SUSTAINABLE REUTILIZATION OF EXCAVATED TRENCH MATERIAL

by

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ABSTRACT

SUSTAINABLE REUTILIZATION OF EXCAVATED TRENCH MATERIAL

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Sustainability is becoming a key factor in most construction projects. In most construction projects, personnel are spending efforts to understand the social, economic and environmental impacts of the various facets of construction projects. Geotechnical engineering can contribute to the sustainability of the project via selecting sustainable materials and construction processes that would to lead several tangible benefits. For example a pipeline generally runs through a long and varying terrain which results in innumerable environmental impacts during a pipeline installation. Therefore, it is necessary for the design engineer and also the owner to estimate these impacts of pipe installation and evaluate various methods to minimize them. As a part of the pipeline layout and construction, large amounts of soil will be excavated during the pipeline installation process. Similarly, large amounts of soil need to be imported for bedding and backfilling of the trench. Both importing new fill material and exporting excavated trench material for landfilling will have serious implications on both the economic and environmental aspects of the construction project.

The main focus of this research is to study and investigate the reutilization of excavated trench material for various applications including pipe backfills. For this purpose, Integrated

Pipeline (IPL) project which is a joint effort between the Tarrant Regional Water District (TRWD) and Dallas Water Utilities (DWU) that will bring additional water supplies to the Dallas/Fort Worth metroplex is considered in this research. Soil samples were collected along the pipeline alignment and comprehensive geotechnical characterization studies including estimation of expansive clay minerals are attempted. Based on these studies, the sampling materials are identified for potential reuse as backfill, bedding and haunch materials.

Economic and environmental benefits of the suggested reuse method of using insitu excavated material versus imported material were also evaluated. To quantify these benefits, a hypothetical section of a pipeline is assumed and both Cost and Carbon footprint analyses were performed on this section. Two different scenarios were considered in this research; one scenario used insitu treated excavated material for bedding and haunch layers while the second scenario used imported material for the same. This analysis showed a difference of more than 100% savings in carbon emissions when insitu treated excavated material is used instead of importing material. The hypothetical section assumed gives an idea of how carbon footprint analysis and cost analysis may be performed and briefly highlights the relative merits.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 General

Sustainability is becoming a key factor in most construction projects. In most construction projects, personnel are spending efforts to understand the social, economic and environmental impacts of the various facets of the projects (Abreu et al., 2008). For example any major pipeline construction project has to overcome the issue of disposal of large amounts of excavated trench material. Though half of the excavated material can be used as a backfill, the remaining half is often dumped in landfills and landfilling is not always cost effective or environmental friendly option.

As per USEPA (2002) report, United States generated 232 million metric tons of municipal solid waste (MSW) which does not include excavated trench material. Out of this 55% is landfilled while the remaining is either recycled or combusted. Hence, landfilling inert waste like the excavated trench material occupies a lot of useful space in landfills which could be otherwise used for non-biodegradable wastes like plastics and glass. Also, as per Goldstien and Madtes (2001) report, several landfills are closed due to various Federal and State regulations which makes finding a landfill close to the project site difficult and hence the material has to travel several miles before it could be dumped; this has a big environmental impact due to traffic pollution.

This problem can be solved by geotechnical reuse of the excavated material back in the pipeline trench or for highway backfill applications. Hence, geotechnical engineering can contribute to the sustainability of the project via selecting sustainable materials and construction processes that would lead several tangible benefits. Several researchers including Azapagic et al. (2004), Jefferis, (2008) and Abreu, et al. (2008) have highlighted the role of geotechnical engineering in the sustainability issues in various projects.

This thesis attempts to suggest a geotechnical solution for a pipeline project to reduce costs and environmental impacts and thereby contribute to sustainable practice. The details of the research project and its objectives are presented in the next section.

1.2 Research Project Details and Objectives

The Integrated Pipeline (IPL) project is a joint venture between the Tarrant Regional Water District (TRWD) and Dallas Water Utilities (DWU) that will bring additional water supplies to the Dallas/Fort Worth metroplex. This project involves design and installation of a 147 mile pipeline that collects and transfers water from lakes such as Richland Chambers, Cedar Creek and Lake Palestine to the metroplex. As a part of the pipe line layout and construction, huge amounts of soil will be excavated during the pipeline installation process. Similarly, large amounts of soil need to be imported for bedding and backfilling. Both importing new material and exporting excavated material can lead to increased costs of the projects and hence it is imperative to explore ways to cut down the materials costs by evaluating the potential reuse of excavated material for bedding, haunch and pipe zone fills as shown in Figure 1.1.

The IPL project is an important construction project where several sustainability issues of a construction project can be evaluated and implemented. This paper describes a few of the sustainability aspects related to geotechnical engineering. As a part of the sustainability endeavor, the potential reuse of local excavated native material is thoroughly evaluated as this alone will have heavy impacts on the sustainability efforts. For example, the reuse of the excavated material in the form of bedding and backfilling will reduce environmental impacts as less landfilling of the excavated material is needed. Both expensive quarry material production and their transportation costs will also be reduced. Overall, this will result in substantial savings in total construction costs. Hence, it is imperative to explore ways to cut down the materials costs by evaluating the potential reuse of excavated material for various pipe zone and foundation applications such as bedding, haunch and backfilling zones as indicated by Figure 1.1. This task needs a thorough geotechnical evaluation of basic and advanced engineering properties of the excavated native soils. Since geotechnical specification properties for backfilling, haunch and bedding zones vary, an attempt is made here to evaluate whether the use of excavated material without any amendment meets the specifications of bedding, haunch and backfilling zones. Amendments of the native materials with chemical treatments are later explored if the native soils do not meet the specifications.

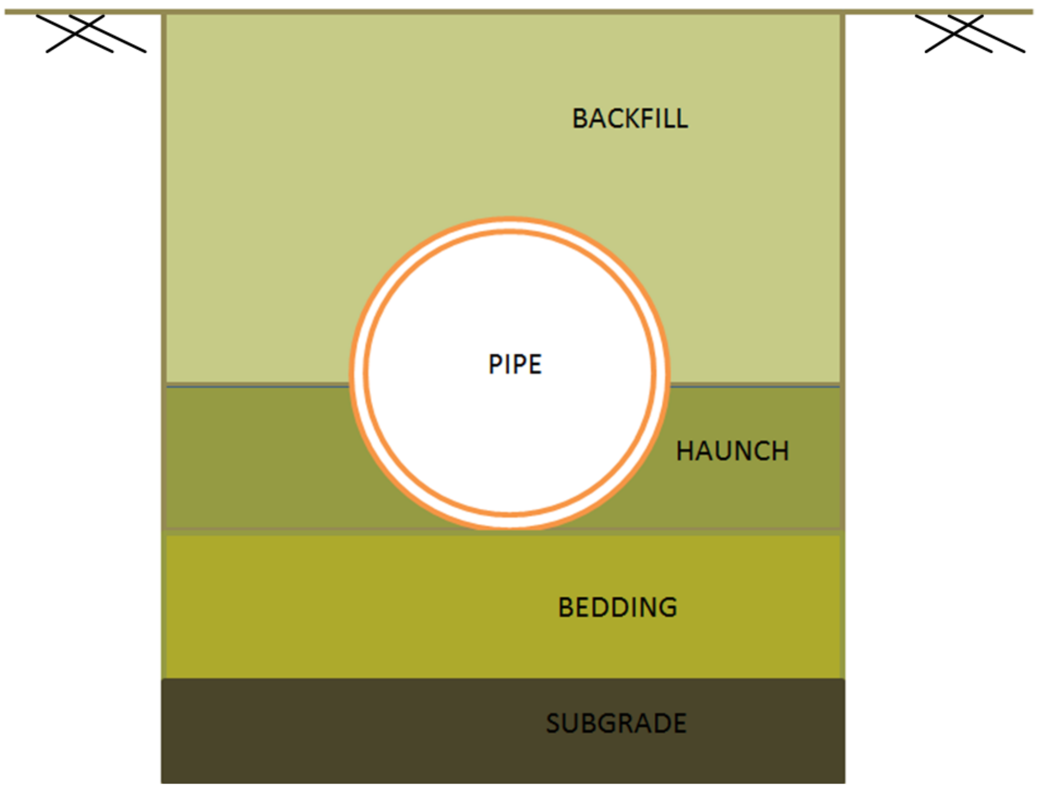


Figure 1.1 Different layers in pipe installation

The main objective of this thesis is to analyze the carbon footprints pertaining to the 147 miles long Integrated Pipeline (IPL) Project funded by Tarrant Regional Water District (TRWD) and City of Dallas based in Texas.

The tasks involved in achieving the above mentioned objective are listed below:

1. Perform a thorough up-to-date literature search on various types of pipe backfill materials, ecological impacts of these materials and sustainable solutions suggested in the past.
2. Conduct basic and advanced geotechnical soil testing to establish the use of native excavated material as a bedding, haunch and backfill materials.
3. Compare the environmental impact of using the native backfill material and procuring the backfill material from a different location by conducting carbon foot print analysis on a selected segment.
4. Compile findings to establish recommendations for this project.

The proposed thesis aims to produce the following outcomes:

- A simplified approach to the carbon footprint analysis and its use to the pipeline projects.
- A constructive analysis illustrating the social, environmental and economic impacts of backfill material through an actual case study.
- Identifying the challenges and potential problems for performing the carbon footprint analysis for large diameter water transmission pipeline projects.

1.3 Thesis organization

Chapter 1 introduces the general nature and the problems associated with disposal of excavated trench material. The later part deals with the IPL project description and the research objective and the various tasks involved in this research.

Chapter 2 presents an overview of the literature review on role of geotechnical engineering in sustainable development. Information is presented on different types of materials that could be used as bedding, haunch and backfill materials along with their ecological impacts. Some of the sustainability issues in the pipeline projects including details on the analysis of Carbon emissions are presented in detail.

Chapter 3 explains the work plan and the experimental program developed to achieve the objective of this research. The details of the soil selection and sampling process and different types of geotechnical tests performed (both basic and advanced) are explained.

Chapter 4 presents the results of the testing program along with detailed discussion on how and where the excavated material can be reused. Test results are analyzed to investigate whether they meet the specifications for bedding, haunch/embedment or backfill materials. Based on this analysis, matrix tables are prepared which highlight the reusability of different types of soils along the pipeline alignment as different pipe backfill materials; these tables are presented in this chapter. Also, cost and carbon emission comparisons are made between a traditional alternative of importing sand and gravel for bedding and embedment versus a modified option of using chemically treated excavated material as bedding and embedment. This analysis is qualitative in nature to indicate reduced costs and carbon emissions due the modified option and hence contains many assumptions which are detailed in this chapter.

Chapter 5 presents the summary and conclusions of the observations and analyses performed in this research. Also, pointers are given for future studies.

CHAPTER 2

LITERATURE SEARCH

2.1 Introduction

This chapter consists of a review of findings from a comprehensive literature search that was conducted as a part of this research. As discussed in Chapter 1, literature search was used as one of the means to understand more about existing research on this topic and to get better knowledge of sustainability and applicability of carbon footprint analysis. The subjects searched include (i) Sustainability in geotechnical engineering (ii) Trench materials and ecological impact of treated and untreated trench materials and their applicability to carbon footprint analysis of such materials (iii) Carbon footprints caused by various sources.

2.2 Sustainability in Geotechnical Engineering

As per the Sustainable Construction Strategy, the most recent report from the UK Strategic Forum for Construction, the economic output of the construction industry is estimated to be more than £1000bn a year and accounts for 8% of the Gross Domestic Product (GDP) of the UK, as well as providing employment for around 3 million workers (Strategic Forum for Construction, 2008). Similar patterns are seen in other countries around the world (MacLeodet al, 2008).

2.2.1 Sustainability analysis

SPeAR® is an assessment tool developed by Arup, founded on indicators such as the UN Environmental Programme and UK government indicators. SPeAR® illustrates the performance of groups of indicators by shading in a segment on the face. The farther the segment is from the center, the weaker it becomes and closer it is to the center of the diagram, the stronger it is in terms of sustainability. Figure 2.3 shows the diagram that can be compared to a dartboard, with the aim being to have as many segments as possible close to the center

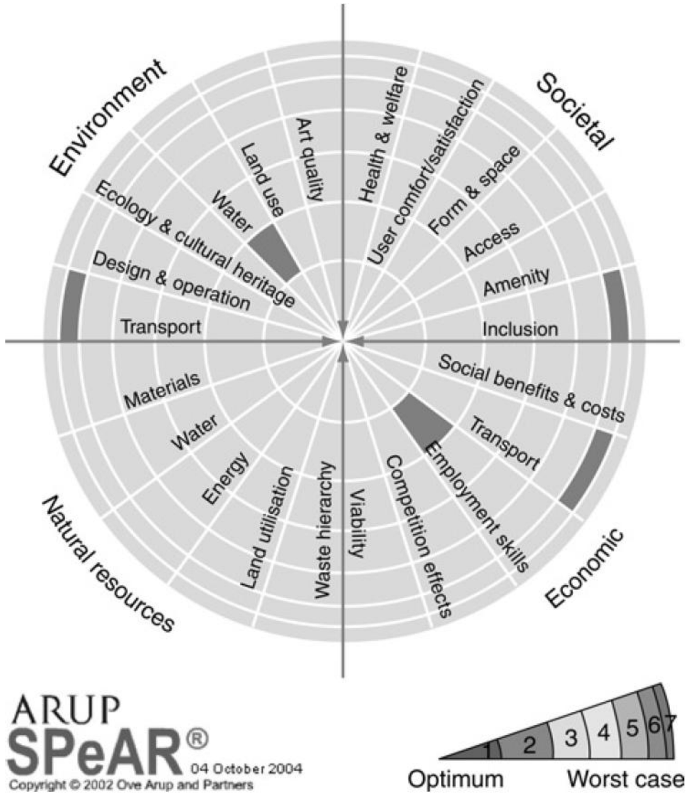


Figure 2.1 An example of the SPeAR® template (Braithwaite, 2007)

After closely examining the systems available for sustainable assessment for construction projects, the Sustainable Project Appraisal Routine (SPeAR®) methodology was chosen to be adapted for the use of geotechnical engineering and is modified as GeoSPeAR (Holt et al, 2009). A more detailed discussion on sustainable indicators is given by Jimenez (2004). In his thesis Jimenez (2004) discusses about social, environmental, economic and natural resource indicators to help understand the impacts of each one these indicators on sustainable development. Jimenez (2004) also developed a qualitative indicator system called Sustainable Geotechnical Evaluation Model (S.G.E.M.) based on color code for comparing different alternative materials for slope stabilization.

There is a lot of emphasis on sustainability in all walks of engineering and most of it is focused on the decisions pertaining to the competing constraints of social, economic and environmental issues (Jefferis, 2008). As per Abreu et al. (2008) sustainable development aims to improve the quality of life now and for future generations. This also means that it is a dynamic process which enables public to realize their potential and improve the quality of life in such a way that protects and enhances the Earth's life support system, simultaneously.

2.2.2 Tools for sustainability analysis

A detailed review of literature on sustainable geotechnology was given by Misra and Das (2011). In their report they discuss the various tools available for sustainability analysis and their application to geotechnical systems. Some of these tools include, quantitative and qualitative assessment tools like Life Cycle Assessment (LCA), Life Cycle Costing(LCC), Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA) and Cumulative Energy Requirement Analysis (CERA) (Wrisberg et al. 2002, Finnveden and Moberg 2004) have been made available that bridge the difference between sustainable process design and practice.

Embodied energy of a material is defined as the sum total of all the energy required to produce that material (Constanza 1980, Brown and Herendeen 1996). It has been used in assessing the sustainability of geotechnical projects (Chau et al. 2006). However, for assessing process sustainability, loss of resource energy that is available to do useful work is often considered a more important parameter than the embodied energy (Bakshi and Hau 2004, Hau 2005). This available energy of a resource to do useful work is termed as energy. Energy per unit mass of a material is a measure of the maximum amount of useful (available) energy that can be extracted when the material is brought into equilibrium with its surroundings (Szargut et al. 1988, Ayers 1998, Bastianoni et al. 2005, Dincer and Rosen 2007, Tsatsaronis 2007). As every energy transformation is inevitably associated with a loss of energy to the surrounding atmosphere where it becomes unavailable to perform useful work, a good measure of sustainability of a process is the energy loss of the process. Hau (2002, 2005), however, criticized both energy and embodied energy for not considering the ecosystem services that went into making the material. Energy of a resource is the sum total of all the ecosystem services that went into making the resource (Odum 1996). Energy approach considers the earth as a closed system with three constant energy inputs: solar energy, deep earth heat and tidal energy. For the purpose of energy calculation, all energy forms are converted to a common base of solar energy with solar emjoules (sej) as the unit.

2.2.3 Alternative materials for sustainable development

A major part of the sustainability related research in geotechnical engineering was focused on introducing novel, environment friendly materials along with reuse of waste materials. Some of the novel environmental materials proposed in the literature are presented here. Vinod et al. (2010) proposed the use of alternate materials like lignosulfonate, which promotes surface vegetation and natural subsurface fauna, for soil stabilization in place of otherwise hazardous coal and fly ash in geotechnical constructions. Saride et al. (2010) suggested the use of recycled or secondary materials like asphalt pavement and cement-stabilized quarry fines as pavement bases. Other examples include the use of recycled glass-crushed rock blends for pavement sub-base (Ali et al. 2011), recycling of shredded scrap tires as a light-weight fill material (Voottipruex et al. 2010), and use of pulverized fly ash to improve the thermal properties of energy piles (Patel and Bull 2011).

Investments made on transportation and processing is reduced when native material is used as backfill. This saves a lot of money that might otherwise be spent on fuels for transportation. The material that is excavated and cannot be reused has to be dumped. Generally, landfills are used for dumping such materials and hence increases the costs associated with these landfills. Use of native materials as backfill hence reduces the space used for landfills also. There are 280 permitted landfills in Texas out of which about 12 landfills are more than 200 ft tall. 3% of total incoming wastes in landfills is reported as soil (TCEQ, 2008).

As discussed in further sections, moving out material from the excavated areas and bringing select backfill material increases the carbon emissions and contributes to the overall carbon footprint of the project. Also, bringing in select backfill involves quarrying of such material elsewhere. This too adds to the carbon footprint of the project.

Figure 2.2 shows the relation of sustainable geotechnical engineering in the overall growth. Large amounts of soil may be moved due to geotechnical works thereby consuming large amounts of energy and natural and man-made materials (Jefferis (2008). Geotechnical engineers can impact the environment changing the earth's surface and soil properties. Addressing sustainability in geotechnical engineering is the basis for addressing sustainability in construction. As shown in Figure 2.1, geotechnical engineering is the first link in the chain of construction and has the capability to impact the entire construction process.

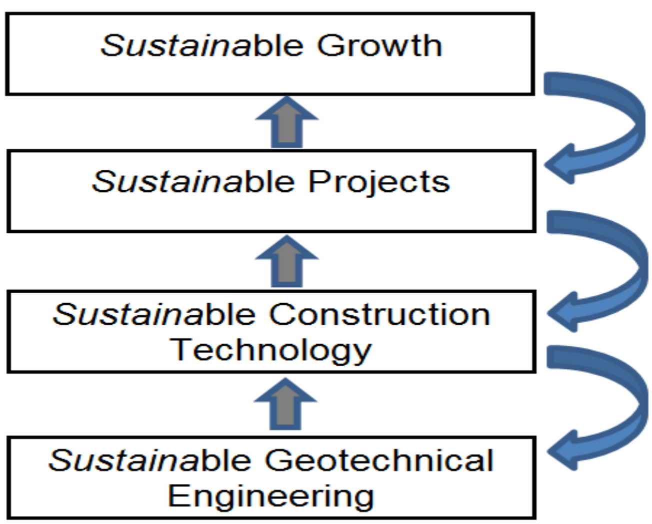


Figure 2.2 Sustainable Geotechnical Engineering
(Abreu et al., 2008)

2.3 Foundation, Bedding, Haunch and Backfill Materials

This section explains the different layers present in a pipeline construction and different types of materials that could be used for each of these layers. Majority of this section is extracted from the book published by Amster Howard in 1996. For a more detailed understanding of these materials and layers the reader is referred to Howard (1996).

2.3.1 Foundation layer

Figure 1.1 in Chapter 1 shows a typical cross section of a trench along with the water transmission pipeline highlighting the different bedding, haunch and backfill layers. In this figure the lowermost layer in the trench is the subgrade over which the rest of the construction rests. The subgrade is also known as foundation of the trench. This layer of the trench may or may not have bedding placed over it. In this thesis, it is considered that the layer of bedding is placed over the layer of foundation. The soil in the foundation is generally undisturbed soil and remains intact in the place. If the strength of the foundation soil is found to be inadequate to support the rest of the construction, it is advisable to replace the foundation soil with an imported material (Howard, 1996). Also, the material that is replacing the foundation soil should be tested and certified before use. If the foundation soil is soft and wet, it must be displaced by dumping rock into the trench. Sometimes, if this material is not strong enough to support the rest of the construction, it is compacted and made suitable for the construction. Stable, uniform support for the pipe prevents excessive settlement or excessive differential settlement of the water transmission pipeline.

There are five different ways to strengthen the foundation material. These are presented in the following:

2.3.1.1 Displacing the soil

Large boulders or rock material is dumped into the trench that displaces the existing soft and muddy soil. The same soil is then replaced back into the trench in a transformed way with higher density and strength.

2.3.1.2 Replacing the soil

The existing soil at the bottom of the trench, i.e., the foundation is first removed and then a different material is brought in to replace that soil

2.3.1.3 Reinforcing the existing soil

Foundations that have soft soils can be reinforced by using dry material or particles that are larger in size. Sometimes, both of these can be used to reinforce the soil. The material that is used to reinforce the soil is first dumped onto the soft soil and then compacted to the desired level of compaction to reach the specified strength. This operation may be repeated if the required strength is not reached. In modern days, geosynthetics are being used for reinforcing the soil.

2.3.1.4 Restoring the soil

It may sometimes be possible to remove the existing soil from the foundation and restore back in a transformed way with higher density and strength.

2.3.1.5 Soil Modification

Chemicals such as admixtures are made to react with the soil such that the properties of the soil change and higher strength is attained.

2.3.2 Bedding layer

The bedding material is placed on top of the foundation as shown in Figure 2.3. As discussed above, bedding is sometimes avoided. This layer of the trench is intended to provide even support for the pipe. The bedding may be compacted or uncompacted depending on the design specifications or standards and guidelines. In modern times, the pipe is placed on the uncompacted bedding so that the pipe sinks into the bedding soil. The depth or thickness of the bedding also varies depending on the type and diameter of the pipe. The use of PCC pipe is considered in this analysis. This is an assumption as the project has exploring the use of other types of pipe materials. Because of the assumption, the bedding thickness is calculated accordingly.

Generally, the minimum thickness of the bedding material is 4 to 6 inches. As a rule of thumb, the bedding thickness is considered equal to the outside diameter of the pipe in inches divided by 12 (Howard, 1996).

2.3.2.1 Typical bedding materials

Often the bedding material is same as that used for the haunch or embedment and can vary from the material excavated from the trench to the material brought from other sources. It is recommended that the material that is used for the bedding layer is free from organic matter, limbs, frozen earth, debris, man-made wastes, etc.

If the soil that is used for the bedding is uncompacted, it is recommended that clean, cohensionless with high permeability should be used. Soils like sands and gravels can be used for this purpose. If the soil that is used for the bedding is to be compacted, any soil other than the ones mentioned above can be used and then compacted.

2.3.2.2 Treated bedding materials

In the research conducted, it was seen that the bedding material was not suitable for several miles of the pipeline. Hence, such material needs to be treated with chemicals or replaced by material brought from a different location. Analysis was done to check the costs incurred due to usage of treated native material as bedding material versus material brought from a different location. Several assumptions have been made for the study which would be discussed further in Chapter 4. Also, the analysis of carbon emissions was made for both the cases.

2.3.3 Embedment

Embedment or sometimes referred to as haunch is the layer that is placed above the layer of bedding. The embedment or the haunch acts as a cushioning material around the pipe. The pipe along with the embedment acts as a structure to support the loads coming from external sources. Each of such systems has been designed to meet specific situations of each pipeline. The design of embedment for a rigid pipe is different from that of a flexible pipe.

In the case of a rigid pipe, the haunch takes the load coming on top of the pipe and distributes it evenly to the bottom of the pipe. The height of the embedment in such case varies from zero, i.e., from the point where the pipe rests on the bedding, to the springline of the pipe. The springline is defined as the horizontal centerline of the pipe, which is an imaginary line situated at the maximum width of the pipe and is parallel to a horizontal plane (Howard, 1996).

In the case of a flexible pipe, the embedment acts as a barrier for the deflection of the pipe. In such situations, the height of the embedment can vary from the springline upto a height of 12 inches over the pipe. Since, this work is based on the assumption that a PCC pipe would be used for the entire project, the calculations for the height of the embedment have been done accordingly. In this case, the height of the embedment was taken from the point where the pipe touches the bedding to the springline; hence this height would be equal to the radius of the pipe. It is assumed that the diameter of the pipe throughout the project is going to be 84", the height of the embedment is calculated as 84/2 = 42" = 3.5 feet.

2.3.3.1 Typical embedment materials

Materials that can be used for embedment or haunch can vary from those that are excavated from the trench to those that are brought from a different place. It can also be washed or crushed rock. It is also necessary that the material does not possess any organic content, stumps or limbs, frozen earth, man-made wastes or debris or any such unsuitable materials. If any materials like slag, shells or cinders are specified for usage, they should first be tested for strength and durability by a trusted source.

The type of pipe that is used dictates the maximum particle size to be used. The maximum particle size is defined as the smallest sieve openings that all particles in the soil would pass. Particles that are larger in size pose the problem or point load on the pipe. These particles can also cause abrasion to the pipe when subjected to vibrations. The best material that can be used an embedment material is crushed rock with 100% passing the 75 mm sieve, less than 25% passing the 9.5 mm sieve and less than 12% passing the 75 micron sieve (ASTM Standard C 822)

Care should be taken during the construction of the embedment. It is recommended that the material used should not be dropped directly on to the pipe since; particles that are larger in diameter can damage the pipe due to impact. It should also be noted that the material should be distributed evenly along the trench and equally on either sides of the pipes so that the pipe does not lose its alignment. Proper care should be taken to make sure that the pipe undergoes minimal movement during the placing of embedment material. When coarser material is placed beside a finer material, there are chances that the finer material moves into the voids that are present in the coarser material. This phenomenon is called migration. It should be checked that the migration is minimum by maintaining compatibility among backfill, embedment, bedding and adjacent materials.

2.3.3.2 Treated embedment materials

In the research conducted, it was seen that the embedment material was not suitable for several miles of the pipeline. Hence, such material needs to be treated with chemicals or replaced by material brought from a different location. Analysis was done to check the carbon emissions due to usage of treated native material as embedment material versus material brought from a different location. Also, the analysis of costs was made for both the cases.

2.3.4 Backfill layer

As shown in Figure 1.1 of Chapter 1, the material placed over the embedment soil and the pipe is termed as the backfill. The backfill material may or may not be in contact with the pipe depending on the height of the embedment. The requirements for backfill depend significantly on the surface use, terrain, etc. and vary from site to site. Generally, the material excavated from the trench is used as backfill, with a few exceptions. This excavated material may need some amount of processing like removing larger particles.

There may be cases where the backfill material would settle unduly. This happens when the soil is dominated by loosely packed soil mass, organics, etc. In such circumstances, the ground surface has to be piled up over the trench or any such arrangements have to be made to ensure that there are no depressions over the pipe.

Erosion of surface soil is also a major concern for any such constructions. To prevent erosion, an additional layer of gravel or boulders may be placed over steep slopes of backfill. Vegetation is also a good option to eradicate soil erosion.

Like in the case of bedding and embedment materials, migration may occur in backfill materials also. Hence, care should be taken to check that the backfill, embedment, bedding and adjacent materials are compatible in order to reduce migration.

2.3.4.1 Typical backfill materials

As per Howard (1996), Any backfill material should not contain stumps and limbs, debris produced from construction, manmade waste, or any other material that is not suitable, especially any material that would prove to be a hazard in the future excavations in the backfill area. Any material that may be prone to high amounts of changes in volume should not be considered to be used as backfill material for roads and highways, shoulders, walks, curbs, runways and aprons. These soils include but are not limited to

- Organic silts or clays
- Fat clays or any such potentially expansive soils
- Materials like claystone, shale, siltstone, mudstone, etc. that are from potentially expansive formation. In case these materials are used, it should be seen that these materials are first treated for expansion before use.

There are two zones that require the use of a maximum particle sized soil in the trench backfill. These are the outer cushion zone and the inner cushion zone as shown in Figure 2.3.

Larger particles may create a point load on the pipe and hence should be avoided. Large rock particles would also create vibrations in a pipeline that is under pressure like a water transmission line and can cause wear in the pipe wall due to abrasion. Sometimes, for specific pipes, the manufacturer may be contacted for information on allowable maximum particles sizes to check the requirements.

If a backfill material that may settle excessively like organic materials, frozen soil and loosely-placed large chunks of soil, is used, the ground surface has to be piled over the trench, or other arrangements should be made to see that there are no depressions over the pipeline. When such a pile of material or mound may not be acceptable, the backfill soil should be compacted to a minimum of 85% of the standard proctor density. Ground and surface water may create wash-outs in trenches on slopes until the backfill soil becomes consolidated over time. In order to avoid erosion, backfill material on steep slopes may also need a layer of riprap such as gravel, cobbles and boulders or may need to be vegetated. Diagonal trenches located on the ground surface may also be useful in diverting the water to the sides in order to prevent erosion down the slope.

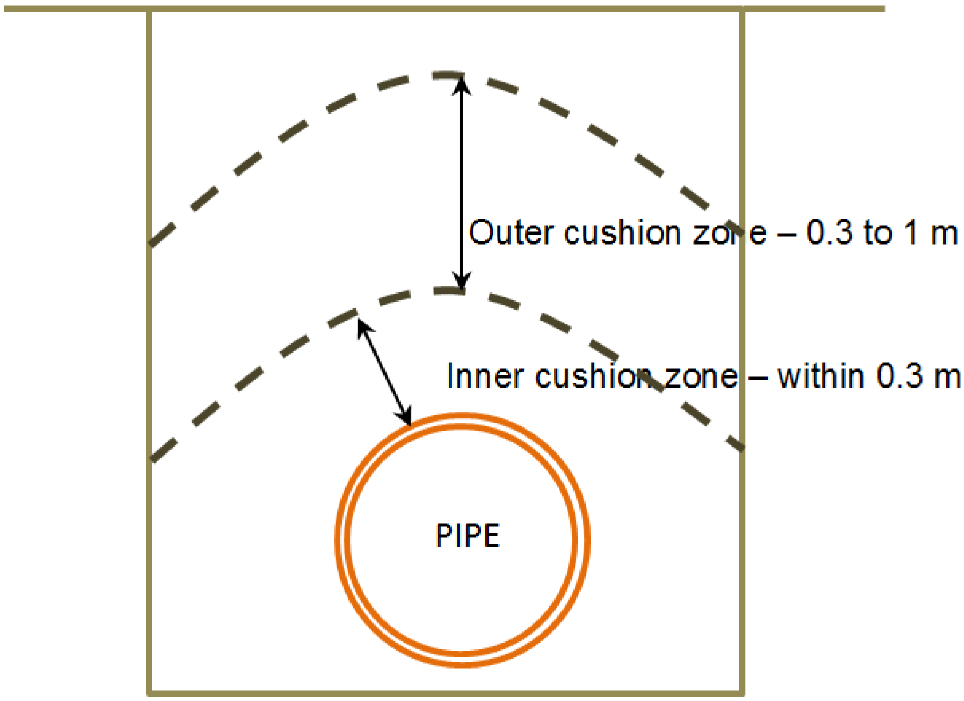


Figure 2.3 Areas of limited particle size (Howard, 1996)

The walls of the trenches and the embedment material must be equally stiff. This can be checked using the Standard Penetration Test or any such testing methods in those areas where the trench walls are suspected of being soft or low density.

Use of heavy equipment should be avoided while placing the backfill within 1 m of the pipe. Hydro-hammers or other similar compaction equipment should be avoided within 1.5 m of the top of the pipe (Howard, 1996). They can be used only if the soil over the pipe has been previously compacted.

It should be considered that the placement of the backfill material over the exposed pipe should minimize any load or impact on the pipe that would push it out of alignment, open a joint or flatten a section of the wall in case of a flexible pipe.

2.4 Carbon Footprints

According to several research studies, the rise in Green House Gas (GHG) emission is very likely the main reason for most of the recently observed increase in the temperature and other climate changes (EPA 2010, IPCC 2007). The term "Carbon footprint" talks about the quantities of carbon dioxide and other greenhouse gases (GHG) released into the atmosphere each year by an entity. The entity may be an individual, a household, organization or a country as a whole. It is usually measured in terms of pounds of carbon dioxide equivalents, and generally includes both direct and indirect emissions (EPA). In a broader sense, a greenhouse gas emission inventory can be termed as carbon footprint. CO_2 may be emitted due to consumption of electricity, fuel combustion, production of materials, solid waste, etc.

The first step towards reduction of carbon footprint in the construction industry is to evaluate the carbon footprint of a given work activity. Within the construction industry, one of the primary GHG contributors is the cement manufacturing sector. It accounts for about 3-4% of global man-made CO_2 emissions. CO_2 emissions for cement manufacturing have been discussed in detail in the coming sections. The transportation of material to and from construction sites, quarries, cement plants, lime manufacturing units, brick kilns, etc., as well as the fuel consumption of the construction equipment used on the site are other causes of large GHG emissions by the construction sector (Spaulding, 2008).

The wastes generated by the construction industry are categorized under solid wastes. Civil engineering projects generate a large amount of carbon footprint which can be reduced by optimizing the design and construction processes and taking into account the environmental impacts of choosing certain methods, designs and materials.

Electricity consumption often produces the largest chunk of CO_2 due to the carbon-intensive inputs for the generation of electricity and the ineffective ways to produce and transport electricity. These are indirect emissions since they are not emitted due to fuel combustion, but rather occur remotely.

EPA defines direct emissions as those that an individual can directly control, such as driving a car or heating a home with natural gas, while indirect emissions are the consequences of activities for which individuals cannot control the amount of emissions. For example, individuals can control the amount of electricity they use at home, but they cannot control the emissions associated with the generation of that electricity, because the electric company controls it.

With increasing concerns of greenhouse gases (GHG) and global warming, there is an immediate need to estimate and reduce the carbon footprints. Some countries are already taking steps in this regard. For example, Canada has developed a carbon trading market where any project will be eligible for carbon credits (Environment Canada, 2009). In the USA, the dialogue for carbon regulation is moving at a fast pace to when and how such a policy will be implemented. The construction industry is also concerned as the construction operations generate the third highest greenhouse gas (GHG) emissions among U.S. industrial sectors (EPA, 2009). To identify and mitigate such risks, it is critical to reliably estimate carbon footprints for a construction project in the initial planning stage.

Carbon footprints are generally estimated by including all greenhouse gases (GHG) that are emitted and are expressed in tons of CO_2 equivalent (tCO_2e). Sometimes, only the CO_2 emitted is estimated and expressed in tons CO_2 (tCO_2) (www.carbontrust.co.uk). "Due to the increasing concerns about the carbon dioxide emissions and global warming, many organizations are taking up carbon footprint projects to evaluate their role in the global warming (Matthews et al., 2008)."

2.4.1 Various sources of carbon emissions

For this study, the carbon emissions due to production of cement, lime, flyash and stone and gravel material is considered. Also, the carbon emissions due to the transportation and installation of these materials are considered. Hence, the carbon emissions due to these materials have been discussed in detail below:

2.4.1.1 Solid waste

As discussed above, construction materials are categorized under solid wastes. Solid wastes also contain municipal solid wastes that are collected on a daily basis from households and industries. Thus collected solid waste is generally dumped into landfills. Class IV landfills accept solid wastes. Figure 2.4 shows a breakdown of solid wastes in the state of Texas for the year 2007.Statistics show that 2% by weight of these solid wastes contain soil.

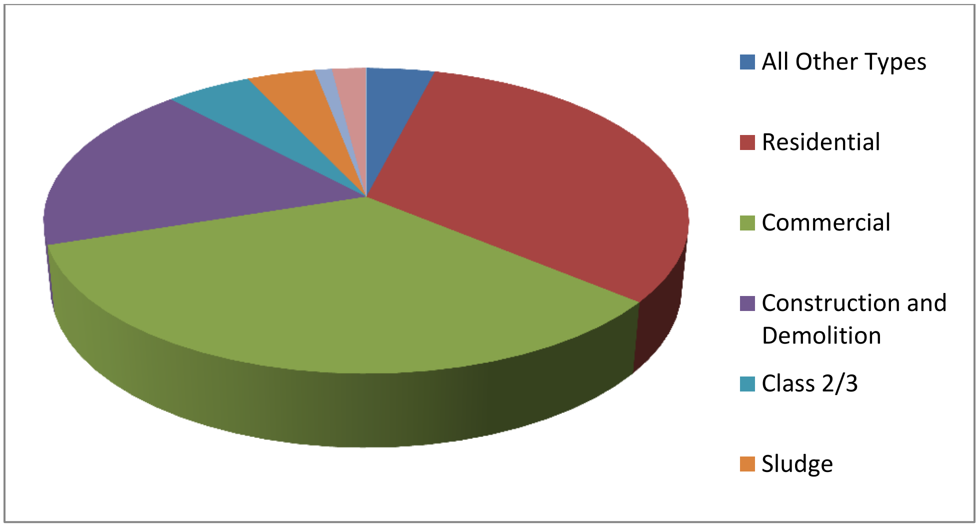


Figure 2.4 Breakdown of Solid Wastes (TCEQ, 2007)

2.4.1.2 Combustion of fossil fuels

Fossil fuels such as coal, oil and gas are used for a range of purposes including production of materials and also powering the vehicular engines. This combustion of fossil fuels is the major contributor to the global CO_2 emissions (EPA, 2011). Vehicles used for the transportation of native material to the landfill for dumping as well as transportation of imported material from the quarry to the site location are considered for this study. Figure 2.5 shows the teragrams of CO_2 equivalents emitted by various sources.

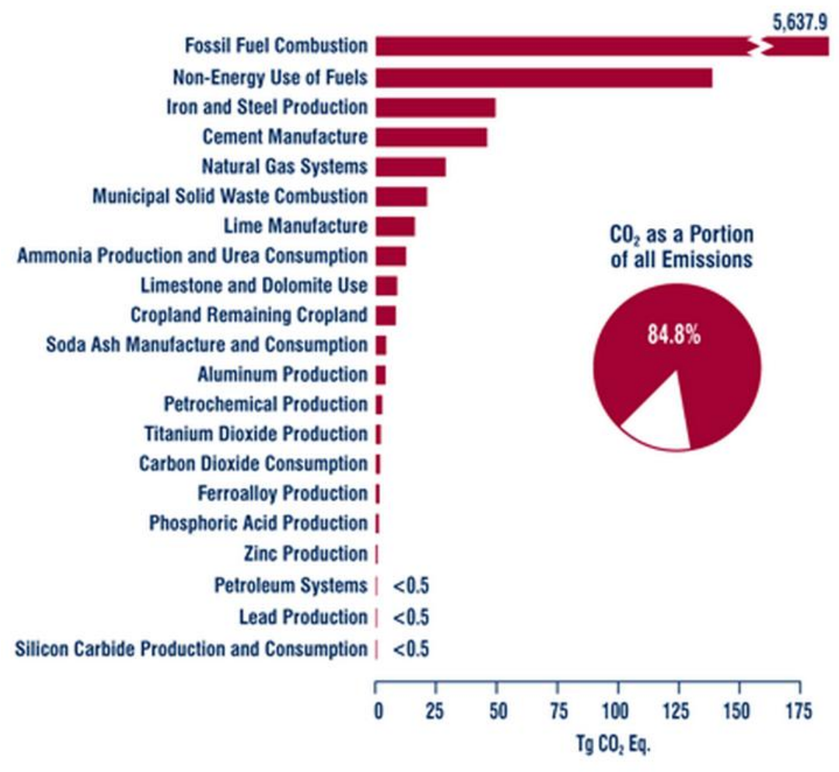


Figure 2.5 2006 Sources of CO_2 emissions
(Source: USGGEI, www.epa.gov)

2.4.1.3 Electricity Generation:

The electric power industry is the single largest source of CO_2 emissions in the United States. It accounts to about 41% of all CO_2 emissions in the country. (www.epa.gov)

2.4.1.4 Cement Manufacturing

While cement is manufactured, CO_2 is emitted as a result of both during combustion of fuel and process-related emissions. Most combustion-related CO_2 emissions result from clinker production, and fuel used for pyro-processing. Figure 2.6 shows a breakdown of the cement industry carbon emissions in United States for the year 2001.

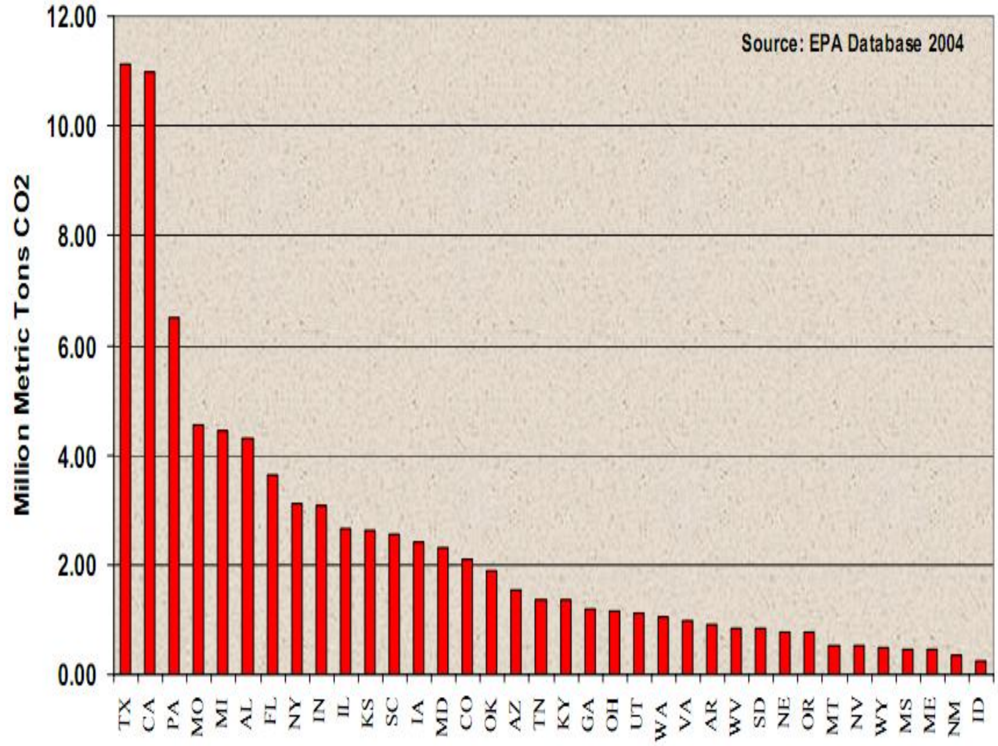


Figure 2.6 Cement Industry CO_2 emissions, 2001 (www.epa.gov)

Cement industry CO_2 emissions for the year 2001 show that Texas is the largest emitter of CO_2 during cement production. The production of cement is increasing about 3% per year (McCaffrey, 2002). Cement is considered as the most energy consuming construction materials after aluminum and steel. The production of one ton of cement emits about one ton of CO_2 into the atmosphere, as a result of de-carbonation of limestone in the kiln during manufacturing of cement and the combustion of fossil fuels (Roy, 1999).

2.4.1.5 Lime Manufacturing

Lime is the byproduct of high-temperature calcination of limestone. Rock that contains atleast 50% calcium carbonate is classified as limestone. When the rock contains 30 to 45 percent magnesium carbonate, it is referred to as dolomite, or dolomitic limestone. Lime can also be produced from aragonite, chalk, coral, marble, and sea shells. Sometimes hydrated lime is produced by making the resulting lime react with water.

The production of lime is basically classified into four processes, viz.,

i) Raw limestone is quarried

ii) Quarried limestone is prepared for the kilns by crushing and sizing

iii) Limestone calcination

iv) Further processing by hydrating

v) Storage and transportation

The carbonate in the limestone is reduced to carbon dioxide is emitted into the atmosphere. Also, the carbon in the fuel is oxidized and released into the atmosphere. It is estimated that 1570 lb of CO_2 is produced per ton of lime produced (www.epa.gov). These estimates are theoretical, based on the production of two moles of CO_2 for each mole of limestone produced.

2.4.1.6 Fly ash Manufacturing

According to the American Concrete Institute (ACI) Committee 116R, fly ash is defined as *"the finely divided residue that results from the combustion of ground or powdered coal and is transported by flue gasses from the combustion zone to the particle removal system"* (ACI Committee 232, 2004). It is filtered from the combustion gases by the dust collection system, using mechanical means or electrostatic precipitators. These particles are generally spherical in shape and finer than Portland cement and lime with a diameter from 150 μm to less than 1 μm. There are two types of fly ash, Type C and Type F. Fly ash produced from burning sub-bituminous coals is referred as ASTM Class C fly ash or high-calcium fly ash, as it typically contains more than 20 percent of CaO. While fly ash produced from the bituminous and anthracite coals is referred as ASTM Class F fly ash or low-calcium fly ash. The color of fly ash can be tan to dark grey, depending upon the chemical and mineral constituents (Malhotra and Ramezanianpour, 1994; ACAA, 2003). Class F fly ash is considered for soil stabilization.

2.4.2 Ecological Impacts of Trench Materials

All around the globe, the consumption of raw materials by the construction industries is adding up day by day resulting with depletion of natural resources. There is a consistent increase in the environmental impacts and CO_2 emissions all over the surroundings. Types of materials such as waste rock, mill tailings, quarried rock, sand, gravel and binder are generally used as backfill materials. Sometimes, the native material is first treated and then used as the backfill material in cases where the native material is not fit for usage. Particularly in recent years, utilization of native soil treated with lime, cement, fly ash or combinations of these, is used as a backfill material.

Production of lime induces heavy environmental issues. Lime production plants are generally located at places where there is less human inhabitance. There is lower energy consumption in the manufacture of lime than the manufacture of cement, giving a material with 50-70% less embodied energy. Roughly for every 100lbs of lime that is used, approximately the same amount of CO_2 is absorbed that a tree does in a year. The fly ash which is a waste material of power plants is a fine material (1µm-200µm) that remains in the power plants' filter after the combustion of pulverized coal (Ibrahim, 2008).

Cement production causes environmental impacts at all stages of the process. These include emissions of airborne pollution in the form of dust, gases, noise and vibration when operating machinery and during blasting in quarries, and damage to countryside from quarrying. Equipment to reduce dust emissions during quarrying and manufacture of cement is widely used, and equipment to trap and separate exhaust gases are coming into increased use. Environmental protection also includes the re-integration of quarries into the countryside after they have been closed down by returning them to nature or re-cultivating them.

Cement manufacturing produces CO_2 both directly when calcium carbonate is heated, producing lime and carbon dioxide, and also indirectly through the use of energy if its production involves the emission of CO_2. After power industry, cement production produces the highest amount of CO_2. 5% of global man-made CO_2 emissions are from cement industry which is nearly 900 kg of CO_2 for every 1000 kg of cement produced. A cement plant consumes 3 to 6 GJ of fuel per ton of clinker produced, depending on the raw materials and the process used. Most cement kilns today use coal and petroleum coke as primary fuels, and to a lesser extent natural gas and fuel oil. Selected waste and by-products with recoverable calorific value can be used as fuels in a cement kiln, replacing a portion of conventional fossil fuels, like coal, if they meet strict specifications. Selected waste and by-products containing useful minerals such as calcium, silica, alumina, and iron can be used as raw materials in the kiln, replacing raw materials such as clay, shale, and limestone. Because some materials have both useful mineral content and recoverable calorific value, the distinction between alternative fuels and raw materials is not always clear. For example, sewage sludge has a low but significant calorific value, and burns to give ash containing minerals useful in the clinker matrix.

The amount of embodied energy and operational energy which is consumed in the process of production, recycling, and reuse are becoming increasingly more important due to the potential shortage of natural resources in the near future and due to the inflation in the energy prices.

2.5 Chapter Summary

There is an urgent need for reliable and appropriate indicators to assist geotechnical engineers to compare project options and understand the impact of each choice and finding ways for sustainable development in geotechnical engineering. World is gaining consciousness towards reducing carbon emissions. This can be observed by various developments globally. Incentives by governments for using alternate fuels, setting target emissions for the future and developing plans to achieve these targets are some of these observations

. Environmental issues, sustainability and carbon footprint are becoming the most important concerns of modern day construction projects due to global warming and increasing greenhouse gas (GHG) emission. This study will be helpful in illustrating the ecological impact of backfill materials for Integrated Pipeline (IPL) Project and will serve as a guideline for the future pipeline projects.

CHAPTER 3

SITE CHARACTERIZATION AND SOIL TESTING METHODS

3.1 Introduction

The pipeline project under review involves design and installation of a 147 mile pipe line which has varying geology and includes several geologic formations. Hence as an initial estimate, 10 locations were selected for this research from which samples were collected with help from Tarrant Regional Water District (TRWD) and Fugro Consultants Inc. These samples were subjected to both basic and advanced geotechnical testing to classify and check if they meet the criteria for using as bedding, embedment or backfill materials. The following sections present the details of the soil selection and sampling process and different types of geotechnical tests performed (both basic and advanced).

3.2 Soil Selection and Sampling

Soil sampling locations were selected such that they are representative of the materials obtained along various segments of the pipe line alignment. A total of 10 different locations were identified with consultations from TRWD and IPL team. Figure 3.1 presents the selected site locations circled in brown along with the other borings planned as a part of the IPL project. Representative cut samples were collected from the field by the Geotechnical Consultants (Fugro Consultants Inc.) under the contract with TRWD and these materials were transported to University of Texas at Arlington for backfill characterization studies. These soils were then subjected to physical tests and clay mineralogy tests as well as engineering studies. Summary of tests and test results are presented in the following sections.

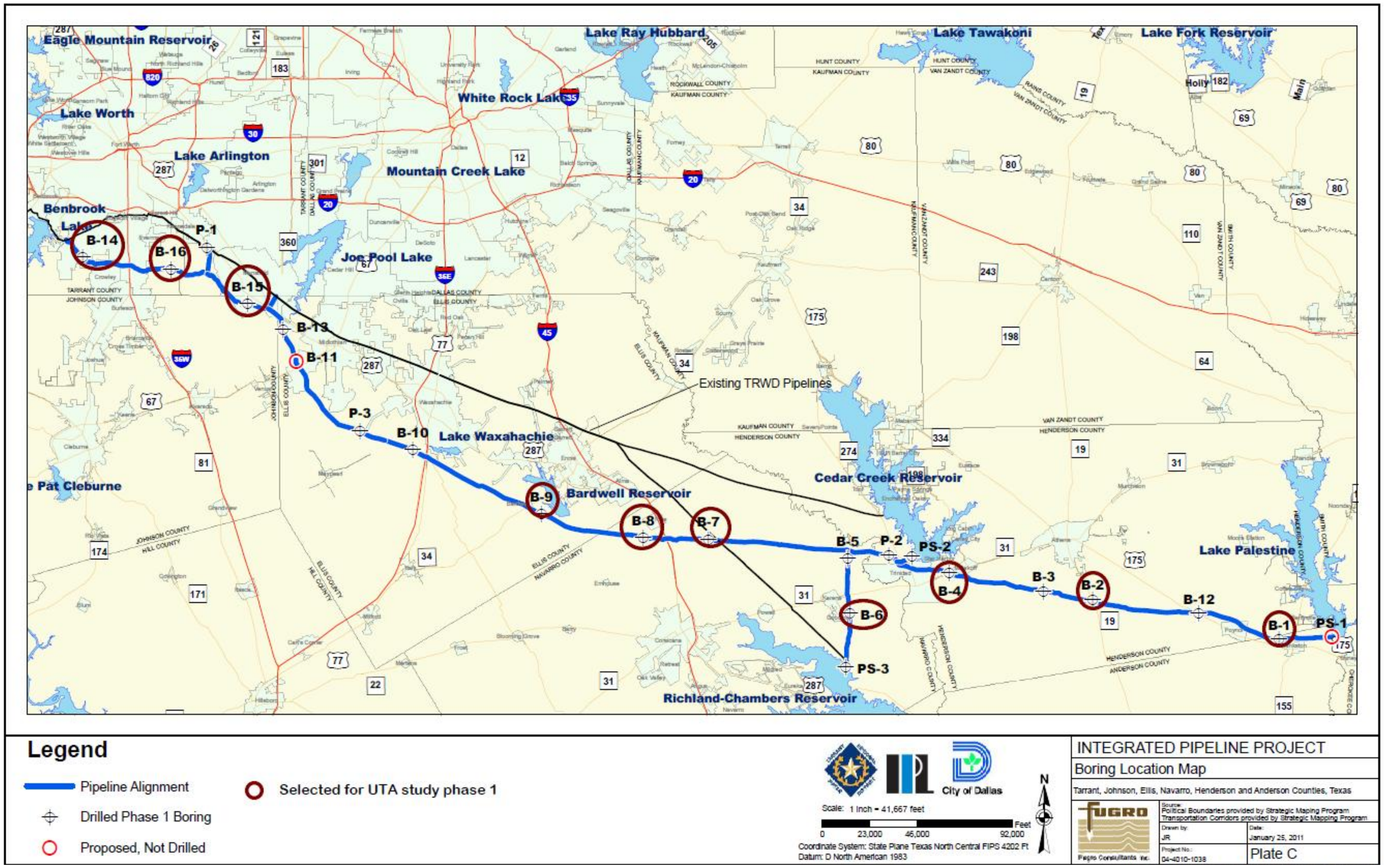


Figure 3.1 Selected boring locations

3.3 Chemical, physical and engineering soil tests

Both basic and advanced soil testing were performed on soil samples from all ten (10) locations.

Four types of chemical soil tests were conducted:

1. Cation exchange capacity (CEC)
2. Specific surface area (SSA)
3. Total potassium (TP)
4. Sulfate analysis

Physical tests performed included:

1. Sieve analysis
2. Hydrometer tests
3. Atterberg limits
4. Standard Proctor compaction

Engineering soil tests performed include the following tests:

1. Unconfined compression strength tests (UCS)
2. Unconsolidated Undrained triaxial compression tests (UU)

3.3.1 Chemical soil tests

3.3.1.1 Cation exchange capacity

Cation exchange capacity or CEC can be used to determine the mineral composition of a given soil. For example, a soil with a high CEC value of 100 meq/100 gm to 120 meq/100 gm indicates a high amount of expansiveness due to the presence of the clay mineral Montmorillonite where as a low CEC indicates the presence of non-expansive clay minerals such as Kaolinite. CEC of a soil can be defined as the capacity or the ability of the soil to exchange free cations that are available in the exchange locations.

One of the earliest methods proposed by Chapman (1965) is the most commonly used method in the field and this method is selected for the current research. The method involves addition of a saturating solution and then removal of the adsorbed cations using an extracting solution. The saturating solution used here is ammonium acetate (NH_4OAc) at pH 7. This solution was added to a prepared soil specimen (preparation involves treating for organics with 30% hydrogen peroxide (H_2O_2)) and set aside for 16 hours after shaking for half hour, to ensure that all the exchange locations are occupied by the ammonium ion (NH_4^+). Then the solution was filtered through a Buchner funnel and washed with 4 different 25 mL additions of NH_4OAc. This step is to bring out all the cations from the soil sample solution that have been replaced by ammonium ions. Excess NH_4OAc was removed by the addition of 8 different 10 mL additions of 2-propanol. Now, all the cation places are replaced by the ammonium ion and excess ammonium is also removed. The CEC of the soil sample can be obtained by measuring the amount of ammonium ions that replaced all the exchange locations. This was done by washing the sample with 8 different 25 mL additions of 1M potassium chloride (KCl) solution. The concentration of NH_4^+ ion in the KCl extract gives the CEC of the soil. Photographic representation of the different steps involved is presented in Figure 3.2

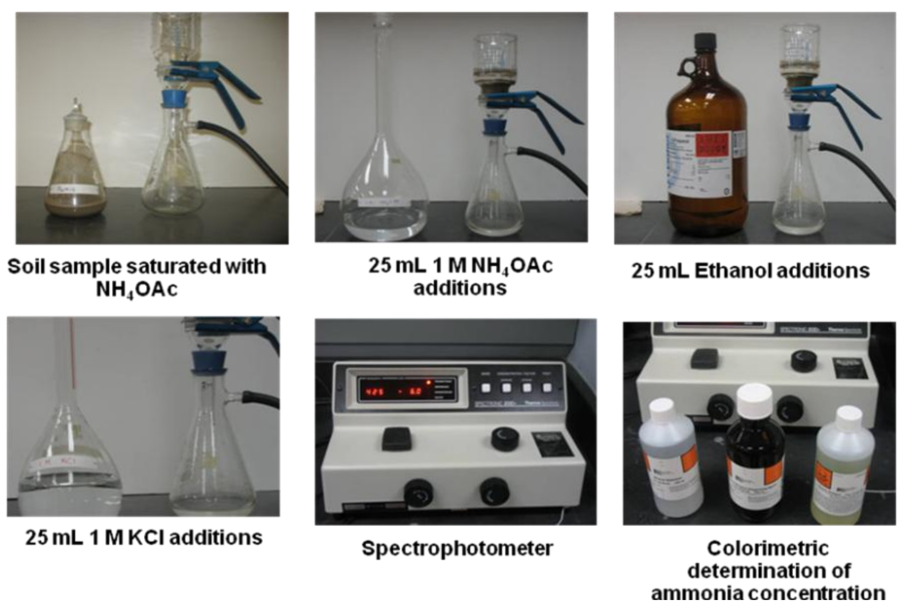


Figure 3.2 Photographs of the various steps involved in the determination of CEC

3.3.1.2 Specific surface area

Specific surface area or SSA of a soil sample is the total surface area contained in a unit mass of soil. This property of the soil is primarily dependent on the particle size of the soil. Soils with smaller particle size have higher specific surface areas. It should be noted here that a soil with high specific surface area has high water holding capacity and greater swell potential.

The most commonly used method in the field of agronomy is adsorption by Ethylene Glycol Monoethyl Ether (EGME) (Carter et al., 1986) and is implemented in this research. This involves saturating prepared soil specimens, equilibrating them in vacuum over a calcium chloride – EGME ($CaCl_2$-EGME) solvate, and weighing to find the point when equilibrium is reached. Specific surface is then determined from the mass of retained EGME in comparison to the amount retained by pure montmorillonite clay, which is assumed to have a surface area of 810 m^2/g (Carter et al., 1986). Test procedures typically take two days to complete. They also indicated that the procedure is repeatable and gives reliable results. Photographic representation of the different steps involved is presented in Figure 3.3.

This method was fully evaluated for geotechnical usage by Cerato and Lutenegger (2002) and concluded that the method is applicable to a wide range of mineralogies and is capable of determining specific surface area ranging from 15 m^2/g to 800 m^2/g.

3.3.1.3 Total potassium

Potassium is the inter layer cation in the clay mineral Illite (Mitchell and Soga, 2003). Hence measuring the amount of potassium ion in the soil gives a direct indication of the presence of the mineral Illite. The test procedure formulated by Knudsen et al. (1984) was followed to obtain the amount of total potassium present in the soil. The method involves a double acid digestion technique developed by Jackson (1958) which uses two acids (Hydrofluoric acid and Perchloric acid) to break the mineral structure of the soil and extract the potassium ions from the structure. Once the potassium is extracted, its concentration in the solution can be obtained with the help of a spectrophotometer or any other suitable device.

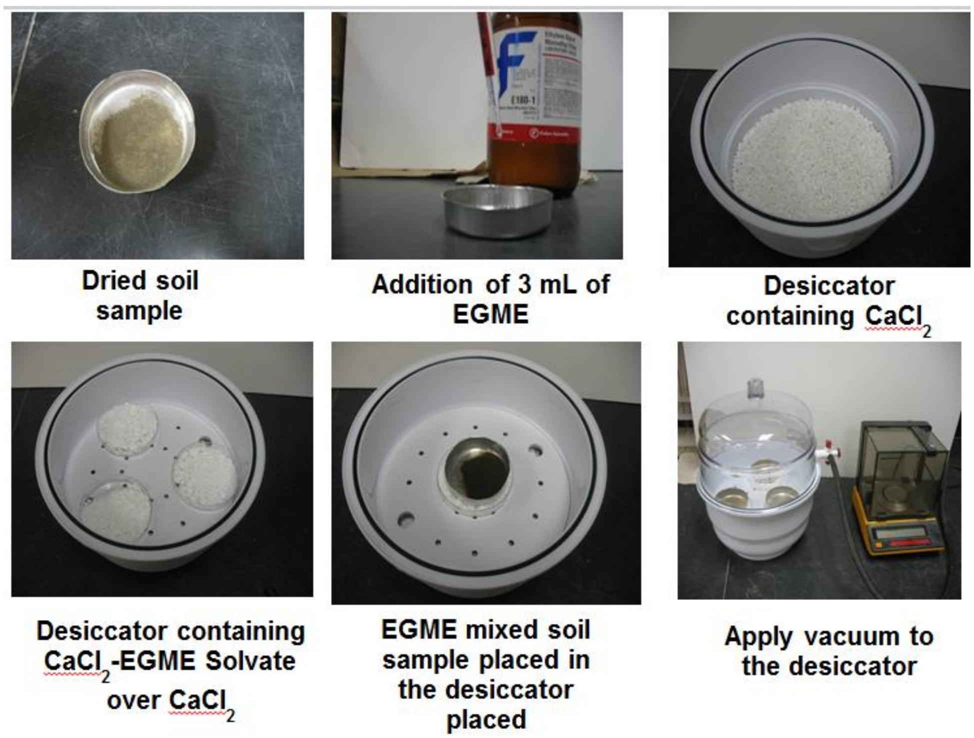


Figure 3.3 Photographs of the various steps involved in the determination of SSA

The test started by taking 0.1 gm of soil in a Teflon digestion vessel. The original method recommended the use of platinum vessels as the hydrofluoric acid used has the ability to dissolve silica and glass is 90% silica. However the usage of platinum vessel was not possible due to cost constraints hence other possible alternatives were looked at and a Teflon vessel was found to have resistance to the acids that are being used in the current test procedure (Hydrofluoric acid, Perchloric acid and Hydrochloric acid) and high temperature tolerance (200^{o}C). Hence, Teflon vessel was finally selected.

An amount of 5 mL of Hydrofluoric acid and 0.5 ml of Perchloric acid were added to 0.1 gm of the soil sample. Hydrofluoric acid dissolves the silicate mineral structure and releases the interlayer cations; Perchloric acid was used as an oxidizing agent to oxidize the organic matter in the soil sample. Then the vessel was placed on a hot plate and heated to 200°C and then cooled, and another addition of HF and $HClO_4$ was made and reheated on the hot plate. The sample was then heated until it was dry. The process was repeated to make sure all the interlayer cations were released and then finally 6N HCl was added and the amount of potassium in this solution was obtained by using a spectrophotometer. Photographic representation of the different steps involved is presented in Figure 3.4.

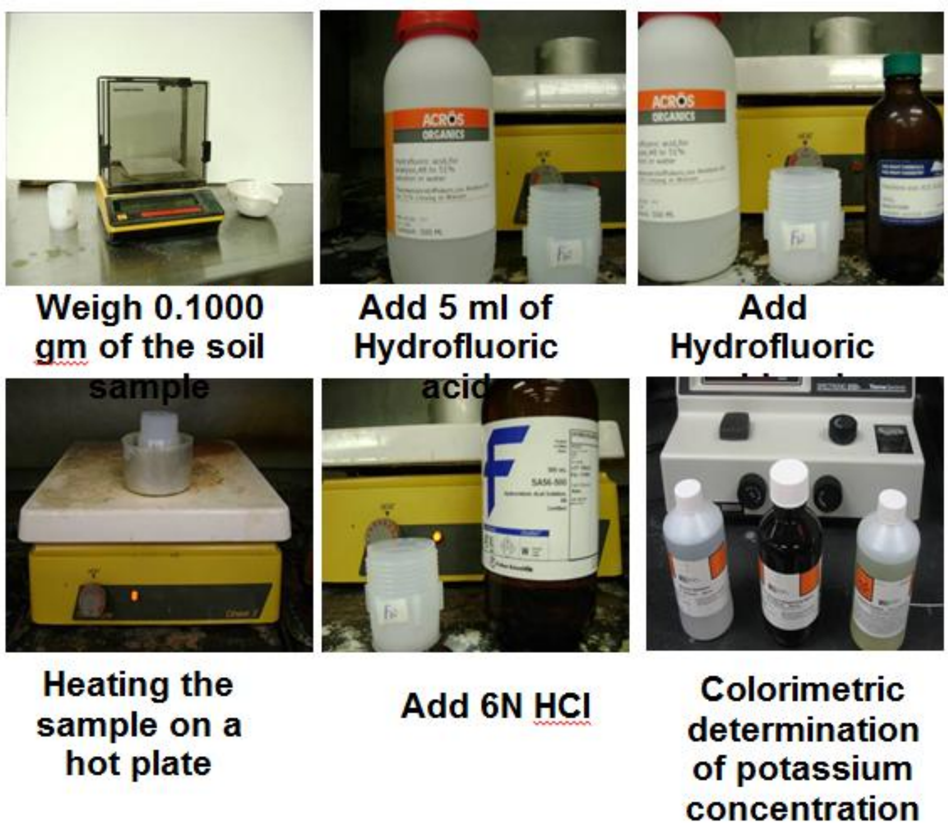


Figure 3.4 Photographs of the various steps involved in the determination of TP

3.3.1.4 Mineral quantification

The chemical properties such as CEC, SSA and TP obtained from above explained testing methods were used to determine clay mineral quantification as per the procedure outlined in Chittoori (2008).

3.3.1.5 Sulfate analysis

This test was performed to assess the amount of soluble sulfates in the soil. The method is a modified procedure from the standard gravimetric method by Clesceri (1989). The procedure started with taking 10 grams of dried soils adding 100 ml of distilled water to it. Then, the solution was placed in a centrifuge at a speed of 14,000 rpm for 30 minutes to separate the soil from the solution. The supernatant was filtered through a Buchner funnel and the soil was discarded. Hydrochloric acid was then added to the solution in order to keep the pH values within the range of 5 to 7. The solution was then heated up to the boiling point.

Barium chloride ($BaCl_2$) was added to the boiling solution to precipitate the sulfate in the form of Barite ($BaSO_4$). Then the solution was placed in an oven at 85^oC for twelve hours. This process allowed the digestion to take place and continue in order to obtain Barite by precipitation process. Then, the solution was passed through 0.1 μm membrane filter. The Barite precipitated from this process was then weighed and soluble sulfate content was calculated. According to Puppala et al. (2003), a smaller pore size filter of 0.1 μm and higher speed of centrifuging of 14,000 rpm with longer time were recommended in order to segregate small particles from the solution. This modified method provided results that matched the ion chromatography measurements. Hence, the modified method is adopted in the present research.

3.3.2 Index tests

3.3.2.1 Sieve analysis

This test was conducted to obtain the grain-size distribution of soils from all the ten regions. The test was conducted according to ASTM D422 method. A soil sample representative of the region from which it was collected was passed through No. 200 sieve using water. The distribution of particle size of the sample portion retained on No. 200 sieve was determined by sieve analysis, while the sample portion passed through No. 200 sieve was determined by hydrometer analysis. Sieve analysis establishes the percentage of the coarse fraction of the soil (Gravel and Sand) while hydrometer analysis establishes the percentage of fine fraction in the soil specimens (Silt and Clay).

3.3.2.2 Hydrometer analysis

Hydrometer Analysis was carried out to study the micro level distribution of silt and clay fraction present in the field soil. This test was performed as per ASTM D422. The procedure involved taking 50 g of the oven dried portion that passed No. 200 sieve (explained in previous section) and mixed with a solution containing a 4% deflocculating agent (Sodium Hexametaphosphate) and soaking for about 8 to 12 hours. The prepared soil was thoroughly mixed in a mixer cup and all the soil solids inside the mixing cup were transferred to a 1000 cc graduated cylinder and filled to mark using distilled water.

The hydrometer readings were recorded at cumulative time of 0.25 min., 0.5 min., 2 min. 4 min., 8 min., 15 min., 20 min., 2 hr., 4 hr., 8 hr., 12 hr., 24 hr., 48 hr., and 72 hr. After taking the readings initially for the first 2 minutes, the hydrometer was taken out and kept in another cylinder filled with distilled water. Necessary temperature corrections, zero corrections and meniscus corrections were made to the hydrometer readings as per procedure. Photographs of sieve analysis and hydrometer analysis are presented in Figure 3.5. A typical gradation curve is presented for B1 soil in Figure 3.6.

a) b)

Figure 3.5 Photographs showing the arrangement for
a) Sieve analysis b) Hydrometer analysis

3.3.2.3 Standard compaction tests

In order to determine the compaction moisture content and dry unit weight relationships of the soils in the present research program, it was necessary to conduct standard Proctor compaction tests on soils to establish compaction relationships. The optimum moisture content of the soil is the water content at which the soils are compacted to a maximum dry unit weight condition. Specimens exhibiting a high compaction unit weight are best in supporting civil infrastructure since the void spaces are minimal and settlement will be less. Compaction tests were conducted on all types of soil to determine moisture content and dry unit weight relationships. Standard Proctor test method using ASTM D698 procedure were followed to determine moisture content versus dry density relationships.

A typical Proctor's standard compaction curve of B1 soils is presented in Figure 3.7.

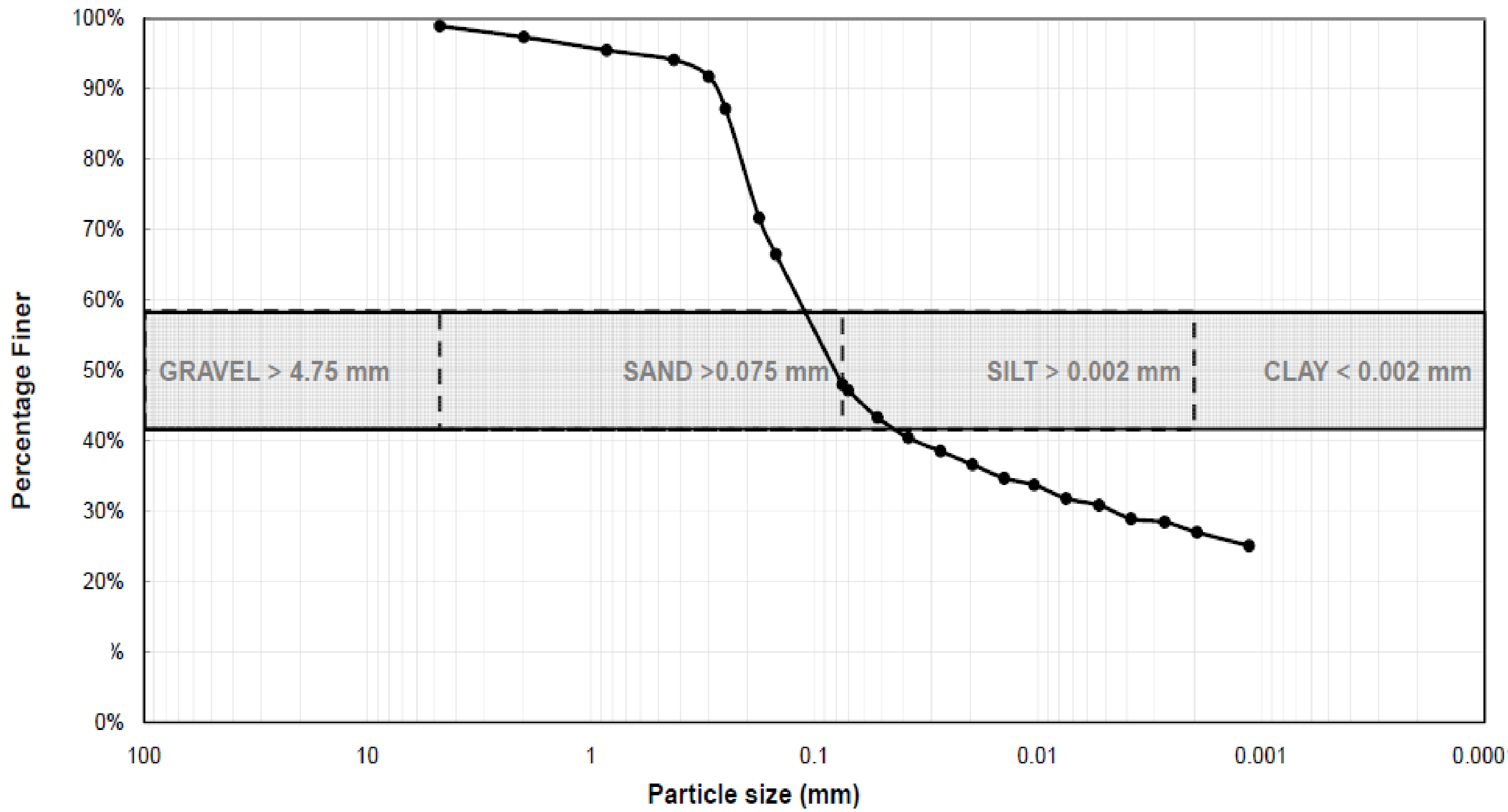
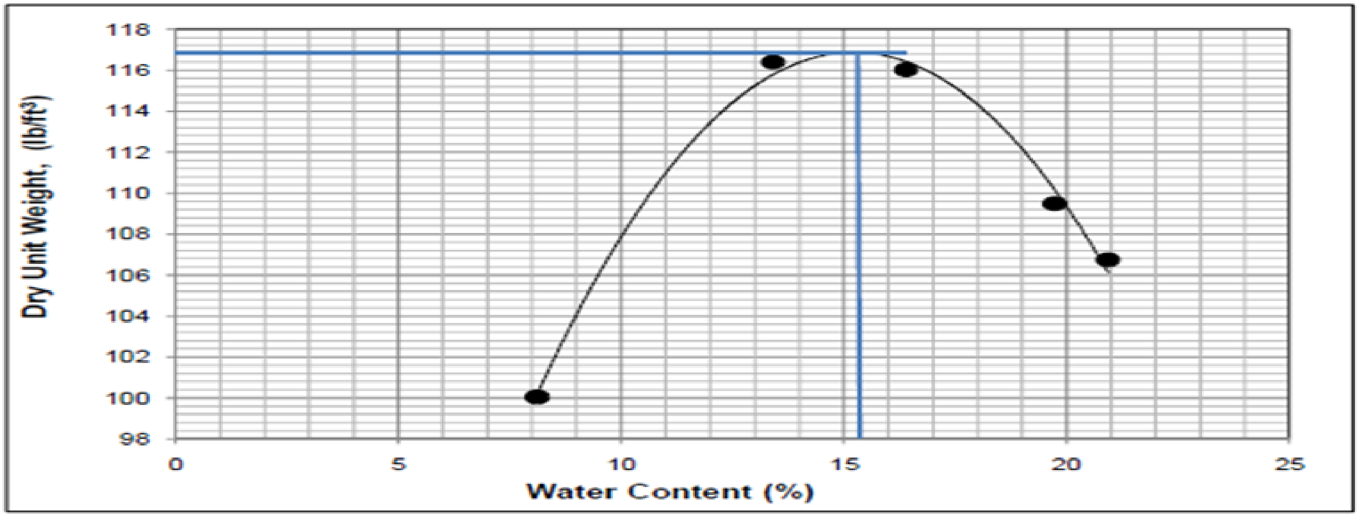


Figure 3.6 Typical gradation curve for soil from boring location B1

Standard Procter Test (ASTM D698)

Maximum Dry Density (MDD) : 116.8 pcf

Optimum Moisture content (OMC) : 15.4 %



Stage	Water Content (%)	Dry Unit Weight (lb/ft^3)
1	8.1	100.0
2	13.4	116.4
3	16.4	116.0
4	19.7	109.5
5	20.9	106.8

Location: B1

Depth: 10' - 15'

Figure 3.7 Typical Proctor's curve for soil from boring location B1

3.3.2.4 Atterberg limits tests

Atterberg limits reveal properties related to consistency of the soil. These include liquid limit (LL), plastic limit (PL) and shrinkage limit (SL) and are essential to correlate the shrink-swell potential of the soils to their respective plasticity indices. Upon addition of water the state of soil proceeds from dry, semisolid, plastic and finally to liquid states. The water content at the boundaries of these states are known as shrinkage (SL), plastic (PL) and liquid (LL) limits, respectively (Lambe and Whitman, 2000). Therefore, LL is calculated as the water content at which the soil flows and PL is determined as the water content at which the soil starts crumbling when rolled into a 1/8-inch diameter thread. These tests are somewhat operator sensitive and take time to perform. The numerical difference between LL and PL values is known as plasticity index (PI) and this property characterizes the plasticity nature of the soil.

Representative soil specimens from different locations were prepared following the above mentioned procedure and were subjected to Atterberg limit tests to determine LL and PL following ASTM D4318 procedure.

3.3.3 Engineering soil tests

3.3.3.1 Unconfined compression tests

The UCS tests were performed as per ASTM D 2166. The specimen was first placed on a platform and then raised at a constant strain rate using the controls of the UCS set up until it came in contact with top plate. Once the specimen was intact, it was loaded at a constant strain rate and as the load approached the ultimate load, failure cracks began to appear on the surface of the specimen. Both deformation and corresponding axial loads on the specimen were recorded using a data acquisition system. The data retrieved contained load (Q) and deformation (d) data and the same were analyzed to determine the maximum unconfined compressive strength (q_u) in psi or kPa. The following expressions show the computation of stress (σ) and strain (ε) corresponding to the load-deformation data.

$$\varepsilon = \frac{\delta}{L} \; ; \; \sigma = \frac{Q}{A_c} \; ; \; A_c = \frac{A}{1-\varepsilon} \text{ and } q_u = \sigma_{\max}$$

where, δ = change in length, L = total length of specimen, A_c = corrected area of cross section of the specimen and A = initial area of cross section. A typical Stress-Strain curve obtained from UCS test is presented for B1 soil in Figure 3.8.

3.3.3.2 Unconsolidated Undrained triaxial test

The Triaxial shear test is the most practical test that can replicate conditions closest to the field. There are several kinds of triaxial tests out of which Unconsolidated-Undrained triaxial test is the quickest and very relevant when analyzed for quick loading conditions. In this study UU triaxial tests were performed as per ASTM D2850. The specimen preparation and loading were similar to the UCS test but for the confining pressures applied in case of UU triaxial test. The confining pressures were applied by filling the triaxial chamber shown in Figure 3.9, with water and pressurizing the water with the help of pressure control devices.

The soil specimen was encased in a rubber membrane to prevent surrounding water leaking into the specimen. Three different confining pressures 7 psi or 50 kPa, 14 psi or 100 kPa and 21 psi or 150 kPa were applied in this study and these stresses were representative of overburden depths up to 30 ft. These stresses are selected such that they are representative of field depths planned for pipe construction. The stress and strain calculations are similar to the UCS test. Along with stress-strain plots, Mohr’s circles were drawn at 10% and 15% strain levels. A typical Stress-Strain curve and Mohr’s circles obtained from UU test were presented for B1 soil in Figure 3.10 and Figure 3.11 respectively.

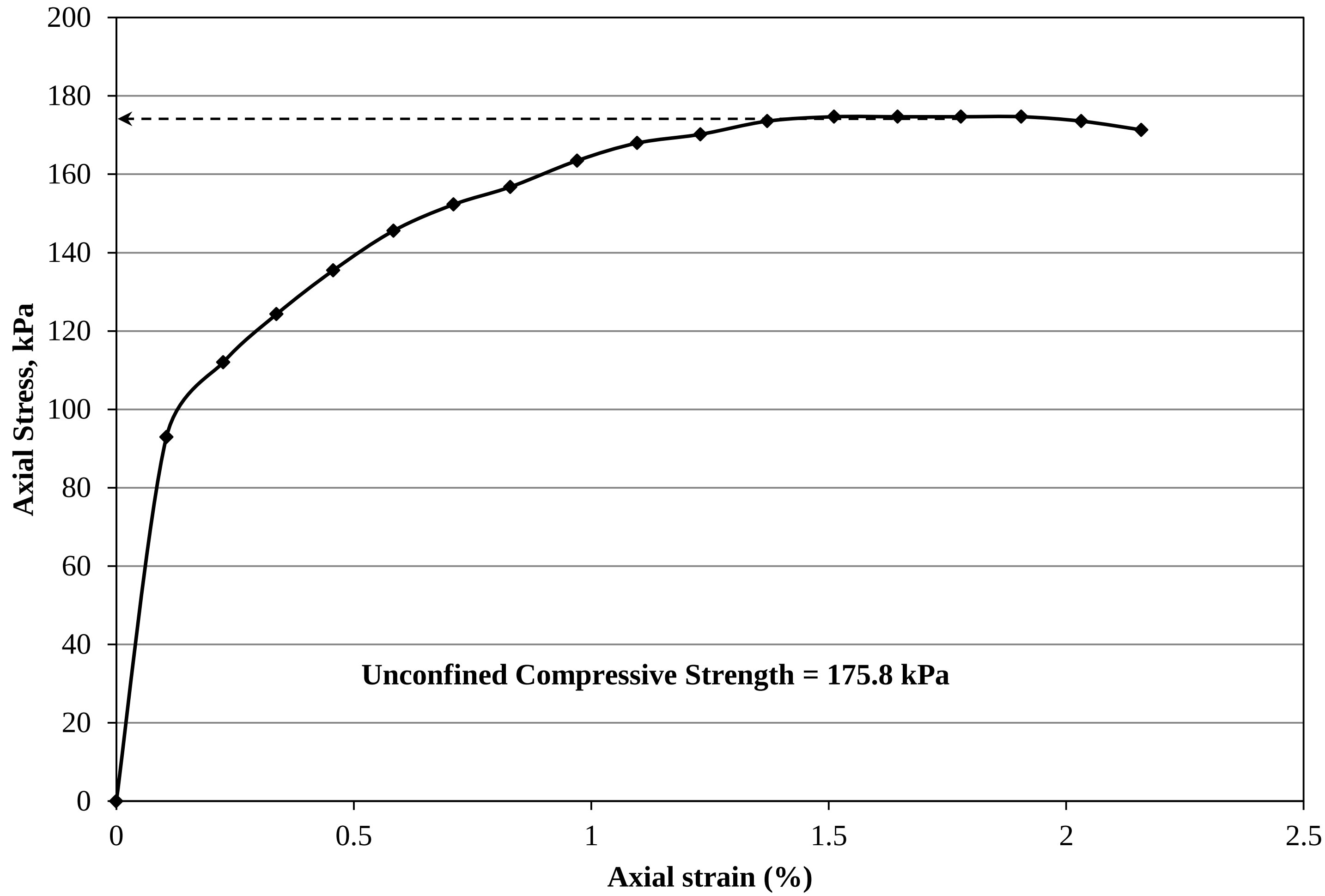


Figure 3.8 Typical Stress-Strain curve for soil from B1 location

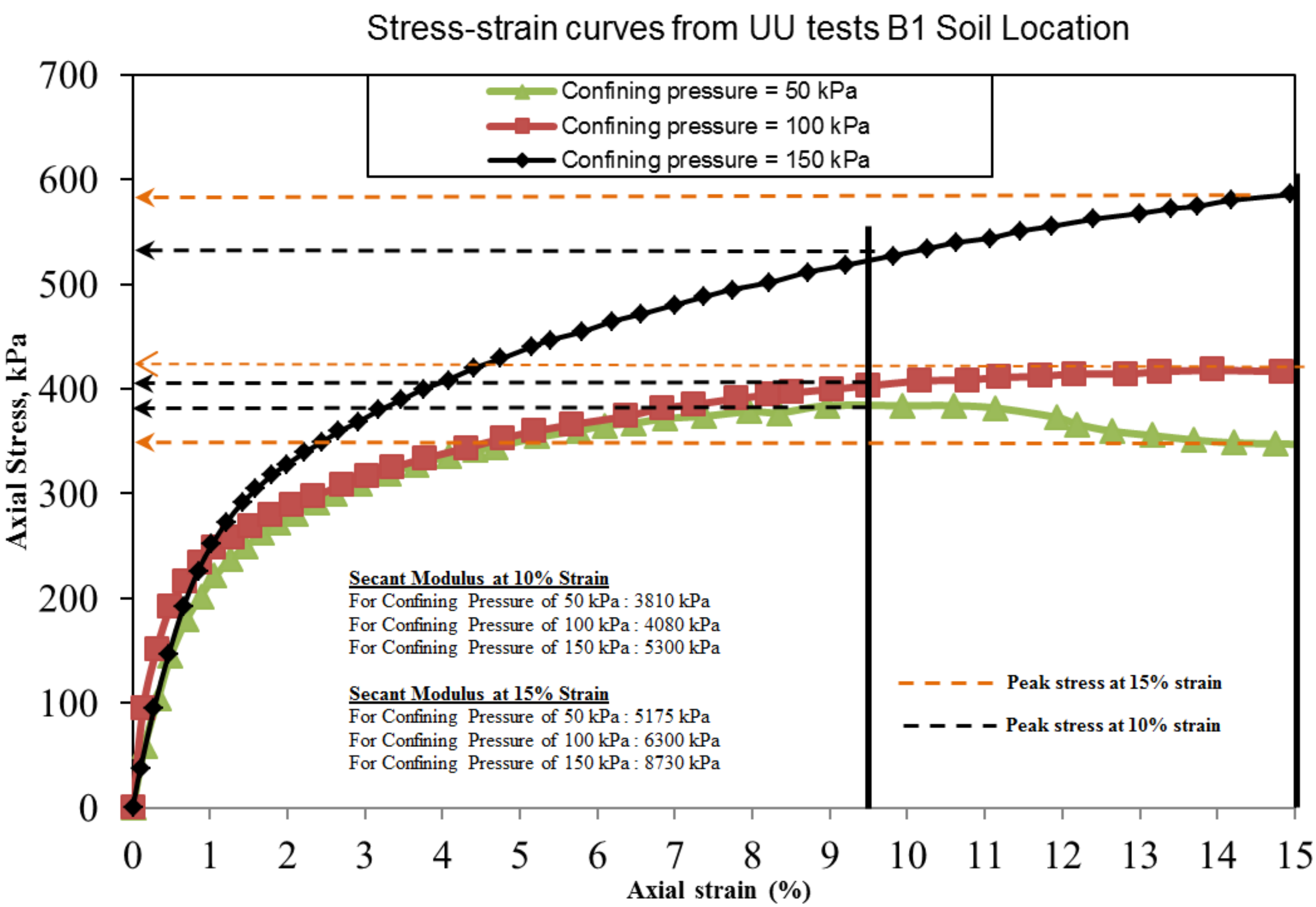


Figure 3.9 Typical stress-strain curve from UU test for soil from B1 location

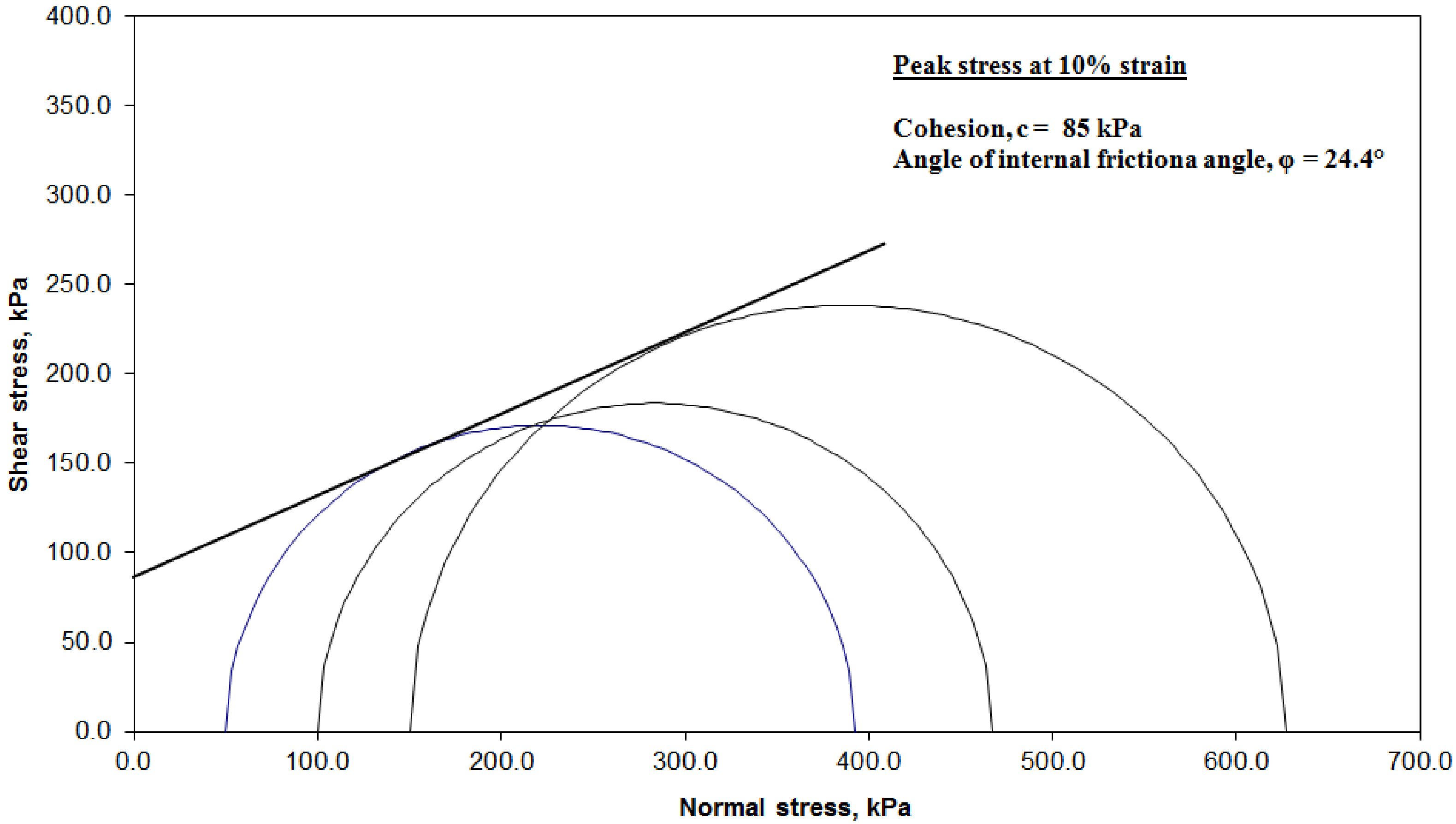


Figure 3.10 Typical Mohr's circles from UU test for soil from B1 location

Figure 3.11 Photograph of UU test setup

3.4 Summary

In this chapter various test procedures followed in the present research to determine the engineering properties of both controlled and treated soils are described. The chemical and mineralogical tests conducted for clay mineral quantification are explained in detail. Basic and advanced geotechnical testing performed is explained and typical results are provided. The next chapter presents the results obtained from all the above mentioned tests that were conducted on all the soils selected for this study along with the observations and discussions.

CHAPTER 4

ANALYSIS OF TEST RESULTS AND DISCUSSION

4.1 Introduction

The results obtained from the testing program explained in the previous chapter were analyzed to understand the material behavior along the length of the pipeline alignment and these observations and discussions are presented here. It should be noted here that these analysis should be considered preliminary as far the IPL project pipeline construction is concerned as only 10 boreholes are studied for a stretch of 147 miles. Nevertheless, this analysis was proven effective in understanding the material properties along the pipeline and to compare and contrast traditional alternative of importing material for bedding and embedment versus the proposed option of using insitu excavated material with chemical treatment both in terms of environmental and economic perspectives. Further studies are being undertaken by the IPL project authorities to verify/strengthen the results presented in this research.

In this chapter, an initial summary of all the test results are presented followed by specific observations regarding the silt content, and the mineral montmorillonite in the soil. Matrix tables are prepared which highlight the reusability of different types of soils along the pipeline alignment as different pipe backfill materials. Also, the methodology, assumptions and results of carbon foot print and cost analyses conducted to compare the two alternatives explained above are presented.

4.2 Summary of test results

Table 4.1 summarizes the results from the chemical tests along with the quantitative mineral information.

Table 4.1 Summary of chemical tests

Sample location ID	B1	B2	B4	B6	B7	B8	B9	B14	B15	B16
CEC, meq/100 g	85	13	96	99	116	112	88	59	93	154
SSA, m^2/g	250	26	192	141	318	195	164	77	138	168
TP, %	1.90	1.03	2.00	1.10	0.94	1.96	2.97	1.80	2.00	2.38
Montmorillonite	35%	3%	37%	32%	56%	41%	33%	17%	45%	30%
Illite	32%	17%	33%	18%	16%	33%	50%	30%	40%	33%
Kaolinite	33%	80%	29%	50%	28%	27%	18%	53%	15%	36%

The above Table 4.1 indicates that most of the soils except B2 and B14 show high amounts of expansive clay minerals (i.e. combined Montmorillonite and Illite minerals) and hence can be considered as problematic soils that could cause heave related damage to pipe infrastructure.Sulfate analysis were performed as per the procedure outlined in Chapter 3. Table 4.2 summarizes all the sulfate analysis results obtained for this research.

Table 4.2 Summary of sulfate analysis performed

Soil Location ID	Soluble sulfates by UTA method (PPM)
B1	66
B2	29
B4	251
B6	25
B7	140
B8	1091
B9	2404
B14	535
B15	284
B16	1424

Soils that contain 2000 ppm or higher are considered to be problematic for sulfate induced heaving, when those soils are treated with calcium based stabilizers. The relevance of this measurement to this study is to assess any heave problems that can arise to pipeline structures if chemical treated soils are used around the pipes. This heave, unlike natural expansive soils, will occur in all directions when the treated soils are exposed to moisture hydration. In addition, this heave induced pressure will be quite significant which can induce severe cracking to concrete structures. It can be observed from Table 4.2 that out of all the soils tested here, B9 location has 2404 PPM of sulfates which could cause problems when stabilized with calcium based stabilizers. Table 4.3 summarizes the index properties of the soils from ten site locations.

Table 4.3 Summary of basic soil testing performed

Site locations	Grain size analysis				Atterberg's limits			Soil Classification	Standard Proctor	
	Sieve Analysis		Hydrometer		LL (%)	PL (%)	PI (%)		MDD, pcf	OMC (%)
	%G	%S	%Si	%C						
B1	1	51	20	28	38	15	23	SC	116.8	15.4
B2	0	58	32	10	Non Plastic			SM	120.3	11.2
B4	1	32	51	16	30	19	11	CL	115.0	13.0
B6	0	22	62	16	40	14	26	CL	108.1	16.2
B7	0	12	78	10	82	20	62	CH	95.5	22.8
B8	0	14	66	20	49	15	34	CL	89.8	18.1
B9	0	45	37	18	53	16	37	CH	102.1	19.0
B14	12	25	61	2	42	19	23	CL	112.3	15.0
B15	0	5	31	64	66	23	43	CH	96.8	21.0
B16	0	14	43	43	52	22	31	CH	105.0	16.5

Note:
SC – Clayey Sand; CL – Lean Clay; CH – Fat Clay; SM – Silty Sand;
%G – Percent Gravel; %S – Percent Sand; %Si – Percent Silt; %C – Percent Clay
LL – Liquid limit; PL – Plastic limit; PI – Plasticity Index; MDD – Maximum dry density; OMC – Optimum moisture content

Most soils, with the exception of B1 and B2, contain high amounts of fines and based on plasticity properties, these materials are either characterized as CL or CH. Table 4.4

summarizes the results obtained from the engineering tests. The removal of soil before laying the pipe represents a scenario of unloading over consolidated clays and replacing the soil after the pipe is installed represents a scenario of loading normally consolidated clays. In both cases, undrained parameters are critical. Hence, UU tests were conducted on the soils. Also, UU tests consume lesser time.

Table 4.4 Summary of engineering tests

Soil location ID	**B1**	**B2**	**B4**	**B6**	**B7**	**B8**	**B9**	**B14**	**B15**	**B16**
+Undrained Cohesion, C_u, kPa	85	30	80	98	82	50	75	80	100	115
+Undrained Cohesion, C_u, psi	12.3	4.4	11.6	14.2	11.9	7.3	10.9	11.6	14.5	16.7
+Angle of internal friction, φ (deg.)	24.4	33.3	22.9	5.7	15	8.5	22.6	26.6	18.5	18.4
++Undrained Cohesion, C_u, kPa	60	N/A	62	100	70	18	70	80	126	80
++Undrained Cohesion, C_u, psi	8.7	N/A	9.0	14.5	10.2	2.6	10.2	11.6	18.3	11.6
++Angle of internal friction, φ (deg.)	30.7	N/A	39.8	8.1	25.4	35	26.6	29.1	15.6	26.6
Unconfined compression strength, kPa	175.8	88.5	188.1	156.6	189.2	182.5	243.0	198.2	229.6	133.0
Unconfined compression strength, psi	25.5	12.8	27.3	22.7	27.4	26.5	35.2	28.7	33.3	19.3

+ Peak stress at 10% axial strain; ++ Peak stress at 15% axial strain

4.3 Observations

Figure 4.1 presents the variation of percent silt in each of the ten soil locations selected for this project along with their USCS classification. It can be observed from this figure that though the soils of boring locations B14, B8, B7, B6 and B4 are classified as CL/CH materials, they still contain high amounts of silts (more than 50%) in their fines. It should be noted that these materials are good for preparing controlled low strength materials (CLSM) or flowable fills, which can be used as bedding and haunch material during pipe installation.

Figure 4.2 presents the variation of mineral Montmorillonite in the clay fraction of the soil along with the soil classification and Plasticity Index information. It can be observed that boring locations B16, B8, B7, B4 and B1 contain more than 35% of Montmorillonite mineral. A Montmorillonite content of more than 20% is considered problematic due to potential swell/shrink behavior. These soils are appropriate for chemical stabilization with additives such as lime and cement.

4.3.1 Soil categories

ASTM C1479M categorizes soil into four different groups based on which one can determine if that soil can be used as bedding, haunch or backfill material for rigid and/or semi-rigid, flexible pipes. Since the type of pipe material is to be determined, an assumption is made here to provide soil categories for rigid pipes. This information is presented in Table 4.5 below and can be generalized for both rigid and flexible pipes.

Table 4.5 Soil categories as per ASTM C1479M

Soil Category	**USCS Classifications**
Category I	SW, SP, GW, GP
Category II	GM, GC, SM, SC with more than 12% fines CL, ML, CL-Ml with more than 30% retained on 75µm sieve
Category III	CL, ML, CL-ML with less than 30% retained on 75µm sieve
Category IV	MH, CH, OL, OH, PT

As per the standard, materials from Category I, Category II and Category III can be used as bedding and haunch materials with varying compaction efforts for different types of installation, while, Category IV materials can only be used as backfill and not as bedding or haunch.

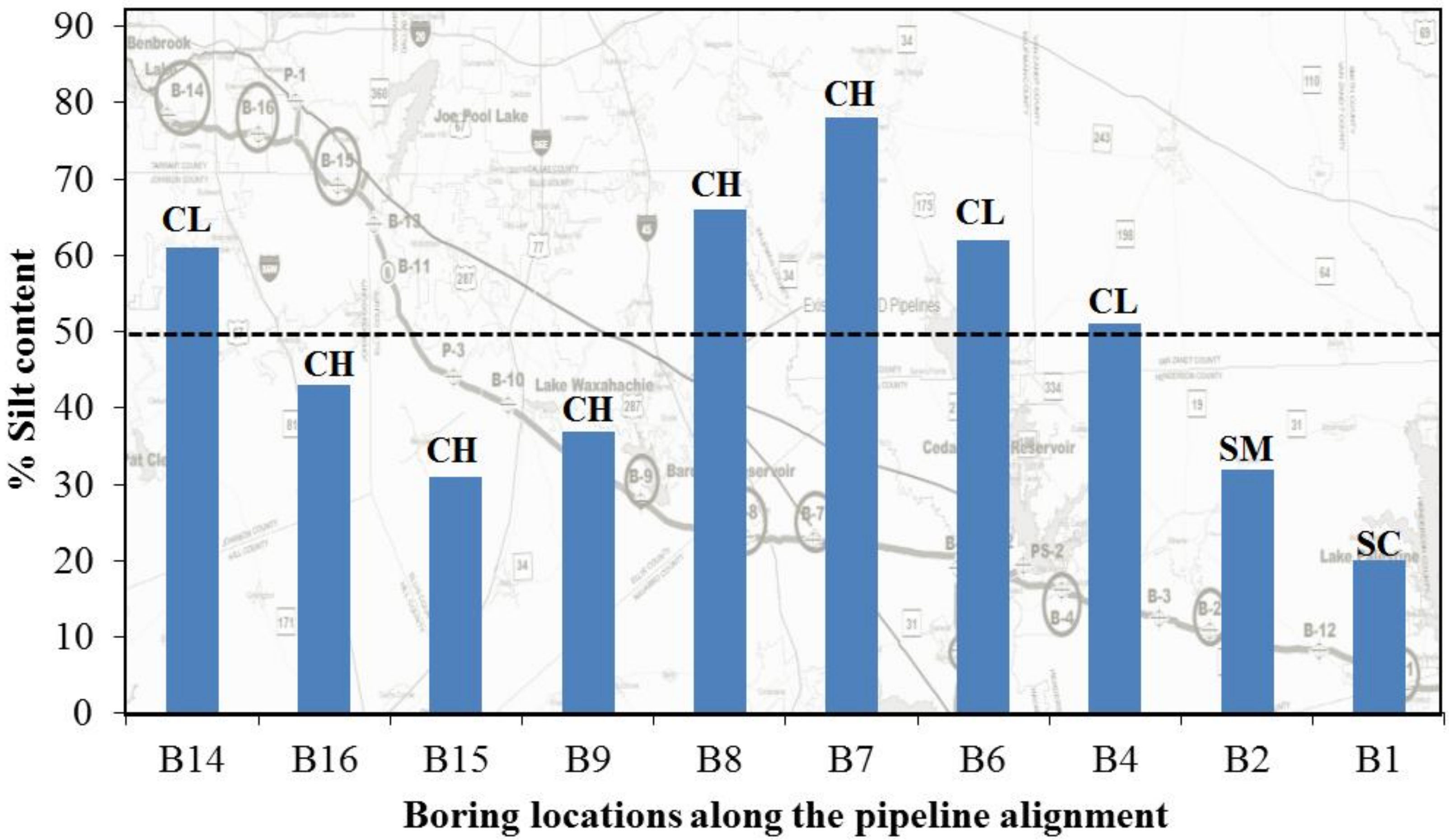


Figure 4.1 Variation of percentage silt content along the pipeline alignment

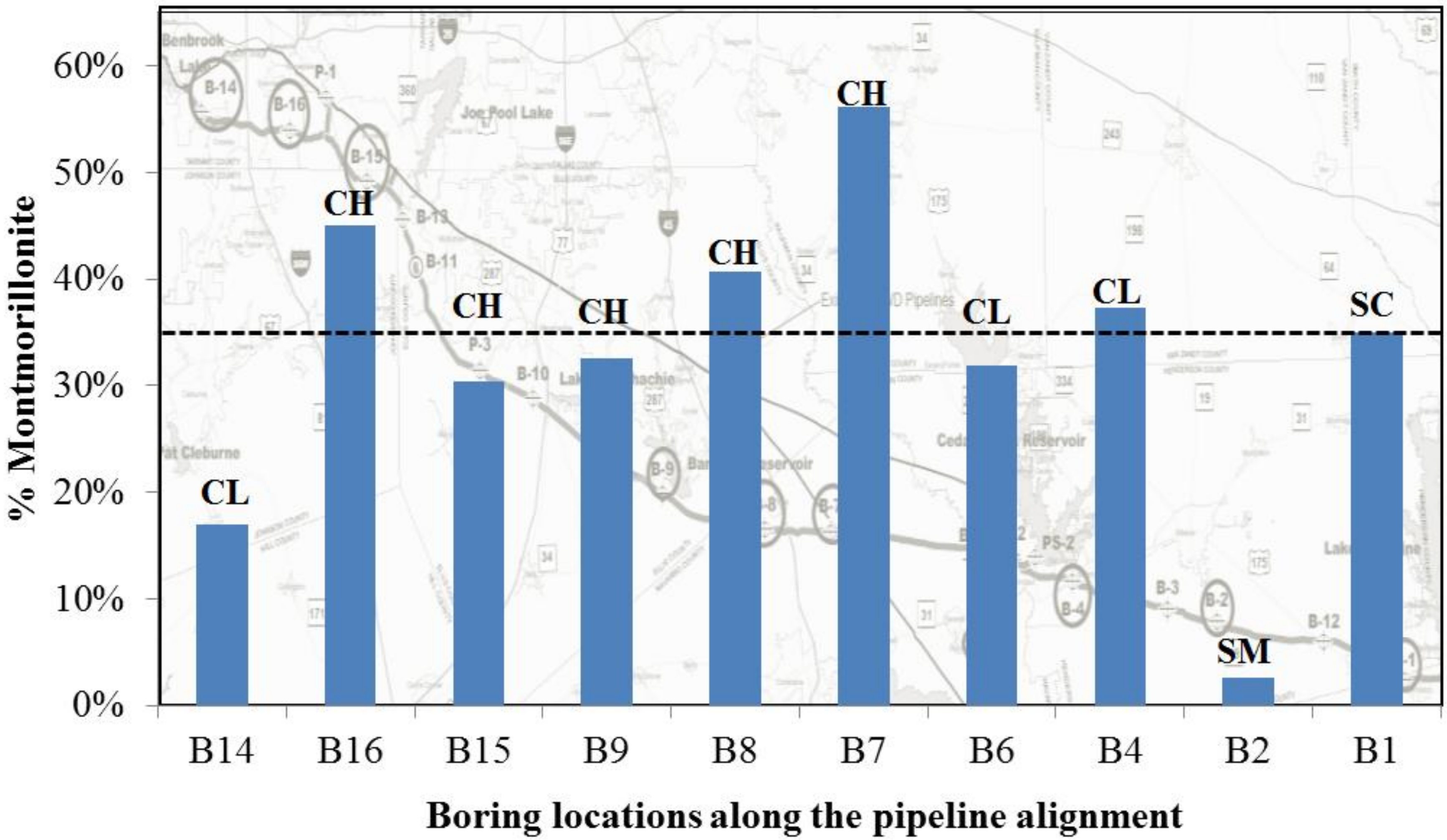


Figure 4.2 Variation of percentage Montmorillonite along the pipeline alignment

Based on Table 4.6 all the soils tested for this research are organized into one of these categories and are presented in Table 4.6.

Table 4.6 Categorization of tested soils as per ASTM C1479

Soil location	**Category**
B1	Category II
B2	Category II
B4	Category II
B6	Category III
B7	Category IV
B8	Category IV
B9	Category IV
B14	Category III
B15	Category IV
B16	Category IV

From this table it can be observed that soils from boring locations B7, B8, B9, B15 and B16 cannot be used as bedding/haunch materials in any type of pipe installation. However, studies must be conducted to see if chemically stabilized soils from these locations can be used for bedding or pipe zone materials.

4.4 Soil Reusability

4.4.1 Use as Trench refill materials

As per the Howard (1996) there are 5 types of installation methods that are under consideration for the IPL project. Table 4.7 below summarizes the different material types recommended as bedding, haunch and backfill for all the five installation types. Also, it should be noted here that the soils that are not recommended for bedding or haunch currently can be used for the same purpose after chemical treatment. To understand the environmental and economic impacts of using the treated material as bedding and haunch versus importing these materials, a separate Carbon foot print and Cost analyses were performed which are presented in later sections.

Table 4.7 Recommended materials
(After Geotech Assessment Report by Fugro Consultants, Inc.)

	Recommended material type
Type 1 installation	
Bedding	Gravel (Category I)
Haunch	Cohesive soils, cohesionless soils, recycled materials (Category I, Category II, Category III)
Backfill	Cohesive soils, cohesionless soils, recycled materials (All 4 Categories)
Type 2 installation	
Bedding	Gravel(Category I)
Haunch	Cohesionless soils, recycled materials(Category I)
Backfill	Cohesive soils, cohesionless soils, recycled materials(All 4 Categories)
Type 3 installation	
Bedding	Cohesionless soils, recycled materials (Category I and Category II)
Haunch	Cohesionless soils, recycled materials (Category I and Category II)
Backfill	Cohesive soils, cohesionless soils, recycled materials (All 4 categories)
Type 4 installation	
Bedding	CLSM (Category I, Category II)
Haunch	CLSM (Category I, Category II)
Backfill	Cohesive soils, cohesionless soils, recycled materials (All 4 categories)
Type 5 installation	
Bedding	Any of the above 4 types (Category I, Category II)
Haunch	Cohesive soils, cohesionless soils, recycled materials (Category I, Category II, Category III)
Backfill	Cohesive soils, cohesionless soils, recycled materials(All 4 Categories)

Matrix tables are prepared here for soil reusability based on these recommendations. Table 4.8 presents one such table showing the reusability of the soil from each of the tested boring locations. It should be noted here that, when soils are being recommended for Type 4 bedding/haunch materials, further laboratory testing is required to check the effectiveness of the CLSM mixes using these insitu soils.

Table 4.8 Matrix table showing the reusability of soil from each of the tested locations

Boring ID	**Tested depths in ft.**	**Soil Classification**	**Recommended use as**		
			Bedding	**Haunch**	**Backfill**
B1	10 - 15	SC	Type 3, Type 4, Type 5	Type 1, Type 2, Type 3, Type 4, Type 5	All installation types
B2	5 - 10	SM	Type 3, Type 4, Type 5	Type 1, Type 2, Type 3, Type 4, Type 5	All installation types
B4	5 - 10	CL	Type 4*, Type 5*	Type 4*, Type 5	All installation types
B6	10 - 15	CL	Type 4*, Type 5*	Type 4*, Type 5*	All installation types
B7	10 - 15	CH	N/A	N/A	All installation types
B8	10 - 15	CH	N/A	N/A	All installation types
B9	10 - 15	CH	N/A	N/A	All installation types
B14	5 - 10	CL	Type 4*, Type 5*	Type 4*, Type 5*	All installation types
B15	10 - 15	CH	N/A	N/A	All installation types
B16	10 - 15	CL	Type 4*, Type 5*	Type 4*, Type 5*	All installation types

* - Further studies need to be conducted to check the effectiveness of the CLSM mixes using this soil type

4.4.2 Use of excavated soil for other applications

Another important application is to use the excavated fill material as a select subgrade/backfill for pavement and other earth structure construction provided they exhibit required soil properties for those applications. If proven viable, the excess of the excavated material (after reuse in the present project) can be used by the nearest City or county for their civil projects.

Based on the plasticity index (PI) of the soils, the soils can be used in different highway/retaining wall applications as select subgrade fill sub-base and base layers. Soils with PI values less than 15 and mostly mixed or granular in nature can be used as a Base or Sub-base Layer and soils with PI values less than 25 can be used as a sub-base or select subgrade layer. If a given soil has PI < 35, they may be used as a select fill under a pavement below sub-base or base layers. Any soil with PI > 35 is often not recommended; however it can be used if stabilized with chemical additives.

Table 4.9 below categorizes the soils tested for this project for different highway applications based on their Plasticity Index numbers.

Table 4.9 Summary of the soil reuse for potential highway applications

Boring ID	**Plasticity Index**	**Use as**		
		Select fill	**Sub-base**	**Base**
B1	23	✓	✓	
B2	Non Plastic	✓	✓	✓
B4	11	✓	✓	✓
B6	26	✓	✓	
B7	62			
B8	34	✓	✓	
B9	37	✓		
B14	23	✓	✓	
B15	43			
B16	31	✓	✓	

Note: Final recommendation depends on other soil properties

It can be observed from this table that boring locations B2 and B4 can be used for all three highway applications explained above, while B7 and B15 cannot be used for any highway application due to its high Plasticity Index. Also, all soil locations except for B7, B9 and B15 can be used for sub-base application.

Again, this recommendation is general and final recommendation of the potential reuse of the material depends on the plasticity and other engineering properties as required by the specifications.

4.5 Carbon Footprint Analysis

As explained above, to understand the impact of using treated native material versus imported material for bedding and haunch carbon foot print analysis is performed whose methodology and the results are presented in the following sections. Some of the assumptions involved in the analysis are presented in the next section.

4.5.1 Assumptions for carbon footprint analysis

The pipeline extends from west to east spanning across the various soil formations of the DFW area. For the purpose of calculations and analysis certain assumptions are made as follows:

4.5.1.1 Geometry assumptions

1. A hypothetical section of width 100 feet is taken at the west most part of the pipeline
2. The thickness of the bedding is taken as 0.583 feet (Howard, 1996)
3. Thickness of the embedment is taken as 3.5 feet (Howard, 1996)
4. Average outside diameter of the pipe is assumed to be 84”
5. PCC is considered since, from previous research it is understood that construction of the pipeline using a PCC pipe has less carbon footprint effect on the overall project (Chilana, 2011)

6. The total height of the trench is considered as 15 feet

Figure 4.3 and Table 4.10 give details of the geometry of the pipeline.

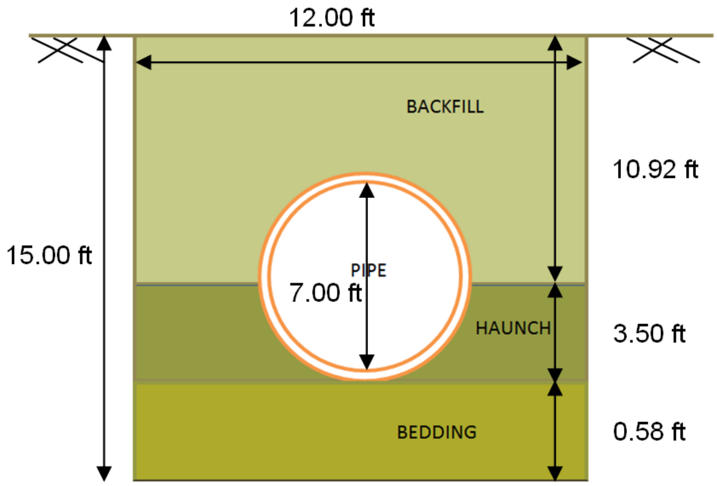


Figure 4.3 Geometry of the pipe section analyzed

Table 4.10 Geometry of the hypothetical pipe section

Geometry		
	ft	**m**
Thickness of bedding	0.58	0.18
Thickness of haunch	3.50	1.07
Thickness of backfill	10.92	3.33
Length of the segment considered	100.00	30.48
Width of the trench	12.00	3.66
Total height of trench	15.00	4.57
Radius of pipe	3.50	1.07

4.5.1.2 Locations and distances assumptions

1. It is assumed that the landfill located at Stephenville, Texas, is used for dumping the excavated material. This landfill is type IV AE landfill and is the closest to the section, hence is apt for dumping the material. Figure 4.4 shows the location and the distance of the landfill from the analyzed section.

2. It is assumed that the backfill material is obtained from the quarry located at North Richland Hills (Sid Parker Stone Company). Figure 4.5 shows the location and the distance of the landfill from the analyzed section.
3. The distances are calculated as shown in Table 4.11 with the midpoint of the section as the reference point

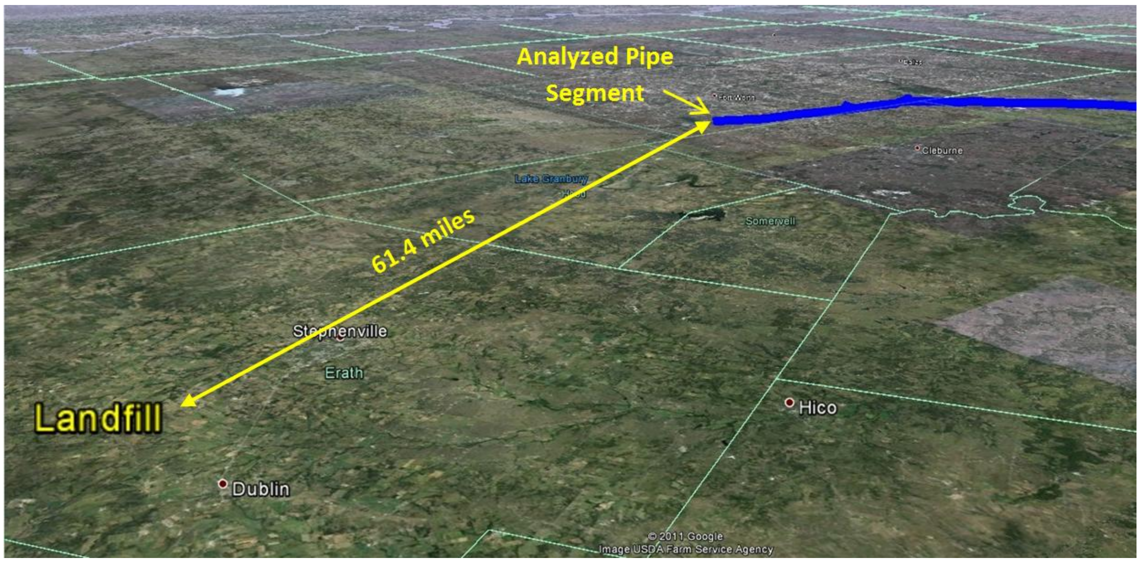


Figure 4.4 Google map showing the location and the distance of the landfill with respect to the analyzed section

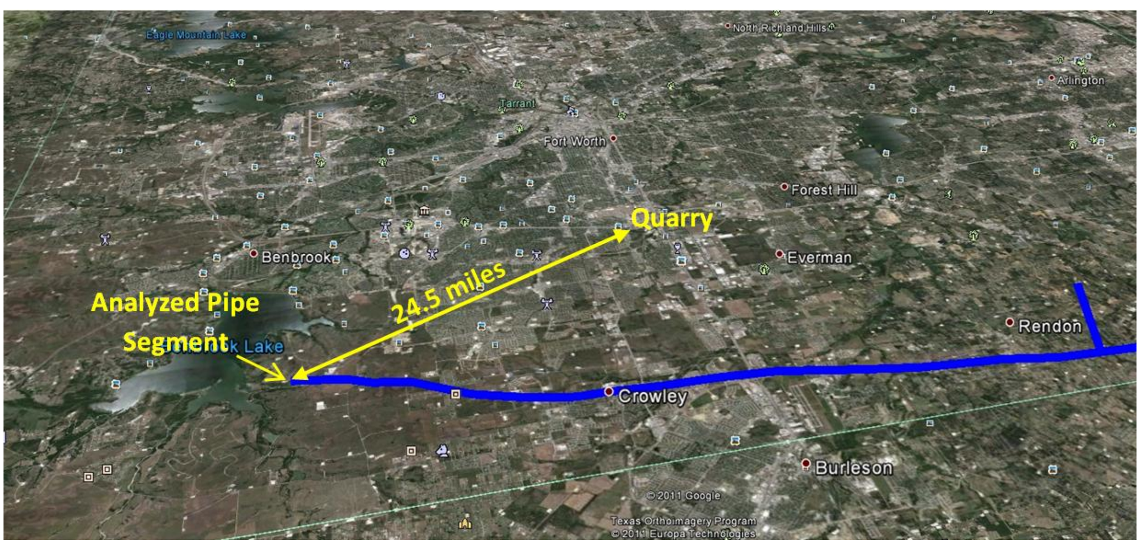


Figure 4.5 Google map showing the location and the distance of the quarry with respect to the analyzed section

Table 4.11 Distances of additive and quarry plants from site

Distances	
	miles
Distance from cement plant to site	15.3
Distance from lime plant to site	40.2
Distance from quarry to site	24.5
Distance from landfill to site	61.4

4.5.1.3 Material properties and additive dosages assumptions

1. Table 4.12 gives the assumed insitu and compacted densities of the excavated and imported materials.
2. For the purpose of calculations, the additive dosages of lime, cement and fly ash are assumed as shown in Table 4.13. It should be noted that the these are assumed numbers and a follow up work needs to be done for determining the accurate dosages required for the treatment.

Table 4.12 Assumed densities

Material	pcf	kg/m^3
Density of insitu soil	85	1361.57
Density after compaction	95	1521.75
Density of imported material	95	1521.75

Table 4.13 Assumed Additive dosages

Additive dosage	
Additive	% by weight of soil
Cement	3
Lime	6
Fly ash	10

4.5.1.4 Carbon emissions assumptions

1. It is assumed that cement and fly ash is supplied by Texas Cement Company located in Midlothian, Texas

2. It is assumed that lime is supplied by Texas Lime Company, a division of United States Lime and Minerals Inc., Cleburne, TX
3. As per McCaffrey (2002), approximately one ton of CO_2 is emitted for every ton of cement produced
4. As per the European Commission (2001), approximately 0.7 tons of CO_2 is emitted for every ton of lime manufactured.
5. According to Hardjito and Rangan (2005), about 0.03 kg of flyash is emitted for every kg of fly ash produced
6. According to EPA (2005), 22.30 lb CO_2 is emitted for every gallon of diesel fuel consumed

Table 4.14 CO_2 emissions

Amount of CO_2 emitted per kg of cement production, (kg/kg)	1
Amount of CO_2 emitted per kg of lime production, (kg/kg)	0.711
Amount of CO_2 emitted per kg of fly ash production, (kg/kg)	0.03
Amount of CO_2 emitted per kg production of imported material (lb)	0.00877
CO_2 emission for each gallon of diesel (lb / gal)	22.30

4.5.2 Methodology of carbon footprint analysis

For the purpose of calculations for the carbon footprint, the following procedure was implemented:

a. The west most section of the pipeline with a length of 100 feet was considered.

b. The volume of the material to be excavated was calculated by multiplying the assumed thickness with the width times the length of the segment.

c. This volume was further multiplied by the assumed density to get the weight of the soil.

d. In the case of using the native material, it was assumed that only some part of the soil that is equal to the volume of the pipe will be dumped. This amount of soil to be dumped is obtained by taking the difference of the material that is excavated and the material that is treated and used again. Figure 4.15 gives the weights and volume calculations for reusing the treated native material.

e. In the case of using imported material, it was assumed that only the backfill material is reused and the material required for bedding and haunch are imported. Table 4.16 gives the weight and volume calculations for using the imported material.

f. Amount of additives required was obtained by multiplying the percentage of dosage required with the weight of the haunch or bedding as the case may be.

g. The amount of imported material required was obtained by multiplying the volume of the bedding and haunch times the density of the imported material.

h. The amount of CO_2 emitted for producing these materials was obtained by multiplying the amount of CO_2 emitted per kg of material production times the total amount of material produced.

i. The CO_2 emitted for the transportation of these materials was calculated by using the distances travelled by the transportation equipment. The distance travelled is divided by the mileage (miles/gallon) of the equipment to obtain the total amount of fuel used. Now, the CO_2 emitted per gallon of diesel consumed by that equipment is assumed and the total CO_2 emitted is calculated by multiplying this assumed number with the total diesel consumed for all trips. Tables 4.17, 4.18, 4.19 show the calculations for these CO_2 emissions.

j. Also, the CO_2 emitted for dumping the excavated material was calculated by considering the distance from the landfill, capacity of the dump trucks, mileage of the trucks, total diesel consumed and the CO_2 emitted per trip. This number is then multiplied by the total number of trips to get the total amount of CO_2 emitted. Table 4.20 shows the CO_2 emissions due to landfilling of the excavated material.

The above analysis is an initial attempt as these numbers may be revised as more information of carbon foot print analyses is being validated.

Table 4.15 Weight and volume calculations– native material

USING TREATED NATIVE MATERIAL AS BEDDING AND HAUNCH/EMBEDMENT					
BEFORE CONSTRUCTION					
Volume Calculations			**Weight calculations**		
	ft^3	m^3		lb	kg
Bedding Volume	696.00	19.71	Bedding Weight	59160.00	26834.52
Haunch Volume	2275.83	64.44	Haunch Weight	193445.66	87745.47
Pipe Volume	3848.34	108.97	Weight of soil occupying pipe volume	327108.69	148374.00
Backfill Volume	11179.83	316.58	Backfill weight	950285.66	431042.30
Total Volume of segment	18000.00	509.70	Total weight of segment	1530000.00	693996.30
AFTER CONSTRUCTION					
Volume Calculations			**Weight calculations**		
	ft^3	m^3		lb	kg
Bedding Volume	696.00	19.71	Bedding Weight	66120.00	29991.53
Haunch Volume	2275.83	64.44	Haunch Weight	216203.97	98068.47
Pipe Volume	3848.34	108.97	Weight of soil occupying pipe volume	365592.06	165829.76
Backfill Volume	11179.83	316.58	Backfill weight	1062083.97	481753.16
Total Volume of segment	18000.00	509.70			
ADDITIVE MATERIAL					
Amount of cement required				8469.72	3841.78
Amount of lime required				16939.44	7683.56
Amount of fly ash required				28232.40	12805.93
LANDFILLED MATERIAL					
Total amount of soil reused				1344407.94	609813.16
Amount of Soil to be dumped in landfill	1953.60	61.83		185592.06	84183.14

Note: These calculations are for 100 feet length of hypothetical section

Table 4.16 Weight and volume calculations – imported material

USING IMPORTED QUARRY MATERIAL AS BEDDING AND HAUNCH/EMBEDMENT					
BEFORE CONSTRUCTION					
Volume Calculations			**Weight calculations**		
	ft^3	m^3		lb.	kg
Bedding Volume	696.00	19.71	Bedding Weight	59160.00	26834.52
Bedding Volume	2275.83	64.44	Haunch Weight	193445.66	87745.47
Bedding Volume	3848.34	108.97	Weight of soil occupying pipe volume	327108.69	148374.00
Bedding Volume	11179.83	316.58	Backfill weight	950285.66	431042.30
Bedding Volume	18000.00	509.70	Total weight of segment	1530000.00	693996.30
AFTER CONSTRUCTION					
Volume Calculations			**Weight calculations**		
	ft^3	m^3		lb.	kg
Bedding Volume	696.00	19.71	Bedding Weight	66120.00	29991.53
Haunch Volume	2275.83	64.44	Haunch Weight	216203.97	98068.47
Pipe Volume	3848.34	108.97	Weight of soil occupying pipe volume	365592.06	165829.76
Backfill Volume	11179.83	316.58	Backfill weight	1062083.97	481753.16
Total Volume of segment	18000.00	509.70	Total weight of segment	1710000.00	775642.92
LANDFILLED MATERIAL					
Amount of imported material required, m^3		84.15		282325.43	128059.99
Amount of material to be dumped, m^3		193.13		647916.03	293889.76

Note: These calculations are for 100 feet length of hypothetical section

Table 4.17 Analysis for CO_2 emissions due to transportation of lime

CO_2 emissions due to transportation of lime		
Distance From Plant	miles	40.20
Truck Capacity	kg	8000.00
Amount of lime required	kg	7683.56
Number of trips required (8000 kg per trip)	Nos.	0.96
Mileage of each truck	mpg	5.40
total diesel consumption of each truck for one way	gal	7.44
total diesel consumption of each truck for two way	gal	14.89
total diesel for all trips	gal	14.30
CO_2 emission for each gallon of diesel	lb./gal	19.35
total CO_2 emission from the diesel consumption	lb.	276.70

Table 4.18 Analysis for CO_2 emitted in the transportation of cement

Analysis for CO_2 emitted in the transportation of cement		
Distance From Plant	miles	15.30
Truck Capacity	kg	8000.00
Amount of cement required	kg	3841.78
Number of trips required (8000 kg per trip)	Nos.	0.48
Mileage of each truck	mpg	5.40
total diesel consumption of each truck for one way	gal	2.83
total diesel consumption of each truck for two way	gal	5.67
total diesel for all trips	gal	2.72
CO_2 emission for each gallon of diesel	lb./gal	22.30
total CO_2 emission from the diesel consumption	lb.	60.68

Table 4.19 Analysis for CO_2 emitted in the transportation of fly ash

Analysis for CO_2 emitted in the transportation of fly ash		
Distance From Plant	miles	15.30
Truck Capacity	kg	8000.00
Amount of fly ash required	kg	12805.93
Number of trips required (8000 kg per trip)	Nos.	1.60
Mileage of each truck	mpg	5.40
total diesel consumption of each truck for one way	gal	2.83
total diesel consumption of each truck for two way	gal	5.67
total diesel for all trips	gal	9.07
CO_2 emission for each gallon of diesel	lb./gal	22.30
total CO_2 emission from the diesel consumption	lb.	202.28

Table 4.20 CO_2 emissions due to land filling

Carbon emissions		
Emissions due to land filling		
Distance from landfill	miles	61.41
Truck capacity	kg	10550.00
Number of trips required	Nos.	8.00
Mileage of each truck	mpg	5.40
Total diesel consumption of each truck for one way	gallon	11.37
Total diesel consumption of each truck for two way	gallon	22.74
Total diesel for all trips	gallon	181.90
CO_2 emission for each gallon of diesel	lb./gal	22.30
Total CO_2 emissions due to landfilling	lb.	4047.18

4.5.3 Results of carbon footprint analysis

Table 4.21 gives summary of the total amount of CO_2 emitted by using cement and fly ash, lime and imported material. From the table, it can be inferred that the amount of CO_2 emitted by using imported material is far more than using a combination of cement and fly ash or lime. Hence it can be concluded that use of insitu treated material is more environmental friendly and can result in considerable reduction in carbon footprint. However, it should be noted that this analysis is preliminary with several assumptions listed above, and for a very minute section of the entire pipeline; hence it is recommended to do more thorough analysis for all the sections of the pipeline to make a more informed decision.

Table 4.21 Summary of comparisons of CO_2 emissions

Total CO_2 emission for using cement + fly ash for treating the native material	lb.	4310.15
Total CO_2 emission for using lime for treating the native material	lb.	4323.89
Total amount of CO_2 emitted for production and transportation of imported material	lb.	27719.68

Note: These calculations are for 100 feet length of hypothetical section

4.6 Cost analysis

As explained above, to understand the impact of using treated native material versus imported material for bedding and haunch cost analysis was performed whose methodology and the results are presented in the following sections. Some of the assumptions involved in the analysis are presented in the next section.

4.6.1 Assumptions for carbon footprint analysis

The assumptions made for Geometry, location and distances, material properties and additive dosages are similar to the carbon footprint analysis and are presented in the previous sections. Various cost assumptions with respect to Landfill cost Diesel, Operator cost for dumping into landfill, Cost for purchase of imported material, Lime, Cement, Fly ash, Cost of mixing the soil ($), Cost of using cement and fly ash are given in Table 4.22. It should be noted that the costs for personnel and the cost for pipeline construction itself is not included in this study.

Table 4.22 Assumed costs of various parameters

Costs		
	Unit	**Cost in $**
Landfill cost	m^3	10.70
Diesel	gal	3.50
Cost for purchase of imported material	m^3	6.00
Lime	kg	0.11
Cement	kg	0.13
Fly ash	kg	0.04
Cost of mixing the soil	m^3	3.00
Cost of using cement and fly ash	m^3	4.50

4.6.2 Methodology of cost analysis

For the purpose of calculations of the cost analysis, the following procedure was implemented:

a. The west most section of the pipeline with a length of 100 feet was considered.

b. The volume of the material to be excavated was calculated by multiplying the assumed thickness with the width times the length of the segment.

c. This volume was further multiplied by the assumed density to get the weight of the soil.

d. In the case of using the native material, it was assumed that only some part of the soil that is equal to the volume of the pipe will be dumped. This amount of soil to be dumped is obtained by taking the difference of the material that is excavated and the material that is treated and used again. Table 4.17 gives the weights and volume calculations for reusing the treated native material.

e. In the case of using imported material, it was assumed that only the backfill material is reused and the material required for bedding and haunch are imported. Table 4.18 gives the weight and volume calculations for using the imported material.

f. Amount of additives required was obtained by multiplying the percentage of dosage required time the weight of the haunch or bedding as the case may be.

g. The amount of imported material required was obtained by multiplying the volume of the bedding and haunch times the density of the imported material.

h. The total cost of these materials was obtained by multiplying the cost of production of these materials times the total amount of each material required.

i. The costs for the transportation of these materials was calculated by using the distances travelled by the transportation equipment, mileage of each equipment, cost per gallon of diesel consumed by that equipment, total diesel consumed for all trips.

j. Also, the cost for dumping the excavated material was calculated by considered the distance from the landfill, capacity of the dump trucks, mileage of the trucks, total diesel consumed and the cost per trip. This number is then multiplied by the total number of trips to get the total cost of landfilling.

k. A comparison between the costs by using the native material versus the imported material is then made.

Table 4.23 gives the costs incurred by using the native material. These calculations are done as per the methodology discussed above.

Table 4.23 Total costs incurred by using treated native material

Landfill costs		
Distance from landfill	miles	61.41
Truck capacity	kg	10550
Number of trips required	Nos.	8.0
Mileage of each truck	mpg	5.4
Total diesel consumption of each truck for one way	gal	11.37
Total diesel consumption of each truck for two way	gal	22.74
Total diesel for all trips	gal	181.49
Landfill operator cost		$ 661.31
Total transportation cost		$ 635.21
Total landfilling cost		$ 1,296.52
Additive costs		
Cost of Cement + Fly ash		$ 947.64
Cost of Lime		$ 845.19
Cost for mixing cement + fly ash		$ 378.69
Cost for mixing lime		$ 252.46
Total Cost of using native material treated with cement + fly ash		**$ 2,622.85**
Total Cost of using native material treated with lime		**$ 2,394.17**

Note: These calculations are for 100 feet length of hypothetical section

Table 4.24 gives the costs incurred due to use of imported material. The calculations for obtaining these costs are done as per the methodology discussed above.

Table 4.24 Total costs incurred by using imported material as bedding and haunch for the hypothetical section

Landfill costs		
Distance from the landfill	miles	61.41
Truck capacity	kg	8000.00
Amount of material required to be dumped	kg	293889.76
Number of trips required	Nos.	36.74
Mileage of each truck	mpg	5.40
Total diesel consumption of each truck for one way	gal	11.37
Total diesel consumption of each truck for two way	gal	22.74
Total diesel for all trips	gal	835.54
Cost to dump the material ($)		2065.67
Cost for transportation for dumping		2924.41
Total cost for dumping the material		4990.08
Cost to purchase and use imported material		
Distance from the quarry	miles	24.49
Truck capacity	kg	8000.00
Amount of material required to be purchased	kg	128059.99
Number of trips required	Nos.	16.01
Mileage of each truck	mpg	5.40
Total diesel consumption of each truck for one way	gal	4.54
Total diesel consumption of each truck for two way	gal	9.07
Total diesel for all trips	gal	145.19
Cost of purchase of material		504.92
Cost for transportation of purchased material		508.18
Total cost for purchase of material		1013.10
Total Cost for using imported material		**$ 6,003.18**

4.6.3 Summary of cost analysis

Table 4.25 gives a summary of the costs incurred by using a combination of cement with fly ash and lime versus the costs incurred by using imported material. It can be observed from the table that the total cost when using imported material for bedding and haunch is more than twice that of the lime or cement treated native material used as bedding and haunch materials. Hence it can be concluded that use of insitu treated material is more economical and can result in considerable savings in project costs. However, it should be noted that this analysis is preliminary with several assumptions listed above, and for a very minute section of the entire pipeline; hence it is recommended to do more thorough analysis for all the sections of the pipeline to make a more informed decision.

Table 4.25 Summary of comparisons of costs

Total Cost of using native material treated with cement + fly ash	**$ 2,622.85**
Total Cost of using native material treated with lime	**$ 2,394.17**
Total Cost for using imported material	**$ 6,003.18**

Note: The above table is for a length of 100 feet of hypothetical section

These results could be further analyzed with the triple bottom line of economic, environmental and social accountability suggested by Abreu et al., 2008. Figure 4.6 shows the integration of the three elements of social, economic and environmental conditions. Sustainability is achieved only when these three conditions are satisfied. In the analysis performed, it is shown that the reuse of native material is beneficial both from the carbon footprint and also the cost aspects. The less usage of pavements for transportation adds to the social impact of triple bottom line of sustainability.

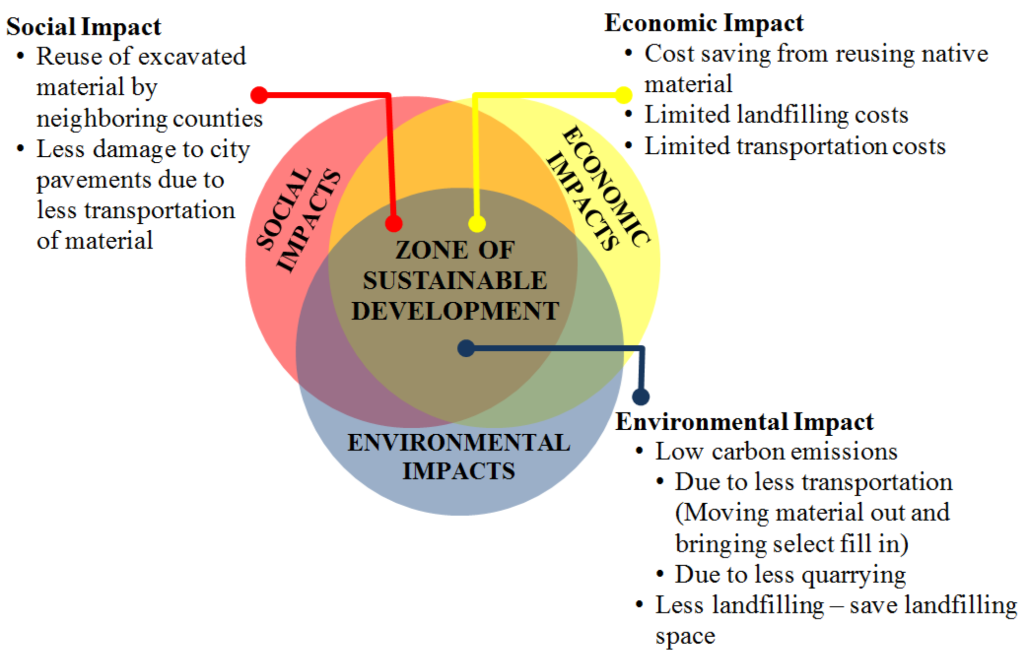


Figure 4.6 Components of sustainability

The cost savings from landfills and transportation clearly indicate the economic importance of using the native material. Table 4.21 clearly indicates the reduction in carbon emissions when native material is used adding to the environmental impact. This sustainability aspect of the project is further summarized in Chapter 5.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Introduction

This chapter gives the summary of the results and the conclusions drawn from the analysis shown in chapter 4. This chapter also includes the recommendations that can be incorporated into further research.

5.2 Summary

Soil sampling locations were selected along the entire pipeline stretch in such a way that they represent the materials found along various segments of the pipe line alignment. A total of 10 different locations were identified with consultations with TRWD and IPL team. Several basic and advanced geotechnical tests were conducted on these soils from all 10 boring locations to check and address if they can be used as bedding, haunch or/and backfill materials. Four types of chemical soil tests were conducted on each of the soil samples, viz., Cation Exchange Capacity (CEC), Specific Surface Area (SSA), Total Potassium (TP) and Sulfate Analysis. The physical tests performed included Sieve analysis, Hydrometer tests, Atterberg limits and Standard Proctor compaction tests. Engineering soil tests were further conducted on all the soil samples that included Unconfined Compression Strength tests (UCS) and Unconsolidated Undrained Triaxial Compression tests (UU). The details of the selection and the tests conducted on the soil samples have been discussed in detail in chapter 3.

To better understand the environmental and economic impacts of using insitu excavated material in place of imported material as bedding and haunch material carbon foot print and cost analyses were performed. For this purpose a hypothetical section of 100 feet was assumed and carbon emissions due to importing material versus using chemical treatment were obtained from literature and oral communications with the quarry owners.

5.3 Conclusions

From the chemical tests conducted to understand the clay mineralogy revealed that most of the soils except B2 and B4 showed high amounts of expansive clay minerals. These soils with high Montmorillonite content in the range of 35% and above should be stabilized to reduce excess stresses on the pipe due to swelling and shrinking related movements that can occur within the top 10 ft of active depth. Other soils with lower percentages may be used as backfill materials with minimal or no treatment.

As showed in Table 4.6 of Chapter 4, Soils from B1 and B2 locations can be used as bedding and haunch materials if Type 3, Type 4 and Type 5 installation methods are employed. This is because, these installation types typically require category I & II material for bedding and haunch as per ASTM C 1479 and B1 and B2 soils are categorized as category II.

Type 4 and Type 5 installations involve flowable fills. As per Howard (1996) soils with high percentage of sands and silts are preferred for use in flowable fill mix designs. Soils from locations B1, B2, B4, B6, B14 and B16 contain silt contents ranging from 20% to 60% and hence can be used as haunch material if Type 4 and Type 5 installation types are employed.

Based on the carbon footprint analysis CO_2 when cement and fly ash is used is found to be about 4310 lb and when lime is used for treatment is found to be about 4323 lb. But when imported material is used, the CO_2 emission was as high as 27719.68 lb. This clearly shows a difference of more than 100% savings in carbon emissions when a combination of cement and fly ash or lime is used instead of importing material. These savings are shown only for a section of 100 feet. If similar analysis is done for entire section, the savings on carbon emissions would be enormous. This difference is primarily because of the carbon emissions due to transport of the materials. This could change if another section is considered which has a quarry or landfill nearer compared to the hypothetical section.

Similarly, the cost for using cement and fly ash was found to be about $2622 and lime was about $2394. This cost increased more than 100% to $6003.18 when imported material was used. Similarly, the cost analysis done on the hypothetical pipe section in Chapter 4 shows a cost saving of more than 100% when a combination of cement and fly ash or lime is used when compared to using material that is imported. These savings are shown only for a section of 100 feet. If similar analysis is done for entire section, the savings on carbon emissions would be enormous. This difference is primarily because of the carbon emissions due to transport of the materials. This could change if another section is considered which has a quarry or landfill nearer compared to the hypothetical section.

It should be noted here that the calculations are results shown in this thesis are done only as a preliminary estimates and may not be considered as a final result.

5.4 Limitations

1. Only ten (10) boreholes were considered along the pipe section at various intervals to analyze the properties of soil lying along the entire pipeline length of 147 miles. This might not present a total view of the soil along the entire stretch of the pipeline.
2. The hypothetical section assumed give only an idea of how carbon footprint analysis and cost analysis may be performed and briefly highlights the relative merits. However, this analysis was performed using carbon emissions information from literature on a more general basis and hence a more detailed analysis using specific carbon emissions must be performed in order to make a thorough analysis.
3. Similarly for the cost analysis, dollar estimates are made on a general basis and though the results show considerable cost savings, project specific estimates must be made for a thorough analysis. Also, the project time lines and the costs for the personnel involved are not considered in this analysis.

5.5 Recommendations for Future Research

1. Further studies using additional borehole data along the pipeline are recommended to get a thorough knowledge of the soil lying along the pipeline.
2. Also, further analysis with a real-time section can be conducted as part of future research considering various sections of the pipeline. This would give a complete cost and carbon footprint analysis of the entire pipeline project. The analysis methodology explained in this research on the hypothetical section can be used as a basis for such analysis.
3. Further research may be done to get accurate CO_2 emissions and better knowledge of the embodied energies of the materials considered in this thesis. The entire carbon footprint may be calculated accordingly. Further cost analysis may also be done using other quarries and landfills located across the pipeline in various counties.

APPENDIX A

BORING LOGS

LOG OF BORING NO. B- 1

INTEGRATED PIPELINE PROJECT
Section No. 19, Parcel No. PROW
Anderson County, TEXAS
PROJECT NO. 04-4010-1038, Phase 1

LATITUDE: 32.06518°
LONGITUDE: -95.52793°

SURF. ELEVATION: 470.0

DEPTH, FT	POCKET PEN / Blows/ft / REC,RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH SOIL (TSF)	UNCONFINED STRENGTH ROCK (PSI)
	P = 4.5+	**SILTY CLAYEY SAND (SC-SM)**, dark yellowish brown and olive brown, moist, loose to very dense, [Queen City Formation]		13	22	17	5	25			
	N = 4	- few calcareous nodules, trace gravel @ 0'-12'		15	25	20	5	28			
	N = 9										
5											
	N = 35			12				35			
	N = 48			12				34			
10	N = 40			15				29			
	N = 20	**CLAYEY SAND (SC)**, olive brown, moist, medium dense to very dense	458.0 / 12.0	16				37			
	P = 4.25			17	33	20	13	34	115	1.4	
15	P = 2.25										
	P = 3.5			17	32	19	13	34	117	1.1	
	P = 4.5										
				16				38	112		
20	N = 29			15				32			
	N = 54			13	35	22	13	27			
	N = 49			12				17			

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COMPLETION DEPTH: 40.0
DATE DRILLED: 12-6-10
WATER LEVEL / SEEPAGE: > 40

KEY:
Note: All depths are measured in feet.
P = Pocket Penetrometer Value, (tsf)
N = Standard Penetration Number

A-20a

LOG OF BORING NO. B- 1

INTEGRATED PIPELINE PROJECT
Section No. 19, Parcel No. PROW
Anderson County, TEXAS
PROJECT NO. 04-4010-1038, Phase 1

LATITUDE: 32.06518°
LONGITUDE: -95.52793°

DEPTH, FT	SYMBOL	SAMPLES	POCKET PEN Blows/ft. REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH SOIL (TSF)	UNCONFINED STRENGTH ROCK (PSI)
				SURF. ELEVATION: 470.0									
				CLAYEY SAND (SC), olive brown, moist, medium dense to very dense *(continued)*	442.0								
			N = 35	**POORLY GRADED SAND WITH SILT (SP-SM)**, very pale brown to very light gray, moist, dense to very dense	28.0	6				10			
30													
			N = 50/5"			6				9			
35													
			N = 50/5"										
40					430.0 40.0								
				Notes: (1) Borehole backfilled with drill cuttings after completion and compacted at surface.									
45													

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Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 12-6-10
WATER LEVEL / SEEPAGE: > 40

KEY:
Note: All depths are measured in feet.
P = Pocket Penetrometer Value, (tsf)
N = Standard Penetration Number

A-20b

LOG OF BORING NO. B- 2

INTEGRATED PIPELINE PROJECT

NORTHING: 32.124
EASTING: -95.817

DFW, Texas
PROJECT NO. 04-4010-1038

SURF. ELEVATION: 442.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	N = 3	**SILTY SAND (SM)**, very pale brown, fine grained, dry, loose, [Queen City Formation]		4				14		
	N = 4									
				3				18		
	N = 9									
5	N = 7	- with some ferrous stains below 5'		12				31		
	N = 10	**SILTY SAND (SM)**, yellowish red, fine grained, dry, loose to medium dense, with some ferrous stains	435.0 / 7.0							
	N = 13			12				33		
10	N = 12	**CLAYEY SAND (SC)**, light gray and reddish yellow, moist, stiff	432.0 / 10.0							
	N = 13			15	33	18	15	47		
	N = 16									
15	P = 4.0	**SANDY LEAN CLAY (CL)**, light gray and reddish yellow, moist, stiff	427.0 / 15.0	18					112	2.1
	P = 4.5			17	46	20	26		113	
				19					112	1.1
	N = 33	- with ferrous cemented seams, more ferrous stained 18.5' - 24'		19	43	19	24	59		
20	N = 37									
	N = 21			25						
	P = 4.5	- 24' - 24.5' light gray fat clay layer	417.0	25	57	24	33	94		

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-13-10
WATER LEVEL / SEEPAGE: 25.0
WATER LEVEL (): 23.0

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B- 2

INTEGRATED PIPELINE PROJECT

NORTHING: 32.124
EASTING: -95.817

DFW, Texas

PROJECT NO. 04-4010-1038

SURF. ELEVATION: 442.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	N = 38	**SILTY SAND (SM)**, light gray and reddish yellow, fine grained, wet, medium dense	25.0	26				40		
	N = 23			25				40		
	N = 19		413.0							
		FAT CLAY (CH), light gray, moist, stiff	29.0							
30	P = 3.25			27	54	20	34	94		
	P = 4.5+									
	P = 4.5+			23					98	2.0
	P = 4.5+									
	P = 4.5+									
35	P = 4.5+			24						
	P = 4.5+									
			404.5							
		FAT CLAY (CH), dark gray, moist, very stiff, with numerous gray sand partings	37.5							
	N = 34			28						
			402.0							
40			40.0							
45										

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-13-10
WATER LEVEL / SEEPAGE: 25.0
WATER LEVEL (): 23.0

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B- 6

INTEGRATED PIPELINE PROJECT

NORTHING: 32.114
EASTING: -96.198

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 340.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 4.5+	**LEAN CLAY (CL)**, dark brown, damp, very stiff, [Wilcox Group]		12	44	17	27	87	103	9.2
	P = 4.5+			13						
	P = 4.5+		337.0							
	P = 4.5+	**FAT CLAY (CH)**, brownish gray, moist, very stiff	3.0	14	57	21	36		113	11.3
	P = 4.5+									
5	P = 4.5+		334.5	17						
	P = 4.5+	**LEAN CLAY WITH SAND (CL)**, very pale brown and light gray, moist, very stiff, sand seams - with ferrous deposits below 6'	5.5							
	P = 4.5+			14	47	16	31	83	114	7.6
	P = 4.5+									
	P = 4.5+									
10				16				79		
	P = 4.5+		328.0							
		SANDY LEAN CLAY (CL), very pale brown and light gray, moist, very stiff, with calcareous deposits	12.0	12						
	P = 4.5+									
	P = 4.5+			13					113	3.3
15	P = 4.5+									
	P = 4.5+			13	35	13	22	70		
	P = 4.5		322.0							
	P = 4.5	**LEAN CLAY WITH SAND (CL)**, very pale brown, moist, very stiff, with few sand seams	18.0							
	P = 4.5			17	44	18	26	71		
20	P = 4.0									
	P = 3.75		318.0							
	P = 3.25	**SANDY LEAN CLAY (CL)**, very pale brown, moist, very stiff, sand seams	22.0	16	31	15	16	69	113	0.9
	P = 2.75		316.5 23.5							
	P = 2.25	- brownish yellow and light gray, with ferrous stains below 23.5'	315.0							

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COMPLETION DEPTH: 40.0
DATE DRILLED: 9-1-10
WATER LEVEL / SEEPAGE: 35.0
WATER LEVEL (10 MINUTES): 26.5

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B- 6

INTEGRATED PIPELINE PROJECT

NORTHING: 32.114
EASTING: -96.198

DFW, Texas
PROJECT NO. 04-4010-1036

SURF. ELEVATION: 340.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
		SANDY LEAN CLAY (CL), brownish yellow and light gray, moist, very stiff, with few sand seams and ferrous stains (continued)	25.0							
30	P = 2.25			21				64		
35	P = 2.0	- increased sand and clayey sand seams below 34'		20				84	104	0.5
40	P = 1.95		300.0 / 40.0	23						
45										

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COMPLETION DEPTH: 40.0
DATE DRILLED: 9-1-10
WATER LEVEL / SEEPAGE: 35.0
WATER LEVEL (10 MINUTES): 26.5

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B- 7

INTEGRATED PIPELINE PROJECT

NORTHING: 32.216
EASTING: -96.417

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 462.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 4.5+	**SANDY LEAN CLAY (CL)**, dark brown, moist, very stiff, [Nacatoch Sand]		5					98	0.8
	P = 4.5+									
	P = 4.5+			12	51	19	32	70		
	P = 4.5+		458.0							
	P = 4.5+	**SANDY LEAN CLAY (CL)**, light gray with brownish yellow, moist, very stiff, moist, very stiff, with calcareous nodules and ferrous deposits	4.0							
5	P = 4.5+			12					123	10.1
	P = 4.5+									
	P = 4.5+			17	57	18	39	63		
	P = 4.5									
	P = 3.5									
10	P = 2.75			41					80	0.8
	P = 3.25		450.0							
	P = 4.0	**FAT CLAY (CH)**, light gray with brownish yellow, moist, very stiff, trace calcareous deposits	12.0							
	P = 3.5			43	101	32	69	85		
	P = 4.5+									
15	P = 4.25		446.0	41					86	0.8
	P = 4.5+	**FAT CLAY WITH SAND (CH)**, light gray with brownish yellow, moist, very stiff, sand seams	16.0							
	P = 4.5+			27	63	27	36	72		
	P = 4.5+									
	P = 4.5+		442.0							
20	P = 4.5+	**SANDY FAT CLAY (CH)**, light gray with yellowish red, moist, very stiff, with sand seams, ferrous stains	20.0							
	P = 4.5+			25	62	27	35	69		
	P = 4.5+									
	P = 4.5+			26					99	3.0
	P = 4.5+									

FUGRO
Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-1-10
WATER LEVEL / SEEPAGE: Dry
WATER LEVEL (): Dry

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B- 7

INTEGRATED PIPELINE PROJECT

NORTHING: 32.216
EASTING: -96.417

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	SYMBOL	SAMPLES	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 462.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
				SANDY FAT CLAY (CH), light gray with yellowish red, moist, very stiff, with sand seams, ferrous stains *(continued)*								
30			P = 4.5+			27	56	25	31	68		
				- 6" hard calcareous sandstone layer at 32'								
35			P = 4.5+			24						
40			P = 4.5	- gray and dark gray with yellowish red ferrous stains at 39'	422.0 / 40.0	29						
45												

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-1-10
WATER LEVEL / SEEPAGE: Dry
WATER LEVEL (): Dry

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B- 8
INTEGRATED PIPELINE PROJECT

NORTHING: 32.220
EASTING: -96.519

DFW, Texas
PROJECT NO. 04-4010-1038

SURF. ELEVATION: 379.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 4.5+	**FAT CLAY (CH)**, dark gray, moist, very stiff to stiff, [Wolfe City Formation]								
	P = 4.5+			15					106	4.9
	P = 4.25									
	P = 2.25			24	75	24	51	92		
	P = 3.25									
5	P = 3.25	- gray, few calcareous nodules below 5'								
	P = 3.25			23					103	2.1
	P = 3									
	P = 1.75	- gray with brownish yellow below 8'								
	P = 1.75			28	62	24	38	92		
10	P = 2.5									
	P = 2.5			28						
	P = 2.5	- trace ferrous deposits below 12'								
	P = 2.25			25					101	0.6
	P = 2.25									
15	P = 3.0									
	P = 3.0			27	70	26	44	89		
	P = 2.75									
	P = 3.0									
	P = 2.75									
20	P = 2.5			30					95	0.6
	P = 2.5									
	P = 2.0									
	P = 1.75		355.0	23	53	24	29			
	P = 2.75	**LEAN CLAY WITH SAND (CL)**, gray with brownish yellow, moist, stiff	24.0							

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-31-10
WATER LEVEL / SEEPAGE: 28.0
WATER LEVEL (): 12.5

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B- 8

INTEGRATED PIPELINE PROJECT

NORTHING: 32.220
EASTING: -96.519

DFW, Texas
PROJECT NO. 04-4010-1038

SURF. ELEVATION: 379.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
		LEAN CLAY WITH SAND (CL), gray with brownish yellow, moist, stiff *(continued)*	351.0 / 28.0							
30	P = 4.0	**WEATHERED SHALE**, highly weathered, dark gray, medium hard, moist, blocky, [Neylandville Formation - Marlbrook Marl]	347.0 / 32.0	35	93	30	63			
		WEATHERED SHALE, dark gray, soft	344.0 / 35.0							
35	35'-40' 97/83	**SHALE**, dark gray, soft to medium hard, some fossils - 20° fractures at 36.3', 36.5', and 37' - 70° fracture at 37.6' - 39.2' fossil parting	339.0 / 40.0	21					106	13.1
40										
45										

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-31-10
WATER LEVEL / SEEPAGE: 28.0
WATER LEVEL (): 12.5

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B- 9

INTEGRATED PIPELINE PROJECT

NORTHING: 32.254
EASTING: -96.678

DFW, Texas
PROJECT NO. 04-4010-1038

SURF. ELEVATION: 459.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 4.5+	**LEAN CLAY (CL)**, dark brown, moist, very stiff, [Wolfe City Formation]		14					103	10.9
	P = 4.5+									
	P = 4.5+		456.0	9	38	18	20	86		
	P = 4.5+	**SANDY FAT CLAY (CH)**, brown, moist, very stiff	3.0							
	P = 4.5+			17	57	23	34	64		
5	P = 4.5									
	P = 1.5	- mottled brownish yellow, very pale brown and light gray, with calcareous deposits below 6'		25					100	1.1
	P = 2.0									
	P = 1.75			30						
	P = 3.0	- trace sand seams, ferrous stains below 9'	449.0							
10	P = 4.5	**FAT CLAY (CH)**, brownish yellow and very pale brown, moist, very stiff	10.0							
	P = 4.5			26	69	26	43	91		
	P = 4.0									
	P = 4.0			21					107	1.8
	P = 4.0									
15	P = 4.5			26				93		
	P = 4.5+									
	P = 4.5+			26	63	20	43			
	P = 4.5+									
	P = 4.5+			21					106	2.1
20	P = 4.5+									
	P = 4.5+									
	P = 4.5+			21	68	24	44	91		
	P = 4.5+	- trace calcareous deposits, blocky, trace fossils below 23'								
	P = 4.5+									

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-31-10
WATER LEVEL / SEEPAGE: Dry
WATER LEVEL (): Dry

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B- 9

INTEGRATED PIPELINE PROJECT

NORTHING: 32.254
EASTING: -96.678

DFW, Texas

PROJECT NO. 04-4010-1038

SURF. ELEVATION: 459.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
		FAT CLAY (CH), brownish yellow and very pale brown, moist, very stiff *(continued)*								
	P = 4.5+			25	68	24	44	90	100	1.9
30										
	P = 4.5+	**SANDY WEATHERED SHALE**, gray with ferrous stains, soft, with sand seams, trace fossils	425.0 34.0	21					104	2.3
35										
	P = 4.5+			21					106	4.2
40			419.0 40.0							
45										

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-31-10
WATER LEVEL / SEEPAGE: Dry
WATER LEVEL (): Dry

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B-14

INTEGRATED PIPELINE PROJECT

NORTHING: 32.804
EASTING: -97.393

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	POCKET PEN, tsf / Blows/ft / REC.,RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 825.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 3.5	**FILL**, mixed brown clay with light brown, limestone fragments	824.0 / 1.0	14					110	3.1
	P = 4.25	**SANDY FAT CLAY (CH)**, dark brown, moist, very stiff, with some calcareous nodules								
	P = 4.5+			23	65	25	40	57		
	P = 4.5+		821.0 / 4.0							
	P = 4.5+	**CLAYEY SAND (SC)**, olive brown and brownish yellow, moist, very stiff, numerous calcareous nodules and deposits								
5	P = 4.5+			10					124	2.5
	P = 4.5+	- with broken limestone >3" diameter below 6'		12	35	17	18	20		
	N = 44									
	N = 50/3"									
10	10'-15' 62/ 37			5						
			813.5 / 11.5							
	N = 50/4"	**WEATHERED LIMESTONE**, very pale brown, hard, occasional clay layer <6" thick, fractured with orange stained faces, [Grayson Marl]								
				9					108	115.5
15	15'-20' 100/ 80									
			807.8 / 17.2							
		SHALE, gray, medium hard	806.8 / 18.2	12					127	5.3
		LIMESTONE, gray, hard, with occasional shale layers <2-ft thick, fine grained								
20	20'-25' 98/ 98									
				6					142	59.6
			801.7 / 23.3							
		SHALE, dark gray, medium hard								

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-14-10
WATER LEVEL / SEEPAGE: DRY TO 11.9'
WATER LEVEL (): Boring from 10'-40' was off-set 2' east of original to core at 10'

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B-14

INTEGRATED PIPELINE PROJECT

NORTHING: 32.604
EASTING: -97.393

DFW, Texas
PROJECT NO. 04-4010-1038

SURF. ELEVATION: 825.0

DEPTH, FT	SYMBOL	SAMPLES	POCKET PEN, tsf / Blows/ft. / REC,RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
			25'-30' 80/ 77	**SHALE**, dark gray, medium hard *(continued)*								
				- 27.7' - 60 degree closed fracture		18					113	6.2
				- 28.6'-28.8' intersecting fractures								
30			30'-35' 20/ 0									
35			35'-40' 100/ 100			17						
						16					126	10.8
40					785.0 40.0							
45												

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COMPLETION DEPTH: 40.0
DATE DRILLED: 9-14-10
WATER LEVEL / SEEPAGE: DRY TO 11.9'
WATER LEVEL (): Boring from 10'-40' was off-set 2' east of original to core at 10'

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B-15

INTEGRATED PIPELINE PROJECT

NORTHING: 32.539
EASTING: -97.135

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 681.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 4.5+	**FAT CLAY (CL)**, brown and very pale brown, moist, very stiff, with calcareous deposits								
	P = 4.5+			14					104	4.0
	P = 4.5+			17	53	24	29	90		
	P = 4.5+									
				24					99	1.9
5	P = 4.5+									
	P = 3.0	- with ferrous stains		21	70	26	44	97		
	P = 3.0									
	P = 4.0									
10	P = 3.5		670.0							
	P = 3.0	**FAT CLAY (CH)**, light gray and brownish yellow, moist, very stiff, ferrous stains, jointed, with few thin silt seams weakly cemented	11.0	24					96	1.1
	P = 4.5+									
	P = 4.25									
	P = 4.25			33					91	0.7
15	P = 3.75									
	P = 4.5+			31	87	29	58	98		
	P = 3.5									
	P = 3.5									
	P = 3.5			35					88	0.2
20	P = 3.75									
	P = 3.5		659.0							
	P = 4.5	**WEATHERED SHALE**, light gray and very pale brown, with ferrous stains, soft, with few silt seams, weakly cemented, [Eagle Ford Formation]	22.0	34	91	31	60			
	P = 4.5+									
	P = 4.5+									

FUGRO
Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-30-10
WATER LEVEL / SEEPAGE: 13.0
WATER LEVEL (10 MINUTES): 13.1

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B-15

INTEGRATED PIPELINE PROJECT

NORTHING: 32.539
EASTING: -97.135

DFW, Texas

PROJECT NO. 04-4010-1038

DEPTH, FT	SYMBOL	SAMPLES	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 681.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
			P = 3.25	**WEATHERED SHALE**, light gray and very pale brown, with ferrous stains, soft, with few silt seams, weakly cemented, [Eagle Ford Formation] *(continued)*	651.5 / 29.5	35	80	29	51		85	0.8
30				**WEATHERED SHALE**, medium gray, soft, slightly weathered	648.0 / 33.0							
35			35'-40' 100/ 100	**SHALE**, very dark gray, medium hard	641.0 / 40.0	17					109	28.3
40												
45												

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-30-10
WATER LEVEL / SEEPAGE: 13.0
WATER LEVEL (10 MINUTES): 13.1

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

LOG OF BORING NO. B-16

INTEGRATED PIPELINE PROJECT

NORTHING: 32.587
EASTING: -97.255

DFW, Texas
PROJECT NO. 04-4010-1038

SURF. ELEVATION: 696.0

DEPTH, FT	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 4.5+	**FAT CLAY (CH)**, brown and reddish yellow, moist, very stiff, with few yellow limonite stains								
	P = 4.5+			27					93	0.5
	P = 4.5+									
	P = 4.5+			21	67	25	42	96		
	P = 4.5+									
5	P = 4.5+	- few ferrous cemented seams below 5.5'								
	P = 4.5+			20					103	2.5
	P = 4.5+									
	P = 4.5+									
	P = 4.5+									
10	P = 4.5+			22	71	27	44	94		
	P = 4.5+	- dark brown, reddish yellow below 11'								
	P = 4.5+									
	P = 4.5+			22					103	3.9
	P = 4.5+		680.0							
15	P = 4.5+	**FAT CLAY WITH SAND (CH)**, dark gray, moist, very stiff, trace ferrous seams	15.0							
	P = 4.5+		678.0	22	65	28	37	81		
	N = 79	**WEATHERED SANDSTONE**, very pale brown and brownish yellow, fine grained, wet, weakly cemented, [Woodbine Formation]	17.0 677.0 18.0							
		WEATHERED SANDY SHALE, gray, with sand seams and layers, ferrous stains								
20				20	39	17	22	51		
	N = 42		673.3							
	N = 78	**CLAYEY SAND (SC)**, gray, fine grained, dense to very dense, with some sandy shale seams	21.7							
	N = 48			26				36		

FUGRO
Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-16-10
WATER LEVEL / SEEPAGE: 17.0
WATER LEVEL (): 15.0

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

LOG OF BORING NO. B-16
INTEGRATED PIPELINE PROJECT

NORTHING: 32.587
EASTING: -97.255

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	SYMBOL	SAMPLES	POCKET PEN, tsf / Blows/ft. / REC./RQD, %	STRATUM DESCRIPTION (SURF. ELEVATION: 696.0)	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
				CLAYEY SAND (SC), gray, fine grained, dense to very dense, with some sandy shale seams *(continued)*	666.0							
30			N = 57	**WEATHERED SHALE**, completely weathered, gray, sandy	29.0	17	52	23	29	86		
			N = 50/5"		660.5							
35			34.42'-40' 96/ 96	**SHALE**, dark gray, medium hard	34.5							
				- 3" gray, fine grained, calcareous cemented sandstone layers at 38.3' and 39.6'		13					126	9.5
40					655.0 40.0							
45												

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 9-16-10
WATER LEVEL / SEEPAGE: 17.0
WATER LEVEL (): 15.0

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE b

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BIOGRAPHICAL INFORMATION

At the time of presentation of this thesis, Rajini Kanth Reddy Karduri has a Bachelors Degree in Civil Engineering from Jawaharlal Nehru Technological University, India and a Post Graduation Diploma in Advanced Construction Management from National Institute of Construction Management and Research, India. He has hands on experience in Project Management and Business Development in real estate and infrastructure projects and is also a PMI ® certified Project Management Professional (PMP). The author joined University of Texas at Arlington as a MS candidate in Geotechnical Engineering and worked under the guidance of Dr. Anand J. Puppala. He had the chance to work in various research projects involving basic advanced soil testing, clay mineralogy and sustainability aspects in geotechnical engineering. His research interests lie in clay mineralogy and geotechnical engineering related ground improvement methods.