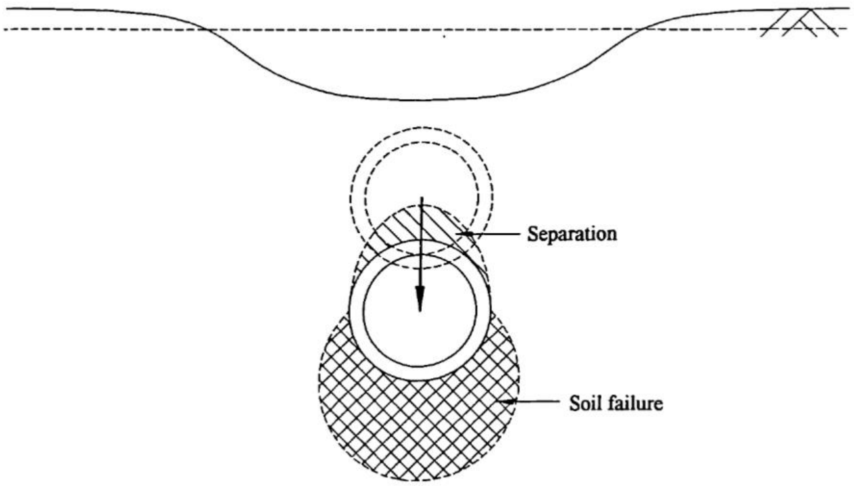

Figure 6: Ground behavior die to downward pipe movement

Horizontal movement of the ground in a direction perpendicular to the longitudinal axis of the pipe may produce a similar effect as upward movement of the soil. Horizontal passive resistance is produced by the soil in front of the pipe. If the depth of burial is too shallow, wedge failure of the soil may occur in front of the pipe.

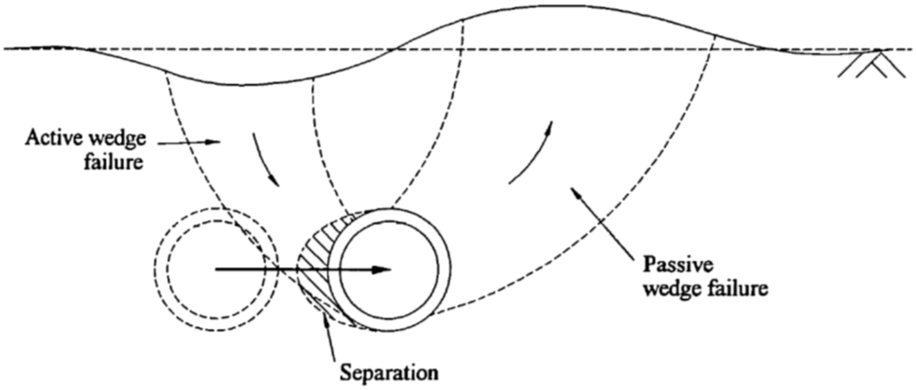

Figure 7: Ground behavior due to horizontal pipe movement

CHAPTER 3

3. THEORETICAL DEVELOPMENT

When considering the stresses in a pipeline to a process piping system it is quite different. A pipeline has unique characteristics which involves the analysis of techniques and code requirements. These elements of pipeline analysis include pipe movement, anchorage force, soil friction, lateral soil force and soil pipe interaction.

The main characteristics of a pipeline include:

- **High allowable stress**

  A pipeline has a rather very simple shape. It is circular and very often runs to several miles before making a turn. And even if a turn is made it is not very a sharp turn compared to process piping. Therefore, all the stresses in the pipeline can be calculated by simple static equilibrium formulas which have proven to be very reliable. Since stresses are predictable, the allowable stress used is considerably higher than used in the plant piping.

- **High pressure elongation**

  The movement of a pipeline occurs usually due to the expansion of a very long line at low temperature difference. Pressure elongation, is actually neglected in process/plant piping , whereas pressure is what actually contributes to much of the total movement and is included in the analysis of stresses in a pipeline.

- **High yield strength pipe**

  A pipeline operating beyond yield strength may not create structural integrity problems. However it may create a rise to undesirable excessive deformations and can always give cause a possibility of strain to follow up. For this reason a high test line pipe with a very high yield to ultimate strength ratio is normally used in a pipeline construction. Yield strength can be as high as 80 % of ultimate strength. All other allowable stress is then based with regards to the yield strength. (ASME B31.4, 2002)

- **Soil-pipe interaction**

  The major portion of a pipeline is usually buried underground. Any pipe movement that occurs has to overcome the soil force. This force can be divided into two categories:

  i) Friction force : This force is created from sliding
  ii) Pressure force : This is the force resulting from pushing

3.1 Forces in the Pipe

There are a number of steps when doing Soil-Pipe interaction analysis.

3.1.1 Wall thickness:

One of the first steps required in stress analysis is calculating the wall thickness required.

As per ASME B31.4 nominal wall thickness for a straight pipe under internal pressure is given by the following expression:

$$t = \frac{PD}{2 \times SMYS \times LF \times F}$$

$$t_{sel} = t + Ca$$

Where,

t	- Minimum wall thickness
Ca	- Corrosion allowance
P	- Design internal pressure
D	- Pipeline outside diameter
SMYS	- Specified minimum yield strength
F	- Applicable design factor
LF	- Longitudinal Joint Factor

3.1.2 Hoop Stress

Hoop stress is the stress in a pipe wall, acting circumferentially in a plan perpendicular to the longitudinal axis of the pipe and produced by the pressure of the fluid in the pipe. The hoop stress, then, is an action which is attempting to pull the pipe apart in a circumferential direction with the "pull" being produced on the pipe wall by the internal pressure of the natural gas or other fluid in the pipe.

$$S_h = \frac{PD}{2t}$$

Where:

S_h - Hoop stress, psi

P - Internal pressure, psi

D - Diameter, in

t - Wall thickness, in

3.1.3 Expansion and flexibility

One of the major tasks of stress analysis is flexibility analysis. A pipeline is classified in to two categories*: restrained lines* and *unrestrained lines*. A pipeline whether it is buried or above ground has both fully restrained portions and moving portions. The moving portions, which are equivalent to the codes unrestrained lines, will generally create significant bending stress. (Technical pipe analsysis, 2013)

Usually in an above ground pipeline restrained portions are always prevented from movement, by the installation of anchors and guides. However in a buried line a large portion is fully restrained by soil friction only.

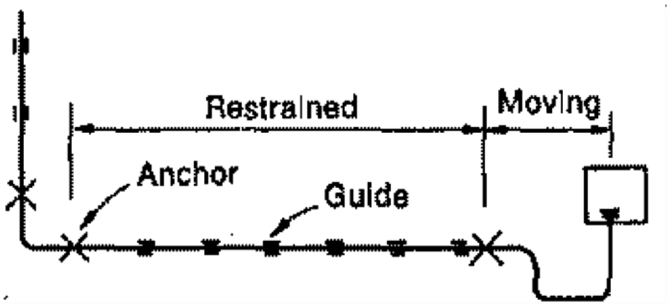

Figure 8: Above ground piping

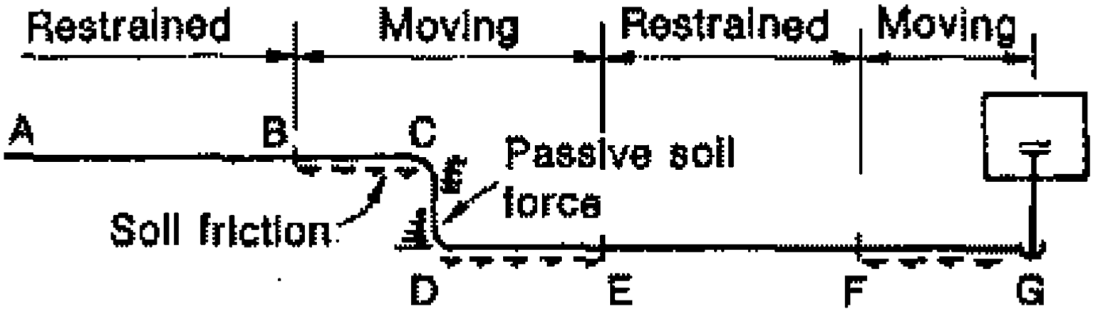

Figure 9: Underground piping

When a line is pressurized and heated, corners C, D and G will starting moving. The movement thereafter creates a soil frictional which is proportional to the length of the moving portion of the pipe. If the total friction force developed along the pipe is sufficient to suppress expansion, the movement will stop. Points B, E and F where the movement stops are called virtual anchor points. Nonmoving portions AB and EF are called fully restrained lines. (Line size , 1999)

3.1.4 Restrained Portions

A force is required to bring the pipe the pipe from its free expanded or contracted position to the original position, to prevent movement of the pipe. In a fully restrained line longitudinal pressure stress is absorbed by the anchor or soil friction and does not come into the picture. Considering a pipeline that has the following properties and features:

L - Length of a pipe section, inch

T_1 - Temperature that the time of installation, °F

T_2 - Maximum operating temperature, °F

α - Linear coefficient of thermal expansion, inch/inch/°F

v - Poisson's ratio (0.3 for steel)

S_h - Hoop stress due to fluid pressure, psi

S_L - Longitudinal stress in the pipe, psi

E - Modulus of elasticity of pipe, psi

Δ - Net free expansion, inch

t - Nominal wall thickness of pipe, inch

When a temperature reaches T_2 the pipe section will expand $\alpha(T_2 - T_1)L$, however the hoop tensile stress will make it to shrink to $\nu ShL/E$. When steel is stretched one inch in one direction, it will shrink 0.3 inch each in both perpendicular directions. This phenomenon of shrinkage is called Possions shrinkage, and 0.3 is the Poisson ratio of steel. (Joshi , Cherian , & Rao , 2001)

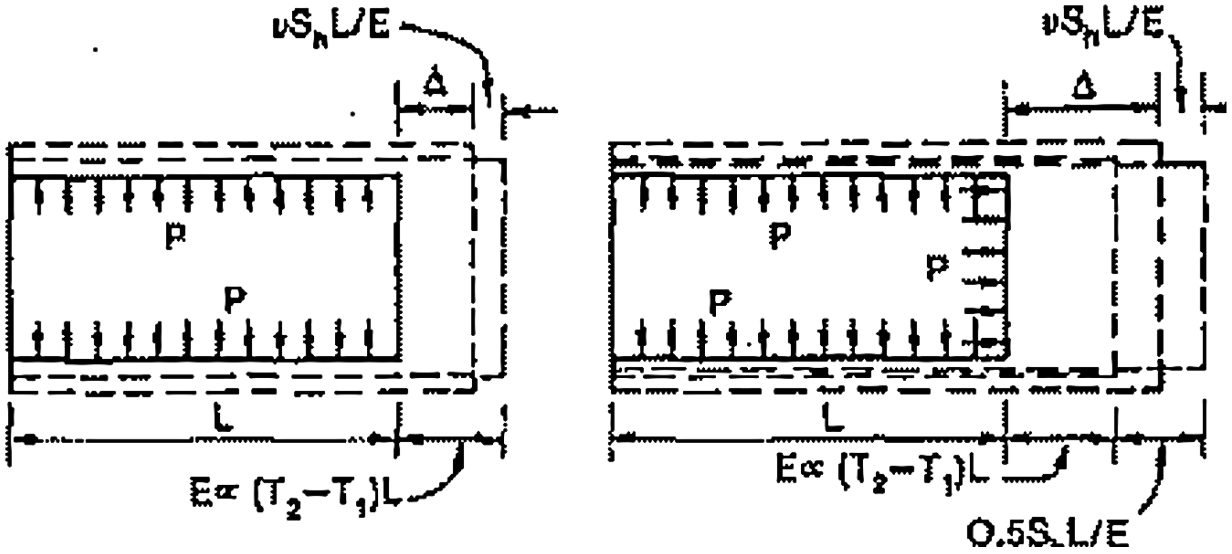

Figure 10: Free expansion of pipe with and without longitudinal pressure

When subtracting the Poission shrinkage from the expansion, net expansion becomes,

$$\Delta = \alpha(T_2 - T_1)L - \frac{\nu S_h L}{E}$$

Also the longitudinal stress which is produced is equivalent to the stress which is required to squeeze Δ back to its original position.

Since,

$$S_L = -\frac{E\Delta}{L}$$

Therefore,

$$S_L = -E\alpha(T_2 - T_1) + \nu S_h$$

This is equations are taken from ASME 31.4. However the sign has been reversed such that the minus means it is a compressive stress. The net longitudinal stress becomes compressive for a reasonable increase of T_2. The combined equivalent stress shall not exceed 90 percent of SMSY.

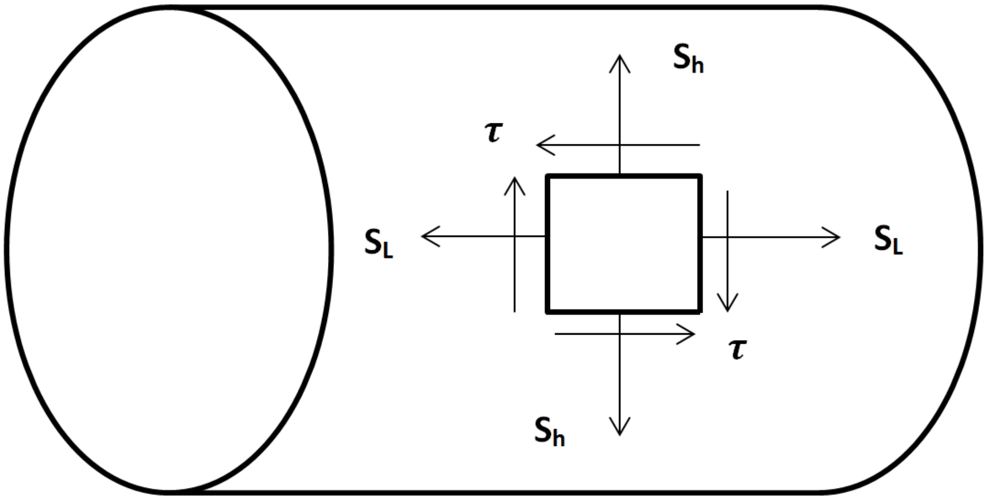

Figure 11: The stresses acting on a pipe wall

From the theory of principle stresses, the maximum shear stress in a pipe can be shown as:

$$\tau_{max} = \sqrt{\frac{(S_h - S_L)^2}{4} + \tau^2}$$

Where τ is shear stress in the principle axes o the pipe. The shear yield stress equals one half of tensile yield stress, an equivalent tensile stress is defined as twice the maximum shear stress. The equivalent tensile stress can be therefore said to be,

$$S_e = 2 \times \tau_{max}$$

$$S_e = \sqrt{(S_h - S_L)^2 + 4\tau^2}$$

S_e is to be limited to 0.9 SMYS.

3.1.5 Anchor Force

An anchor is usually installed to limit the end movement of the pipe. It is the anchor that separates the restrained position from the moving portion of the line. The anchor force comes from both sides, the longitudinal stress from the restrained side and pressure force from the moving side. Since longitudinal pressure stress equals to $0.5S_h$ the anchor force can be therefore expressed as:

$$F = A(0.5S_h - S_L)$$

Or

$$F = A[(0.5 - \nu)S_h + E\alpha(T_2 - T_1)]$$

Where the A is the area is the area of the pipe $A = \pi Dt$

3.1.6 Moving Parts (Unrestrained lines)

Usually the temperature change in a pipeline is not very high. The expansion due to pressure effect is significant and is usually ignored. When the pipeline reaches an operation temperature of T_2, the pipe expands in every direction. (Peng, 1988)

When considering the longitudinal direction, the thermal expansion is

$$\alpha(T_2 - T_1)L$$

Applying the longitudinal pressure, the pipe will expand $0.5S_hL/E$ in the longitudinal direction but will shrink in the diametrical directions. Adding the radial pressure or the *Hoop stress*, the pipe shrinks to $0.3S_hL/E$ in the longitudinal direction due to Possion effect.

Therefore the net longitudinal expansion is :

$$\Delta = \alpha(T_2 - T_1)L + \left(\frac{0.5S_hL}{E} - \frac{0.3S_hL}{E}\right)$$

Now since strain $\varepsilon = \Delta/L$ we can use the net longitudinal expansion to get the expansion rate

$$\varepsilon = \alpha(T_2 - T_1) + \frac{0.2S_h}{E}$$

The net expansion rate is equivalent to strain resulting from a pull by a force having the same magnitude as the anchor force. Therefore we can say that, the anchor force is referred to as potential expansion force. (Chaun, 1978)

3.2 Soil forces

The major portion of a pipe line is normally buried. The soil-pipe interaction analysis is the most important part of pipeline stress analysis.

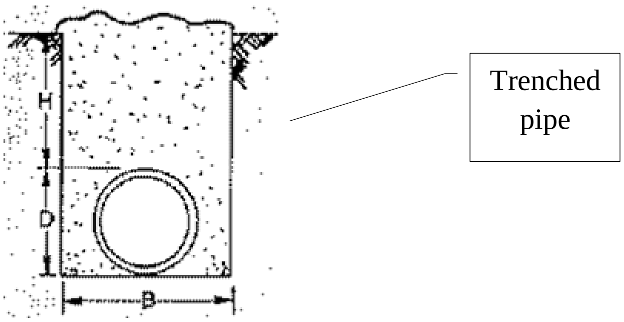

Figure 12: Pipeline trenched in a certain depth of soil cover

A pipe line buried in a ditch or a trench. Because of the soil backfill and the pipe's own weight, the pipe receives a soil pressure acting at its surface. The pressure creates a bending stress on the pipe wall and at the same time produces a soil friction force against any axial pipe movement. Except in highway or railroad crossings, the bending stress created by uneven soil pressure is negligible.

3.2.1 Axial friction force

The friction force is the first soil force that affects any pipe movement. The axial pipe movement gives rise to axial friction force. Theoretically, friction force is equal to the product of the friction coefficient and the total normal force acting all around the pipe.

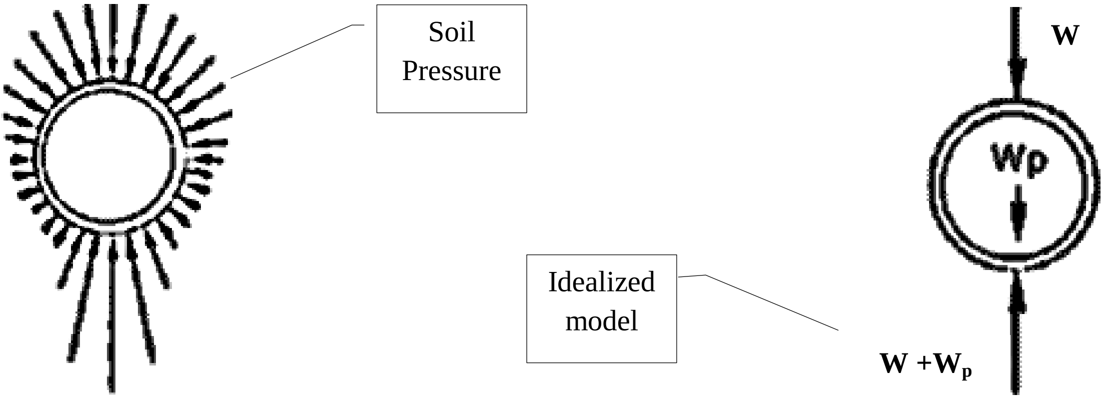

Figure 13: Soil Pressure distribution

The normal force acting on the pipe surface can be divided into top force, *W*, and bottom force, *W* + *Wp*, where *Wp* is the weight of the pipe and its content. When the soil cover depth ranges from one to three times the pipe diameter, the force can be taken as the weight of the soil with addition over the pipe.

Therefore the axial friction force is given by:

$$f = \frac{\mu\left(W + W + W_p\right)}{12}$$

Or

$$f = \frac{\mu\left(2\gamma DH + W_p\right)}{12}$$

Where,

f - Axial friction force, lbs/in

μ - Coefficient of friction between pipe and soil

γ - Density of backfill soil, lbs/ft^3

D - Outside diameter of pipe (1-3 times the diameter), ft

H - Depth of soil cover to top of pipe, ft.

W_p - Weight of pipe and content, lbs/ft

The soil density and friction coefficient are obtained from soil tests performed along the pipe line route while doing the initial survey. However in this thesis we will be using various soil densities and their respective friction coefficients to compare how the soil-pipe forces various for each type.

3.2.1.1 Coefficient of friction sub axial friction force

The friction force is the force exerted by a surface when an object moves across it - or makes an effort to move across it.

Type of Soil	**Friction Coefficient**
Slit	0.3
Sand	0.4
Gravel	0.5
Concrete	0.45

Table 1: Friction Coefficients for some Common Materials with steel
http://www.engineeringtoolbox.com/friction-coefficients-d_778.html (Engineering tool box, 2013)

3.2.1.2 Density of backfill soil sub axial friction force

Density, as applied to any kind of homogeneous monophasic material of mass *M* and volume *V*, is expressed as the ratio of *M* to *V*. Under specified conditions, this definition leads to unique values that represent a well-defined property of the material. The soil bulk or dry density is the ratio of the mass of the solid phase of the soil to its total volume.

Soil Type	**Dry Density** γ	
	g/cm^3	**lb/ft^3**
Clay	1.20	74.9135
Clay Loam	1.28	79.9077
Slit loam	1.28	79.9077
Loam	1.36	84.9020
Sandy loam	1.44	89.8962
Sand	1.52	94.8905
Concrete	2.40	149.8271
Rock	2.40 -3.50	149.8271 – 218.4978

Table 2: Typical values of dry density of various soil types, concrete and rocks
http://web.ead.anl.gov/resrad/datacoll/soildens.htm (Carter, 2002)

3.2.1.3 Angle of internal friction

It is basically the angle that the pipe makes with soil while displacement takes place.

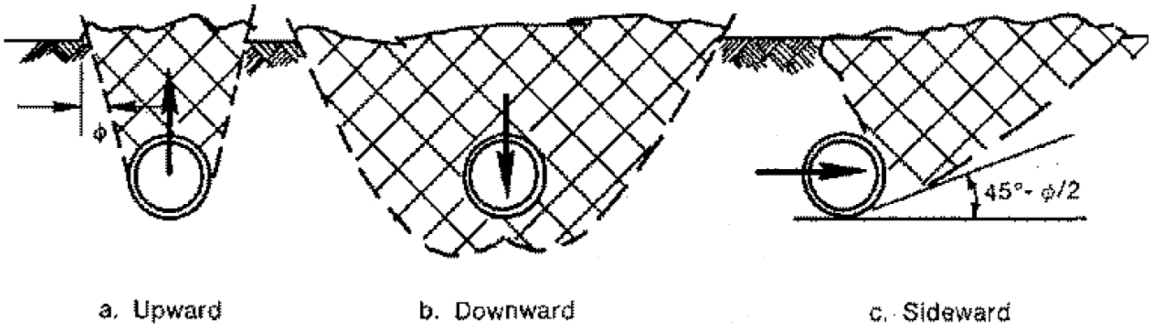

Figure 14: Angle of internal friction made due to lateral soil forces

Soil Type	$\theta°$ degree
Slits	26 – 35
Sand: Rounded grains	
Loose	27 – 30
Medium	30 – 38
Dense	35 – 38
Sand: Angular grains	
Loose	30 – 35
Medium	35 – 40
Dense	40 – 45
Gravel with sand	34 – 48

Table 3: Angle of Internal Friction for different soil types
http://www.geotechnicalinfo.com/angle_of_internal_friction.html (Geo, 2001)

3.2.2 Lateral Soil Force

The lateral force can be ideally classified as into two stages;
Elastic stage, where resistance force is proportional to pipe displacement
Plastic stage, where resistance remains constant regardless of displacement.

Though the elastic constant can be evaluated directly by tested or published methods, they are generally very sensitive to the data gathered. An alternate method is to calculate from the more reliable ultimate resistance. It has been studied that the displacement required to reach ultimate resistance is about 1.5 to 2 percent of the pipe bottom depth. (Talesnick, Xia, & Moore , 2011)

When a pipe moves horizontally (figure 7), it creates a passive soil pressure at the front of the pipe surface. At the same time the pipe receives an active soil force at the back side. Due to this arch action, a void is created behind the pipe as soon as it moves a small distance. The active soil force can therefore be disregarded. The only lateral force is the passive soil force.

The lateral force is given by the formulae:

$$U = \frac{1}{2}\gamma(H + D)^2 \tan^2\left(45 + \frac{\theta}{2}\right)$$

Where,

U - Ultimate soil resistance, lbs/ft

θ - Angle pipe makes with soil while displacement takes place

γ - Density of backfill soil, lbs/ft^3

D - Outside diameter of pipe (1-3 times the diameter), ft

H - Depth of soil cover to top of pipe, ft.

From previous studies elastic constant can be calculated from ultimate resistance by taking 1.5 percent of the total depth as yield displacement. Taking 1.5 percent of the total depth as the yield displacement, the elastic constant can be written as: (Liangchaun, 1978)

$$K = \frac{U}{0.015(H + D) \times 144}$$

Or

$$K = 0.2315\gamma(H + D)\tan^2\left(45 + \frac{\theta}{2}\right)$$

Where,

K - Elastic constant, lbs. /inch

θ - Angle pipe makes with soil while displacement takes place

γ - Density of backfill soil, lbs/ft^3

D - Outside diameter of pipe (1-3 times the diameter), ft

H - Depth of soil cover to top of pipe, ft.

Elastic constant *K* is a constant value or coefficient that expresses the degree to which a material possess elasticity. In an elastic material that has been subjected to strain below its elastic limit, the elastic constant is the ratio of the unit stress to the corresponding unit strain.

3.2.3 Soil End Force

The soil end force acting on the vertical entry leg can be calculated aby adding the side shears to the lateral force. (Liangchaun, 1978)

$$Q = \frac{\gamma}{2}(H + D)^2 \tan^2\left(45 + \frac{\theta}{2}\right) D + \frac{(H + D)^3 \gamma K_o tan\theta}{3 \tan\left(45 + \frac{\theta}{2}\right)}$$

Here, K_o is the coefficient of lateral soil pressure is found out by,

$$K_o = 1 - sin\theta$$

3.2.4 Longitudinal Pipe Movement

One of the major problems that buried pipelines face is the flexibility issues. The flexibility problem originates from the expansion of the pipe. Therefore, the first step of flexibility analysis is to determine longitude movement.

When considering a pipeline pump station or a pigging station. Point ***A*** is a pig launcher. When the line is heated up, the end of pipe ***B*** will start to move. The movement produces a friction force (*f*), simultaneously an end resistance (*Q*) develops because of soil passive force and pipe stiffness. The moving portion of the pipe will extend gradually downstream to a point ***C*** where the movement stops.

As the moving portion extends, the friction force also increases, and when the moving boundary reaches a point ***C***, the friction force plus end force developed is enough to suppress the expansion completely. Point ***C*** is sometimes called virtual anchor point and the moving length (*L*) is called the active length.

At the scraper barrel end, the stress is tensile and equal to the pressure stress. The tensile stress is reduced gradually due to end force and friction force, and then eventually becomes compressive if the line is hot enough. Finally, at C, the compressive stress reaches maximum and stays the same for the entire fully restrained portion.

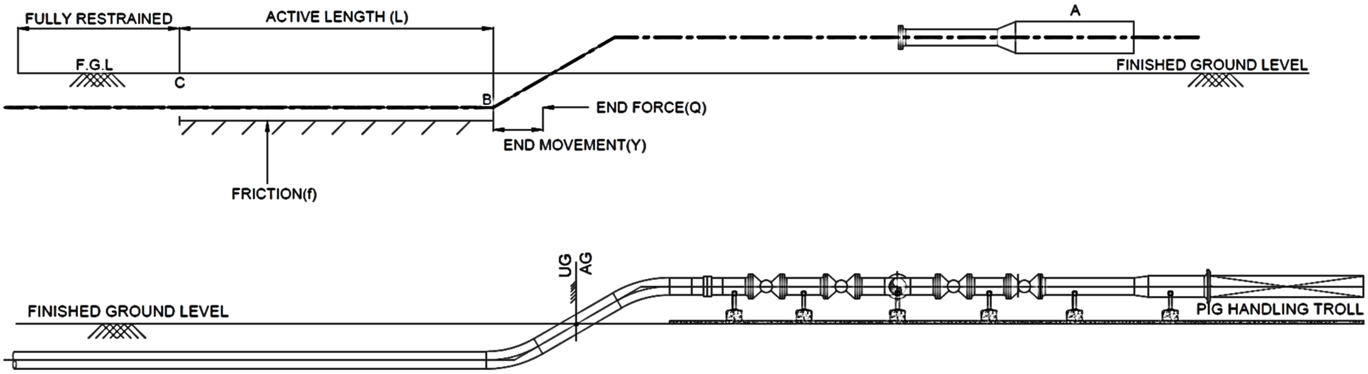

Figure 15: Force distribution during longitudinal movement

The active length of the line can be determined by equating friction force plus end force with the required anchor force. The active length is given by the following formulae: (Liangchaun, 1978)

$$fL + Q = F$$

Or

$$L = \frac{F - Q}{f}$$

Where,

L - Active length, inches

F - Anchor force or expansion force, lbs

Q - End resistance force, lbs.

f - Soil friction force, lbs/in.

Once the active length is determined, the end movement or the end displacement (*y)* can be calculated by multiplying the average expansion rate with the length. The rate of expansion at point C is zero, and the rate of expansion at the end B is equivalent to the pull of the potential expansion force in this case anchor force(F) minus the end force(Q)

$$y = \frac{1}{2}\left(0.0 + \frac{1}{AE}(f - Q)\right)L$$

Applying $L = \frac{F-Q}{f}$ in equation:

$$y = \frac{1}{2AEf}(F - Q)^2$$

Where,

y - End delefction/movement, inches

F - Anchor force or expansion force, lbs

Q - End resistance force, lbs.

f - Soil friction force, lbs/in.

3.2.5 Lateral Pipe Movement

The lateral pipe movement in a buried pipeline is caused by the longitudinal movement of a pipe which connected in the perpendicular direction. (Bhattacharya, 2012)

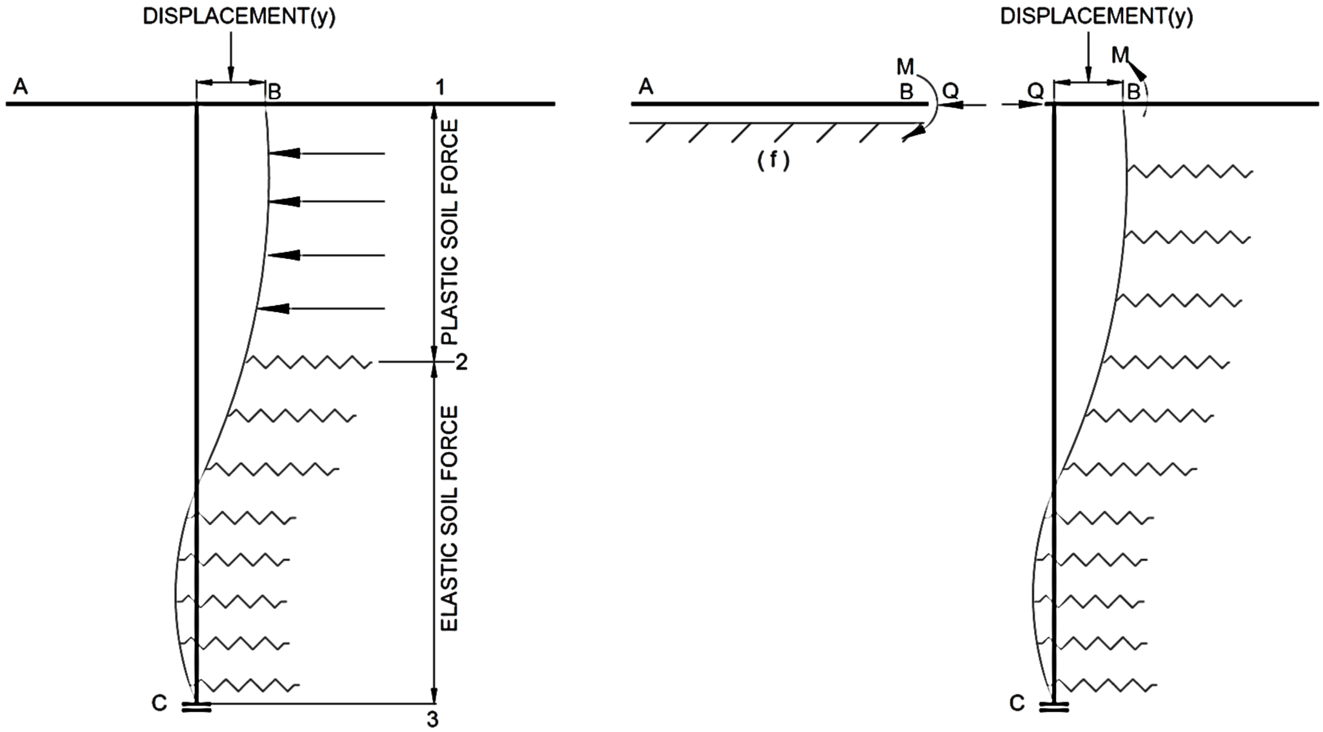

Figure 16: Lateral movement of buried pipeline.

Considering a long main line pipe making a 90 degree turn to enter a pigging station or pump station. The expansion of the pipe *AB* will cause the station pipe BC to move in the lateral direction. The lateral movement at corner *B* is *y* inches. This decreases gradually towards a point *C* where displacement is virtually zero.

Due to the large movement, the soil in the region 1-2 is in the plastic stage which offers a contact passive force. The soil which is in the rejoin 2-3 is still in the static range that offers a resisting force which is proportional to the local displacement. The extent of the region 1-2 depends on the magnitude of the end movement.

The elastic plastic soil force analysis generally requires a FEA software. However in the piping system, the system can be conventionally treated as a guided cantilever elastic system which can be easily analyzed. (Super Civil, 2010)

In figure 15 the pipe AB is considered to be guided, allowing no rotation at the corner B. The soil force is considered to be completely elastic, offering a resistance which his proportional to the local displacement. For the analysis, the system is cut into two free bodies. The long pipe

AB is exactly as the longitudinal pipe movement system, except a moment M exists. Now since the end movement does not affect the longitudinal movement, the displacement for the first section of cantilever AB is same as the displacement of the longitudinal pipe movement.

$$y = \frac{1}{2AEf}(F - Q)^2$$

Here, since there are two unknowns (*y* and *Q)* we get another equation from the second section of the cantilever BC. Leg BC actually represents one-half of an infinite beam on elastic foundation that is loaded with a concentrated force. The situation in leg BC is a beam on elastic foundation problem. The case is not quite the same as an ordinary problem where elastic modulus changes with depth and the end, is free to rotate.

The displacement for the beam BC can be therefore found out by:

$$y = \frac{QB}{K}$$

And the moment M is given by:

$$M = \frac{Q}{2\beta}$$

Where.

Y - End displacement, inches

Q - End force, lbs

K - Soil elastic constant, lbs.in^2

E - Modulus of elasticity of pipe, psi

I - Moment of intertia of pipe, in^4

M - End bending movement, in-lbs

β - Constant $\sqrt{\frac{K}{4EI}}$, here *I* is moment of inertia

Once the moment is calculated, the bending stress can be found out by the formulae:

$$Bending\ stress = \frac{M}{Z}$$

Here Z is the section modulus (inches^3) given by:

$$Z = \frac{0.0982(D_o^4 - D_i^4)}{D_o}$$

From the two equations of end displacement we have:

$$y = \frac{1}{2AEf}(F - Q)^2 \qquad \& \qquad y = \frac{QB}{K}$$

Equating both the equations we get:

$$Q = C - \sqrt{C^2 - F^2}$$

Where

C is a constant represented to simplify the formula:

$$C = F + \frac{AEf\beta}{K}$$

Once the end force is determined, the end displacement as well as the moment can be calculated.

CHAPTER 4

4. EXPERIMENTAL AND CALCULATIONS

The various soil forces and well as the soil pipe interaction analysis for a gas pipeline was investigated. The pipeline is a gas pipeline for a city gas distribution project in Kota, Gujarat. The problem of this project was that the surveyed soil data differed from the actual soil properties on the actual site. During construction it was found out that the soil was in fact hard rock which hindered construction methods such as trenching. The pipeline route had to be blasted such that the pipe can be laid. This caused delay in project schedule and exceeded project costs to a great amount. This report will look into the stress and soil pipe interaction analysis of the Kota pipeline and mainly compare how these values would differ for different soil types as stated by the surveyor.

Details of the pipeline:

Wall thickness	- 6.4mm or 0.251969 inches
Class and Design Factor	- Class 4 having design factor of 0.5
Corrosion allowance	- 0.5mm
SMYS	- 414 N/mm^2 or 60045.623 psi
Length	- 12400m or 7.7km
Operating pressure	- 19 kg/cm^2 or 270.24 psi
Design Pressure	- 49 kg/cm^2 or 696.94 psi
Available Gas Pressure	- 52 to 53 kg/cm^2
Operating temperature	- 23°C or 73.4°F
Design temperature	- 60°C or 140°F

Material - API 5L X42 (42000 psi)

Operating Pressure - 16 to 19kg/cm^2

Soil Temperature - 25°C (1m below ground level)

Pipeline roughness - 45 microns

Design flow - 0.984 MMSCFD

4.1 Soil and pipe force calculations

Calculations done considering: Soil type – Slit, Angle (θ) of internal friction 35°, Dry density (γ) as 90lbs/ft, Backfill Height (*H)* of 4 feet, coefficient of friction (μ) as 0.4 lb/ft^3.

1. **Hoop stress**

$$S_h = \frac{PD}{2t}$$

$$S_h = \frac{696.94 \times 8}{2 \times 0.251969}$$

$$\therefore \boldsymbol{S_h = 11603.9\, psi}$$

2. **Compressive longitudinal stress at fully restrained portion**

$$S_L = -E\alpha(T_2 - T_1) + (0.3S_h)$$

Modulus of elasticity of the pipe (E), depends on the material and varies to the load supplied accordingly, however in for onshore pipeline application having X42 steel the modulus is taken as:

$$E = 29 \times 10^{6}\ psi$$

The linear co-efficient of thermal expansion (α). When an object is heated or cooled, its length changes by an amount proportional to the original length and the change in temperature.

$$\alpha\ of\ steel = 6.7 \times 10^{-6}\ in/in°\text{F}$$

Therefore applying all these values to find the longitudinal stress:

$$S_L = -E\alpha(T_2 - T_1) + (0.3S_h)$$

$$S_L = -\left((29 \times 10^{6}) \times (6.7 \times 10^{-6}) \times (140 - 77)\right) + (0.3 \times 11063.9)$$

$$\therefore \boldsymbol{S_L = -8921.73}$$

3. **Equivalent tensile stress at the fully restrained portions.**

$$S_e = \sqrt{(S_h - S_L)^2 + 4r^2}$$

$$\boldsymbol{S_e = 19985.63\ psi}$$

Now the $SMYS = 60045.623\ psi$

$$S_e < 0.9 \times SMYS$$

Stress checks are usually done to determine the wall thickness calculations. This is not our scope, as the wall thickness has already been determined.

4. Anchor Force

$$F = A(0.5S_h - S_L)$$

Or

$$F = A\big((0.5 - v)S_h + E\alpha(T_2 - T_1)\big)$$

$$F = \pi Dt\big(0.2S_h + E\alpha(T_2 - T_1)\big)$$

$$F = 3.14 \times 8 \times 0.251969 \times \big((0.2 \times 11063.9) + (29 \times 10^6) \times (6.7 \times 10^{-6}) \times (140 - 77)\big)$$

$$\boldsymbol{F = 91530.40 lbs}$$

5. Thermal Expansion

Net longitudinal expansion, Δ

$$\Delta = \alpha(T_{2-}T_1)L + \left(\frac{0.5S_hL}{E} - \frac{0.3S_hL}{E}\right)$$

$$\Delta = \alpha(T_{2-}T_1)L + \left(\frac{0.2S_hL}{E}\right)$$

Strain is given by, $\varepsilon = \Delta/L$

$$\varepsilon = \alpha(T_{2-}T_1) + \left(\frac{0.2S_h}{E}\right)$$

Therefore the thermal expansion,

$$\varepsilon_t = \alpha(T_{2-}T_1)$$

$$\varepsilon_t = 6.7 \times 10^{-6}(140 - 77)$$

$$\varepsilon_t = 4.221 \times 10^{-4}\ in/in$$

Inches/inches means expansion of $4.22x10^{-4}$ inches per 1 inch, however it is more feasible to calculate per 100 feet of pipe. (Engineering toolbox, 2014)

$$\varepsilon_t = 5.0652 \times 10^{-3}\ in/feet$$

$$\varepsilon_t = 0.50652\ in/100feet$$

The pressure expansion is given by:

$$\varepsilon_p = \left(\frac{0.2S_h}{E}\right)$$

$$\varepsilon_p = \left(\frac{0.2 \times 11063.9}{29 \times 10^6}\right)$$

$$\varepsilon_p = 7.630 \times 10^5\ in/in$$

Similarly we calculate the pressure expansion per 100 feet of pipe.

$$\varepsilon_p = 9.156 \times 10^{-4} in/ft$$

$$\varepsilon_p = 0.09156\ in/100ft$$

Therefore the total expansion:

$$\varepsilon = \varepsilon_t + \varepsilon_p$$

$$\varepsilon = 0.50652 \frac{in}{100ft\ pipe} + 0.09156 \frac{in}{100ft\ pipe}$$

$$\therefore \boldsymbol{\varepsilon = 0.598 \frac{in}{100ft\ pipe}}$$

4.2 Soil- Pipe Interaction Calculations:

1. **Axial friction force :**

$$f = \frac{\mu\left(2\gamma DH + W_p\right)}{12}$$

$$W_p = W_{steel} + W_{content}$$

$$W_{steel} = material\ of\ the\ steel\ pipe$$

$$W_{steel} = \rho_{steel} \times Area \times gravity$$

$$\rho_{steel} = 7850 \frac{kg}{m^3}\ \ or\ 490.06 \frac{lb}{ft^3}$$

$$gravity = 9.81 \frac{m}{second}\ \ or\ 32.174 \frac{ft}{second}$$

$$W_{steel} = 490.06 \times \left(\pi \left(\frac{8}{12 \times 2} \right)^2 - \pi \left(\frac{8 - 2(0.2519)}{12 \times 2} \right)^2 \right) \times 32.174$$

$$W_{steel} = 671.55\ lb/second$$

$$W_{content} = Natural\ Gas, negligible$$

$$\therefore W_p = \ W_s + W_c = 671.55\ lb/second$$

Now finding soil friction force:

$$f = \frac{0.4\left(\left(2 \times 90 \times \frac{8}{12} \times 4 \right) + 671.55 \right)}{12}$$

$$\boldsymbol{f = 38.385\ lbs/inches}$$

2. Soil end force (longitudinal)

$$Q = \frac{\gamma}{2}(H + D)^2 \tan^2\left(45 + \frac{\theta}{2}\right) D + \frac{(H + D)^3 \gamma K_o tan\theta}{3 \tan\left(45 + \frac{\theta}{2}\right)}$$

$$K_o = 1 - sin\theta$$

Considering γ as 90lbs/ft^3 and angle of internal friction as 35°

$$Q = \frac{90}{2}\left(4 + \frac{8}{12}\right)^2 \tan^2\left(45 + \frac{35}{2}\right)\left(\frac{8}{12}\right) + \frac{\left(4 + \frac{8}{12}\right)^3 90(0.426 \times tan35)}{3 \tan\left(45 + \frac{35}{2}\right)}$$

$$\boldsymbol{Q = 2884.341369\ lbs}$$

3. Active length

$$L = \frac{F - Q}{f}$$

$$L = \frac{91530.40lbs - 2884.341369lbs}{38.385lb/in}$$

$$\boldsymbol{L = 2309.393217\ inches\ or\ 192.4494\ feet}$$

4. Longitudinal movement

$$y = \frac{1}{2AEf}(F - Q)^2$$

$$y = \frac{1}{2} \times \frac{1}{\pi(8 - 0.251969)0.251969} \times \frac{1}{29 \times 10^6} \times \frac{1}{38.385} \times (91530.40 - 2884.3413)^2$$

$$\boldsymbol{y = 0.5755146\ inches}$$

Therefore there will be 0.5755146 inches of deflection at the pipe overheads.

5. Lateral soil forces

$$U = \frac{1}{2}\gamma(H + D)^2 \tan^2\left(45 + \frac{\theta}{2}\right)$$

$$U = \frac{1}{2}90\left(4 + \frac{8}{12}\right)^2 \tan^2\left(45 + \frac{35}{2}\right)$$

$$\boldsymbol{U = 3616.368885\ lbs/ft}$$

6. Elastic constant

$$K = 0.2315\gamma(H + D)\tan^2\left(45 + \frac{\theta}{2}\right)$$

$$K = 0.2315 \times 90\left(4 + \frac{8}{12}\right)\tan^2\left(45 + \frac{35}{2}\right)$$

$$\boldsymbol{K = 358.7954\ lb/in^2}$$

7. End force (lateral)

Finding constant values:

$$\beta = \sqrt{\frac{K}{4EI}}$$

$$I = \frac{\pi(D_o^4 - D_i^4)}{65}$$

$$I = 0.491(8^4 - 7.490602^4) = 53.8656\ in^4$$

Value in accordance with ASME B31.4:

$$\boldsymbol{I = 46.1\ in^4}$$

$$\therefore \beta = \sqrt{\frac{358.7954}{4 \times 29 \times 10^6 \times 46.1}}$$

$$\boldsymbol{\beta = 2.590 \times 10^{-4}\ in^{-1}}$$

$$C = F + \frac{AEf\beta}{K}$$

$$C = 91530.40 + \frac{(2.590 \times 10^{-4}) \times (\pi(8 - 0.251969) \times 0.251969) \times (29 \times 10^6) \times (38.385)}{358.7954}$$

$$C = 91530.40 + 6326.3610$$

$$\therefore \boldsymbol{C = 97856.76106\ lbs}$$

Applying values to determine the lateral end force:

$$Q = C - \sqrt{C^2 - F^2}$$

$$Q = 97856.76106 - \sqrt{97856.76106^2 - 91530.40^2}$$

$$\therefore \boldsymbol{Q = 63242.72401\ lbs}$$

8. Lateral movement

$$y = \frac{QB}{K}$$

$$y = \frac{63242.72401 \times (2.590 \times 10^{-4})}{358.7954}$$

$$y = \ 0.0456523\ inches$$

Yield displacement check:

$$yeild\ displacement = 0.015(H + D) = 0.07ft\ or\ 0.84\ inches$$

$$lateral\ displacement\ (y) < yeild\ displacment$$

9. End moment (*M*)

$$M = \frac{Q}{2\beta}$$

$$M = \frac{63242.72401}{2 \times (2.590 \times 10^{-4})}$$

$$\therefore M = 122090200.8\ in.lbs$$

10. Bending stress

$$Bending\ Stress = \frac{M}{Z}$$

$$Z = \frac{0.0982(8^4 - 7.49^4)}{8}$$

$$Z = 11.5\ inches^3$$

$$Bending\ Stress = \frac{122090200.8}{11.5}$$

$$\boldsymbol{Bending\ Stress = 10616539.2\ psi}$$

Stress check:

$$Bending\ stress < SMYS\ (60045.623\ psi)$$

In the same way soil pipe forces as well as the soil pipe interaction analysis was done with different soil types like clay, slit, sand, concrete and rock to see how this pipeline would behave in all the various ground properties.

CHAPTER 5

5. RESULTS AND DISCUSSION

The soil pipe forces as well as the soil pipe interaction analysis was done with different soil types like clay, slit, sand, concrete and rock to see how this pipeline would behave in all the various ground properties.

1. Ground type – Clay

   Dry density (γ) as 77.4106 lbs/ft, Backfill Height (*H)* of 4 feet, coefficient of friction (μ) as 0.3 lb/ft^3.

2. Ground type – Slit

   Dry density (γ) as 82.40485 lbs/ft, Backfill Height (*H)* of 4 feet, coefficient of friction (μ) as 0.3 lb/ft^3.

3. Ground type – Sand

   Dry density (γ) as 92.38335 lbs/ft, Backfill Height (*H)* of 4 feet, coefficient of friction (μ) as 0.4 lb/ft^3.

4. Ground type – Concrete

   Dry density (γ) as 149.8271 lbs/ft, Backfill Height (*H)* of 4 feet, coefficient of friction (μ) as 0.45 lb/ft^3.

5. Ground type – Rock

   Dry density (γ) as 225 lbs/ft, Backfill Height (*H)* of 4 feet, coefficient of friction (μ) as 0.6 lb/ft^3.

5.1 Tabulated Results

5.1.1 Ground type – Clay

Table 4: Tabulated results of clay ground profile

Clay Property	***θ***	**Soil friction force (f)**	**Dry Density(γ)**	**Soil End Force(Q)**			**Active Length (L)**		**Long Movement (y)**	**Lateral Soil Force (U)**	**Elastic Con (K)**	**Beta (β)**	**C**	**End force (Q)**	**End displacement(y)**	**End Moment (M)**	**Bend Stress (S)**
				Passive Soil force	Side shears	Q	inches	feet	inches	lb/ft	lb/in^2	in^{-1}	lbs	lbs	inches	in-lbs	psi
Loose consistency/ compactness	25	27.11023308	77.4106	1384.580072	449.8031014	1834.383173	3308.567158	275.71393	0.834251192	2076.870107	206.0551842	0.000196355	96125.33857	66760.9935	0.063618287	170000449.2	14755650.61
Loose consistency/ compactness	27	27.11023308	77.4106	1496.42209	447.0796652	1943.501755	3304.542162	275.378513	0.832222631	2244.633134	222.6996731	0.000204132	95950.29274	67164.1377	0.061564252	164511667.5	14279236.89
Loose consistency/ compactness	29	27.11023308	77.4106	1619.555252	441.1311468	2060.686399	3300.219638	275.018303	0.830046869	2429.332878	241.0245263	0.000212364	95778.95203	67569.1719	0.05953453	159087855.7	13808462.42
Medium consistency/ compactness	31	27.11023308	77.4106	1755.531575	432.3375463	2187.869122	3295.52832	274.62736	0.827688695	2633.297363	261.260717	0.0002211	95611.09884	67976.5866	0.057527202	153723883.2	13342881.86
Medium consistency/ compactness	33	27.11023308	77.4106	1906.180173	421.0533037	2327.233477	3290.387665	274.198972	0.825108505	2859.270259	283.6804564	0.000230391	95446.52854	68386.8934	0.055540415	148414802.2	12882065.76
Medium consistency/ compactness	35	27.11023308	77.4106	2073.66878	407.609385	2481.278165	3284.705504	273.725459	0.822261211	3110.503169	308.6063502	0.0002403	95285.04832	68800.6288	0.053572379	143155826.6	12425598.69
Medium consistency /compactness	37	27.11023308	77.4106	2260.581832	392.3151274	2652.896959	3278.375098	273.197925	0.819094881	3390.872748	336.4230176	0.000250896	95126.47627	69218.3591	0.051621355	137942311.7	11973077.51
Medium consistency/ compactness	39	27.11023308	77.4106	2470.020385	375.4598731	2845.480258	3271.271386	272.605949	0.815549032	3705.030577	367.5919622	0.000262261	94970.64044	69640.686	0.049685652	132769734.9	11524109.66
Dense consistency/ compactness	41	27.11023308	77.4106	2705.731144	357.3144164	3063.045561	3263.246176	271.937181	0.811552468	4058.596717	402.6707742	0.00027449	94817.37805	70068.2523	0.047763614	127633677	11078311.57
Dense consistency/ compactness	43	27.11023308	77.4106	2972.27473	338.1322884	3310.407019	3254.121892	271.176824	0.807020488	4458.412095	442.3381715	0.000287692	94666.53474	70501.7495	0.045853621	122529803.2	10635306.98
Dense consistency /compactness	45	27.11023308	77.4106	3275.247407	318.1508979	3593.398305	3243.683351	270.306946	0.801851287	4912.871111	487.4269981	0.000301999	94517.96389	70941.9264	0.043954075	117453844.9	10194725.4
Dense consistency/ compactness	47	27.11023308	77.4106	3621.576636	297.5925445	3919.169181	3231.666823	269.305569	0.795921226	5432.364954	538.9682087	0.000317565	94371.52598	71389.5991	0.042063395	112401581	9756200.432
Dense consistency	49	27.11023308	77.4106	4019.919919	276.6653201	4296.585239	3217.745288	268.145441	0.789078578	6029.879879	598.2502251	0.000334574	94227.08806	71845.6634	0.040180013	107368818.7	9319368.162
Dense consistency/compactness	51	27.11023308	77.4106	4481.210357	255.5639112	4736.774268	3201.508282	266.792357	0.78113516	6721.815536	666.9001271	0.000353249	94084.52318	72311.1094	0.038302364	102351373.6	8883865.393

5.1.2 Ground type – Slit

Table 5: Tabulated results of Slit ground profile

Soil Property	θ	Soil friction force(f)	Dry Density (γ)	Soil End Force(Q)			Active Length (L)		Longitudinal Movement (y)	Lateral Soil Force (U)	Elastic Constant(K)	Beta (β)	C	End force (Q)	End displacement(y)	End Moment(M)	Bending stress (S)
				Passive Soil force	Side shears	Q	inches	feet	inches	lb/ft	lb/in^2	in^{-1}	lbs	lbs	inches	in-lbs	psi
Loose consistency/ compactness	25	27.77613308	82.40485	1473.908135	478.8227594	1952.731	3224.987396	268.7489	0.812103726	2210.862203	219.3491143	0.000203	96093.31	66833.9778	0.061727732	164948518.2	14317154.53
Loose consistency/ compactness	27	27.77613308	82.40485	1592.965793	475.923617	2068.889	3220.805442	268.4005	0.809998925	2389.44869	237.067445	0.000211	95919.49	67236.18331	0.059733512	159619572.7	13854614.24
Loose consistency/ compactness	29	27.77613308	82.40485	1724.043059	469.5913219	2193.634	3216.314357	268.0262	0.807741578	2586.064588	256.5745509	0.000219	95749.34	67640.26485	0.057762963	154353883.8	13397564.47
Medium consistency/ compactness	31	27.77613308	82.40485	1868.792079	460.2303904	2329.022	3211.440097	267.62	0.805295201	2803.188119	278.116307	0.000228	95582.66	68046.71175	0.055814221	149146466	12945572.51
Medium consistency/ compactness	33	27.77613308	82.40485	2029.159976	448.2181295	2477.378	3206.098978	267.1749	0.802618769	3043.739964	301.9824864	0.000238	95419.23	68456.03418	0.053885487	143992512.1	12498221.08
Medium consistency/ compactness	35	27.77613308	82.40485	2207.454337	433.9068581	2641.361	3200.195237	266.6829	0.799665591	3311.181506	328.516508	0.000248	95258.88	68868.76728	0.05197502	138887372.3	12055106.61
Medium consistency/ compactness	37	27.77613308	82.40485	2406.426339	417.6258707	2824.052	3193.617971	266.1348	0.796381911	3609.639509	358.1278055	0.000259	95101.41	69285.47584	0.050081132	133826535.2	11615837.51
Medium consistency/ compactness	39	27.77613308	82.40485	2629.377104	399.6831768	3029.06	3186.237244	265.5198	0.79270515	3944.065657	391.3076569	0.000271	94946.66	69706.75969	0.048202179	128805608.3	11180032.53
Dense consistency/ compactness	41	27.77613308	82.40485	2880.295064	380.3670413	3260.662	3177.899084	264.8249	0.788561671	4320.442596	428.6496262	0.000283	94794.47	70133.25988	0.046336556	123820300	10747319.16
Dense consistency/ compactness	43	27.77613308	82.40485	3164.035071	359.9473523	3523.982	3168.418992	264.0349	0.783863921	4746.052607	470.8762194	0.000297	94644.68	70565.6659	0.044482688	118866401.7	10317332.1
Dense consistency/ compactness	45	27.77613308	82.40485	3486.554442	338.6768352	3825.231	3157.573391	263.1311	0.778506722	5229.831663	518.8740129	0.000312	94497.14	71004.72425	0.042639022	113939769.3	9889711.668
Dense consistency/ compactness	47	27.77613308	82.40485	3855.227572	316.7921317	4172.02	3145.088268	262.0907	0.772362425	5782.841358	573.7404747	0.000328	94351.72	71451.24854	0.040804027	109036305.7	9464102.23
Dense consistency/ compactness	49	27.77613308	82.40485	4279.270513	294.514759	4573.785	3130.623851	260.8853	0.765274495	6418.905769	636.847151	0.000345	94208.29	71906.13173	0.03897618	104151941.9	9040150.609
Dense consistency/ compactness	51	27.77613308	82.40485	4770.32173	272.051964	5042.374	3113.753669	259.4795	0.757048956	7155.482595	709.9260946	0.000364	94066.72	72370.36091	0.037153961	99282617.73	8617504.396

5.1.3 Ground type – Sand

Table 6: Tabulated results of Sand ground profile

Soil Property	**θ**	**Soil friction force(f)**	**Dry Density(γ)**	**Soil End Force(Q)**			**Active Length (L)**		**Longitudinal Movement (y)**	**Lateral Soil Force (U)**	**Elastic Constant(K)**	**Beta (β)**	**C**	**End force (Q)**	**End displacement(y)**	**End Moment (M)**	**Bending stress (S)**
				Passive Soil force	Side Shears	Q	inches	feet	inches	lb/ft	lb/in^2	in^{-1}	lbs	lbs	inches	in-lbs	psi
Loose consistency/compactness	25	38.81057744	92.39335	1652.564263	536.8620754	2189.426339	2301.97512	191.83126	0.578142679	2478.846395	245.9369745	0.000214518	97551.50497	63810.13322	0.05565814	148729387.4	12909371.04
Loose consistency/compactness	27	38.81057744	92.39335	1786.0532	533.6115207	2319.664721	2298.619375	191.5516146	0.576458313	2679.079801	265.8029888	0.000223013	97322.1287	64249.77196	0.053906684	144049153.8	12503137.45
Loose consistency/compactness	29	38.81057744	92.39335	1933.018672	526.5116721	2459.530344	2295.015574	191.2512978	0.574652174	2899.528009	287.6746003	0.000232007	97097.60754	64691.90688	0.052173521	139417806.1	12101147.06
Medium consistency/compactness	31	38.81057744	92.39335	2095.313087	516.0160784	2611.329166	2291.104299	190.9253583	0.572695144	3142.969631	311.827487	0.000241551	96877.65636	65137.0775	0.05045707	134831114	11703032.65
Medium consistency/compactness	33	38.81057744	92.39335	2275.119581	502.547781	2777.667362	2286.818401	190.5682	0.570554502	3412.679372	338.5865463	0.000251701	96662.00699	65585.84827	0.048755795	130284977.4	11308438.39
Medium consistency/compactness	35	38.81057744	92.39335	2475.025453	486.5018043	2961.527257	2282.081035	190.1734196	0.568193032	3712.53818	368.3368237	0.000262527	96450.40681	66038.81331	0.047068206	125775410.1	10917018.25
Medium consistency/compactness	37	38.81057744	92.39335	2698.115354	468.2473573	3166.362711	2276.80321	189.7336008	0.565567923	4047.17303	401.5373814	0.000274103	96242.61743	66496.60165	0.045392846	121298522.4	10528434.63
Medium consistency/compactness	39	38.81057744	92.39335	2948.090544	448.1297841	3396.220329	2270.880659	189.2400549	0.562629375	4422.135817	438.7390464	0.000286519	96038.41353	66959.88334	0.04372829	116850505.5	10142356.92
Dense consistency/compactness	41	38.81057744	92.39335	3229.422904	426.472291	3655.895195	2264.189832	188.682486	0.559318844	4844.134356	480.60733	0.000299879	95837.58181	67429.37645	0.042073138	112427615.4	9758460.161
Dense consistency/compactness	43	38.81057744	92.39335	3547.555754	403.57748	3951.133234	2256.582678	188.0485565	0.555566794	5321.333631	527.9523152	0.000314303	95639.92	67905.85534	0.040426005	108026156.7	9376423.606
Dense consistency/compactness	45	38.81057744	92.39335	3909.168512	379.7287098	4288.897222	2247.879793	187.3233161	0.551289787	5863.752768	581.7680425	0.000329933	95445.23596	68390.1604	0.038785522	103642467.2	8995929.366
Dense consistency/compactness	47	38.81057744	92.39335	4322.529443	355.1913061	4677.720749	2237.861299	186.4884416	0.54638669	6483.794164	643.2850067	0.000346939	95253.3469	68883.20959	0.037150325	99272900.48	8616660.96
Dense consistency/compactness	49	38.81057744	92.39335	4797.9717	330.2136368	5128.185337	2226.254551	185.5212126	0.54073368	7196.95755	714.0410026	0.000365521	95064.07858	69386.01242	0.035519047	94913809.5	8238301.823
Dense consistency/compactness	51	38.81057744	92.39335	5348.544475	305.0280697	5653.572545	2212.717334	184.3931112	0.53417758	8022.816713	795.9780296	0.000385924	94877.26464	69899.68688	0.033890318	90561527.86	7860533.719

5.1. 4 Ground type – Concrete

Table 7: Tabulated results of Concrete ground profile

Soil Property	**θ**	**Soil friction force(f)**	**Dry Density(γ)**	**Soil End Force(Q)**			**Active Length (L)**		**Long Mov (y)**	**Lateral Soil Force (U)**	**Elastic Cons (K)**	**Beta (β)**	**C**	**End force (Q)**	**End displacement(y)**	**End Moment(M)**	**Bending stress (S)**
				Passive Soil force	Side Shears	Q	inches	feet	inches	lb/ft	lb/in^2	In^{-1}	lbs	lbs	inches	in-lbs	psi
Loose consistency/ compactness	25	55.14864963	149.8271	2679.834762	870.5874163	3550.422179	1595.324426	132.9437022	0.39456321	4019.752143	398.8168377	0.000273173	98249.11273	62540.95963	0.042837957	114471361.7	9935852.668
Loose consistency/ compactness	27	55.14864963	149.8271	2896.303375	865.3162448	3761.61962	1591.494823	132.6245686	0.392671172	4344.455063	431.0320059	0.000283992	97993.16079	62995.39506	0.041505438	110910610.3	9626787.582
Loose consistency/ compactness	29	55.14864963	149.8271	3134.625835	853.8029733	3988.428809	1587.382135	132.2818446	0.390644339	4701.938753	466.4994949	0.000295445	97742.62646	63452.61228	0.040186008	107384838.5	9320758.645
Medium consistency/ compactness	31	55.14864963	149.8271	3397.806049	836.7830864	4234.589135	1582.918557	131.9098797	0.388450513	5096.709073	505.6663502	0.000307598	97497.1916	63913.17137	0.038878482	103890872	9017490.337
Medium consistency /compactness	33	55.14864963	149.8271	3689.384236	814.9425975	4504.326834	1578.027454	131.5022878	0.386053654	5534.076355	549.0594326	0.000320524	97256.55697	64377.6592	0.037581703	100425627.5	8716715.028
Medium consistency /compactness	35	55.14864963	149.8271	4013.55602	788.9220867	4802.478106	1572.621134	131.0517611	0.383412947	6020.334029	597.3031405	0.000334309	97020.44066	64846.69436	0.036294548	96986099.59	8418171.868
Medium consistency/ compactness	37	55.14864963	149.8271	4375.323537	759.3202718	5134.643809	1566.598036	130.5498363	0.380481648	6562.985305	651.1418992	0.000349051	96788.57667	65320.93267	0.035015917	93569348.79	8121605.704
Medium consistency/ compactness	39	55.14864963	149.8271	4780.688835	726.6971701	5507.386005	1559.839172	129.9865977	0.377205663	7171.033253	711.468942	0.000364862	96560.71358	65801.07359	0.03374473	90172488.91	7826766.027
Dense consistency/ compactness	41	55.14864963	149.8271	5236.903612	691.5769003	5928.480512	1552.203546	129.3502955	0.373521754	7855.355418	779.3634768	0.000381875	96336.61337	66287.86761	0.032479922	86792675.16	7533405.916
Dense consistency/ compactness	43	55.14864963	149.8271	5752.794879	654.4501682	6407.245047	1543.522199	128.6268499	0.369355286	8629.192318	856.1391521	0.000400242	96116.05035	66782.12495	0.031220439	83427091.95	7241280.982
Dense consistency /compactness	45	55.14864963	149.8271	6339.194126	615.776475	6954.970601	1533.590396	127.7991996	0.36461734	9508.791189	943.4079258	0.000420146	95898.8101	67284.72573	0.029965234	80072940.45	6950148.295
Dense consistency /compactness	47	55.14864963	149.8271	7009.509354	575.9860784	7585.495433	1522.157209	126.846434	0.359201032	10514.26403	1043.165196	0.000441802	95684.68866	67796.63228	0.028713262	76727425.77	6659765.264
Dense consistency/ compactness	49	55.14864963	149.8271	7780.497034	535.4817375	8315.978772	1508.911493	125.7426244	0.352976743	11670.74555	1157.904684	0.000465465	95473.49159	68318.90373	0.027463472	73387743.51	6369888.473
Dense consistency/compactness	51	55.14864963	149.8271	8673.318025	494.6402648	9167.95829	1493.46271	124.4552258	0.345785935	13009.97704	1290.775579	0.000491447	95265.03327	68852.714	0.026214806	70051065.35	6080272.432

5.1.5 Ground type – Rock

Table 8: Tabulated results of Rock ground profile

Rock Property	***θ***	**Soil friction force(f)**	**Dry Density(γ)**	**Soil End Force(Q)**			**Active Length (L)**		**Longitudinal Movement (y)**	**Lateral Soil Force (U)**	**Elastic Constant(K)**	**Beta (β)**	**C**	**End force (Q)**	**End displacement(y)**	**End Moment(M)**	**Bending stress (S)**
				Passive Soil force	Side Shears	Q	inches	feet	inches	lb/ft	lb/in^2	In^{-1}	lbs	lbs	inches	in-lbs	psi
Loose consistency/compactness	25	93.5776395	225	4024.390925	1307.388107	5331.779032	921.1456009	76.76213341	0.223209321	6036.586387	598.9156065	0.00033476	100833.4857	58530.10653	0.03271504	87420955.78	7587939.238
Loose consistency/compactness	27	93.5776395	225	4349.46855	1299.472226	5648.940776	917.756311	76.47969259	0.221569777	6524.202826	647.2941232	0.000348018	100479.081	59027.54592	0.031736195	84805290.57	7360905.474
Loose consistency/compactness	29	93.5776395	225	4707.364776	1282.182389	5989.547164	914.1164844	76.1763737	0.219815768	7061.047163	700.5567507	0.000362053	100132.1777	59528.76579	0.030764947	82209928.04	7135633.935
Medium consistency/compactness	31	93.5776395	225	5102.590659	1256.623097	6359.213756	910.1661112	75.84717594	0.217919997	7653.885989	759.3748313	0.000376946	99792.33546	60034.38956	0.029800459	79632628.38	6911930.213
Medium consistency/compactness	33	93.5776395	225	5540.462661	1223.824558	6764.287219	905.8373692	75.48644743	0.215852075	8310.693992	824.5395682	0.000392787	99459.13986	60545.07367	0.02884191	77071198.42	6689603.944
Medium consistency/compactness	35	93.5776395	225	6027.281476	1184.74875	7212.030226	901.052647	75.08772059	0.213577793	9040.922214	896.9886396	0.00040968	99132.20057	61061.51322	0.027888493	74523482.64	6468468.035
Medium consistency/compactness	37	93.5776395	225	6570.558969	1140.294787	7710.853757	895.7220624	74.6435052	0.211058236	9855.838454	977.8399724	0.000427745	98811.14927	61584.4483	0.026939412	71987354.34	6248337.892
Medium consistency/compactness	39	93.5776395	225	7179.308603	1091.303665	8270.612267	889.7403074	74.14502562	0.208248697	10768.9629	1068.434962	0.000447121	98495.63783	62114.67142	0.025993879	69460706.7	6029030.65
Dense consistency/compactness	41	93.5776395	225	7864.420473	1038.562467	8902.98294	882.9825961	73.58188301	0.20509735	11796.63071	1170.39429	0.000467969	98185.33668	62653.03611	0.02505111	66941443.8	5810364.386
Dense consistency/compactness	43	93.5776395	225	8639.150379	982.8081025	9621.958481	875.299398	72.9416165	0.201543604	12958.72557	1285.690701	0.000490478	97879.93329	63200.46694	0.024110321	64427471.34	5592157.32
Dense consistency/compactness	45	93.5776395	225	9519.764304	924.7306187	10444.49492	866.5095156	72.2091263	0.197516069	14279.64646	1416.744923	0.000514869	97579.13081	63757.97153	0.023170724	61916686.91	5374226.968
Dense consistency/compactness	47	93.5776395	225	10526.39746	864.9761468	11391.37361	856.3908731	71.36590609	0.192930026	15789.59619	1566.553508	0.000541407	97282.64679	64326.65475	0.022231528	59406969.85	5156389.26
Dense consistency/compactness	49	93.5776395	225	11684.21356	804.1495226	12488.36308	844.6680996	70.3890083	0.187684301	17526.32033	1738.861353	0.000570405	96990.21201	64907.73593	0.021291925	56896170.16	4938457.584
Dense consistency/compactness	51	93.5776395	225	13024.99051	742.8166171	13767.80713	830.9955593	69.24962994	0.181657431	19537.48576	1938.397695	0.000602244	96701.56946	65502.56978	0.020351098	54382096.6	4720241.742

5.2 Thermal expansion

5.2.1 Temperature variance

Diameter – 8 inches

Thickness – 0.251969 inches

Pipe Material Grade – API 5L X42 (42000 psi)

									Thermal Expansion				
Oper Pressure	Design Pressure	Oper Tem	Design Tem	Ambient Temp	Sh	S_L	S_e	Anchor Force	Longitudinal Expansion	in/ 100ft	Pressure Expansion	in/100ft	Total Expansion
270.24	**696.94**	**73.4**	**140**	**77**	**11063.9007**	**-8921.7**	**19986**	**91530.41**	**0.0004221**	**0.50652**	**7.63028E-05**	**0.091563316**	**0.598083316**
270.24	696.94	123.4	190	77	11063.9007	-18637	29701	153052.3	0.0007571	0.90852	7.63028E-05	0.091563316	1.000083316
270.24	696.94	173.4	240	77	11063.9007	-28352	39416	214574.2	0.0010921	1.31052	7.63028E-05	0.091563316	1.402083316
270.24	696.94	223.4	290	77	11063.9007	-38067	49131	276096.1	0.0014271	1.71252	7.63028E-05	0.091563316	1.804083316
270.24	696.94	273.4	340	77	11063.9007	-47782	58846	337618	0.0017621	2.11452	7.63028E-05	0.091563316	2.206083316
270.24	696.94	323.4	390	77	11063.9007	-57497	68561	399139.9	0.0020971	2.51652	7.63028E-05	0.091563316	2.608083316

Table 9: Thermal expansion rate during temperature change

5.2.2 Pressure Variance

Diameter – 8 inches

Thickness – 0.251969 inches

Pipe Material Grade – API 5L X42 (42000 psi)

									Thermal Expansion				
Oper Pressure	Design Pressure	Oper Tem	Design Tem	Ambient Temp	Sh	SL	Se	Anchor F	Longitudinal Expansion	in/100ft	Pressure Expansion	in/100ft	Total Expansion
270.24	270.24	73.4	140	77	4290.05155	-10954	15244	82951.1	0.0004221	0.50652	2.95866E-05	0.035503875	0.542023875
270.24	320.24	73.4	140	77	5083.79999	-10716	15800	83956.41	0.0004221	0.50652	3.50607E-05	0.042072828	0.548592828
270.24	370.24	73.4	140	77	5877.54843	-10478	16355	84961.72	0.0004221	0.50652	4.05348E-05	0.04864178	0.55516178
270.24	420.24	73.4	140	77	6671.29687	-10240	16911	85967.03	0.0004221	0.50652	4.60089E-05	0.055210733	0.561730733
270.24	470.24	73.4	140	77	7465.0453	-10001	17466	86972.34	0.0004221	0.50652	5.14831E-05	0.061779685	0.568299685
270.24	520.24	73.4	140	77	8258.79374	-9763.3	18022	87977.65	0.0004221	0.50652	5.69572E-05	0.068348638	0.574868638
270.24	570.24	73.4	140	77	9052.54218	-9525.1	18578	88982.96	0.0004221	0.50652	6.24313E-05	0.07491759	0.58143759
270.24	620.24	73.4	140	77	9846.29062	-9287	19133	89988.27	0.0004221	0.50652	6.79055E-05	0.081486543	0.588006543
270.24	670.24	73.4	140	77	10640.0391	-9048.9	19689	90993.58	0.0004221	0.50652	7.33796E-05	0.088055496	0.594575496
270.24	720.24	73.4	140	77	11433.7875	-8810.8	20245	91998.89	0.0004221	0.50652	7.88537E-05	0.094624448	0.601144448

Table 10: Thermal expansion rate during pressure change

5.2.3 Pressure and Temperature Variance

Diameter – 8 inches

Thickness – 0.251969 inches

Pipe Material Grade – API 5L X42 (42000 psi)

									Thermal Expansion				
Oper Pressure	Design Pressure	Oper Tem	Design Tem	Ambient Temp	Sh	SL	Se	Anchor F	Longitudinal Expansion	in/100ft	Pressure Expansion	in/100ft	Total Expansion
270.24	270.24	73.4	140	77	4290.05155	-10954	15244	82951.1	0.0004221	0.50652	2.95866E-05	0.035503875	0.542023875
270.24	320.24	123.4	190	77	5083.79999	-20431	25515	145478.3	0.0007571	0.90852	3.50607E-05	0.042072828	0.950592828
270.24	370.24	173.4	240	77	5877.54843	-29908	35785	208005.5	0.0010921	1.31052	4.05348E-05	0.04864178	1.35916178
270.24	420.24	223.4	290	77	6671.29687	-39385	46056	270532.7	0.0014271	1.71252	4.60089E-05	0.055210733	1.767730733
270.24	470.24	273.4	340	77	7465.0453	-48861	56326	333060	0.0017621	2.11452	5.14831E-05	0.061779685	2.176299685
270.24	520.24	323.4	390	77	8258.79374	-58338	66597	395587.2	0.0020971	2.51652	5.69572E-05	0.068348638	2.584868638
270.24	570.24	373.4	440	77	9052.54218	-67815	76868	458114.4	0.0024321	2.91852	6.24313E-05	0.07491759	2.99343759
270.24	620.24	423.4	490	77	9846.29062	-77292	87138	520641.6	0.0027671	3.32052	6.79055E-05	0.081486543	3.402006543
270.24	670.24	473.4	540	77	10640.0391	-86769	97409	583168.8	0.0031021	3.72252	7.33796E-05	0.088055496	3.810575496
270.24	720.24	523.4	590	77	11433.7875	-96246	107680	645696	0.0034371	4.12452	7.88537E-05	0.094624448	4.219144448

Table 11: Thermal expansion rate during both temperature and pressure change

5.3 Graphical Analysis

5.3.1Angle of internal friction Vs Longitudinal end force

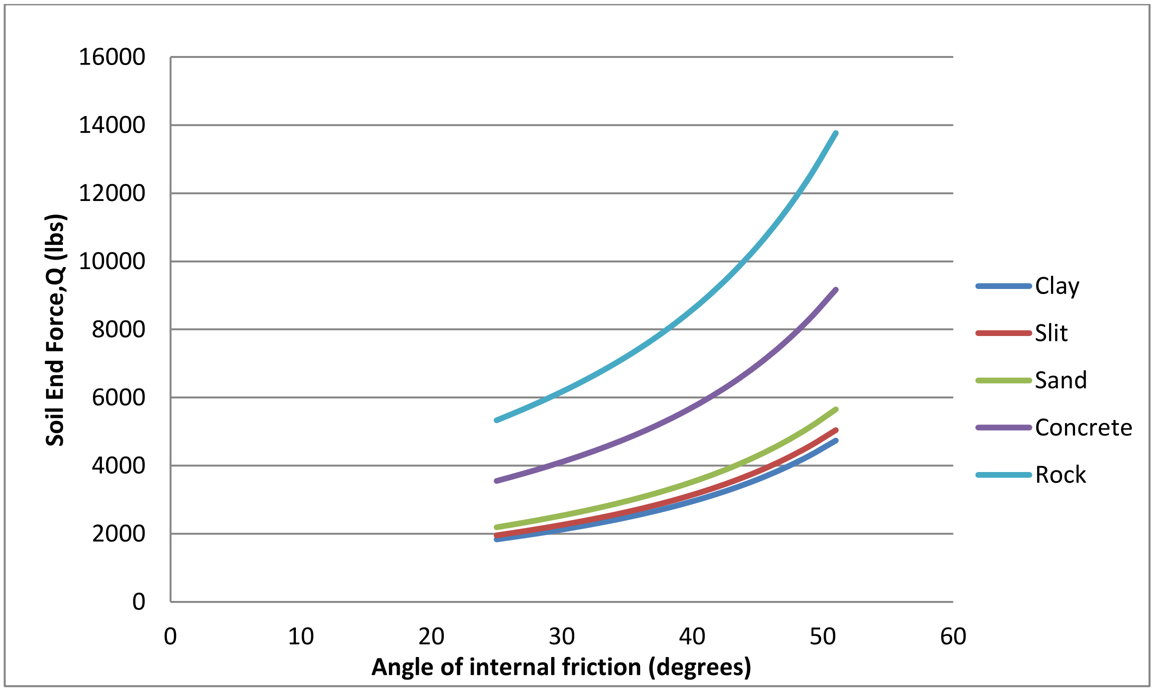

Figure 17: Graph – Angle of internal friction Vs Longitudinal end force

5.3.2 Angle of internal friction vs Lateral end force

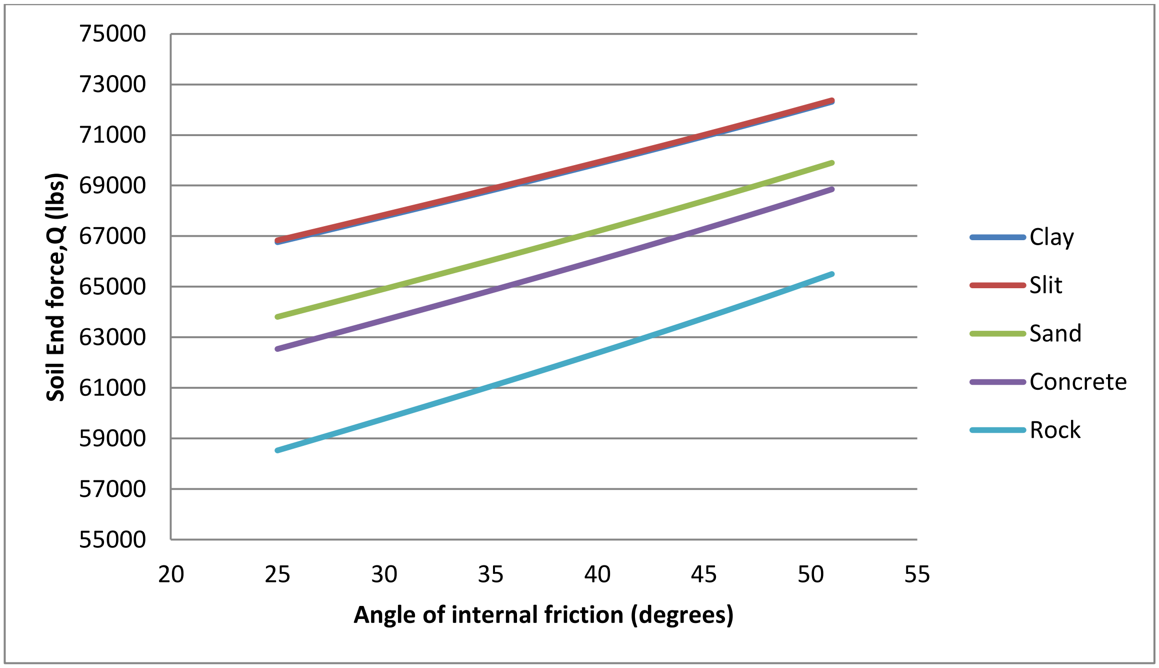

Figure 18: Graph - Angle of internal friction Vs Lateral end force

5.3.3 Longitudinal soil end force Vs Longitudinal Displacement

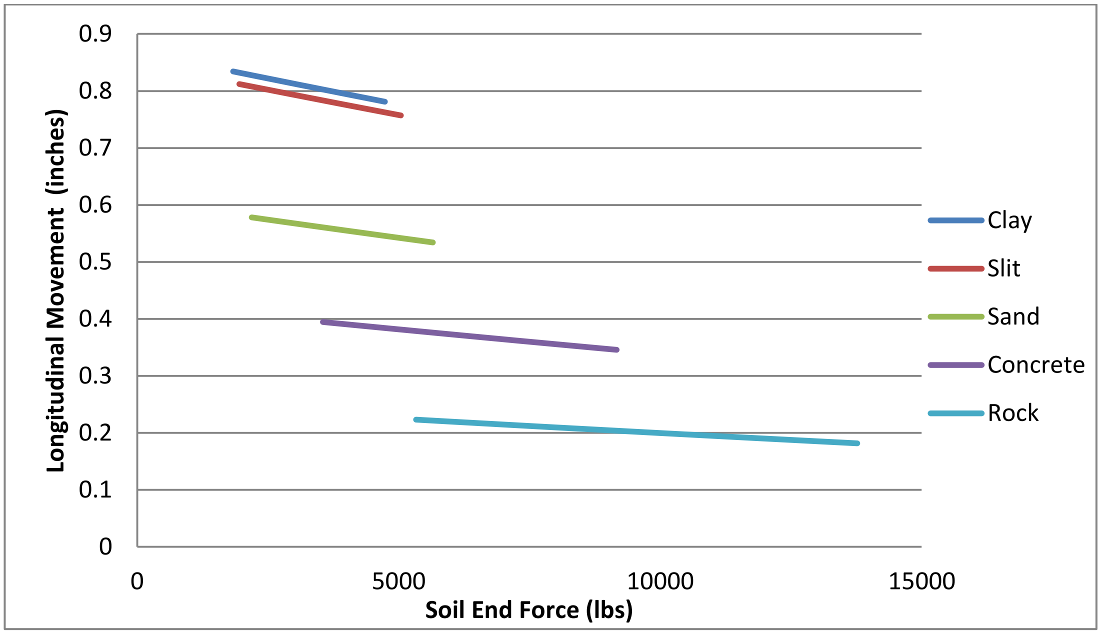

Figure 19: Graph - Longitudinal soil end force Vs longitudinal movement

5.3.4 Longitudinal Soil End Force Vs Lateral Movement

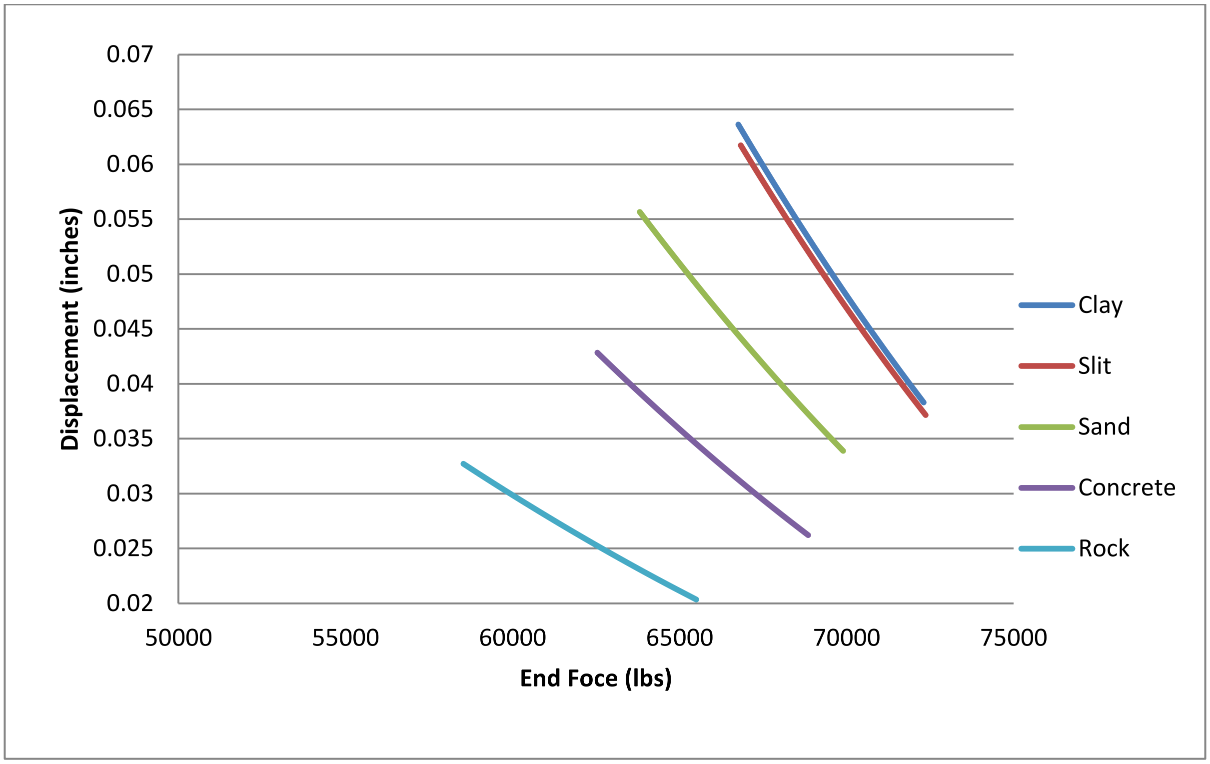

Figure 20: Graph - Longitudinal soil end force Vs Lateral movement

5.3.5 Ground Profile Vs Longitudinal Displacement

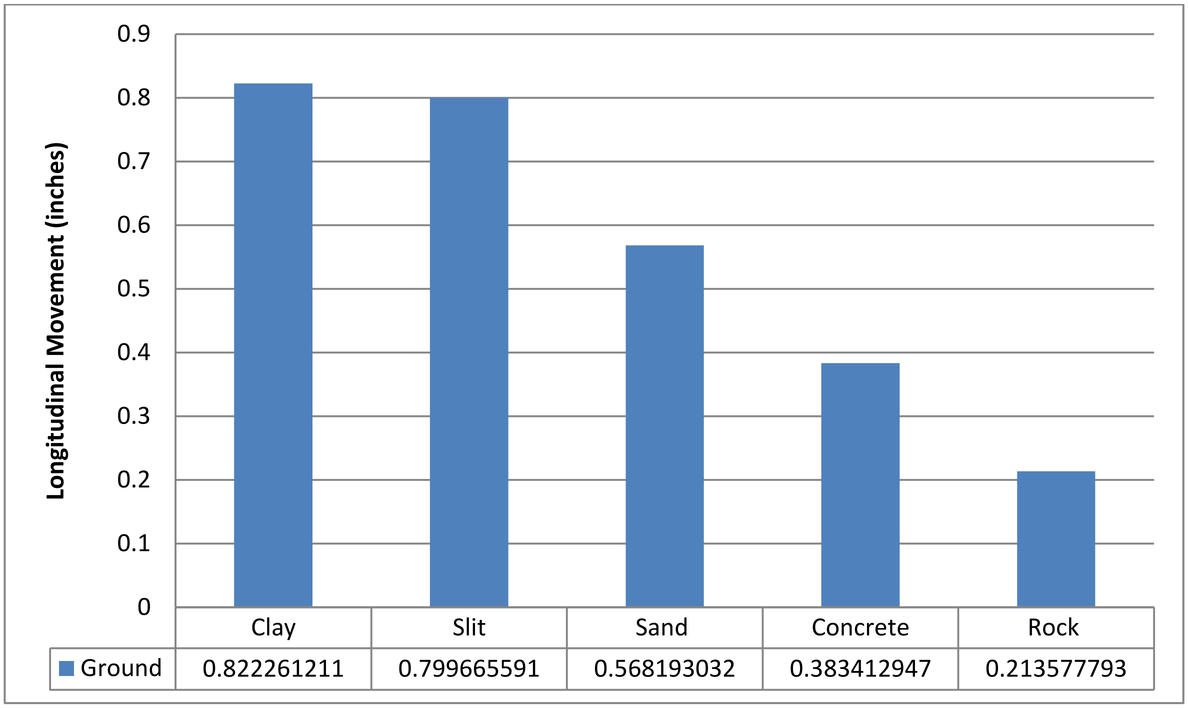

Figure 21: Ground profile Vs Longitudinal displacement

5.3.6 Ground Profile Vs Lateral Displacement

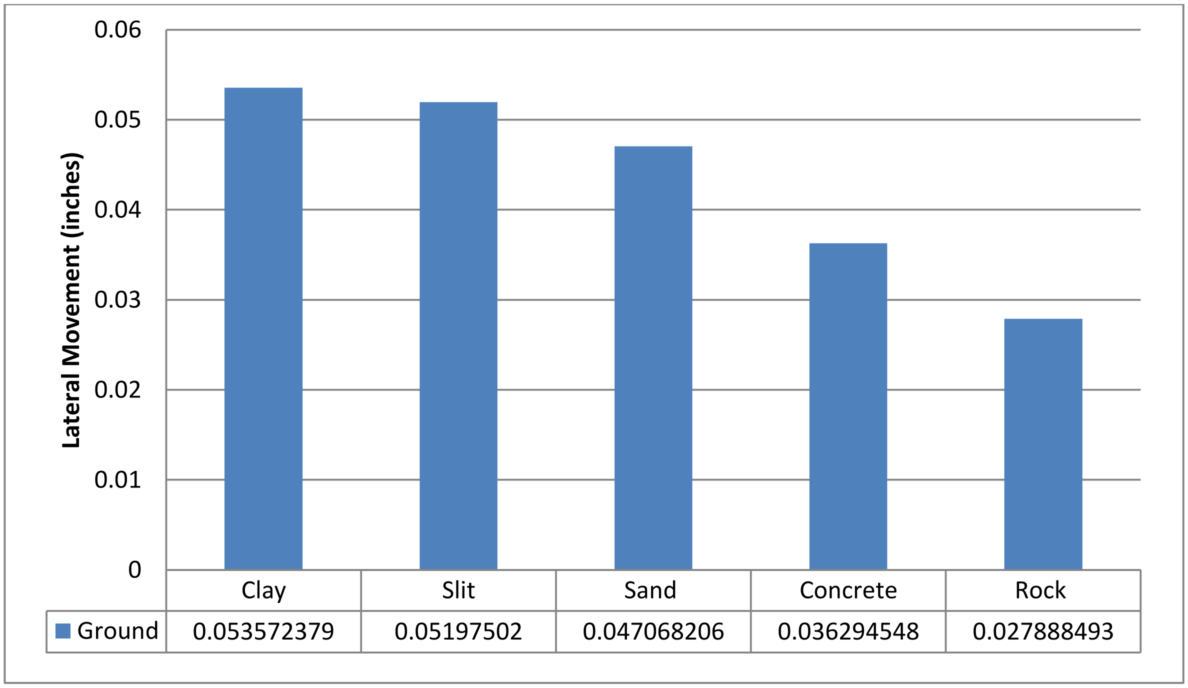

Figure 22: Graph - Ground profile Vs Lateral displacement

5.3.7 Ground Profile Vs Bending Stress

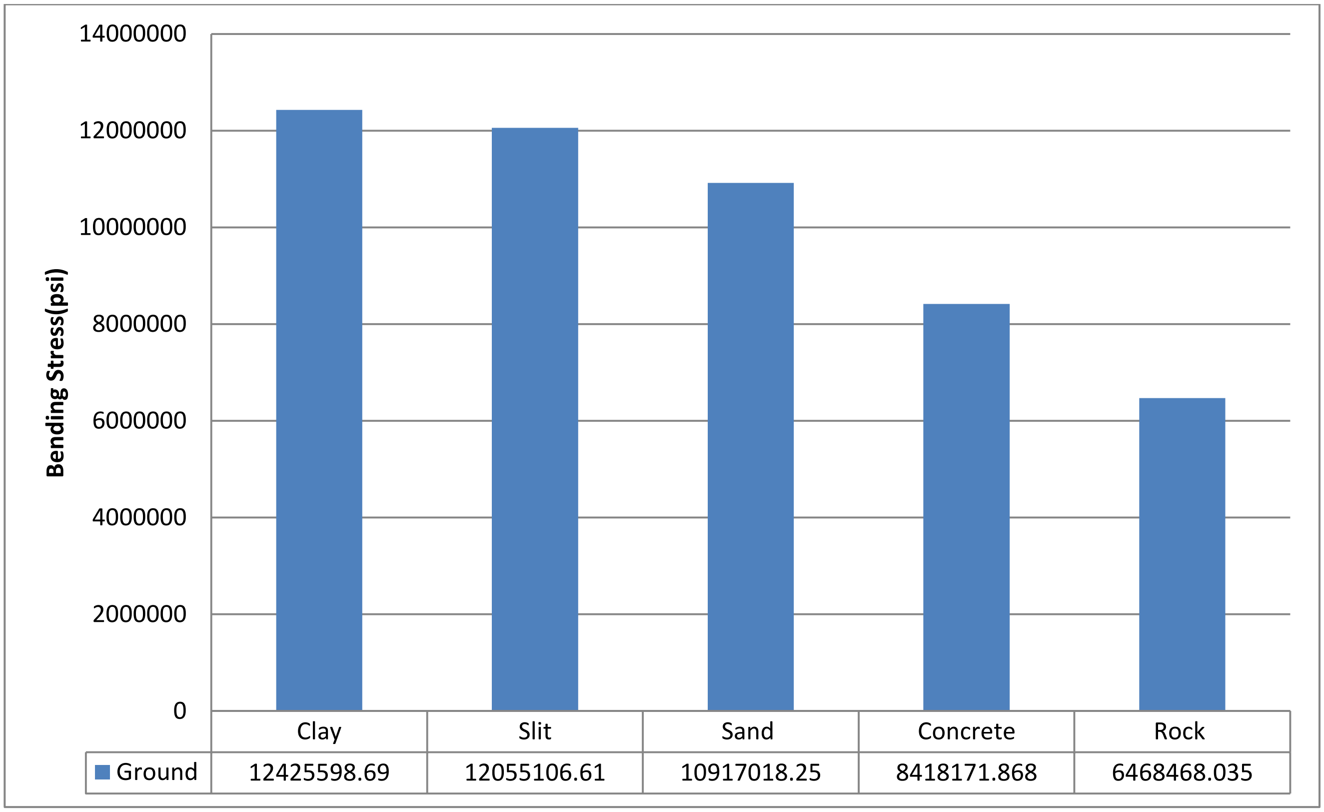

Figure 23: Ground profile Vs bending stress

From the figure 17, it can be seen that as the angle of internal friction increases the longitudinal end force also increases. We can see that the ground profile for rock provides the highest end force. The ground profile having clay has a lower end force compared to other ground profiles for the same internal angle.

From figure 18, the graph plots values of soil end force with that of the angle of internal friction. For each ground profile the end force increases as the angle of internal friction increases. It can be seen that the end force for both clay and slit seem to be almost very similar to each other for the same angle of friction. It is also interesting to see that the soil end force (lateral) is lower for the rock ground profile. With clay and slit having the highest amount of end force, and rock the least.

From figure 19 it can be seen that the longitudinal movement or the displacement is dependent on the soil end force. As the end force increases the movement decreases. Also, it is noticeable that the longitudinal movement varies only by very minimal amounts as end force varies, even with at high differences.

Figure 20 depicts that as the end force increases the lateral movement decreases. Highest displacement is caused by clay ground profile and rock has the lost displacement out of the lot. Also the bending stress is lowest for rock ground profile as the ground is very compact and stiff. This is very dangerous as it can cause excessive vibrations and increase of vibrations in the soil-pipe interface, which can damage the pipeline.

CHAPTER 6

6. CONCLUSIONS

From the results of this project it was found out that the wall of a pipeline is very thin compared with that of a plant piping for the same process parameters and boundary conditions. The wall thickness calculated by the code formulae is enough to ensure the structural integrity of the main pipeline. However for crossings it should be noted that a thicker pipe is used to improve structural integrity.

When considering fully restrained lines which are retrained by either the soil friction or mechanical anchors, the longitudinal stress eventually becomes compressive for a moderate temperature change. The longitudinal stress needs to be considered along with the hoop stress for determining the equivalent stress and should be limited to 0.9 SMYS.

Temperature plays an important role in equivalent stress. As the equivalent stress is used to determine the wall thickness, the temperature rise or fall also will determine the wall thickness. The internal pressure will reduce longitudinal compressive stress at fully restrained sections of the line. The pressure also increases the expansion rates at unrestricted profiles.

The anchor force, which is required to prevent pipe movement at fully restrained sections of the pipeline, should be equal to the sum of force required to resist the longitudinal stress at the restrained side along with the pressure end force at the unrestrained side.

During the soil pipe interaction analysis of the buried pipeline, the pipe expands towards the end or towards a bend in the line profile. However the central portion of the line will be fully restrained by the soil friction force. The total movement at the free end is inversely proportional to the soil friction force, whereas the movement is directly proportional to the square of the temperature differences between the operating and installation temperatures.

To prevent very high stresses developed in the pipeline bends or ends, proper care should be taken to reduce the stresses such that it is in the allowable range. The installation of an anchors and the installation of soft materials or softer soils (which act as shock absorbers) behind the pipe of the lateral legs can be used to reduce stresses. Stress build up can also be reduced by using/ installing a thicker wall pipe near the bend area.

Analysis allows to pre determine the how the pipeline would behave if it was located at different conditions. This soil pipe interaction allows the stress analysis of the pipeline and pre determines stress values.

One of the major factors that affect soil pipe interaction analysis is to determine the soil characteristics. If the soil data is available and survey is carried out properly the analysis can be done effectively. Even though different ground profiles were analyzed in this study, proper soil correlation formulas are still needed for further analysis. The various ground profile studied in this analysis, for the same pipeline provides a clear physical picture of the various processes taking place. It allows for a comparison of how the pipeline would behave if it was constructed in different ground profiles.

With regards to the Kota project the analysis allowed the determination of how the pipeline would behave in different ground profiles. All the stress analysis along with the soil pipe interactions were studied and compared. This data can be used for comparison of surveyor data as well as engineering data if at all any physical soil analysis is carried out at site. It can be concluded that soil survey data is an important factor for soil pipe interaction. Faulty survey data and wrong interpretation of data can lead to huge losses for every party involved in a project. Huge economic losses can be prevented if proper analysis and proper engineering methods are followed.

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