DYNAMIC AND STATIC ANALYSES OF OIL AND GAS PIPELINES

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IN

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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ABSTRACT

DYNAMIC AND STATIC ANALYSES OF THE OIL AND GAS PIPELINES

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In this study, a numerical calculation on interaction between soil and steel pipelines was performed. Properties of soil and pipe may cause significant effects on the movements of buried pipelines. To improve the understanding of the behavior of buried pipelines subjected to dynamic and static loading, different oil and gas pipes have been considered in this study. Earthquake load of magnitude 5.4 with time shaking of 10 sec and surface loads (50, 100, 150 and 200 kPa) have been used. To simulate numerically this effects, 2D finite element method PLAXIS is performed. The results are discussed and fitted by univariate linear and non-linear analysis. Some influential factors such as soil types (clay, loose and dense sand), soil layers (one, two and three soil layers), underground water table, static water loads (of height 20m above soil), burying depth, pipe diameter and pipe thickness are discussed in details. Based on the results, it can be concluded that these factors are important items on pipeline displacement for both static and dynamic loads. Some significant comparisons and conclusions are drawn.

Keywords: Pipeline diameter, Pipeline thickness, Displacement, PLAXIS-2D, Soil properties, Earthquake.

ÖZ

PTROL VE GAZ BORU HATLARININ STATİK VE DİNAMİK ANALİZİ

Hassan, Marwan Adil

İnşaat Mühendisliğinde Yüksek Lisans

Tez Yönetcisi: Doç Dr. Yasin Dursun Sarı

Haziran 2014, 119 Sayfa

Bu çalışmada, toprak ve çelik boru hatları arasındaki etkileşim üzerine bir sayısal analiz yapıldı. Toprak ve boru özellikleri gömülü boru hatlarının hareketleri üzerinde önemli etkilere neden olabilir. Dinamik ve statik yüklemeye maruz boru hatlarının davranışını inç elemek için, farklı petrol ve gaz boruları bu çalışmada dikkate alınmıştır. Süresi 10 sn ve büyüklüğü 5.4 olan deprem yükü ve 50, 100, 150 ve 200 kPa değişken yüzey yükleri kullanılmıştır. Bu etkileri simüle etmek için, 2D sonlu elemanlar sayısal metodu, PLAXIS, kullanılmıştır. Sonuçlar tartışılmış ve tek değişkenli doğrusal ve doğrusal olmayan matematiksel modelleme ile ifade edilmiştir. Toprak tipleri (kil, gevşek ve yoğun kum), toprak katmanları (bir, iki ve üç toprak katmanları), yeraltı su tablası, statik su yükleri (toprak üstünde yükseklik 20m), gömme derinliği, boru çapı, boru kalınlığı gibi faktörler çalışıldı. Sonuçları dikkate alındığında, bu faktörlerin hem statik hem de dinamik yükler etkisinde boru hattının deplasmanına sebep olabilecek önemli öğeler olduğu sonucuna varılabilir. Bazı önemli karşılaştırmalar ve sonuçlar verilmiştir.

Anahtar Kelimeler: Boru çapı, Boru kalınlığı, Deplasman, PLAXIS-2D, Toprak özellikleri, Deprem.

DEDICATION

I would like to dedicate this thesis to my father and mother, whose affection, love, encouragement and prays day and night make me able to get such success and honor.

To my wife, who supported me each step of the way

To my precious daughter Zainab, who is the joy of my life

I dedicate my thesis work to my dearest brothers Hassan and Shahad

Also I dedicate this thesis to my wife's family

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CHAPTER 1

INTRODUCTION

1.1Overview

The prime media of transporting fluid are pipelines. Pipelines that are used to transport a fluid between two distant stations usually run underground through most of their length. These pipelines are used to transport water, petroleum, natural gas and several other fluids. Pipelines are also used as utility corridors. The loading on these pipelines depends on the installation technique, site conditions and the intended use. The load to be resisted by a buried pipe is shared by both the pipe and the surrounding soil depending on the ratio of the stiffness of the two components. Buried fluid supply pipelines can be subject to both transient ground deformation and permanent ground deformation in the event of an earthquake. Transient ground deformation is caused by the passage of seismic waves (ground shaking).Permanent ground deformation is caused by surface faulting or secondary effects which give rise to localized ground failure (liquefaction, landslides and densification of surface soil layers). Buried pipelines can be subject to both transient ground deformations and permanent ground deformations in the event of an earthquake. Analytical modeling of the response of buried pipelines has progressed rapidly in the last decades.

1.2Objective of the study

The primary objective of this thesis is to study the mechanical behavior of oil and gas steel buried pipelines using suitable finite element software. Three diameter values in combination with three different wall thicknesses for each of them are considered. They are typical sizes for oil and gas transmission pipelines (Vazouras et

al., 2012). In this study, effects of various soil such as clay, loose sand and dense sand on the response of underground pipes due to surface load and earthquake ground motionsare studied. Based on PLAXIS-2D software, effects of various parameters such as pipe diameter, pipe wall thickness, burial depth of pipe, soil type, multi burying soil and underground water table are investigated. The overall objective of this study was to compute the pipeline displacement. Based on the obtained results, a simplified linear and nonlinear equation is predicted. A verification study to the previous work of Rajkumar and Ilamparuthi (2008) was also performed for buried pipes under static loading conditions.

1.3 Outlines of the study

The thesis is divided into eight chapters. Following this introduction, chapter two presents the review of literature on the subject. The literature discussed includes a summary of earthquake effects, explaining the mechanism of earthquake-induced ground movements and their interactions with buried pipelines. This chapter constitutes a detailed treatment of the behavior of buried pipelines subject to surface load as well as ground shaking. Some details about the used finite element software PLAXIS-2D are also included in this chapter.

A verification study has been presented in Chapter Three to a previous work on the response of buried pipeline crown deflection to the Netlon Geogrid reinforcement.

Chapter Four constitutes a detailed treatment of the behavior of buried pipelines subject to ground shaking. The key factors influencing both the seismic action and pipeline vulnerability are explained

Chapter Five gives the details of the parametric study of the buried pipelines subjected to surface static load. The effects of various parameters such as soil and burying condition are investigated.

Under surface static load, the response of buried pipeline in soil layers is considered in Chapter Six. The study is performed in the framework of two as well as three soil media.

In chapter seven, the influence of underground on pipeline displacement has been investigated for different values of water depths and soil media. Chapter Eight presents the main suggested conclusion of the research.

CHAPTER 2

LITERATURE SURVEY

2.1 Past work review

An earthquake is a ground shaking due to the sudden liberation of energy in the earth's crust. This energy may originate from different sources such as dislocations of the crust, volcanic eruptions, or even by man-made explosions or the collapse of underground cavities, such as mines or karsts. Earthquake manifestation may be explained by the theory of large scaled tectonic processes, referred as "plate tectonic". Plates are large and stable rigid rock slabs with a thickness of about 100km, forming the crust or lithosphere and part of the upper mantle of the earth. Large tectonic forces take place at the plate edges due to relative movement of the lithosphere – asthenosphere complex. These forces rouse physical and chemical changes and affect the geology of the adjoining plates. However, only the lithosphere has the strength and the brittle behavior to fracture, thus causing an earthquake (Elnashai and Sarno, 2008).

Earthquake shaking was created by two types of elastic seismic waves: body and surface. At small distances from the source, the shaking felt was mostly a combination of these waves. Body waves travel through the earth's interior layers. They include two waves, longitudinal or primary waves (P- waves) and transverse or secondary waves (S- waves). P and S waves are also termed "preliminary tremors" because in most earthquakes they are felt first (Kanai, 1983).

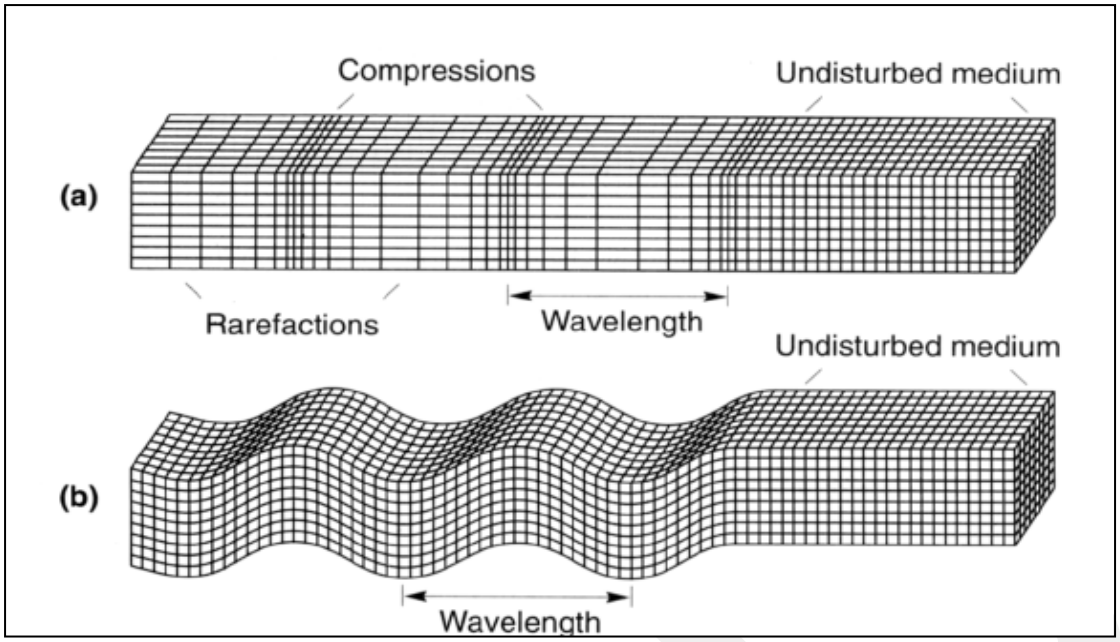


Figure 2.1 Travel path of body waves: (a) primary wave, (b) secondary wave (adapted from Bolt, 1993).

P-waves generate alternate push (or compression) and pull (or tension) along the rock, where the medium expands and contracts as the waves propagate. P-waves are seismic waves with relatively little damage potential. S-waves propagation causes vertical and horizontal side to side motion, which causes shear stresses in the rock over their paths (also defined as shear waves). Their propagation can be separated into two components, one of them horizontal (SH) and the other vertical (SV), both produce significant damage. P-waves travel faster, (1.5-8 kilometers per second), while S-wave are slower (50%-60% of the speed of P-waves), where the speed of body waves governed by the density and elastic properties of the rock and the path in which they pass through (Elnashai and Sarno, 2008).

Surface waves, in which propagate across the outer layers of the earth's crust, caused by constructive interference of body waves travelling parallel to the ground surface and various underlying boundaries. Surface waves classify into Love (L-waves) and Rayleigh(R-waves)(Figure 2.2). These waves stimulate large displacements and hence are also called "principal motion". They are most distinct at distances further away from the earthquake source. Surface waves were most eminent in shallow earthquake while body waves were equally well represented in earthquake at all depths. Because of their long period in earthquake activity, surface waves cause severe damage to structural systems (Kanai, 1983).

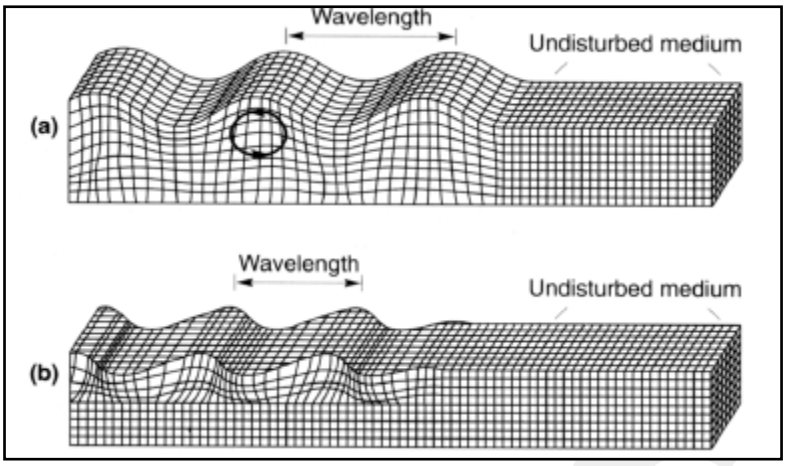


Figure 2.2Travel path of body waves: (a) Rayleigh wave, (b) Love wave (adapted from Bolt, 1993).

Body waves are reflected and refracted at interfaces between different layers of rock. When reflected and refracted occur, some of the energy transformed among layers. Immaterial whether the incident wave was P or S, the reflected and refracted waves, also describe as "multiple phase waves" each consists of P and S waves, such as PP, SS, PS and SP. Their name referred to the travel path and mode of propagation. For example, SP starts as S and then continues as P (Reiter, 1990). However, when P and S waves reach the ground surface, they are reflected back to move upwards and downwards, which lead to significant local amplification of the shaking at the surface. It was shown that seismic waves are affected by soil properties and local topography (Kramer, 1996).

Modern lifestyle was confirmed by a set of infrastructures that satisfy fundamental basic needs of the individuals and the communities. These infrastructures were depicted as lifelines and their intent cover: (i) Supplying energy (electric power, gas, petroleum), (ii) govern the water cycle (potable water treatment and supply, wastewater and storm water collection and treatment), (iii) civilian communication (telephone, television, internet), and (iv) transportation (roads, railroads, airports, and harbors) (Duke and Moran, 1975). Lifelines are playing a decisive role at health, safety, environment, economy, flux of goods, information and people, which contributing to the evolution and humans wellbeing in modern societies. During its activity, natural scourge, such as earthquakes, which represent a significant devastating potential. The direct effects of earthquakes are surface faulting and ground shaking, with secondary actions such as liquefaction, landslides, densification and tsunami (Chen and Scawthorn, 2003). The formal recognition of Lifeline

earthquake engineering came in 1970 with the establishment of American Society of Civil Engineering (ASCE) (ASCE/TCLEE, 1991).

The term pipe is defined herein as a closed circular cross section canal, made of any suitable material such as steel or plastic. The term pipeline refers to a long line of connected segments of pipe, with pumps, valves, control devices, and other equipment/facilities needed for operating the system. Their purpose was transporting a fluid, mixture of fluids, solids, fluid solid mixture. The term pipeline also includes a relatively large pipe spanning a long distance. Pipelines are least appreciated mode of transport, and poorly understood due to the fact that most of them underground and invisible, but they are safe, economical means of transportation and vitally significant to the economic wellbeing and security of most nations. To avoid any damage, they are usually buried in the ground by construction techniques such as conventional trenching and backfilling, or micro tunneling methods, thus their design depend on the flow requirements and the operating pressure. For buried pipelines, additional design requirements are needed such as the maximum and minimum cover depth, the trench geometry and backfill properties (Liu, 2003).

There are three fundamental technologies for estimating earthquake resistance of buried pipelines shown in Figure 2.3:

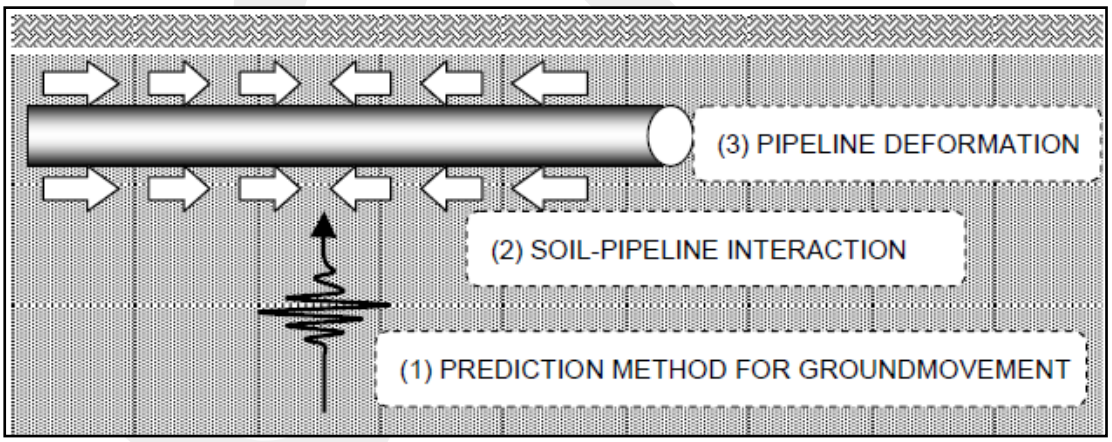


Figure 2.3 Earthquake resistances of buried pipelines

The resulting fracture in the earth's crust is called a fault. There are several parameter used to describe fault motion:

1- Azimuth (ϕ): The angle between the trace of the fault plane and the northerly direction $0 \le \phi \le 360^{\circ}$

2- Dip (δ) : The angle between the fault and the horizontal plane $0 \le \delta \le 90^{\circ}$.

3- Slip or rake (λ): The angle between the direction of relative displacement and the horizontal direction $-180 \le \lambda \le 180^{\circ}$

4- Relative displacement (Δu): The distance travelled by a point on either side of the fault plane.

5- Area (S): Surface area of the highly stressed region within the fault plane.

The orientation of fault motion was defined by the angles ϕ, δ and λ, (Figure 2.4). Several fault mechanism exist depending on how the plates move with respect to one another(Figure 2.5).

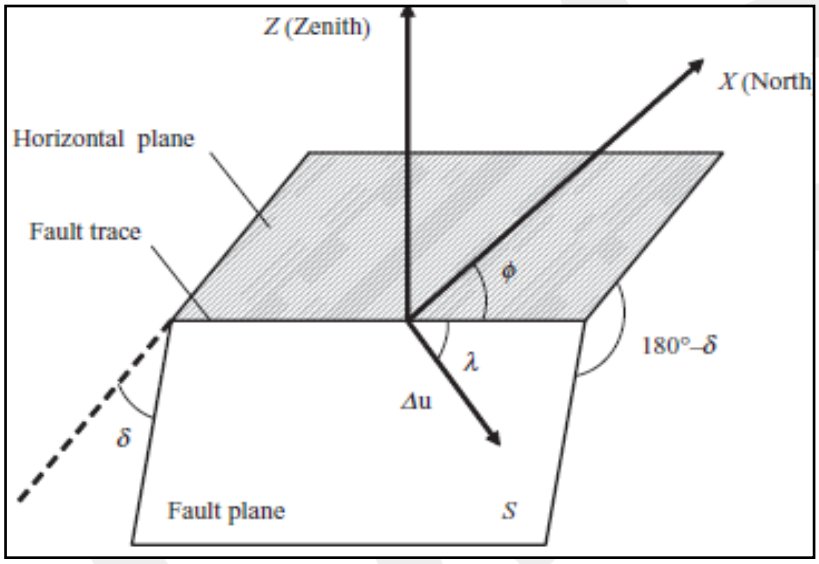


Figure 2.4Parametersof fault motion(Elnashai and Sarno, 2008)

When underground pipe subjected to explosion loads is filled with fluid, the internal pressure exerted on the internal wall of the underground pipe due to the carrying fluid opposes the followings: external pressure on the external surface of the underground pipe due explosion loadings vis-à-vis overburden of soil layer on the underground pipe, resultant self-weight of the filled underground pipe as well as the soil-pipe interaction. Therefore the resultant pressure and stress acting on the underground pipe due to accidental explosions would be reduced (Demeter, 1996).

In the soil-pipe interaction and response study of underground empty pipes due to accidental explosion loads, various parameters are included in the analysis such as Young's modulus of ground medium, Poisson's ratio of ground medium, density of ground medium, unit weight of ground medium, Young's modulus of pipes, Poisson's

ratio of pipes, density of pipes, unit weight of pipes, thickness of pipes, diameter of pipes, depth of burial of pipes, length of pipes, size (length, breadth and depth) of the ground medium, contacts between the ground media and pipe materials and volume change in pipes and explosive load parameters whether the explosions are surface accidental or underground accidental andother required observed parameters like displacement, pressure, stress, strain, etc(Olarewaju, 2012).

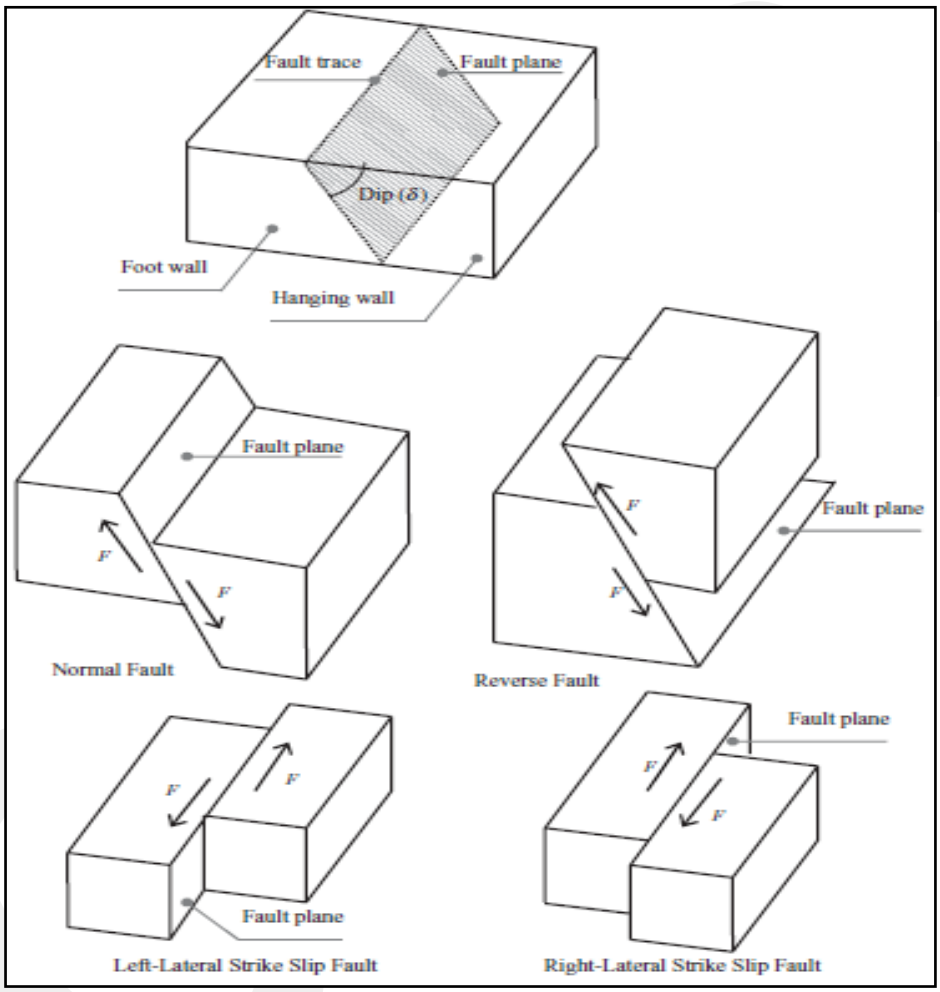


Figure 2.5Fundamental fault mechanisms(Elnashai and Sarno,2008)

The soil-pipe system is highly statically indeterminate. This means that the interface pressure between the soil and the pipe cannot be calculated by statics alone, as the stiffness properties of both soil and pipe must also be considered. Soil above the pipe zone should be capable of maintaining a specified soil density. Also, in order to eliminate pressure concentrations, the soil should be uniformly compacted around the pipe. Soil properties representing the backfill should be used to compute axial soil

spring forces. Other soil spring forces should generally be based on the native soil properties. Backfill soil properties are used to determine horizontal and upward vertical soil spring forces when the surrounding backfill soil is not influenced by soils outside the pipe trench. The expressions for maximum soil spring force are based on laboratory and field data on pipeline response.

Pipelines are used extensively in the offshore oil and gas industry for the transportation of product between production plants and the mainland, or between remote subsea well-heads and a centralized production facility. It is typical for the fluid within the pipe to be at a higher pressure and temperature than the ambient pressure and temperature of the surrounding water. The pipelines may be placed on the soil surface, but it is more usual that they are placed into trenches, which are subsequently backfilled.

Burial of the pipeline has two advantages:

(a) The pipeline becomes protected against damage by marine vessel activity, for example the laying of drag anchors or fishing equipment such as trawls boards.

(b) Heat loss along the length of the pipe is minimized. Temperature has a significant impact on the viscosity of the fluid and hence flow rate (the pipe is also insulated to mitigate this effect). To assess the integrity of the pipelines against such ground deformation, it is important to quantitatively evaluate the interaction between the pipelines and the surrounding soils.

Over the years, researchers have tried to understand the complex behavior of buried pipelines subjected to ground ruptures due to landslides, earthquakes, faults and uplift forces in shallow trenches. Seismic hazard of pipelines is well demonstrated and documented during past several earthquakes all over the world. Seismic hazard related to pipelines can be attributed to two hazards (O'Rourke et al., 1985): transient ground deformation (TGD) or permanent ground deformation (PGD) or a combination of the two (Eguchi, 2002). The damage due to (PGD) is intense for shorter spans. O'Rourke (1998) defines the distinction between these two effects: “PGD involves the irrecoverable movement of the ground that often is the result of ground failure, but also may result from modest levels of volumetric strain and shear distortion. TGD involves ground waves and soil strains associated with strong shaking. Although ground cracks and fissures may result from TGD, the magnitude of this residual deformation will normally be less than the maximum TGD during strong shaking.All of the collateral earthquake effects, plus faulting, can give rise to

permanent ground deformation. Pipelines are subjected to tension or compression depending on its orientation with ground deformation. Pipeline when subjected to compression can lead to both material and geometric failure, where as in case of tension only material failure occurs".Sakanoue (2008) predicted that the soil-pipeline interaction decreased when full-scale experiments were conducted. In case of dense backfill conditions, the force decreased gradually when the displacement between soil and pipe reached to such a degree that the maximum force was attained. Furthermore, in case of loose sand backfill, the decrease in the force was not spotted.

Permanent ground deformations (PGD) generally are critical when working with high-pressure pipelines, for which there is concern related to system supply and safety. During earthquakes PGD can be caused by surface faulting, seismic settlement, lateral spreading due to soil liquefaction, landslides, and the consolidation of relatively cohesion-less fills and loose natural deposits. All these sources of permanent deformation involve some distribution of the ground movement, and the differential ground movement results in bending and tension or compression depending on the relative orientation of the motion and the pipeline layout.

The performance of buried pipeline systems in areas subjected to ground deformations is an important engineering consideration, and there is a need for further research to advance the current fundamental understanding of this problem. Earthquakes in two different ways affect pipelines; wave propagation and permanent ground deformation. Wave propagation not only causes pipe breakages in large scale earthquakes but also is the main cause of pipe leakages in small scale earthquakes. Leakage is the main defect caused by wave propagation in water and wastewater pipelines. Leakages in different circumferences create exfiltration or infiltration. In potable water pipelines leakages are the main cause of water loss and water pollution whereas leakage in the wastewater pipelines is the main cause of wastewater overflow and soil pollution. Leakages may cause significant health and environmental pollution issues alongside considerable pressure on system capacity and cost (Zare and Wilkinson, 2010).

An understanding of pipeline response to vertical and lateral ground movements is essential in pipeline design. These movements may arise from offshore slope failures, earthquake-induced faulting, landslide and liquefaction, urban excavation and tunneling, and excessive ground settlement. Under such circumstances, loads are induced in a pipeline by relative motion between the pipeline and surrounding soil.

Various experimental and numerical studies have been published on the quantification of soil-buried pipeline interaction effects due to the static movement of a pipeline relative to its surrounding soil. Such movements may result from seismic fault rupture, slope instability, ground subsidence due to underground works, or liquefaction (Trautmannand O'Rourke, 1985).

The soil–pipeline interactions under lateral and upward movements in sand were investigated with particular attention to the peak forces exerted on a pipe embedded deeper than the conditions given in the ASCE Guideline. The review of various analytical solutions available for the peak forces on pipes or strip anchors shows that there are large differences in the computed peak dimensionless forces for deep embedment conditions. The analytical solutions for assessing the peak forces on pipeline showed that there were large uncertainty in the actual values for deep embedment condition, and limited information relating the changing of the peak force from shallow to deep embedment conditions was achieved. The analytical solutions offered a wide range of predicted peak dimensionless forces, especially as *H*/*D* (relative burial depth and pipe diameter) and ϕ_{peak} (peak friction angle) increase. The numerical analysis was also expanded to deeper embedment ratios of as large as 100 (Yimsiri et al., 2004).

di Prisco and Galli (2006) were performed some experimental and numerical results on the mechanical interaction between a buried pipe and the surrounding soil, to evaluate the stresses along pipes induced by slope instabilities, fault displacements and settlements due to liquefaction of sand strata. They considered several inclined loading directions, and coupling effect exists between vertical and horizontal loading directions, when experimental and numerical results were calculated. To describe the effect of the geometrical and geotechnical parameters, two different densities are taken into account, as well as several depths to diameter ratios. Numerical simulations proved that for axial direction no remarkable coupling was clear among the load components.

More studies by Olson (2009), O'Rourke (2010), Turner (2004) and Paulin et al. (1998) dealt with additional factors such as deep embedment conditions, the effect of sand water content, and the response under cyclic displacements.There are two fundamental approaches for estimating strains caused by seismic wave propagation:

*The ASCE approach(2001) , based on the assumption that a buried pipeline follows the ground motion

*The Japanese Gas Association (JGA) methodology (Japan Society of Civil Engineers 2000), based on direct measurements of ground strain at multiple locations during the 1994 Kobe earthquake in Japan.

Usually, in the area of lifeline earthquake engineering, the wave propagation hazard is characterized by the peak amplitude of ground motion parameters as well as the ground strain. In particular, ground strain, which is closely related to PGV, controls the behavior of buried pipelines, while facilities are more sensitive to
. Different ground motion parameters are therefore appropriate for different types of structure(O'Rourke and Liu, 1999).

Over the years there have been a number of approaches to the problem. Newmark and Hall(1975) were one of the first to publish simplified analysis methods for the fault crossing problem. They assumed the pipeline intersects a right lateral strike-slip fault at an angle such that the strike-slip fault results primarily in tensile strain in the pipe, and the pipe was strongly attached to the soil with no relative displacement between them.

Kennedy et al. (1975) extended the ideas of Newmark and Hall, and inserted some refinements for evaluating the maximum axial strain. The effects of lateral interaction and the influence of large axial strains on the pipe's bending stiffness were considered in their analysis. The results show that the pipe bending stiffness becomes very small (roughly 0.5% of the initial stiffness) when axial strain was beyond the yield strain. As a result, the bending strain in the pipe is relatively small in this approach.

In 1985 Wang and Yeh (1985) further modified this model by dividing pipe in to three regions depending on the curvature of pipeline. To evaluate pipeline strain, Ariman and Lee (1991) introduced the use of the finite element method in pipeline response analysis. Takada et al. (1998) proposed a model for the fault response analysis of the pipe. It is noted that two tendencies existed on present studies for investigations of the buried pipeline crossing an active fault, they are: (1) available simplified analytical and semi-empirical methods for the analysis of earthquake effects on the buried pipeline were only applicable to strike-slip and normal faults, and cannot be used for the case of reverse fault; (2) Seldom had experimental

researches done for the problem because of difficulties of implementation, especially for full-scale pipeline tests.

Takada et al. (2001) pointed out a simplified method to evaluate the maximum axial strain considering the deformation of the pipe cross-section by relating pipe bending angle and the maximum axial strain. Karamitros et al. (2007) introduced number of improvements in the method previously proposed by Wangand Yeh(1985). Considering most unfavorable combination of axial and bending would not necessarily take place at the end of high curvature portion, but might occur within the zone or closer to the fault crossing point. Kokavessis and Anagnostidis(2006) proposed a finite element method to simulate buried pipeline behavior under permanent ground-induced actions, using contact elements to describe the soil-pipe interaction.

Trifonov and Cherniy (2010) suggested an analytical model to analysis the nonlinear stress–strain of buried steel pipelines crossing active fault. They mentioned that a strike-slip and normal-slip fault crossings can be analyzed considering material and large displacement nonlinearities. Additionally, notable experimental works on the effects of strikes lip faults on buried high-density polyethylene (HDPE) pipelines have been reported in series of papers submitted by Ha et al. (2008) and Abdoun et al.(2009).

The finite element code PLAXIS was used to study the effects of several parameters such as dilatancy angle, density ratio of natural soil, diameter and burial depth of pipe, underground water table and thickness of the saturated soil layer on uplift of pipe. The results predicted that the dilatancy angle shows increasing nature with the decreasing of the uplift of pipe, and deeper pipe burying shows more effectiveness when the sand become denser. Furthermore larger diameter pipes undergo more uplift (Saeedzadeh and Hataf, 2011).

Vazouras et al. (2012) examined the behaviorof buried steel pipelines crossing active strike-slip faults. The vertical fault plane is crossed by the pipeline at an angle ranging between zero and 45 degrees, causing significant plastic deformation in the pipeline. They investigate the effects of the crossing angle for several soil and pipe parameters. The response under various conditions of soil cohesion, friction and stiffness parameters on the structural response of the pipe was examined. Permanent ground deformations (PGD) generally are critical when working with high-pressure pipelines, for which there is worry related to system supply and safety. During earthquakes,

PGD can be caused by surface faulting, seismic settlement, lateral spreading due to soil liquefaction and landslides.

In strike-slip fault, the predominant motion was horizontal which deforms a continuous pipe primarily in tension or compression, depending on the pipe-fault intersection angle. In the normal and reverse faults the predominant ground displacement was vertical. When the overhanging side of the fault moves downwards, the fault is normal and mostly causes tension and bending in horizontal pipe, while when it moves upwards, the fault is reverse and causes compression and bending in horizontal pipe. An oblique fault is a combination of strike-slip and normal or reverse fault (Shakib and Zia-Tohidi, 2004; Bolvardi and Bakhshi,2010; Tarinejad et al., 2011).

Study of the actual earthquakes effects on the buried pipelines networks was usually carried out using the damage functions or fragility curves that present the number of failures per unit area versus peak ground acceleration or velocity. In 1993, O'Rourke and Ayala (1993) presented the damage rate versus the peak ground velocity (PGV) for different kind of concrete pipe, cast iron, asbestos cement, etc based on the available information of four earthquakes in the United States and two earthquakes in Mexico.

In 2002, Chen et al. (2002) conducted a study about the damage to gas and water supply systems due to Chi-Chi, Taiwan, earthquake of 1999, and obtained the damage functions. They concluded that the best input parameter for determining the rate of damage to the gas pipes is peak ground acceleration. In 2006 Shih and Chang (2006) examined damages to the water pipelines in Taiwan due to Chi-Chi earthquake. They classified the causes of the failures in buried pipelines subjected to that earthquake as 48% associated with ground vibrating and wave propagation, and 52% due to PGDs, so the failure due to PGDs has a higher percentage. Damage functions present just an overall sense of the damage in a specific network and cannot offer any information about occurred failure levels, their location or reduction of the network's performance.

To have a better understanding of the damages, researchers have proposed using analytical and numerical methods for calculation of the pipelines response caused by PGDs. An important challenge in analysis and design of buried pipeline against the earthquake effects was how to model soil-pipeline interaction. Actually, these phenomena are considered in ASCE Technical Council on Lifeline Earthquake

Engineering (TCLEE) recommendations (ASCE, 1984), which proffering bilinear springs instead of soil environment.

Response analyses of buried pipelines were investigated by different methods. Many closed form solutions to the pipe-soil interaction problem based on “beam on elastic foundation” was proposed. Some of these studies were accomplished by using analytical methods. Since the response of the pipe to faulting depends on several factors, to simplify the analysis process, some assumptions were used by analytical methods which consequently led to low accuracy of the estimated responses. Some other researchers have also studied these effects via numerical methods. In these studies, some parameters such as soil-pipe interaction which considerably influenced the responses were not taken into account (Shakib and Zia-Tohidi, 2004).

Among the major earthquakes that shook Taiwan, the Ji-Ji earthquake (or called Chi-Chi earthquake) that took place on September 21, 1999 was the most drastic one in the past 100 years. Because of the shallow focal depth, most of the energy released by the earthquake was transferred to the surface and caused widespread damage. Necessary lifelines such as bridges and highway systems, telecommunication systems, water distribution systems, and natural gas supply systems were all hardly damaged. A GIS database and analysis procedures were established to study the damage patterns of natural gas and water pipelines in the Ji-Ji earthquake (Chen et al., 2002). The resulting damage was analyzed considering the corresponding pipeline material and diameters. The repair rates (RR) (number of repairs per km) were calculated, and the correlation between RR and seismic parameters such as the peak ground acceleration, peak ground velocity, and spectrum intensity was also analyzed. Operational vibrations were often the cause of pipe damage. Material failure increases with vibration velocity. The amplitude and frequency of the vibration were the determinant factors causing pipe damage. Vasilyev and Fromzel (2003) performed an analytical study about piping flow-induced vibration. Pipeline damage caused by wave propagation for relatively flexible pipe materials was found to be somewhat less than damage of relatively brittle materials.

Tromans(2004) presented of a post-earthquake investigation into water pipeline damage in the town of Düzce, Turkey, caused by the Kocaeli and Düzce earthquakes in 1999. This work focuses on the influences of the transient ground strains caused by the passage of seismic waves on the behavior of buried water supply pipelines subject to earthquake effects. To identify earthquake-related pipe breaks, temporal variations

in pipeline repair statistics before and after the earthquakes were analyzed. A reasonable correlation was found between pipeline damage and building damage. As a result of the Kocaeli earthquake, the locative variation in pipeline damage rates was used to deduce the locative distribution of peak ground velocity based on the pipeline fragility relationship. The peak ground velocity estimates are beneficial for prognostic of earthquake-induced pipeline damage rates. Tromans predicted the amplitude of ground motion reduced with distance from the source of seismic energy release. This is due to the spread of the wave front as it moves away from the source, and an elastic attenuation, which is caused by material damping. In the instant locality of the fault rupture, body waves will dominate the motion while ground motion at large distances to the source is generally dominated by surface waves because of the geometric attenuation is different for the two types of waves. Assuming that the earthquake rupture zone represented as a point source, the amplitude of body waves decreases in proportion to $1/R$ (R is the distance from the rupture zone), while the amplitude of surface waves decreases in proportion to $1/\sqrt{R}$.

Sakanoue and Yoshizaki(2004) pointed out that Earthquake-induced Permanent Ground Deformation which occurs as surface fault, liquefaction induced soil movements, and landslides, can cause serious damage to buried pipelines. For the pipelines constructed, the pipe stiffness should be increased with larger diameter, thickness or strength, or the soil-pipe interaction should be reduced. Lightweight backfill had significant effect for increasing the earthquake-resistance of buried pipelines. Sakanoue and Yoshizaki use both EPS blocks (Expanded Poly Styrene) and EGW(Expanded Glass Waste) for backfill, the lateral forces on the pipes could be reduced to approximately half that with normal backfill. Experimental results showed that lightweight backfills had 56% and 34% reduction, respectively, on the soil-pipe interaction in the case that the cover-depth was 0.9m.

Karimian(2006) investigated soil-pipe interaction of relatively large diameter steel pipelines by a full-scale physical modeling facility. The results referred to the fact that in hard soil, pipe buried in sand in a convenient wide trench with sufficient horizontal distance from the trench boundary may efficiently reduce the lateral soil resistance. The relative stiffness of the soil in comparison to the backfill and the capability of the backfill to move as a coherent block become critical in reducing the lateral soil loads. The increase in normal soil stress on the pipe surface due to constrained dilation of

sand in the shear zone was found to be the key reason for these high soil loads.Scawthorn et al. (2006) showed that the instant effect of the earthquake on wastewater pipelines represented around 12% of the total real damage. They also detected that UPVC and steel pipes suffered more damage compared with ductile iron and cast iron pipes. The authors mentioned that failure in UPVC pipes was in the joints due to pull out and body breakage whereas in ductile iron pipes, the damage was due to a seismic joint type failure. The authors also declared that joint failure in steel pipes occurred in their threaded joints.

Toprak and Taskin (2007) estimated pipeline damage for each damage relationship and earthquake scenario. The results show that the variation in ductile pipeline damage assessment by various relationships was higher than the variation in brittle pipeline damage assessment for a particular scenario earthquake. Pineda-Porras and Ordaz (2007) proposed a seismic intensity parameter using peak ground velocity (PGV) and peak ground acceleration (PGA) to estimate damage in buried pipelines due to seismic wave propagation.

According to Newmark and Hall's theoretical model, Guha and Berrones (2008) illustrated the performance of one of the high pressure gas pipeline in the state of Gujarat(India), under the fault movement and soil liquefaction. Based on the result from the study some recommendations were made to minimize the effect of earthquake on the existing pipeline. So the stiffness of the pipeline depends on various physical parameters of the pipe such as diameter, thickness and material property.

The performance evaluation of buried pipelines in areas prone to ground movement is a key consideration in natural gas distribution systems. In modeling the response to axial loading of flexible polyethylene pipes (PE), in addition to the nonlinear stress-strain response of the pipe, it is important to consider the change in normal stresses on the pipe due to: (i) Soil dilation in the annular shear zone, (ii) frictional degradation aspects at large displacements, and (iii) the change in pipe diameter. Wijewickreme et al. (2008) developed an analytical procedure to incorporate the above factors and to predict the soil loads during axial pull-out, axial strain, and mobilized frictional lengths.

Lee et al. (2009) have presented an analysis considering the soil - pipeline interaction, which has been developed for 2D and 3D nonlinear analyses of steel, reinforced concrete, and composite structures by considering both the material inelasticity and geometric nonlinearity. A Korean buried gas pipeline was for the

comparative earthquake time-history analysis. For this purpose, various parameters such as the type of buried gas pipeline, end-restraint conditions, soil characteristics, single and multiple earthquake input ground motions, and burial depths were selected. Younan (2012) presented a method for simulating seismic wave propagation motions along buried pipelines in earthquake area. This wave propagation modeled using a single input motion propagated along the pipeline axis with a speed arbitrarily chosen from either shear or surface wave speed ranges. Results confirmed that the potential impact of seismic wave propagation on buried steel oil/gas pipelines was small.

Usually, the damage rates in buried pipes due to an earthquake are estimated based on empirical vulnerability curves. However, these curves only account for pipe characteristics such as pipe material and joint type. An original methodology developed by Sousa et al. (2012) aims at accounting for the effect of the pipe structural condition in the estimation of the damage rates. As an application, the results estimated the failure rates of sewers of a wastewater subsystem of Lisbon city for different seismic scenarios. Sousa predicted that the main cause for the differences between the various empirical sensibility curves that have been proposed is the quality of construction, maintenance strategies, nearby structures, soil conditions or water table level.

Behaviors of buried pipelines located in nonlinear cemented slopes and excited by dynamic loading of earthquakes in North Tehran area, was analyzed by ABAQUS program. The influence of two parameters on slope deformation pattern and buried pipe strains were conducted numerically. These two parameters were relative geometry of pipe in the slope and boundary conditions of edge planes. It was deduced that placing pipe in the slope toe, produces lower strains. As a result, it was suggested that the pipe passage be in lower parts of the slope for more safe conditions(Jafarzadeh, 2012).

Recently, finite element models of the pipeline and soil are established using the package ABAQUS to carry out stress-strain analysis of buried pipeline caused by static and seismic loads(El- Centro earthquake) and also effect of buried on stress and displacement of pipe line. The results show displacement in the upper of pipeline more than bottom of pipeline and also increasing in depth of buried pipe line decrease the displacement (Alamatian, 2013).

Jeon(2013) performed an analysis to examine the confidence level when RR (Repair Rate of pipeline) recommended in HAZUS (Hazard in US) was directly used for the

damage estimation of pipelines in Korea due to earthquake loading. The numerical analyses using ABAQUS program to compare stresses and strains mobilized in buried pipelines constructed by the design criteria and construction specifications of both Korea and the US. The results show that differences in the stress and strain rates are less than 10 %. This implies that RR in HAZUS used for earthquake damage estimation of pipelines with a 90% confidence level in Korea.

Considering the interaction between the pipeline and soil around, 3D dimensional finite element model was developed for response analysis of buried pipelines under faults caused by permanent ground deformation(Hongjing et al., 2008). The results indicate that seismic response of buried pipeline increases with the increase of the soil displacement. Shallow embedment can improve pipe performance.

Saberi et al. (2011) considered a 3D finite element model for response analysis of buried pipe in bent area under seismic wave propagation. The effects of soil properties, bend angles, pipe diameter to thickness ratio, and embedment ratio on response characteristics (e.g. the maximum axial strain in bend and pipe-soil relative displacement) were analyzed. Results indicated increasing the surrounding soil stiffness raises the strain response of pipe in bent region. The majority of maximum axial strain values occurred in vicinity of 135° elbow angle.

Assuming horizontal pipeline, the response of buried steel pipelines crossing an active normal fault was investigated using various capabilities of finite element simulation tools. Advanced nonlinear numerical simulations were used to treat the complexity of the physical problem associated with the surrounding soil and the pertinent pipeline-soil interaction(Gantes and Melissianos, 2013).

Shih and Chang (2006) performed a seismic analysis of underground polyvinyl chloride (PVC) pipelines and demonstrated that there was no significant difference between the analysis results and the empirical equation used by Hazard, i.e., earthquake loss estimation software developed by the Federal Emergency Management Agency (FEMA).

Using the CRISIS 2007 software, Hesari and Zarbakht, (2012)analyzed the seismic hazard and risk assessment of the existing route of the 3rd Azerbaijan natural gas buried pipeline in Iran. The major seismic sources along the pipeline were identified and the geometrical parameters as well as the seismicity rates were determined. The seismic hazard assessment of the ground vibrations along thepipeline have been performed in the framework of the Probabilistic Seismic Hazard Analysis.

They employed the HAZUS methodology for loss estimation. Accordingly, fragility curves and repair rates were calculated for the considered pipeline.

For the seismic design of a pipeline crossing the fault, the fault displacement is usually estimated with the empirical relationship between magnitude and fault displacement. It should be noticed this fault displacement may under-estimate the fault displacement imposed on the buried pipeline. Based on those strong ground motion records near the causative faults, the maximum displacement of fault movement (MFD) is larger than permanent fault displacement (PFD) (Liu and Jia, 2012).

The basic function of a gas system was to transport gas from sources to costumers. A gas distribution system was basically formed by pipelines, reduction stations, valves and demand nodes. Those systems are essentially located underground. As consequences gas networks are subjected to both transient ground deformation due to seismic waves, which was felt over a wide geographical area, and ground failure due to geotechnical hazards such as liquefaction and landslide, which determine localized ground failure. Esposito (2011) tried to understand the effect of the earthquake (2009 L'Aquila (central Italy)) on the gas distribution system, and to obtain the repair rate (RR) as a function of the level of ground shaking experienced, expressed in terms of peak ground velocity (PGV) (parameter for characterization of ground motion amplitude). Esposito determined methodologies for the probabilistic seismic risk analysis of gas distribution networks and to apply these methods to a real gas system. The process make use of probabilistic seismic hazard analysis, empirical relations to estimate pipeline response, fragility curves for the evaluation of reduction cabins vulnerability, performance indicators to characterize the functionality of the gas network.

Many gas systems are composed by pipelines manufactured by steel, polyethylene, which have significantly different mechanical properties and perform differently under seismic load. Therefore properties as material, joint type, design procedures, degree of deterioration may influence performance of lifeline systems. Damage to one lifeline system may affect other systems. For example loss of electricity can affect the flow pressure in the gas system or water system, a break in a water trunk line along a main street can block the traffic. A gas distribution system is essentially composed by pipelines, reduction stations, valves and demand nodes,where those systems are essentially located underground. Both types of waves

are of interest when considering the response of buried pipelines to seismic ground shaking. S-waves are normally considered more hazardous to buried pipelines as they carry more energy than P-waves while, in the case of surface waves, R-waves are the most important, inducing axial strains in buried pipelines of much more significance than the bending strains induced by L-waves(O'Rourke and Liu, 1999).

Liu et al. (2010) proposed a 3D parametric finite element model to predict the limit load-bearing of buried natural gas steel pipeline under deflection loads. According to the numerical results, the pipeline show stronger deflection load – bearing ability under the sandy soil environment than under the viscous soil environment. Besides, effects of the soil types and model sizes on the maximum deflection displacement of pipeline were further explored.

In 2005 Gou and Stolle (2005) surveyed the effects of scaling factor, for determining of interaction forces between pipe and soil in laboratory tests. They showed that the effect of pipe diameter and burial depth should be considered for evaluating of maximum interaction force and presented some correction coefficients based on the scaling factor for different burial depths.

Finite element program ABAQUS was employed to simulate the mechanical behavior of buried steel pipe lines crossing an active strike-slip fault (Vazouras et al., 2010).The fault is normal to the pipeline direction and moves in the horizontal direction, causing stress and deformation in the pipeline, which allows for the investigation of several soil and pipe parameters on pipeline deformation and strength. The influences of shear soil strength, soil stiffness, horizontal fault displacement, width of the fault slip zone were investigated. The results depicted the critical fault displacement, and the corresponding critical strain versus the pipe diameter-to-thickness ratio.

With finite element method, Vazouras et al. (2011) examined the structural response of buried butt-welded steel pipelines, crossing active strike-slip tectonic faults, which are vertical and perpendicular to the pipeline axis. They considered for large strains and displacements, nonlinear material behavior, as well as for contact and friction on the soil-pipe interface. Additionally, steel pipelines of various diameter-to-thickness ratios, and typical steel material for pipeline applications were used. The effect of various soil and pipeline parameters on the mechanical response of the pipeline were investigated, with emphasis on pipe wall "kinking" or fracture. The effects of cohesive and non-cohesive soils were also investigated. The authors

examined the influence of internal pressure on the structural response of the steel pipeline. Numerically, the results determined the fault displacement at which the pipeline failure occurs, which are presented in a graphical form showing the critical fault displacement, the corresponding critical strain versus the pipe diameter-to-thickness ratio, and can be used for efficient pipeline design against significant ground-induced deformations due to active strike-slip faults.

Using the finite element program ABAQUS, the response of steel pipelines under strike-slip fault movement was studied numerically (Vazouras et al., 2011). The pipeline was considered to cross the vertical fault plane at angles ranging between zero and 45 degrees. The main goal of the study was the prediction of the influences of the crossing angle for several soil and pipe parameters. In a rigorous manner, the study was modeled the nonlinear material behavior of the steel pipe and the surrounding soil, the interaction between the soil and the pipe, as well as the distortion of the pipeline cross-section and the significant deformation of the surrounding soil.

To simulate pipe-soil nonlinear interaction, two ends of each element are connected to axial, lateral and vertical soil springs modeled as elastic perfectly-plastic spring elements. Considering the nonlinearity of soil-pipeline interaction, an improved analytical methodology of submarine buried steel pipelines surrounded by homogeneous site soils across active strike-slip faults is derived(Li et al., 2012a).

Lin et al. (2012) investigated the responses of buried pipelines under large fault movements using numerical models and small-scale experiments. The numerical models were built up by ABAQUS commercial software considering different types of soil and pipelines. Lin et al. predicted that the size effect is an important issue for small-scale experiments, like the size of pipelines, soil pressures, boundary conditions set up at the two ends, which might affect the behavior of pipelines. The pipeline is assumed horizontal and normal to fault plane, which can be completed for the investigation of several soil and pipe parameters on pipeline deformation and strength.

According to Li et al. (2012b)high-density polyethylene (HDPE) pipes appear good performance to resist the ground deformation; the severe responses generally locate in the vicinity of the fault zone, and decrease gradually with the position of pipe section far away from the fault area. Additionally, some of the pipeline parameters , such as diameter, thickness of the wall, the angle of pipeline crossing fault, and loading levels, have important influences on the responses of the pipeline under the reverse fault movement. The study based on an in-situ experiment on full-

scale HDPE pipelines with a butt fusion welding connector and water pressure inside subject to the action of an artificial reverse fault.

Resonance phenomenon may occur when the frequency of the hydrodynamic forces induced by a vortex shedding approach the natural frequency of the pipelines. A resonating span can experience significant deflections and associated stresses. Therefore, studying the hydrodynamic around the pipeline and calculating the natural frequency of the marine pipeline in free spans accurately are very important.

Free spans or suspended spans normally occur in subsea pipelines due to the irregularity of seabed and by scouring phenomena around the installed non-buried pipeline. This kind of vibration may cause fatigue damage to the pipeline. In order to study the hydrodynamic around the pipeline, calculating the natural frequency of the marine pipeline in free spans accurately is very important. Several parameters such as pipeline profile, axial forces, seabed soil and boundary conditions influence the natural frequency of the pipeline. The soil characteristic is an important factor which should be considered in determining the natural frequency of pipeline in free span. Different design guidelines, (e.g. DNV(1998), ABS (2001)), proposed a simple formulation to calculate the first natural frequency based on the pipelines specifications. Xu et al. (1999) applied the modal analysis to incorporate the real seabed condition to assess pipelines fatigue and natural frequency.

Bruschi et al. (1996) discussed the geotechnical hazard for a pipeline routed across steep slopes and irregular terrains affected by earthquakes. The integrity of both natural and artificial load-bearing supports is assessed. The response of the offshore pipeline to direct excitation from soil or through discontinuous are commented on. Some applications are given in order to point out topical aspects and major design issues for currently operating offshore pipelines crossing seismic active seabed.

Choi (2001) studied the effect of axial forces on free spanning of offshore pipelines. The results indicated that the axial force has a significant influence on the first natural frequency of the pipe. DNV (2006) guidelines proposed a formulation to calculate the first natural frequency based on the pipelines specifications, axial forces and static deflection.

Model tests are carried out to analyze seismic response of free spanning submarine pipelines. Hydrodynamic force model was presented for evaluation ofdynamic response of free spanning submarine pipelines subjected to three dimensional earthquakes. Three dimensional finite element model was conducted to

simulate the experimental conditions, which were compared with experimental results. The comparison studies show that developed models could satisfactorily predict dynamic response on the free spanning submarine pipeline under earthquakes (Li et al., 2008).

Submarine pipelines are usually laid unburied. Free spanning may be caused in the line by seabed unevenness, topology changes, scouring, or sand waves. In seismically active areas, the free spanning are prone to severe ground excitations. In the frame of numerical finite-element model, Zeinoddini et al.(2012) discussed the seismic performance of the submarine pipeline free spanning, and the water/pipeline interaction during the event is its focal point, considering both random earthquake and harmonic excitations. Furthermore the effects from type, frequency, intensity, and direction of excitation and the free-span length on the pipeline response have been investigated.

Geotechnical applications in offshore engineering often involve large displacements of structural elements, such as a foundation or pipeline, relative to the seabed sediments. Quantification of soil-structure interaction must therefore consider geometric non-linearity due to changes in the surface profile, or distortion of initially horizontal soil layers, in addition to the material non-linearity that is an intrinsic aspect of soil behavior. Randolph et al. (2008) applied a simple and powerful approach to a variety of offshore foundation and anchoring problems, including surface penetration of pipelines, deep penetrometer response. The effectof non-homogeneous soil strength including soil layering, have also been investigated. Randolph et al. found that the soil heave to either side of the pipe during penetration, leading to small increase in resistance.

Numerical method was used to solve the finite element model (FEM),which was established to obtain the nonlinear dynamic response model of pipeline under seismic loads(Feng et al., 2012). A field pipeline was taken as an example, where the influences of seismic intensity, spring stiffness, resistance ratio, and site type, etc., on the response law, stress, deformation, and acceleration of pipeline were investigated. The results show that the seismic response of pipelines increases with increasing earthquake intensity, damping ratio and stiffness coefficient(when the damping ratio keeps stationary). Whereas the displacement decreases gradually and basically has an inverse proportion with stiffness coefficient. The displacement and the stress

gradually decrease under the same stiffness coefficient. The results indicate that the soft soil could reduce the damage of pipeline in earthquake.

Mehdi et al. (2012) attempted numerically using(ABAQUS software) to estimate the natural frequency of free spanning pipelines and influence of soil characteristic in support of pipeline in free span. The results indicated that the pipeline frequency increases with shortening of pipeline length and fixity against rotation at the ends of the pipe. Additionally, the natural frequency in the pipeline increased when soil stiffness increased. The natural frequency would not depend on the boundary conditions of the pipeline.

The numerical code ABAQUS is employed to simulate the interaction effects for a pipeline installed in a trench backfilled with loosely deposited dry sand, focusing on shallow buried pipelines subjected to lateral displacements relative to the surrounding soil. The numerical methodology is validated against the literature experimental measurements, for pipelines buried in uniform dry loose and medium sand (Kouretzis et al., 2013).

2.2 Analysisprogram PLAXIS-2D

PLAXIS is Dutch company developing software, with the same name, that is using the finite element method (FEM) for modeling of geotechnical problems. The software portfolio includes two and three dimensional simulation of soil and soil-structure interaction. PLAXIS governs three main theories in its FEM-code; deformation, groundwater flow and consolidation. Additional, there is an extension-program for dynamic calculations. In this thesis the versions; “PLAXIS-2D Version 8.2” has been used and only static and dynamic calculation are covered.

In modeling with PLAXIS, the general procedure is to define the geometry with elements and corresponding materials, define loads and boundary conditions, create a FEM-mesh, define the initial condition, andperformed the FEM-calculations. For each new project to be analyzed, it is important to create the geometry model first. A geometry model is a 2D representation of a real three-dimensioned problem and consists of point's lines and clusters. It should include a representative division of the subsoil into distinct soil layers, structural objects, construction stages and loading. The model must be sufficiently large so that the boundaries do not influence the

results of the problem to be studied[PLAXIS-2D, 2011].There are three types of components in a geometry model:

1. Points: Points determines from the start and the end of lines. Points can also be used for the positioning of anchors, point forces, point fixities and for local refinements of the finite element

2. Lines: Lines are used to define the physical boundaries of the geometry, the model boundaries and discontinuities in the geometry such as walls or shells, separation of distinct soil layers or construction stage. A line can have several functions or properties.

3. Clusters:Clusters are areas that are fully enclosed by lines. PLAXIS automatically recognizes cluster based on the input geometry lines. Within a cluster, the soil properties are homogeneous. Hence, clusters can be regarded as parts of soil layers.

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CHAPTER 3

REVISION STUDY

3.1 Preface

There are several lifeline utilities in urban and non-urban areas that could suffer severe damages from earthquakes. Oil and gas transferring pipelines, water supply and sewage system and traffic tunnels are examples of these lifelines that their failure could exacerbate the damages of earthquakes. Since the occurrence of the San Francisco earthquake, in 1906, there are several publications and reports that discuss the severe damages caused the incident of high-intensity earthquakes. Wide damages were produced due to the failure of water pipeline systems, which obstructed the firefighting trials, where there are much more damage observed in many buried pipelines of cities located in seismic areas. The buried pipelines can be affected by the surrounding soil, where to maintain their function as lifelines supporting people's lives, and at least prevent disasters caused by leakage of the contents, it is important to consider the effect of earthquakes in the design and maintenance of such lifelines.

These earthquake damages are caused by either transient ground deformation (TGD) or permanent ground deformation (PGD), or both. The first one occurs as a result of wave propagation or ground shaking effects while the second surface faults, liquefaction-induced soil movements and landslides (Trautmannand O'Rourke, 1985). The values of these factors determine the predominant influence for each of them. The seismic waves mainly damages weakened pipelines either by corrosion or at welds of poor quality. The combined effect of both seismic wave propagation and permanent ground deformation phenomena in pipeline damage estimation is a subject still complex to address, especially if the objective is to estimate damage due to future earthquakes (Karamitros et al., 2007).

It was reported that buried pipelines such as gas and water pipelines were damaged by PGD in the 1906 San Francisco, the 1964 Niigata, the 1971 San Fernando, the 1979 Imperial Valley, the 1983 Nihonkai-chubu, the 1989 Loma Prieta, the 1994 Northridge, the 1995 Hyogoken-nanbu earthquakes, the 1999 Kocaeliearthquake in Turkey, the 1999 Chi-Chi earthquake in Taiwan, the 2008 great Wenchuan, China earthquake and the 2011 Tōhoku earthquakeand tsunami in Japan. It is worthy mentioned that the underground structures are totally buried structures, slightly buried structures and in parallel to ground surface. These can be any structures of diver's shapes, shelters, basement, silos, storage facilities, shafts, tunnels, pipes, etc. These structures are constructed by different materials such as steel, plain and reinforced concrete, timber, clay, fiber glass, etc. Underground pipes are used for various services(Olarewaju et al., 2010).

The design of buried pipelines was usually based on the beam hypothesis loaded by the surrounding soil, where the interaction forces are mainly depending on the geometry, inclination of the slope, pipeline path and position of the pipeline with respect to the landslide. Moreover many important parameters should be considered in the design of pipeline, such as external load, thermal stress, earthquake and dynamic load, truckload and etc. The buried pipes were laid in trenches and backfilled with various materials. So it is important to estimate the stress and strain behavior of the buried pipe in the trench condition. This behavior may be significantly influenced by the interface friction angle between backfill and walls, properties of pipe, backfill material and surface loading. As a matter of fact it is acknowledged that underground structures suffer less damage from earthquakes than structures on the ground surface (Bardet and Davis, 1997).

First researches on the buried pipelines were performed in 1930 by the classic method of Marston (1930) and then other numerical, analytical and experimental researches continue this study with attention to science of their time, where the methods of beam on the elastic bed model (Winkler model), cable modeletc were considered. Marston's equation for positive projecting conduits (buried in fill), which is a vertical slip surface model, was used by the American Water Work Association for designing pipelines supported by piles or piers (Choobbasti et al.,2009). The seismic parameters related to damage in buried pipelines are Mercalli modified intensity (MMI), peak ground acceleration (PGA), peak ground velocity (PGV), maximum

ground strain, and the novel composite parameter PGV^2/PGA (Pineda and Ordaz, 2010).

Since the mid-70s, there have been advances in the development of models to better grasp how earthquakes affect buried pipelines. The work of Newmark and Hall (1975) was among first attempts to predict the pipeline mechanical response under afault displacement using a simplified analytical model. This model consists of a long cable with small displacements, and relates the soil slip friction on the pipe directly to the earth static pressure. This was further developed by Kennedy et al. (1975). They imposed the pipeline as a cable, neglecting the pipeline bending stiffness. This restricts the use of the model to the case of large fault movements in projection to the axial pipe direction. Kennedy and Kincaid (1983) suggested that the friction between the pipe and the surrounding soil was non-uniform. To describe the soil-pipe interaction, Kokavessis and Anagnostidis (2006) proposed a Finite Element Method to simulate buried pipeline behavior under permanent ground-induced actions. Lee et al. (2009) studied the seismic behavior of a buried gas pipeline under earthquake excitations. Wilson (2012) investigated the failure analysis of a buried pipeline transporting gas.

A geogrid is a particular dimensions segment with sufficient size bars forming rectangular cell. The geogrid geometry efficaciously increases the angle of internal friction and cohesion and to improve the load bearing capabilities and distribute the loaded area. Geogrids, made of polymeric materials, have been used for many applications, such as walls, slopes, roads, building foundations, pipelines etc. Previously, geogrids were manufactured with a rectangular or square shape apertures, while recently with a triangular aperture shape have been introduced. The new geogrids are manufactured with ribs oriented in three equilateral directions and expected to have a more stable grid structure, which can provide more uniform resistance in all directions(Dong et al., 2011). Geogrids are usually made from polypropylene (PP), high density polyethylene (HDPE) and polyester (PET).

Mohri et al. (2000) conducted the laboratory test for buried pipe(1100mm diameter) using fiberglass reinforced plastic mortar pipe. Five cases of backfilling methods were used. Results show that the method using geogrid with gravel as backfill material increased the uplift resistance of buried pipes. But the tests did not investigate the effectiveness of lateral force, such as the thrust force. Three backfills soils (sandy, clayey, and pure sand) in combination with four different geosynthetics (one

geotextile and three geogrids) were investigated at various loading conditions. The results reveal that the stress-deformation behavior of the geotextile and geogrid interfaces with sandy and clayey backfills can be defined as hyperbolic. For the pure sand-geogrid interfaces, the relationship is followed by displacement hardening and softening behavior (Hossain et al., 2012).

According to Jewell et al. (1985) the soil-geogrids interaction could be identified into three main mechanisms: (1) soil shearing on plane surfaces of the grids, (2) soil bearing on lateral surfaces of the grids, and (3) soil shearing over soils through the apertures of the grids. The first two are the skin friction and passive pressure resistance of the soil- geogrid contact area, while the third is the interfacial shear on the surface of a rupture zone created during shearing. The ratio of size of soil particles to the grid apertures has significant influence on the size of the rupture zone. As this ratiodecreases, the size of the rupture zone increases. Therefore, the used geogridwas dependent on the grain size distribution of the soil that will be placed around it.

Mohri et al. (2001) executed a series of tests for buried pipelines(1100-mm diameter) to investigate the efficiency of geogrids in promoting the float up resistance of buried pipes due to buoyancy, where a geogrid and gravel backfill material employed to increase the float up resistance of buried pipes. In case of shallow depths of soil cover, the geogrid reinforcement can lead to a decrease in cover to extremely shallow depth. The geogrid reinforced tests show that the forces preventing pipe floatation are contributed to by the dead weight of the overlying soil as well as bending mode deformation of the reinforced layers surrounding the pipe.

Tafreshi andKhala(2008) conducted a laboratory tests on high-density polyethylene (HDPE) pipes buried in reinforced sand subjected to repeated loads to simulate the vehicle loads. Settlement of the soil surface and the radial deformations of the pipe were measured throughout the test. These variables examined in the testing program include density of the sand, number of reinforced layers and embedment depth of the pipe. The results show that using the geogrid reinforcement reduces the percent vertical diameter change and settlement of soil surface up to 56% and 65% respectively, which increase the safety of embedded pipes.

In the frame of the numerical softwareFLAC the responses of geogrids with rectangular and triangular apertures was investigated when subjected to uniaxial tensile load at different directions relative to the orientations of ribs in air. The numerical results demonstrated the stress–strain behavior of the geogrids, which were

different at different loading directions relative to the orientations of ribs. The influences of aperture shape, elastic modulus and cross-section area of the ribs on the tensile stiffness of the geogrid were also calculated. The geogrid with triangular apertures had more uniform tensile stiffness and strength distributions than that with rectangular apertures. An increase of the elastic modulus and cross-section area of thegeogrid ribs could increase the stiffness of the geogrid with triangular apertures (Donget al., 2011).

Numerically, Tran et al. (2013) investigated soil-geogrid interaction, where this behavior depends on many factors such as the properties of the geogrid material, the backfill soil, and the interface condition. Modeling this interaction depends on the geometry of geogrid, which was a defying numerical problem that requires the nature of the soil and the different modes of resistance that contribute to the pullout capacity of the geogrid layer. A comparative study with experimental data was performed to validate the numerical calculation results.

Rajkumar and Ilamparuthi (2008) conducted numerical and laboratory tests for flexible PVC pipes buried in sand bed and subjected to surface pressures, with and without NetlonGeogrid reinforcement. The test results reveal that the increase in cover height offered better protection to the buried flexible PVC pipes, but this can be reduced with the presence of geogrid reinforcement. Also the existence of geogrid effectively reduced the load coming over the pipe. Rajkumar and Ilamparuthi find that the 2D Finite element analysis could not sufficiently model the observed behavior of the soil-pipe interaction and hence needs to be treated with caution. Moreover, in the presence and absence of geogrid reinforcement, they measure the variation of the vertical crown deflection due to the applied surface pressure, with a noticeable difference between the numerical and experimental results for both cases.

This study has discussed numerically the behavior of flexible PVC pipes buried in dense sand bed subjected to surface pressures with and without geogrid reinforcement, that was described by Rajkumar and Ilamparuthi (2008).

3.2 Material properties and modeling

The finite difference analysis package, PLAXIS 2D is used in the numerical analyses. The software could treat the behavior of PVC pipes in dense sand under

surface pressure with and without NetlonGeogrid reinforcement. The results compare with experimental and finite element results of Rajkumar and IIamparuthi(2008).

The model has been analyzed as a plain strain condition with 15-node elements. Mohr-Columb plasticity model has beenconsidering to solid element which symbolized soil around the pipe. To specify the soil model in numerical analyses with PLAXIS -2D software, many material parameters have been considered such as: Dry unit weight of the soil, Young's modulus, Poisson 's ratio, Constant Cohesion, Angle of internal friction and Dilation angle, where the soil dimensions are (1200mm × 600mm). The index and engineering properties of the soil are summarized in Table 3.1.

Table 3.1Properties of materials used in the numerical analysis

Properties	**Dense sand**	**PVC Pipe**	**Netlongeogrid**
Dry unit weight (kN/m^3)	17	-	-
Young modulus (kN/m^2)	19000	$9.33\ 10^5$	-
Poisson ratio	0.3	0.31	-
Friction angle (°)	42	-	-
Dilation angle (°)	12	-	-
Axial stiffness(kN/m^3)	-	-	60
Diameter(mm)	-	200	-
Thickness(mm)	-	5	-

Based on the experiment results that presented by Rajkumar and IIamparuthi(2008), the behavior of PVC pipe embedded in dense sand and subjected to different surface loads have been investigated in the frame of 2D Finite element code of PLAXIS(2002). The software could simulate two problems: In the first one the vertical crown deflectionon the pipe under 50,100,and 150kPa with 400mm backfill cover in dense sand are studied withoutgeogrids reinforcement. To reduce the effect of surface load on the pipe and increase the performance of it, thegeogrid reinforcement is used in the second case of the model. Hence the numerically simulated model is as illustrated in the Figures 3.1and 3.2 for pipeline without and with geogrid, respectively.

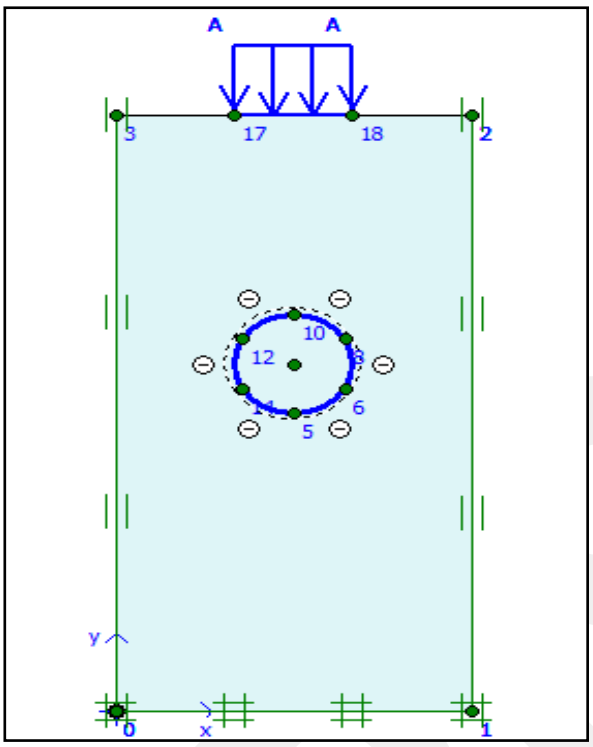


Figure 3.12D numerical configuration of pipeline system.

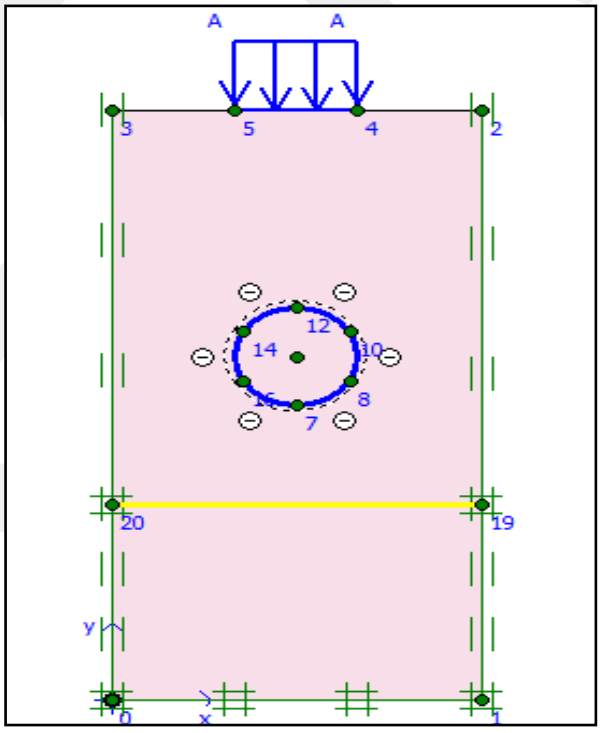


Figure 3.22D numerical configuration of pipeline system with geogrid.

3.3 Numerical computations and discussion

The crown deflection has been computed by means of Rajkumar and Ilamparuthi (2008) parameters listed in Tables 3.1 for PVC pipe buried in dense sand with 400mm of backfill cover with and without geogrid reinforcement. Results achieved are classified in Figure3.3 for backfill without geogrid reinforcement and Figure3.4 when the backfill has geogrid reinforcement. Figures 3.3 and 3.4 also depict the experimental and finite element results that were presented by Rajkumar and Ilamparuthi(2008). On the other hand, the magnitudes of the modified experimental data have also been plotted.

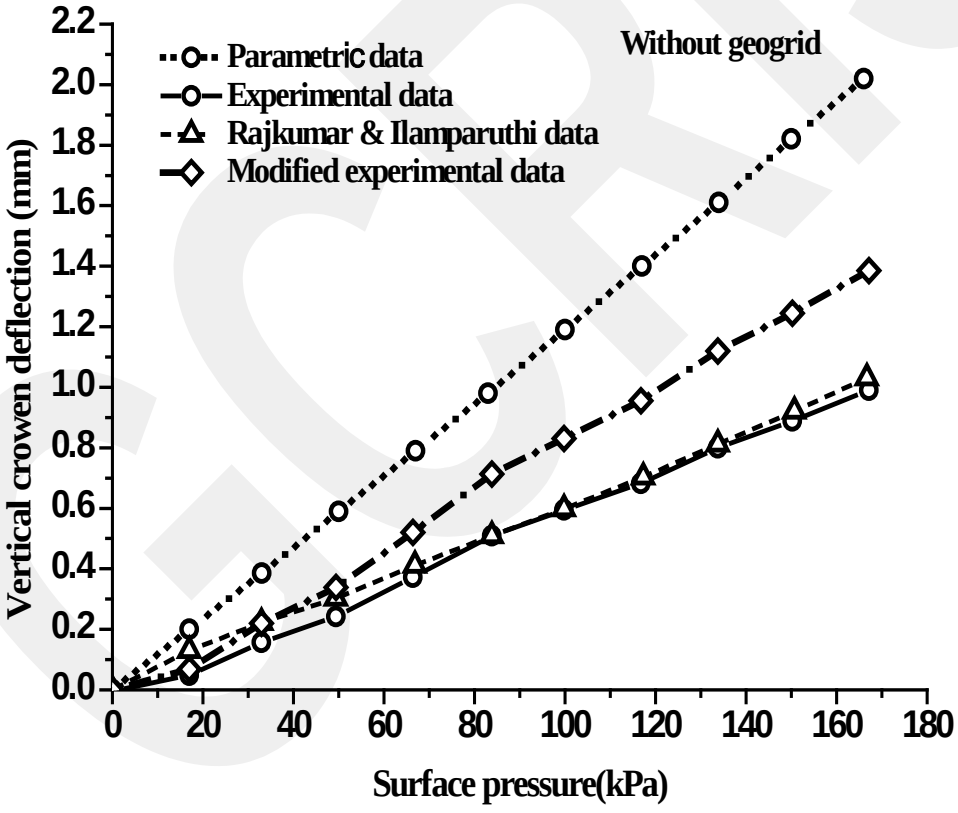


Figure 3.3Numerical and experimentaldatafor backfill without geogrid.

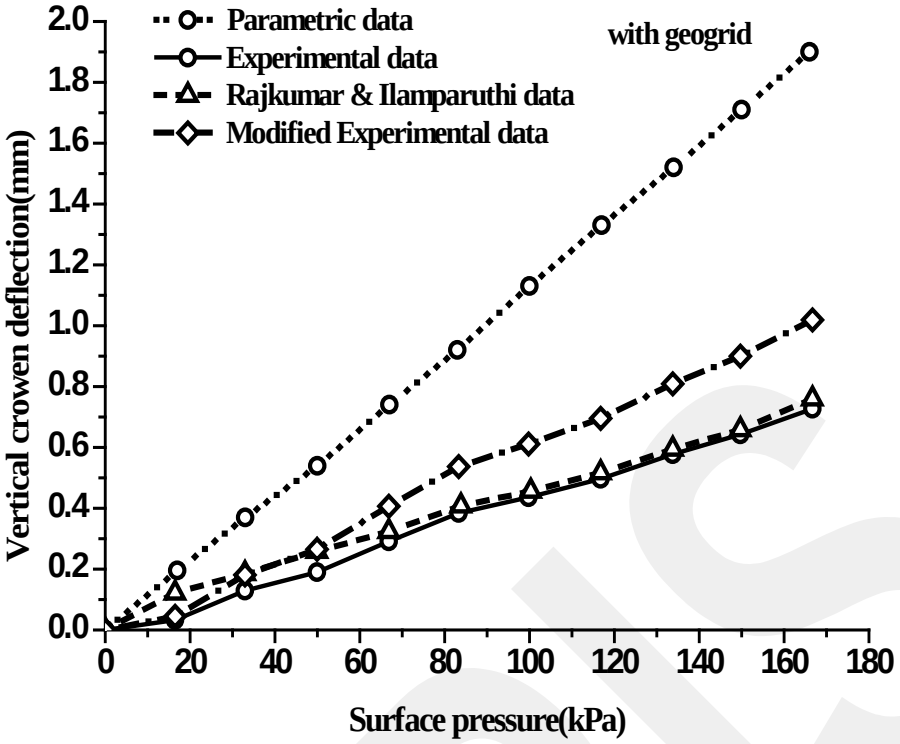


Figure 3.4Numerical and experimentaldatafor backfill withgeogrid.

By examining the curves in Figures3.3 and 3.4, we found that the experimental results should be multiplied by a factor equal to 1.4 to make them as close as to reality, while Rajkumar and Ilamparuthi (2008) had multiplied the applied load in the FEM results by a reduction factor equal to 0.6 (the third dimensions of tank in the experiment), which is in fact incorrect because the results have a great deviation from scientific reality, since the experimental results must bemultiplied by a factor of 1.4 in percent (1-0.6), which is related to the third dimension ofexperimental model; (0.6 m) and PLAXIS- 2D model (1m). As the numerical analysis is carried out by 2D model the third dimension (thickness) is assumed to be unit, 1 meter for all calculations.

CHAPTER 4

BURIED OIL AND GAS PIPELINES UNDER EARTHQUAKE EXCITATIONS

4.1 Preface

The performance of buried natural oil and gas pipeline systems in areas subjected to earthquake events is an important engineering consideration for natural gas and oil utility owners since the failure of such systems poses a risk to public property and safety, in addition to the associated utility and customer business disruption.This interacting system is modeled rigorously through finite element program PLAXIS-2D, which accounts for the pipeline displacements. Considering steel pipelines of various diameter and thickness, and typical steel material for pipeline applications (X65), thischapter focuses on the effects of various soil and pipeline parameters on the structural response of the pipe. Upland earthquake (28/2/1990) with5.4 load magnitude has been used.

In order to investigate the effects of the diameter and thickness, results are obtained for 762 – 1060 mm (30 - 42in) diameterX65steel pipelines with thickness ranging between 6.35 and 17.5mm, embedded at different levels.A real case of (Malkoclar-Ankara Hatti)gas pipeline of diameter (914mm) has been studied in this chapter. Both cohesive soils(clay) and non-cohesive soils (loose sand) are considered.The properties of soil, steel pipeare presented in Tables4.1 and 4.2. The numerically simulated geometry soil model is as shown in the Figure 4.1.

Table 4.1Soil Properties

Properties	**loose sand (Lin et al., 2012)**	Clay (Jeon,2013)
Unit weight(kN/m³)	18.9	15
Young modulus(kPa)	25000	5000
Poisson ratio	0.3	0.35
Cohesion (kPa)	5	10
Friction angle (°)	30	20
Dilatancy angle (°)	0	0

Table 4.2X65 steel pipeline properties

Diameter (mm)	**Thickness (mm)**	**Young modulus (GPa)**	**Poisson ratio**
762 (Lee et al., 2009)	6.35 12.7 17.5	200	0.3
914 (Vazouras et al., 2010)	6.35 9.53 12.7		
1060 (ANSI)	6.35 9.52 12.7		

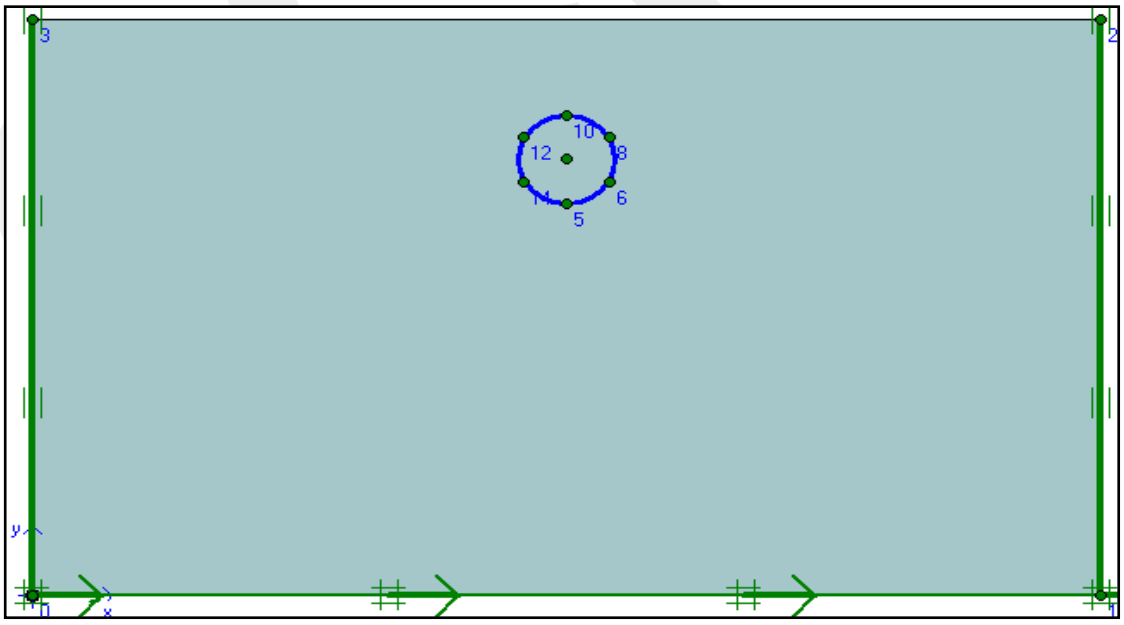


Figure 4.1Geometry model

4.2 Effects of pipe diameter

Figures4.2 and A-1 represent the variation of pipeline displacement before earthquake events whereas the displacements after earthquake are shown in Figure A-2. Figures 4.3 show the relationship between the displacement and pipe diameter (D) under different burying depths for two different values of pipe thickness (t), and illustrated for two different soil types such as clay and loose sand. The relationship between the maximum displacement and pipe diameter of the dented pipeline can be fitted by apolynomial function mode. Table 4.3 lists out the polynomial coefficients ofthis fitting.

Table 4.3Values of polynomial coefficients under different depths

Soil	t(mm)	Polynomial coefficients	Depth(m)			
			1m	1.5m	2m	2.5m
Clay	6.35	a	18.1411	18.4474	18.4635	18.1133
		b_1	-9.027E-4	-0.00124	-8.015E-4	5.701E-4
		b_2	7.348E-7	9.738E-7	7.530E-7	-
	12.7	a	17.7910	17.9272	17.8304	18.0292
		b_1	-1.322E-4	-8.171E-5	5.368E-4	6.039E-4
		b_2	2.752E-7	2.842E-7	-	-
Loose sand	6.35	a	18.9788	18.8246	19.6049	20.4291
		b_1	6.7105E-5	5.875E-4	-9.533E-4	-0.00254
		b_2	-	-1.935E-7	7.258E-7	1.636E-6
	12.7	a	18.9588	18.9522	19.0652	19.7688
		b_1	6.710E-5	2.350E-4	2.684E-4	-0.001
		b_2	-	-	-	7.167E-7

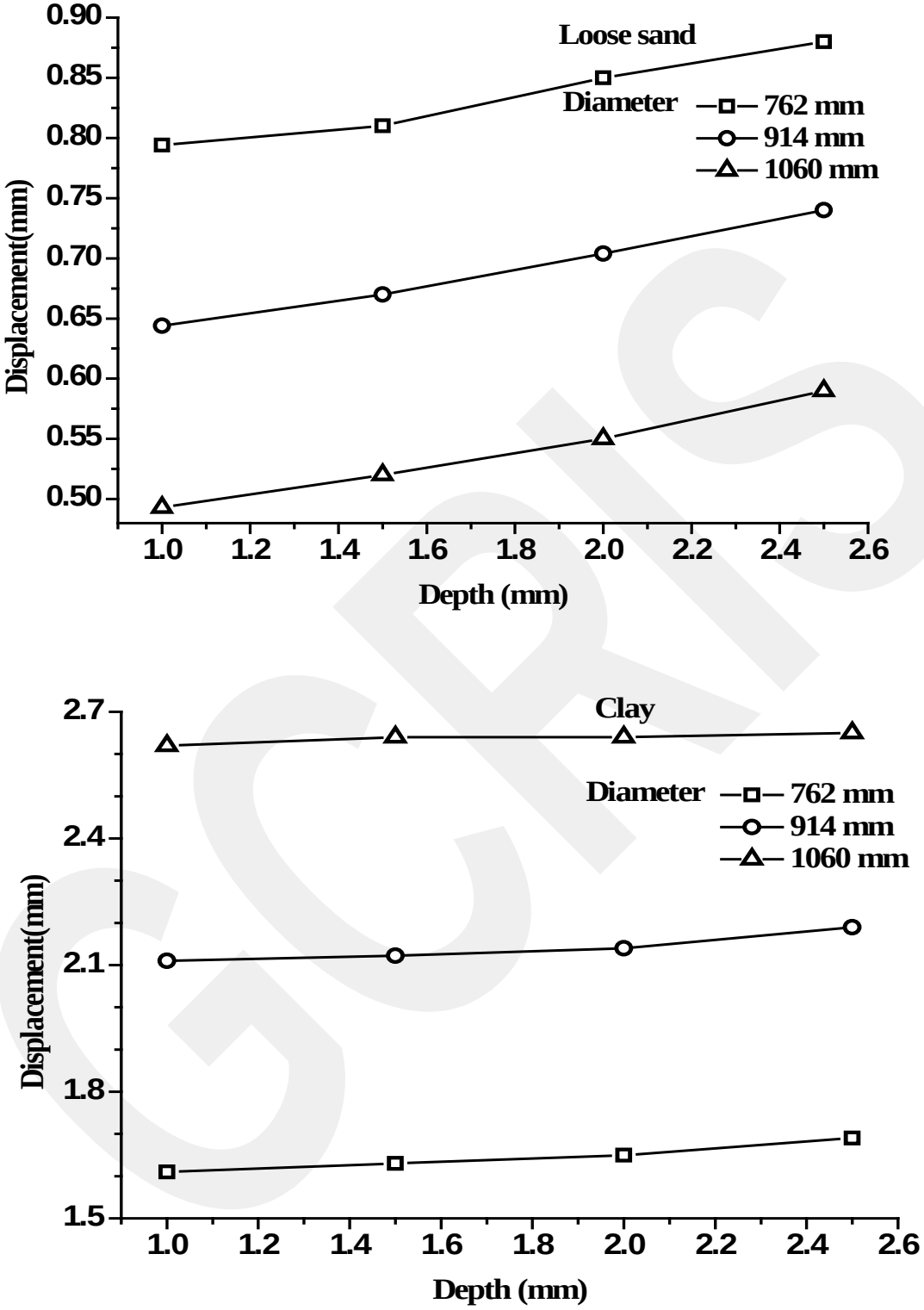


Figure 4.2Pipe displacement variations with burying depth before earthquake event

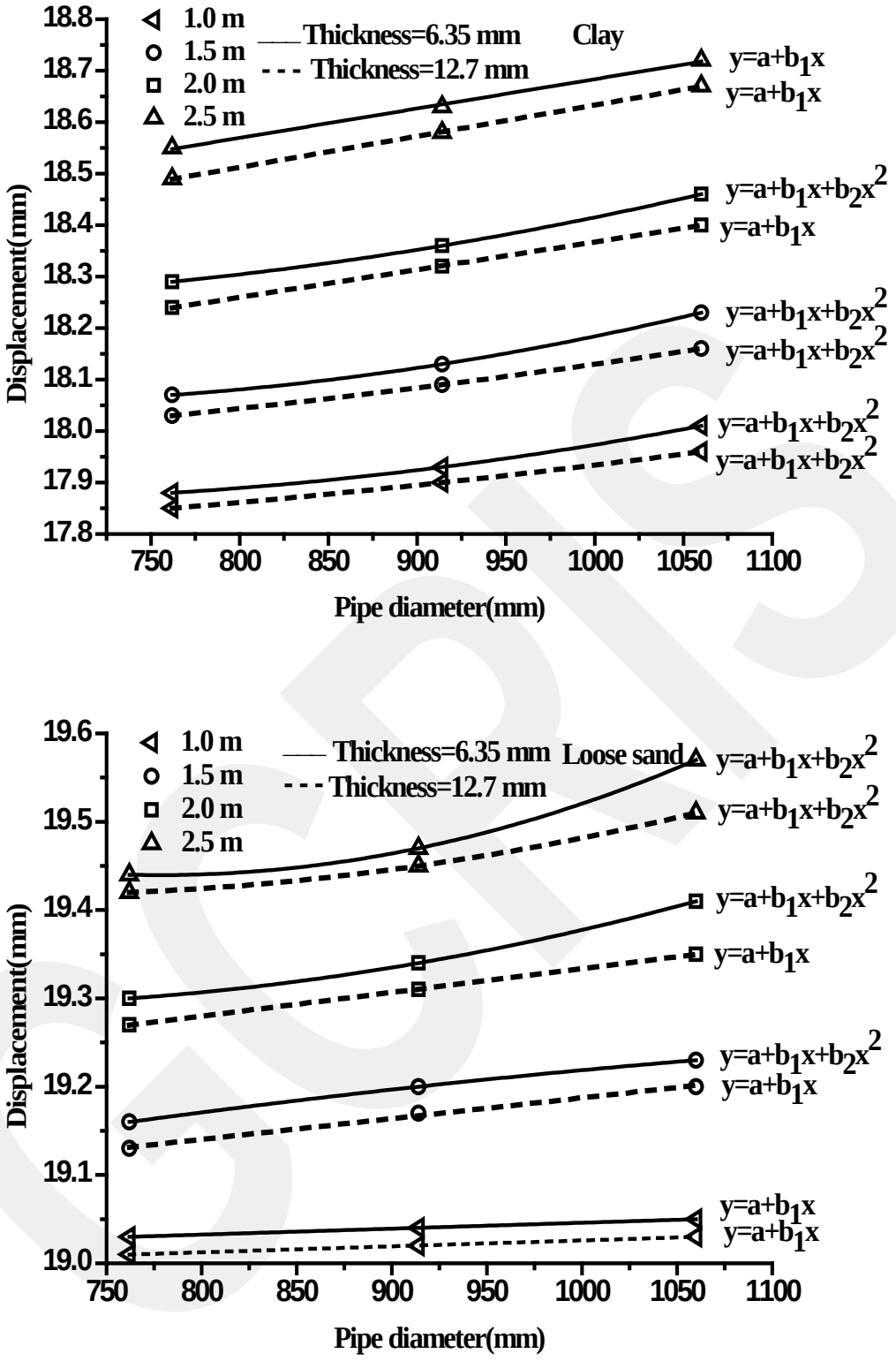


Figure 4.3Relationship of displacement and pipe diameter in clay and loose sand

As can be seen from these Figures, at different values of depth, the pipe displacement increased with the increase of the pipe diameter. This is due to the fact that the friction force between pipe and soil is almost proportional to pipe perimeter almost.

4.3 Soil conditions

Burial depth of pipe is one of the most effective parameters in pipeline displacement analysis. Four different buried depths can be considered here: 1, 1.5, 2 and 2.5m, respectively. Figures 4.4- 4.7 shows the variation of pipe displacement with buried depthwhen the other parameters are unchanged.

Table 4.4 Values of polynomial coefficients under different pipe thickness

Diameter	**Soil**	**Polynomial coefficient**	**Pipe thickness (mm)**				
			6.35	9.52	9.53	12.7	17.5
762mm	Clay	A	17.609	-	-	17.599	17.598
		b_1	0.201	-	-	0181	0.173
		b_2	0.07	-	-	0.07	0.07
	Loose sand	A	18.753	-	-	18.751	18.741
		b_1	0.274	-	-	0.268	0.268
914mm	Clay	A	17.63	-	17.64	17.62	-
		b_1	0.221	-	0.209	0.209	-
		b_2	0.07	-	0.07	0.07	-
	Loose sand	A	18.679	-	18.669	18.709	-
		b_1	0.391	-	0.391	0.321	-
		b_2	-0.03	-	-0.03	-0.01	-
1060mm	Clay	A	17.639	17.630	-	17.66	-
		b_1	0.332	0.299	-	0.229	-
		b_2	0.04	0.05	-	0.07	-
	Loose sand	A	18.591	18.581	-	18.607	-
		b_1	0.467	0.467	-	0.0789	-
		b_2	-0.03	-0.03	-	0.0223	-

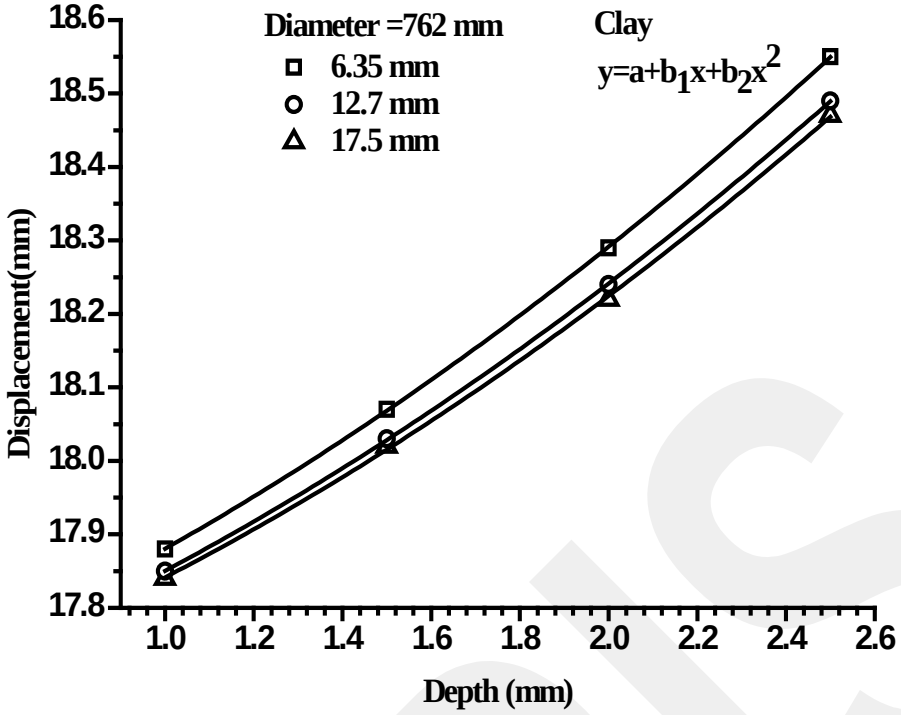


Figure 4.4 Effect of burial depth on pipe displacement of 762mm diameter for claysoil

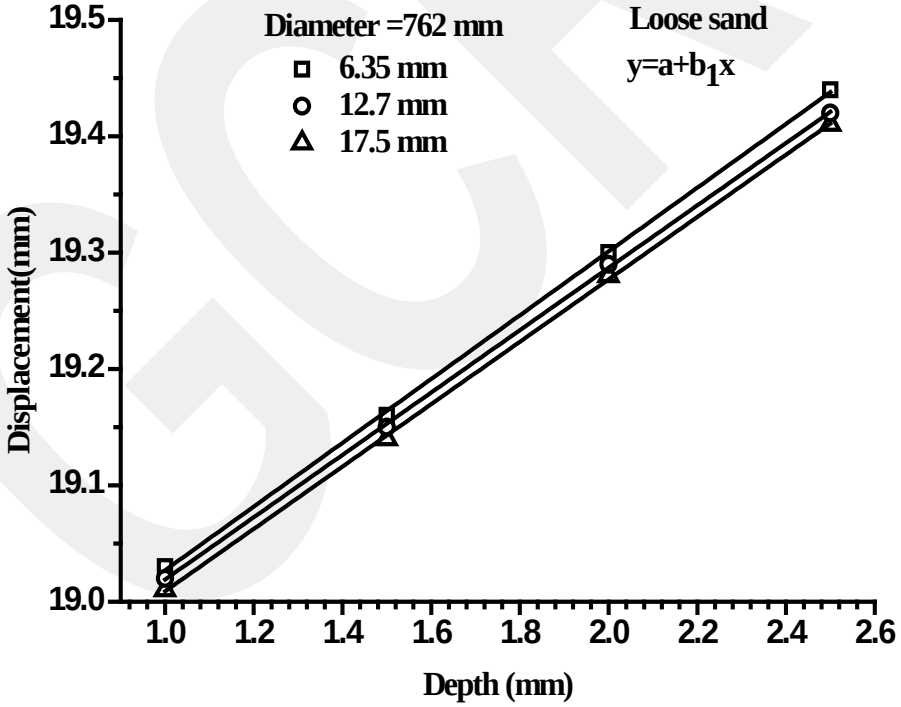


Figure 4.5 Effect of burial depth on pipe displacement of 762mm diameter for loose sand

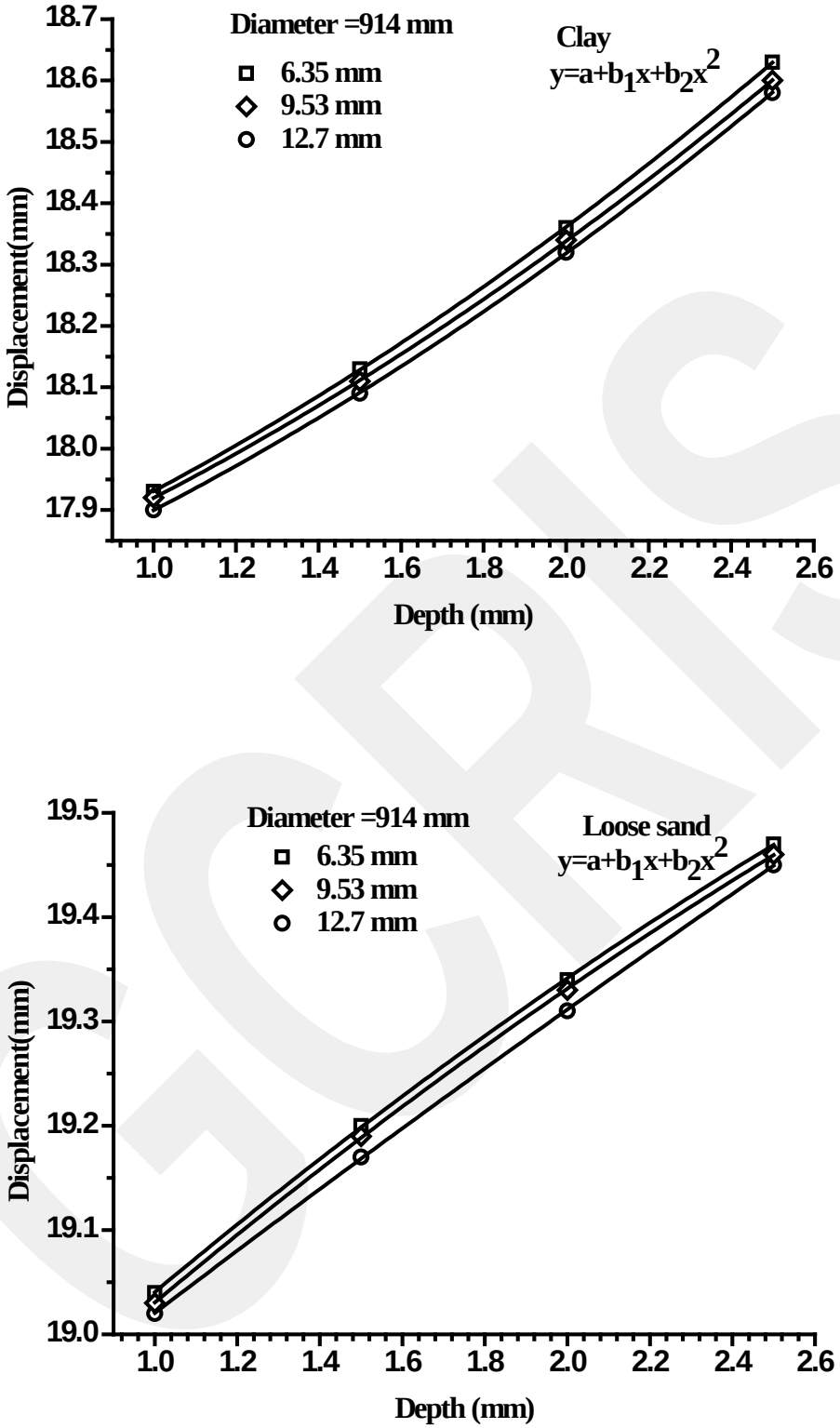


Figure 4.6 Effect of burial depth on pipe displacement of 914mm diameter for clay and loose sand

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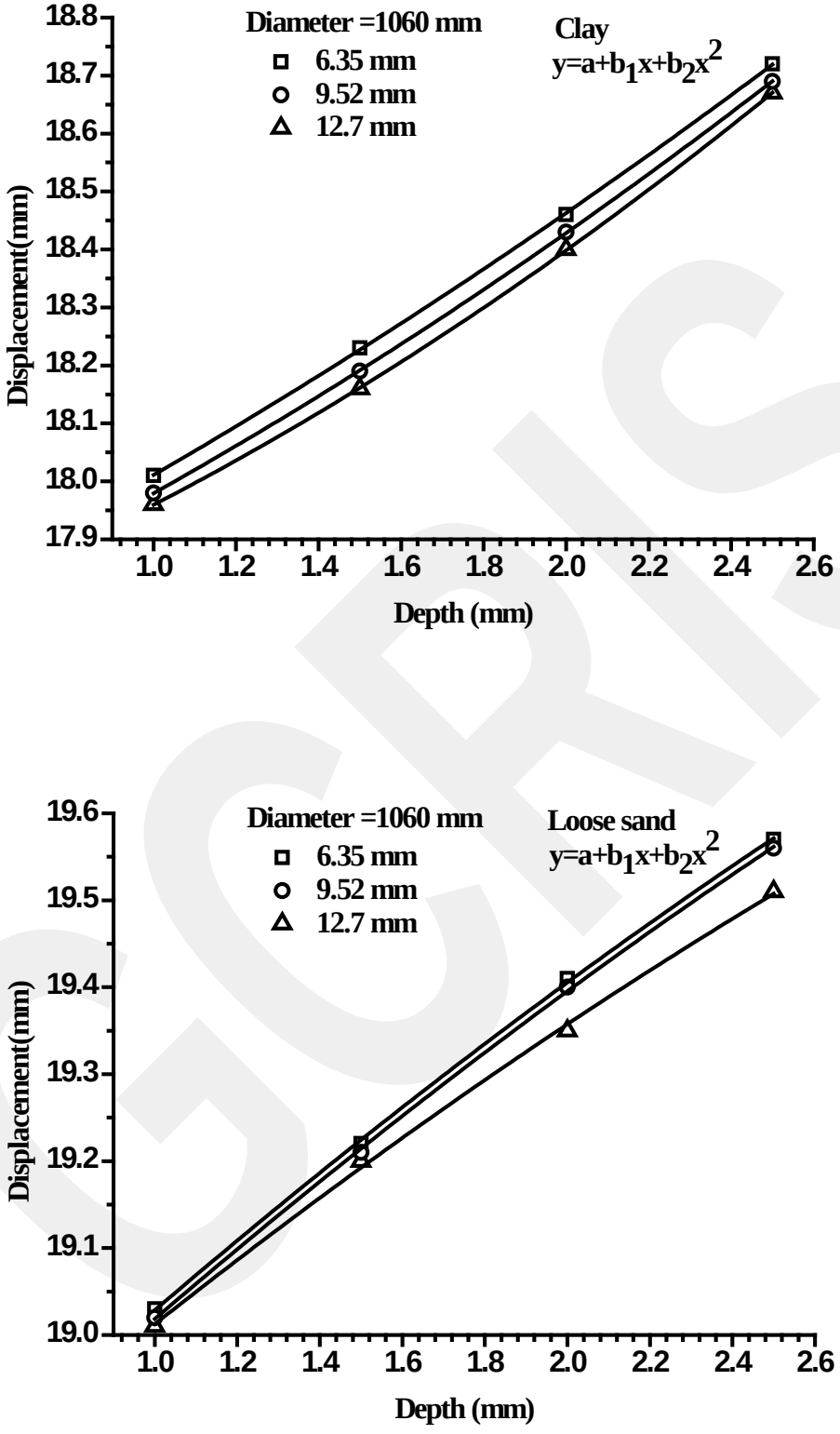


Figure 4.7Effect of burial depth on pipe displacement of 1060mm diameter for clay and loose sand

These Figures indicate that by increasing the burial depth, the pipe displacement increases for different diameter values and soil media.This means that the predicted interaction forces increases with the increases of burial depths. Due to their easy deformation and absorbing more energy, buried pipelines have good performance to resist earthquake when buried depth is shallower. In other word, the deeper buried depth, the poorer performance of the pipe.The relationship is a polynomial function with real coefficients that are listed in Table 4.4. These results are in accordance with Saeedzadeh and Hataf(2011)(Figure A-3) and Hongjing et al. (2008).Their studies have been conducted under earthquake loading on effects of several parameters including dilatancy angle and density ratio of natural soil, diameter and burial depth of pipe, excess pore water pressure, underground water table, and thickness of the saturated soil layer on uplift of pipe (Saeedzadeh and Hataf, 2011). Different pipeline diameter (100-300cm) and burial depth (0.5-1.5m)were used in the finite element (FE) code of PLAXIS program.Moreover Hongjing et al. (2008) develop a 3-D model for the seismic response analysis of the buriedpipeline-soil system due to the fault generated large ground deformation over the depths of up to 9m was used.

Recently, Thusyanthan (2012) summarized the soil classification, according to whether the soil behaves in a drained or undrained manner. Soil behavior depends on the rate of loading (i.e. the rate at which force is applied to the soil). The soil behaves in undrained manner if the rate of loading greater than the rate at which water is able to move in or out of soil inter-particle voids, While the drained behavior occurs when the rate of loading is slower. In other words depends on the permeability of the soil. Due to small permeability, clay behaves in an undrained manner, and the strength is given as undrained shear strength, Whereas sand is considered drained, because water can move in or out inter-particle space at a greater rate than the rate of loading, and the strength can be given in terms of friction angle.

As a summary, in this section, two different material properties of clay and loose sand used to the numerical analysis are investigated. The material parameters can be shown in Table 4.1.Thus, one should expect that these listed soil properties affect the pipe–soil interaction induced by soil movement. Figures 4.4 – 4.7 also predict that for each values of pipe diameter, the pipeline displacement depends on the type of soil surrounding that pipe. For a given pipe diameter and wall thickness, pipes buried in loose sand have more response to the earthquake events, and the displacement in clay

soil is less than that occurs in loose sand. These results are accordance with (Feng et al., 2012).

4.4 Effects of pipe thickness

To predict the effects of different pipe thicknesses, numerical calculations are performed on 6.53, 9.52, 9.53, 12.7and17.5mm thick pipes. The geotechnical investigations revealed that the pipeline thickness is a factor that needs to be taken into account.The commercially available finite element analysis program PLAXIS-2Dis used to study the variation of steel pipes displacement with the wall pipe thickness, and results obtained are illustrated in Figures 4.8-4.10 for different burying depths in clay and loose sand.Table 4.5 refers to the fitted polynomial coefficient for the variables under study.

Table 4.5 Polynomial coefficients for the variable under study

Diameter	**Soil**	**Polynomial coefficients**	**Depth (m)**			
			1.0	1.5	2.0	2.5
762mm	Clay	a	17.9291	18.1404	18.3668	18.6482
		b_1	-0.0092	-0.0135	-0.01421	-0.01847
		b_2	2.368E-4	3.781E-4	3.324E-4	4.737E-4
	Loose sand	a	19.0417	19.1717	19.3117	19.4564
		b_1	-0.00178	-0.00178	-0.00178	-0.00271
914mm	Clay	a	17.9592	18.1623	18.4004	18.6815
		b_1	-0.00444	-0.0054	-0.00634	-0.00825
	Loose sand	a	19.0682	19.2292	19.3692	19.4902
		b_1	-0.00412	-0.00444	-0.00444	-0.00317
1060mm	Clay	a	18.0583	18.2983	18.5199	18.7683
		b_1	-0.00787	-0.0011	-0.00945	-0.00787
	Loose sand	a	19.0499	19.2399	19.3103	19.4703
		b_1	-0.00315	-0.00315	0.02826	0.02826
		b_2	-	-	-0.00198	-0.00198

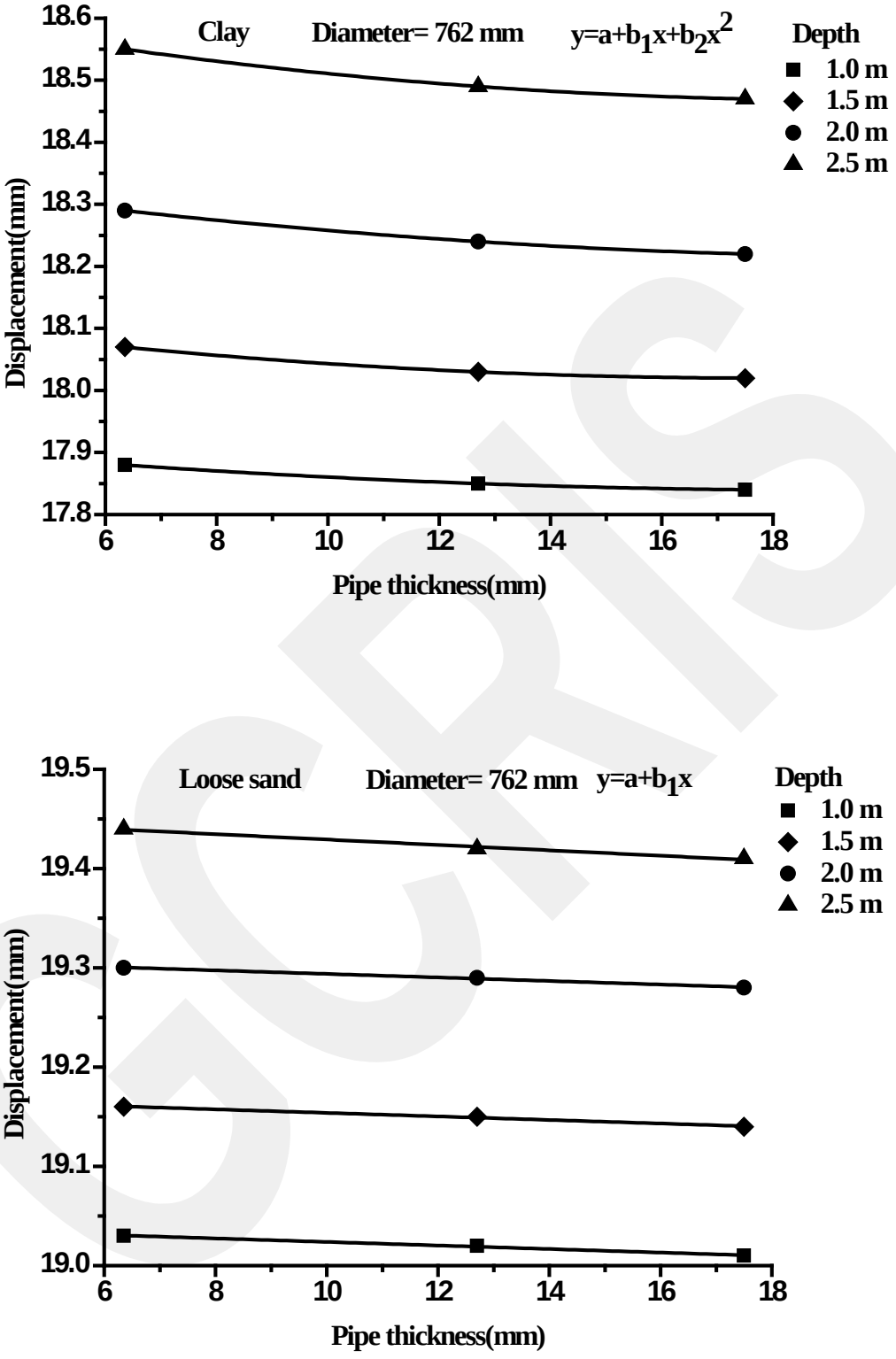


Figure 4.8Function of displacement versus pipe thickness for burying depth in clay and loose sand soils for pipe diameter 762mm

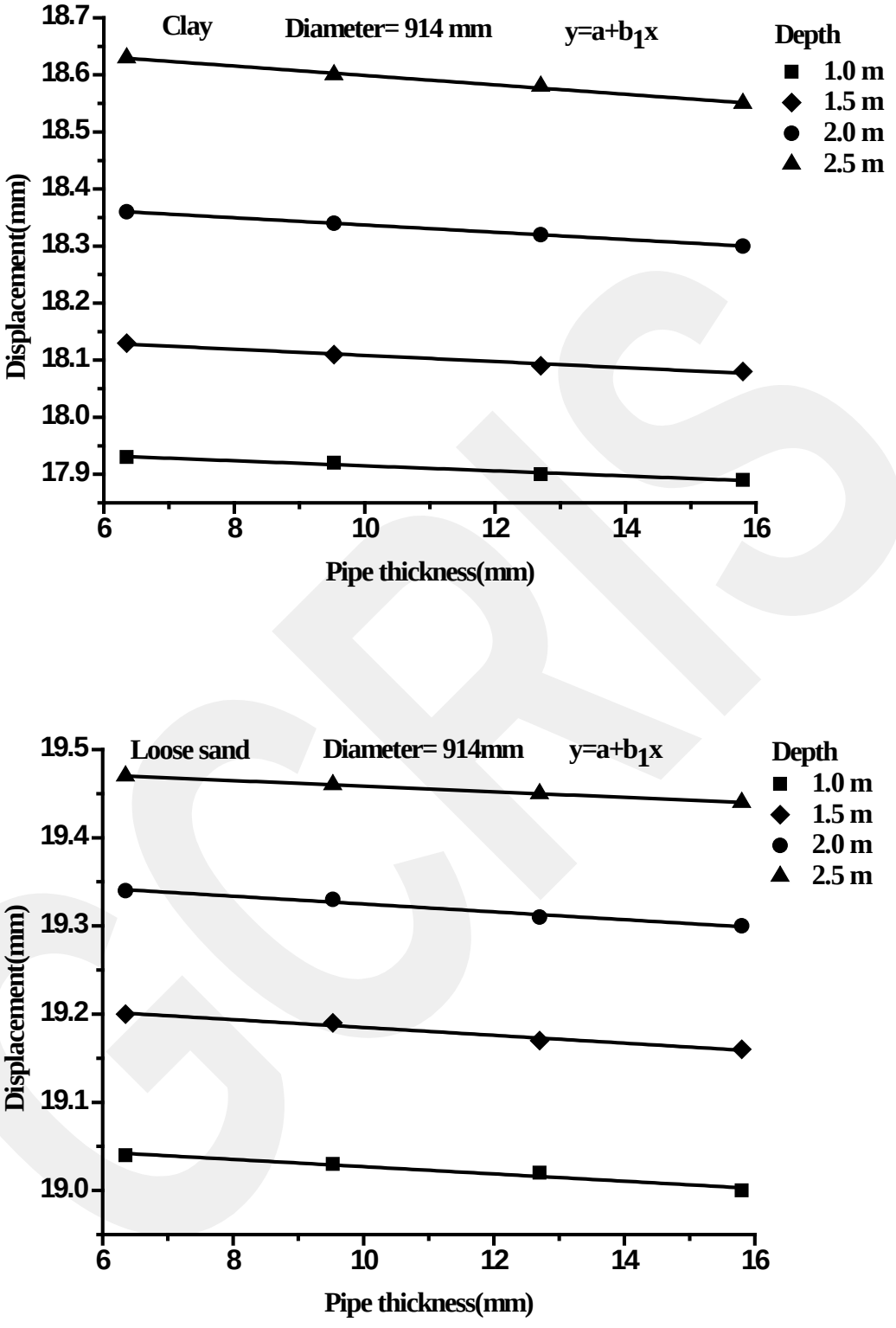


Figure 4.9Function of displacement versus pipe thickness for burying depth in clay and loose sand soils for pipe diameter 914mm

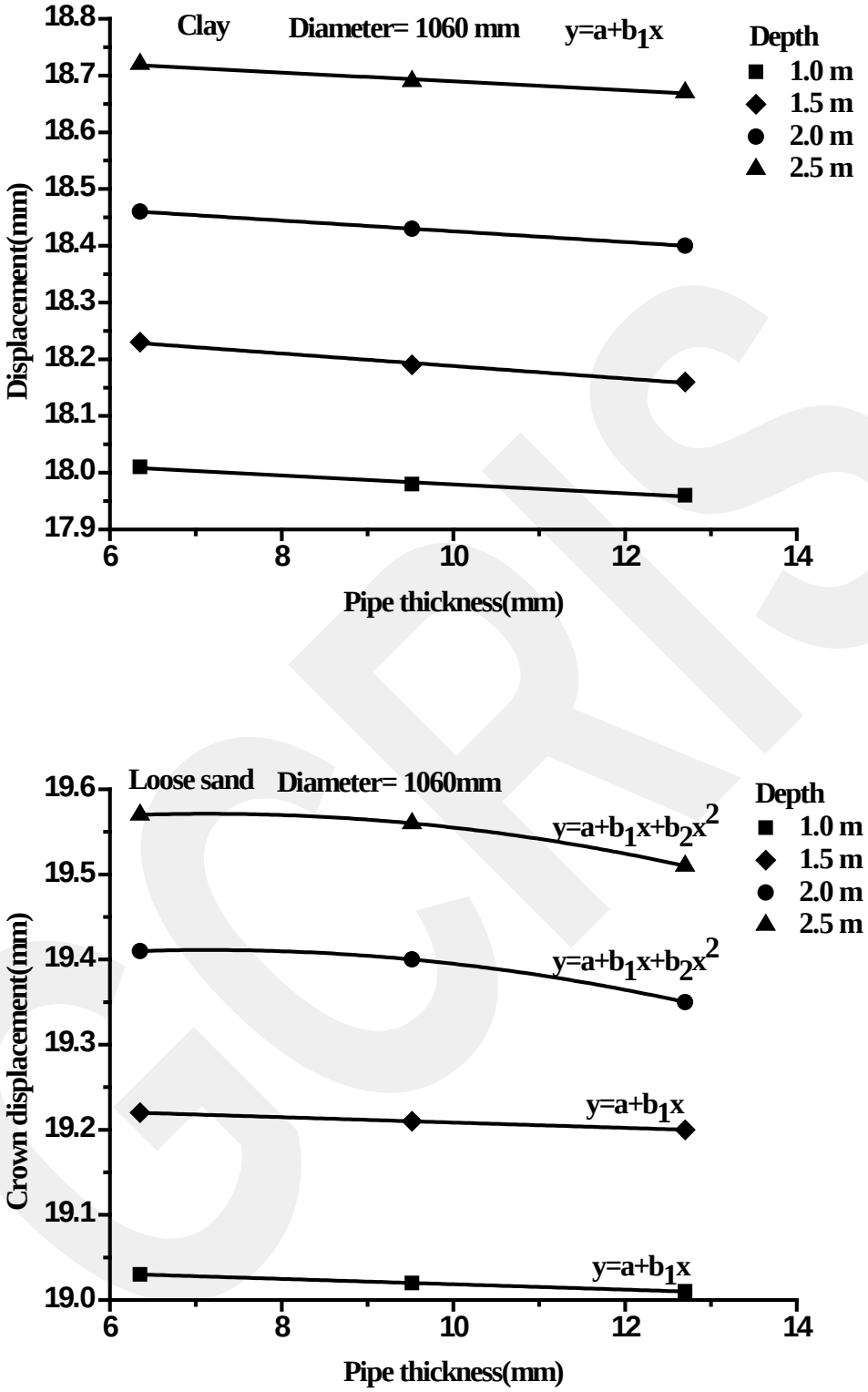


Figure 4.10Function of displacement versus pipe thickness for burying depth in clay and loose sand soils for pipe diameter 1060mm

According to these figures, it is found that the predicted displacement decreases where pipe wall thickness increases or the rigidity of the pipe increases. It is worthy mentioned that the pipe ability to resist soil movement is proportional to the wall-thickness of pipe when the diameter is the same.

GCRIS

CHAPTER 5

BURIED OIL AND GAS PIPELINES SUBJECTED TO SURFACE LOADING

5.1Preface

Various parameters affect the displacement of pipelines that should be inspected. Subsequently, the behavior of buried pipelines has been investigated by many researchers. Most of the studies mainly deal with the numerical modeling of buried pipelines and soil-pipeline interaction. The purpose of this chapter is to study the static properties of buried pipeline due to surface loads (50,100,150 and 200 kPa), where Malkoclar-Ankara Hatti gas steel pipeline is taken as an example. The finite element program of PLAXIS-2D is used to perform the present analyses, where parametric studies are carried out to investigate the effect of different soil, pipeline and burial depths characteristics on the response of gas steel pipeline. We focus our attention on crown displacement, since this generally most critical case for the integrity of a pipeline. The geometry of soil model is shown Figure 5.1. The properties of soil and steel pipeline are shown in Table 4.1 and4.2, respectively.

5.2 Influence of soil conditions

Using three different values of diameters with three values of thicknesses for each one, the effect of soil conditions such as type of soil and burial depth have been calculated under surface load (Figure B-1), and results obtained are illustrated in Figures 5.2 – 5.10 from the smaller diameter to the higher one with their own thicknesses respectively, and their curve fitting parameters are listed in Table 5.1. Figure 5.11 describes the variation of increment ratio $(IR = \Delta d / \Delta Q)$ of crown

displacement (Δd) with load variation ΔQ, and the coefficients of curve fitting are listed in Table 5.2.

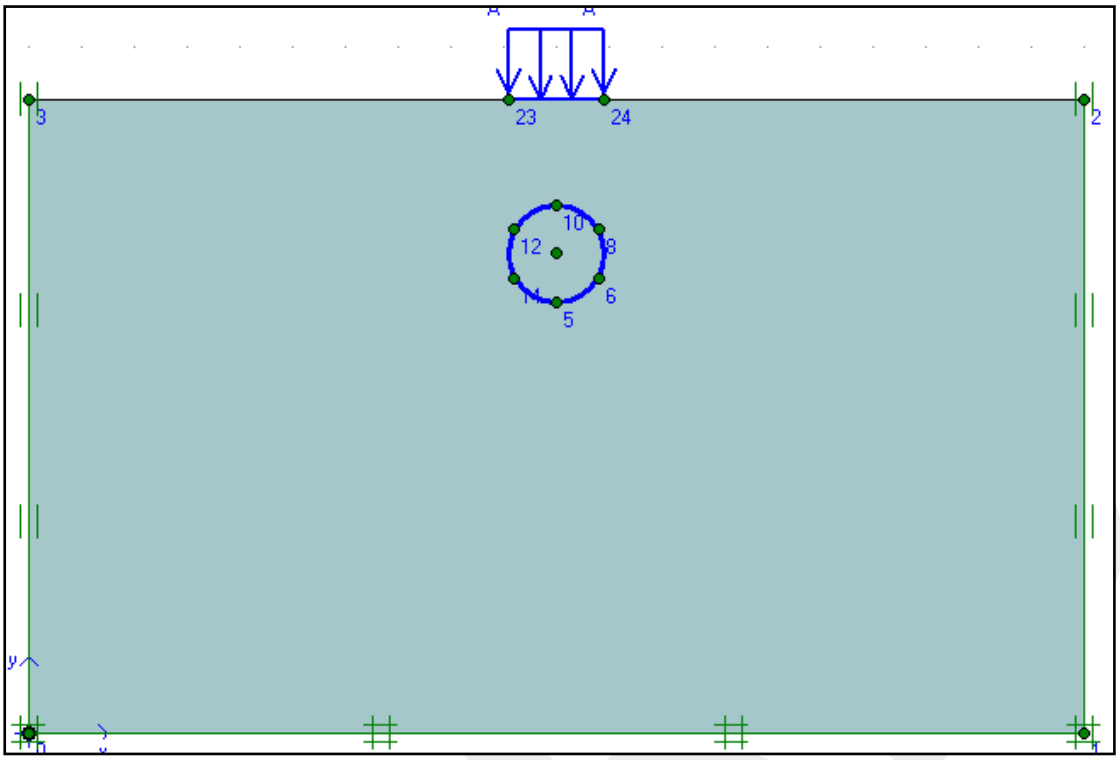


Figure 5.1Schematic diagrams of soil-pipe system:

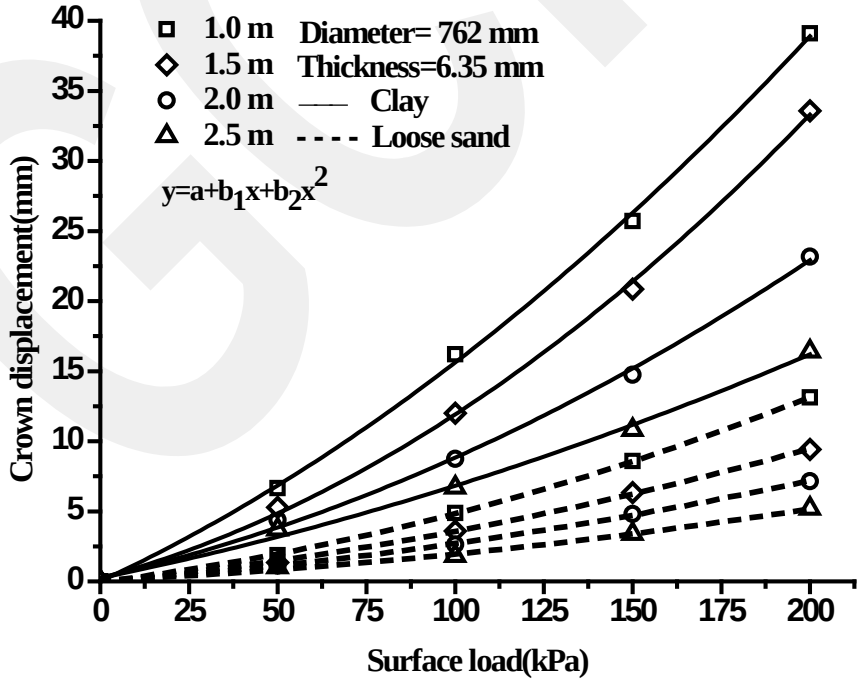


Figure 5.2 Displacement–load curves for buried pipe having D=762mm and t=6.35mm

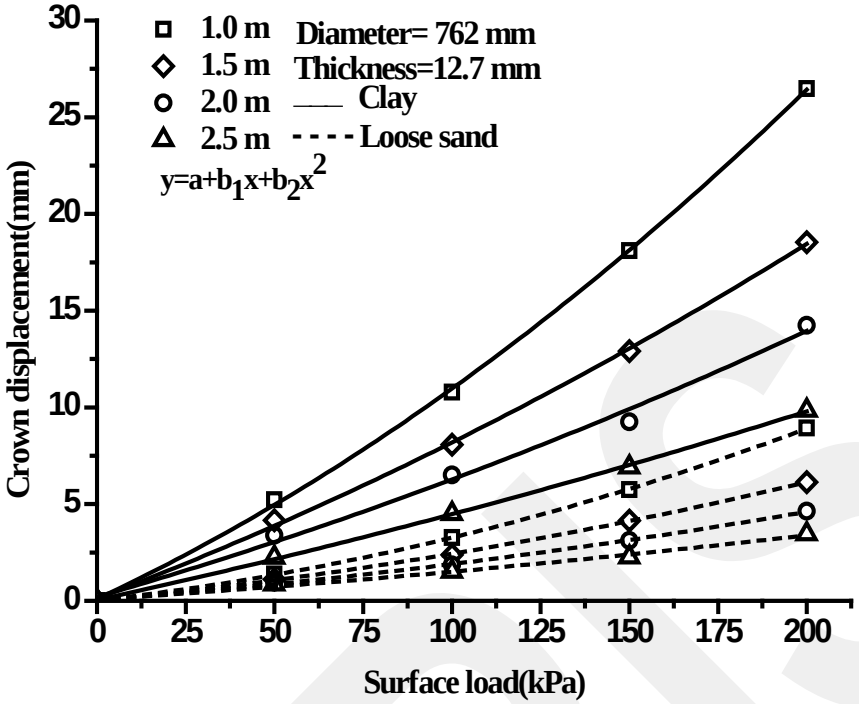


Figure5.3 Displacement–load curves for buried pipe having D=762mm and t=12.7mm

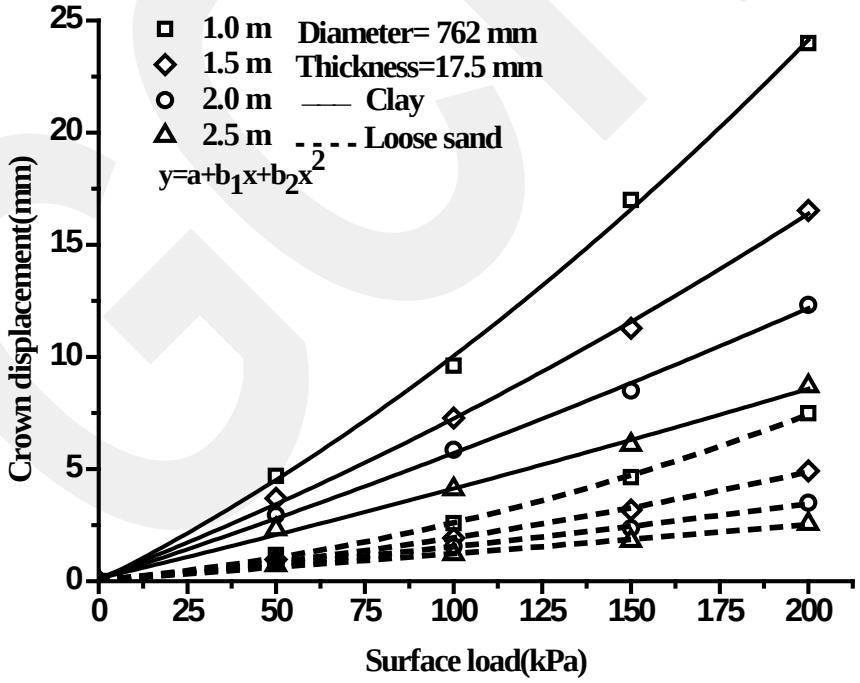


Figure 5.4Displacement – load curves for buried pipe having D=762mm and t= 17.5mm

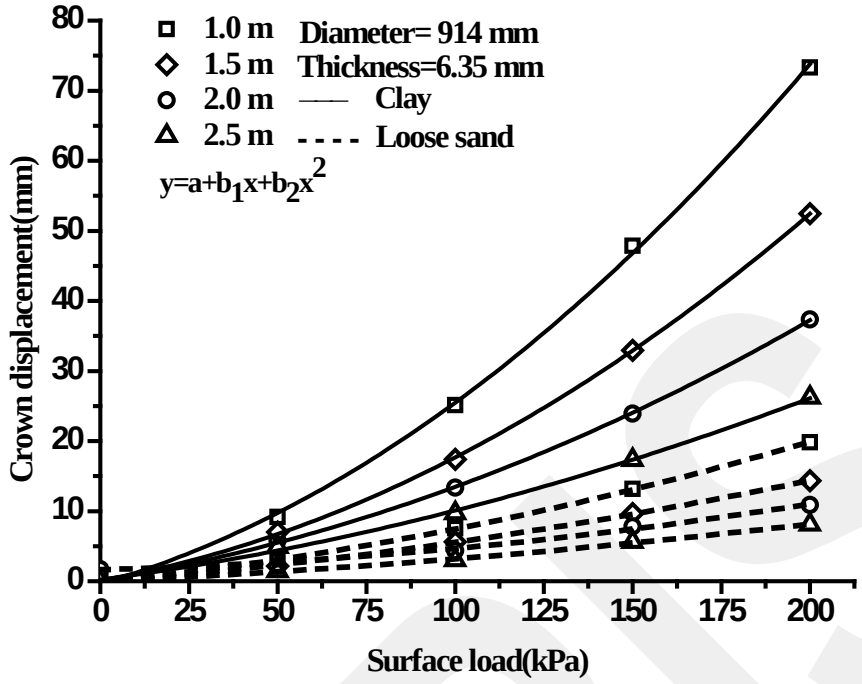


Figure 5.5 Displacement – load curves for buried pipe havingD=914mm and t= 6.35mm

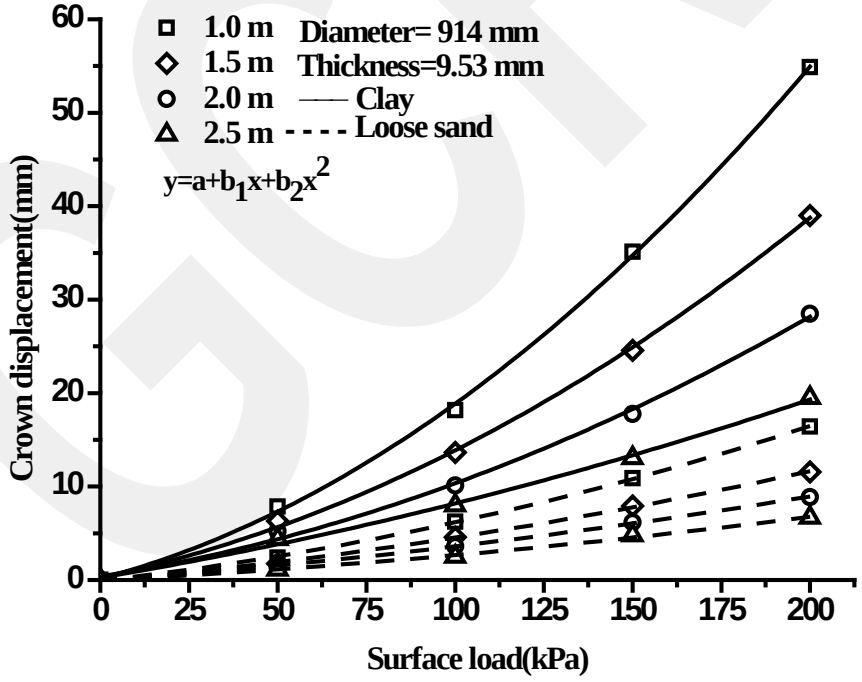


Figure 5.6 Displacement – load curves for buried pipe having D=914mm and t=9.53 mm

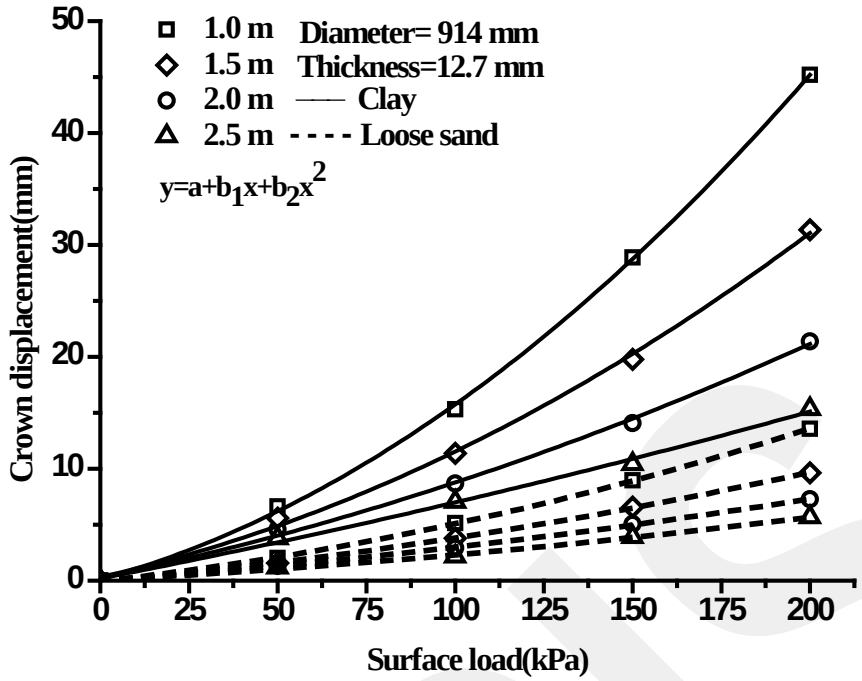


Figure 5.7Displacement – load curves for buried pipe havingD= 914mm and t= 12.7mm

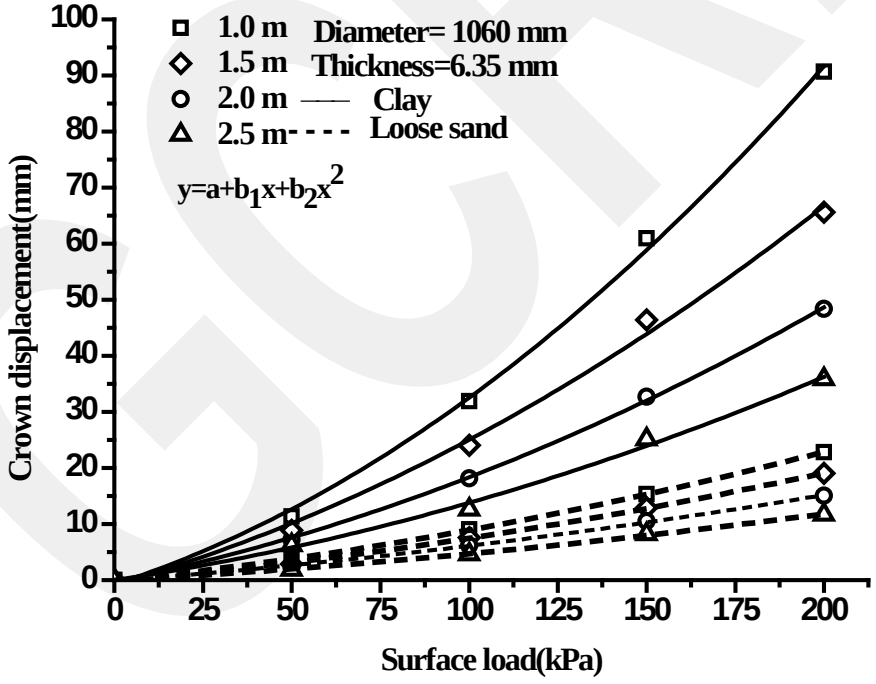


Figure 5.8 Displacement – load curves for buried pipe having D=1060mm and t= 6.35mm

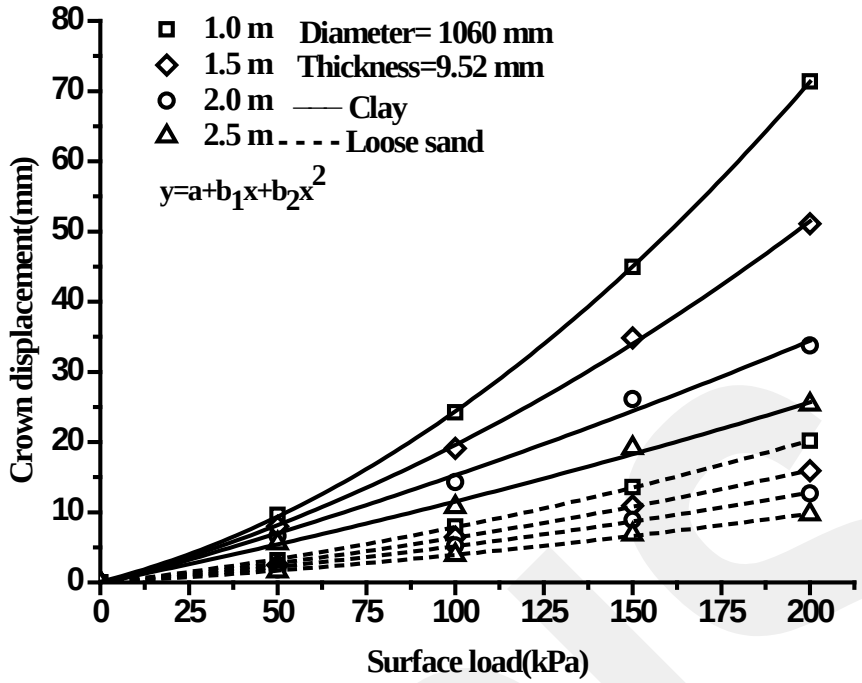


Figure 5.9Displacement – load curves for buried pipe having D=1060mm and t=9.52mm

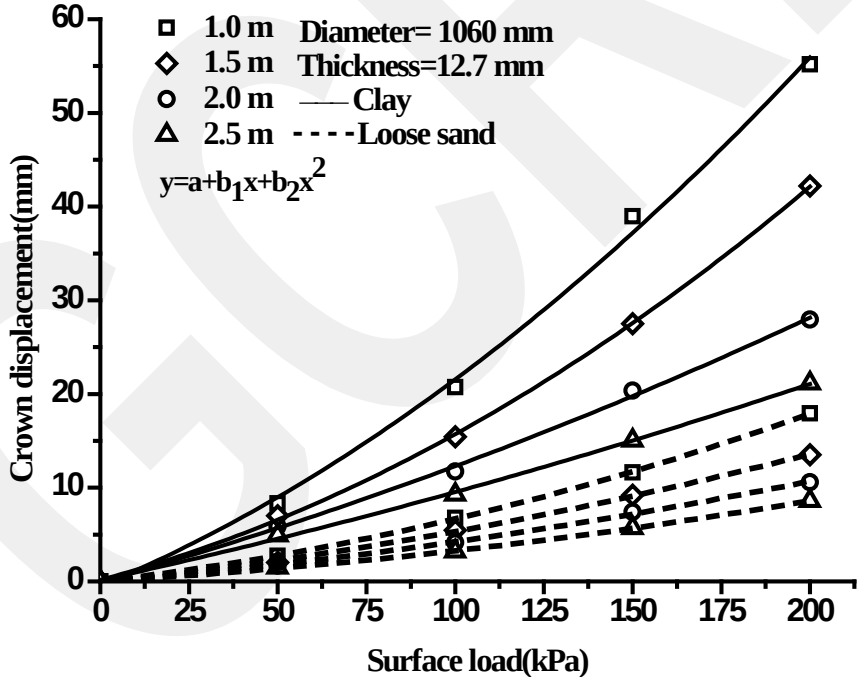


Figure 5.10Displacement – load curves for buried pipe having D=1060mm andt= 12.7mm

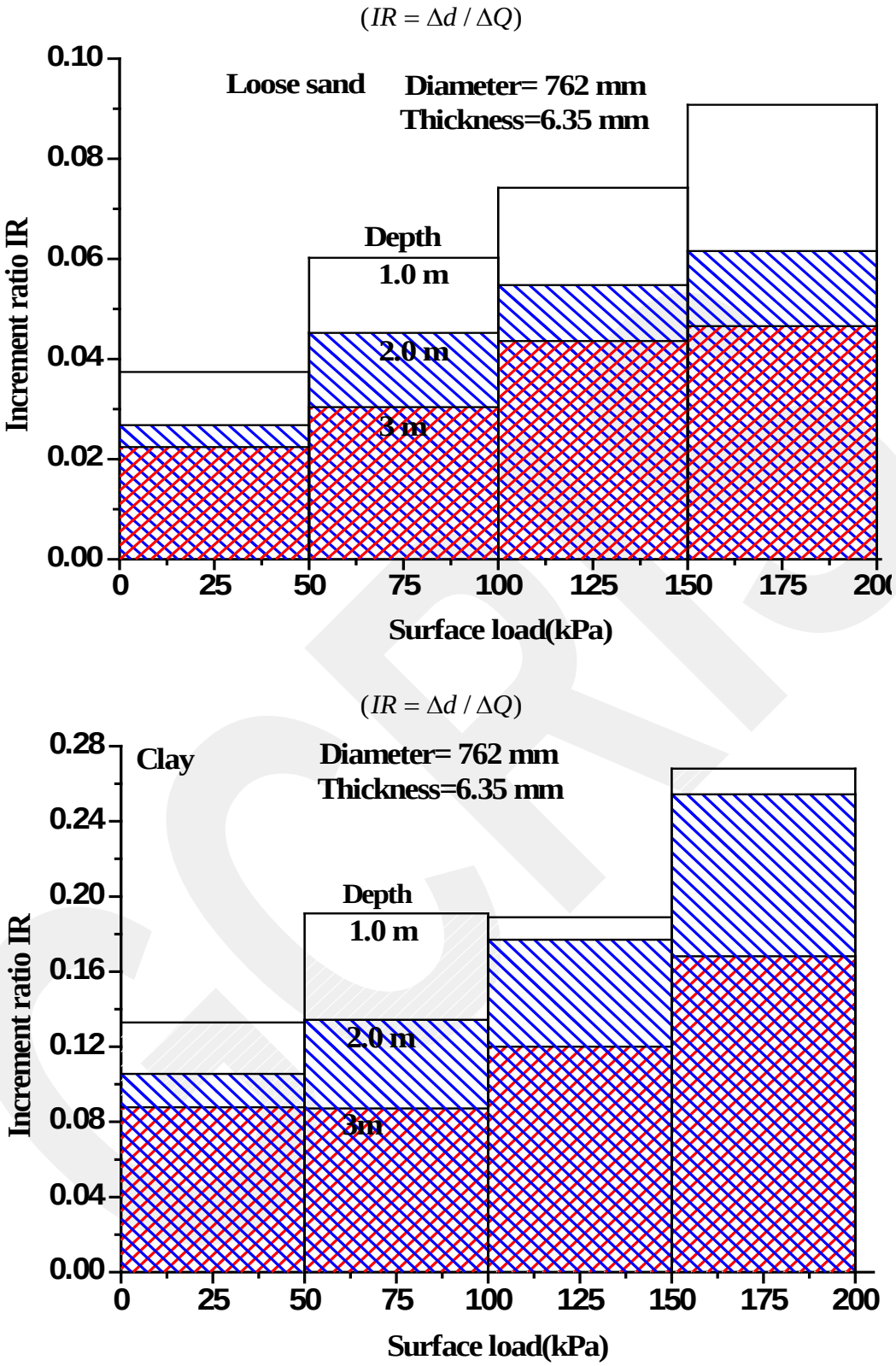


Figure 5.11 Variation of increment ratio of crown displacement with load variation

Table 5.1 Polynomial coefficients of load- displacement curve fitting

D mm	**t mm**	**Depth m**	**Clay**			**Loose sand**		
			Polynomial coefficient			Polynomial coefficient		
			a	b_1	b_2	a	b_1	b_2
762	6.35	1	0.00314	0.1177	3.83E-4	-0.03914	0.0314	1.72E-4
		1.5	0.228	0.0682	4.86E-4	-0.06229	0.0250	1.13E-4
		2	0.2568	0.0580	2.76E-4	-0.014	0.0184	8.80E-5
		2.5	0.2425	0.0518	1.39E-4	0.0637	0.0121	6.71E-5
	12.7	1	0.104	0.0856	2.3E-4	0.0200	0.0204	1.2E-4
		1.5	0.1254	0.0695	1.10E-4	0.0188	0.0176	6.45E-5
		2	0.2088	0.0526	8.05E-4	0.0429	0.0143	4.23E-5
		2.5	0.0474	0.0398	4.42E-5	0.0654	0.0121	2.22E-5
	17.5	1	0.0108	0.0800	2.02E-4	0.0545	0.0141	1.13E-4
		1.5	0.1337	0.0610	1.01E-4	0.0512	0.0135	5.29E-5
		2	0.0988	0.0518	4.25E-5	0.0440	0.0128	1.04E-5
		2.5	0.1213	0.0378	2.22E-5	0.0439	0.0113	5.11E-6
914	6.35	1	-0.3560	0.1458	0.0011	-0.0831	0.0510	2.44E-4
		1.5	0.1022	0.0895	8.60E-4	-0.0745	0.0402	1.60E-4
		2	0.1334	0.0811	5.22E-4	1.6494	0.0135	1.66E-4
		2.5	0.2057	0.0681	3.07E-4	0.0057	0.0229	8.91E-5
	9.53	1	0.1502	0.1002	8.68E-4	-0.0642	0.0420	2.08E-4
		1.5	0.2845	0.0793	5.65E-4	-0.07886	0.0339	1.23E-4
		2	0.3828	0.0601	3.94E-4	-0.0654	0.0282	8.37E-5
		2.5	0.2508	0.0635	1.58E-4	-0.0368	0.0200	6.94E-5
	12.7	1	0.1362	0.0867	6.92E-4	-0.0348	0.0342	1.69E-4
		1.5	0.3265	0.0706	4.15E-4	-0.0382	0.0283	1.01E-4
		2	0.2620	0.0657	1.94E-4	-0.0140	0.0233	6.6E-5
		2.5	0.1974	0.0613	6.62E-5	0.0422	0.0171	5.48E-5
1060	6.35	1	-0.7514	0.2036	0.0012	-0.0968	0.0653	2.47E-4
		1.5	-0.7820	0.1787	7.94E-4	-0.1351	0.0557	2.02E-4
		2	-0.2271	0.1270	5.86E-4	-0.1514	0.0486	1.39E-4
		2.5	-0.0017	0.0946	4.32E-4	-0.0882	0.0360	1.17E-4
	9.52	1	0.0885	0.1290	0.0011	-0.0785	0.0571	2.22E-4
		1.5	-0.1708	0.1366	6.07E-4	-0.1074	0.0490	1.57E-4
		2	-0.3625	0.1386	1.76E-4	-0.1588	0.0416	1.15E-4
		2.5	-0.0568	0.1029	1.27E-4	-0.0711	0.0307	9.25E-5
	12.7	1	-0.4782	0.1585	6.17E-4	0.0048	0.0440	2.27E-4
		1.5	0.1671	0.1011	5.43E-4	-0.1042	0.0402	1.41E-4
		2	-0.004	0.1051	1.78E-4	-0.0685	0.0321	1.08E-4
		2.5	0.1345	0.0832	1.07E-4	0.0322	0.0218	1.04E-4

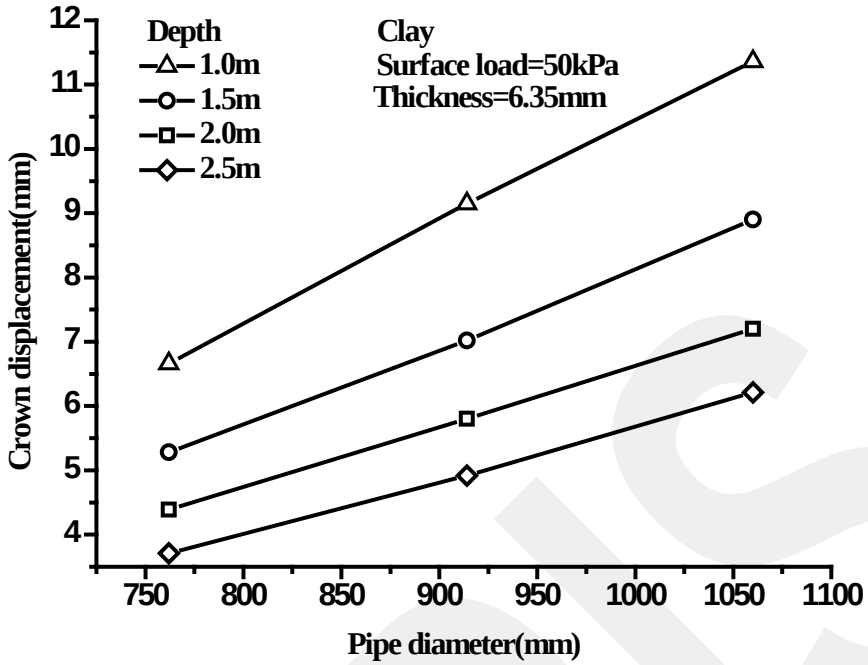
Table 5.2 Fitting coefficients of increment ratio curves

Soil	Polynomial parameters	Depth(m)		
		1.0	1.5	2.0
Clay	a	1.489E-16	9.942E-4	-5.461E-16
	b_1	0.00288	0.003	0.00415
	b_2	5.1E-6	-2.353E-5	-6.767E-5
	b_3	-2.32E-7	7.44E-8	4.42E-7
	b_4	8.4E-10	-	-9.32E-10
Loose sand	a	0.00164	4.685E-4	9.2E-4
	b_1	7.248E-4	5.812E-4	4.208E-4
	b_2	-1.44E-6	-1.394E-6	-9.6E-7

In general, we can clearly observe an increasing in the crown displacement of pipe when increasing surface load and an increase of burial depth causes the pipe displacement to decrease. It is worth noting that the loose sand causes less crown pipe displacement than clay soil. These result are in agreement with the findings byRajkumar and Ilamparuthi (2008) (Figures B2 and B3) and Bildik et al. (2012)(Figures B4 andB5). Bildik et al (2012) use buried non-pressure concrete and polyethylene pipes with diameter 1.0m and D/t =0.1. They used the PLAXIS-2D to predict the behavior of pipe-soil interaction in loose and dense sand.

5.3 Effect of pipe properties

In this section, the effect of pipe conditions includes both the effect of pipe diameter and wall pipe thickness on pipe crown displacement, where the numerical results are plotted in Figures 5.12 – 5.19 and 5.20 – 5.22, respectively. The numerical calculations have been conducted under surface loads of 50,100,150 and 200 kPa in both type of soil (clay and loose sand) for different effective levels of burial depth (1,1.5,2and2.5m), and the polynomial coefficients of the displacement-pipe thickness relationship are given in Table 5.3.



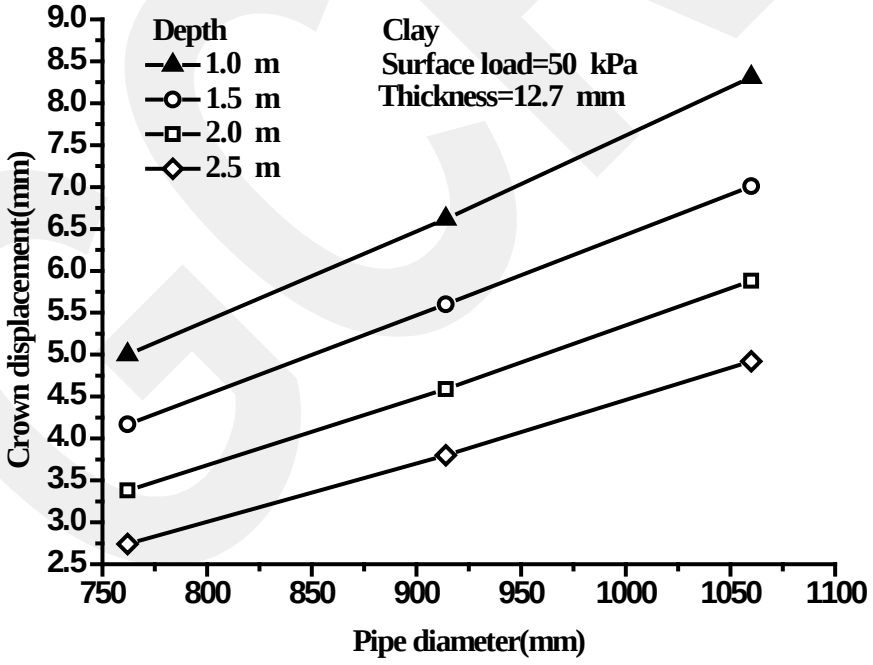


Figure 5.12Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for clay soil under 50kPa surface load

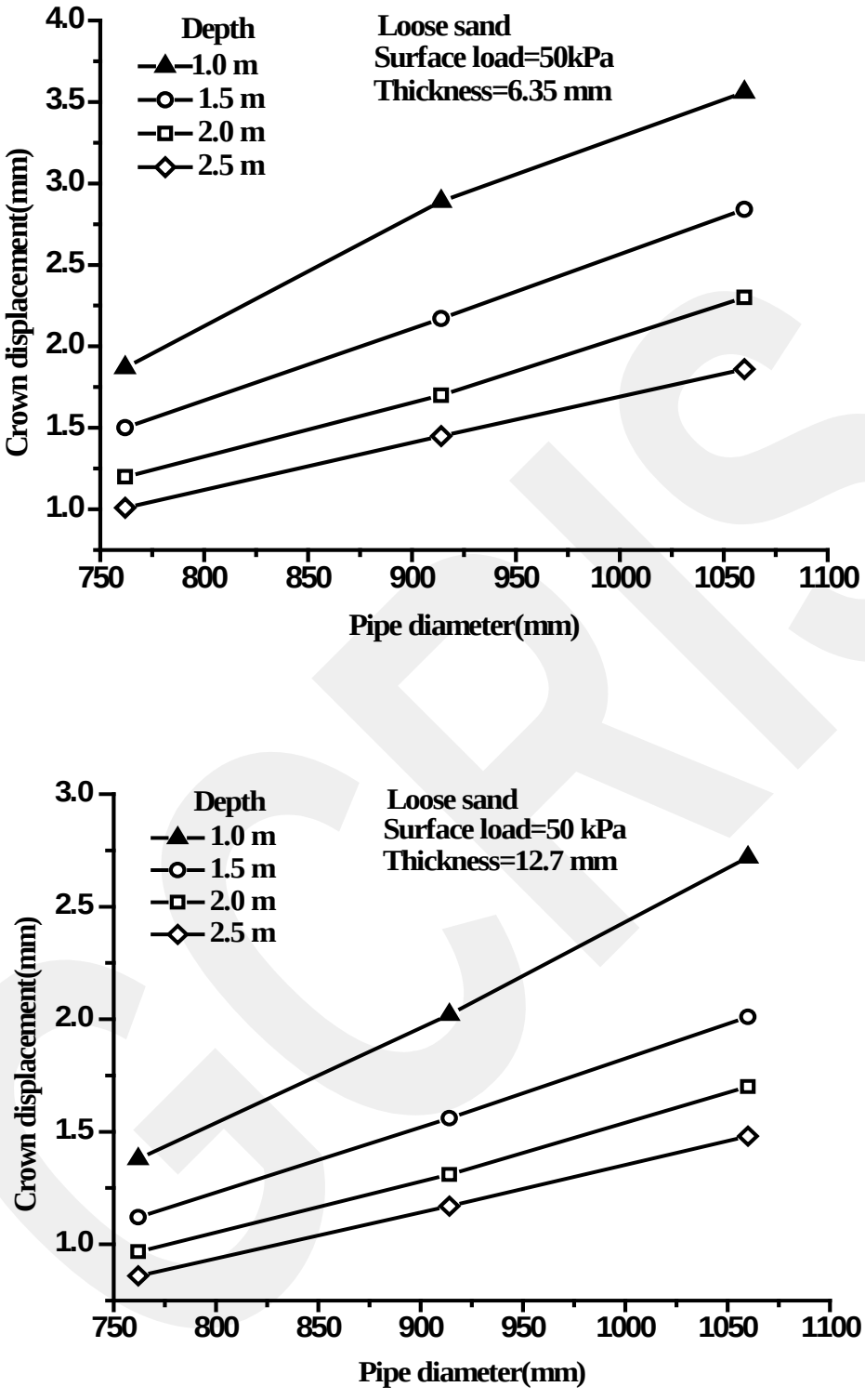
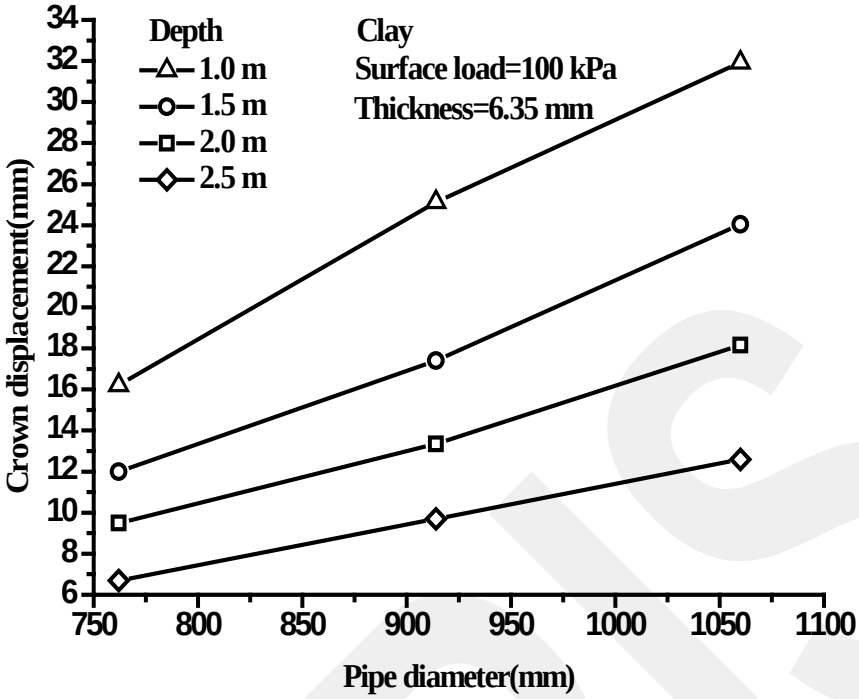


Figure 5.13 Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for loose sand soil under 50kPa surface load



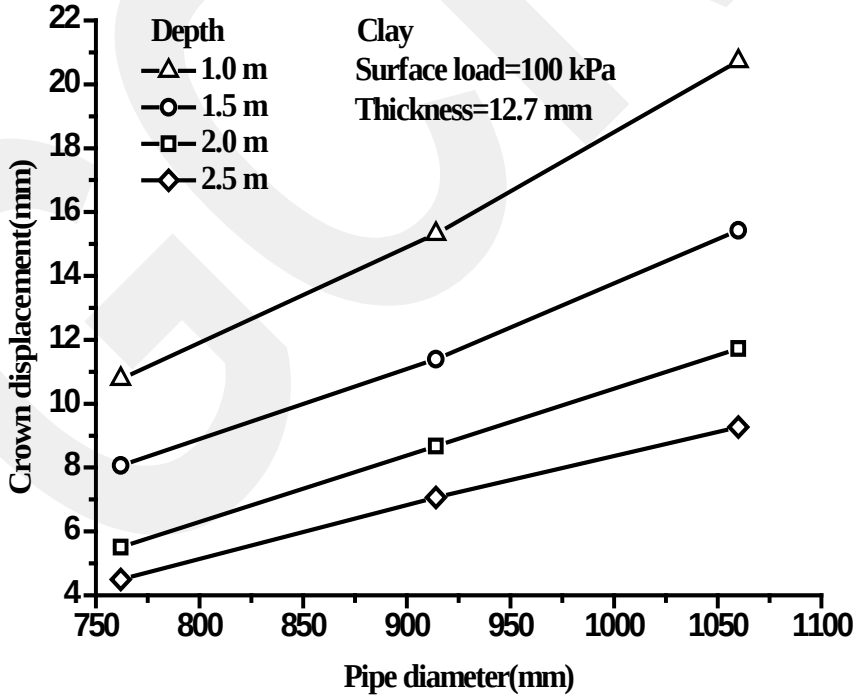


Figure 5.14Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for clay soil under 100kPa surface load

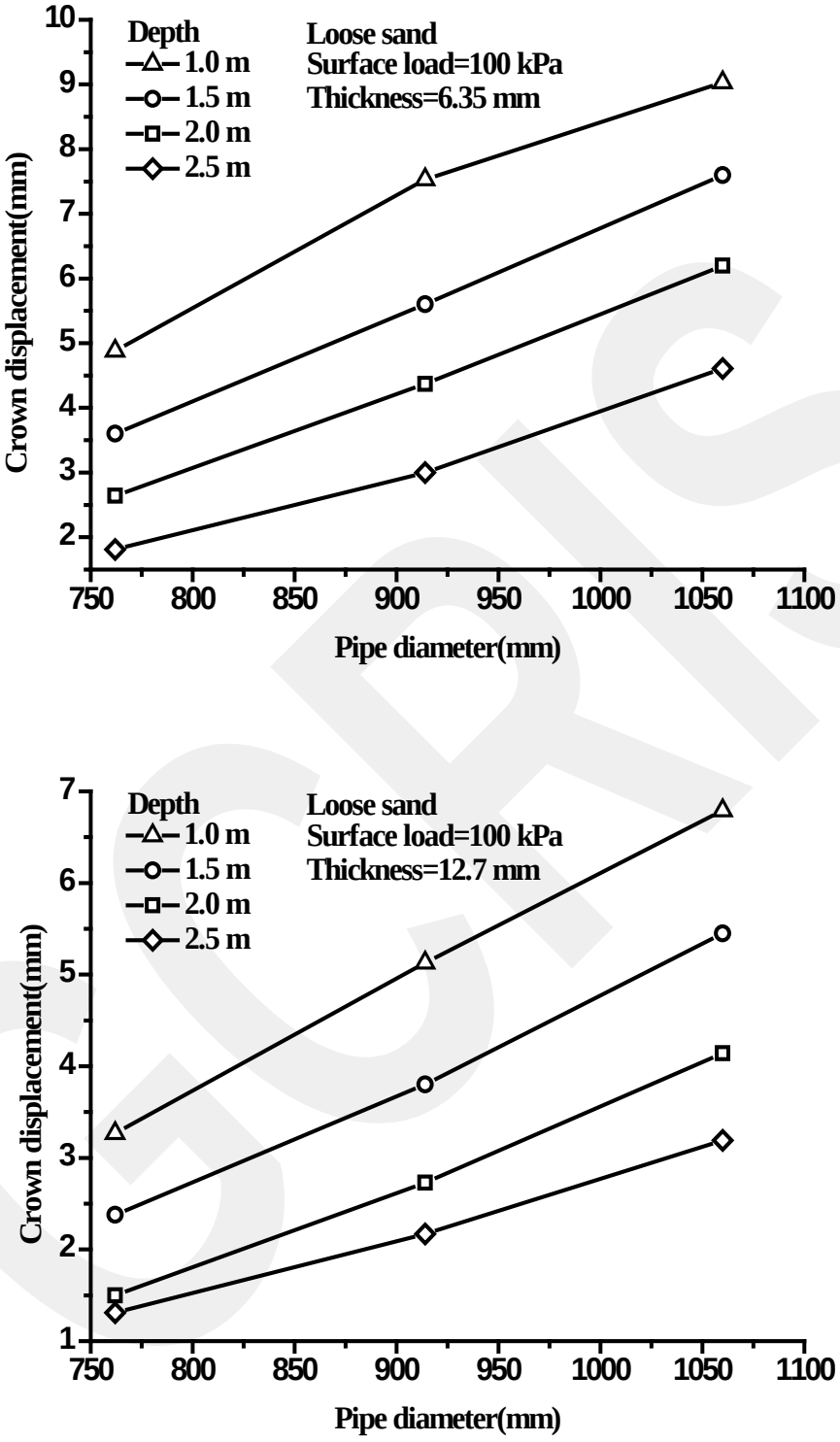
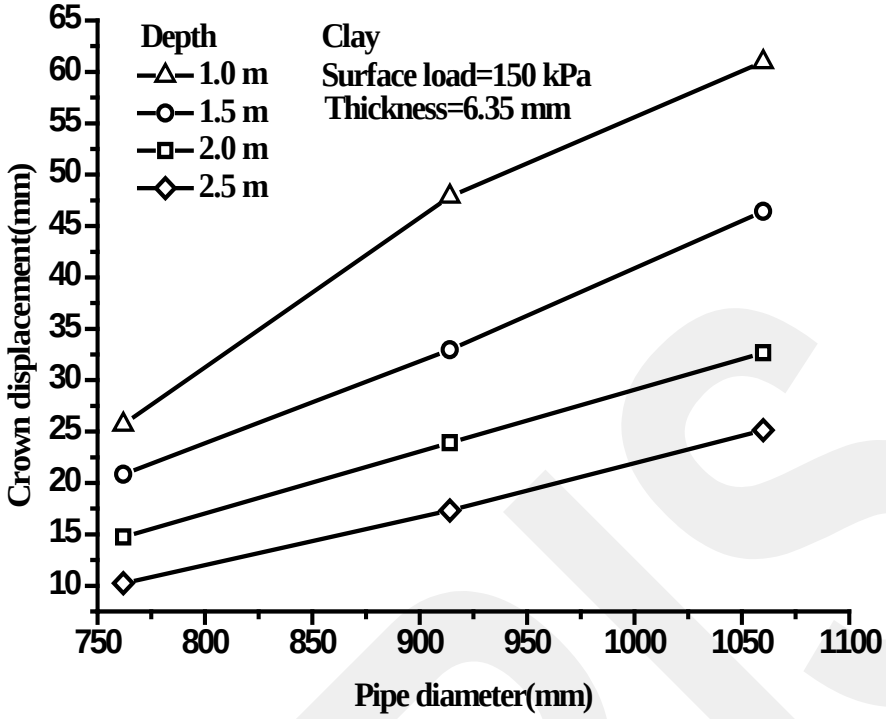


Figure 5.15 Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for loose sand soil under 100kPa surface load



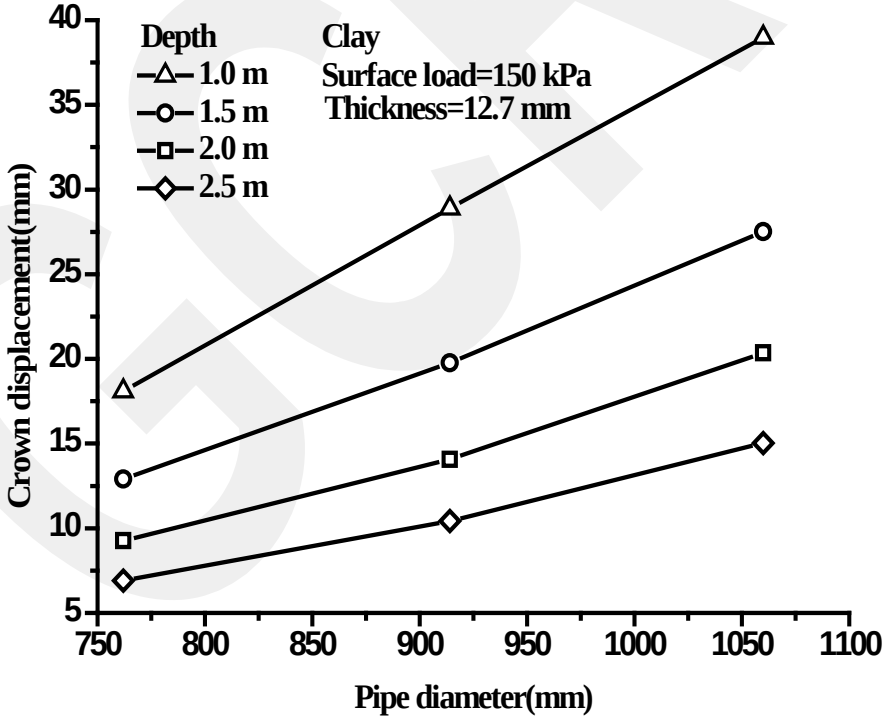


Figure 5.16Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for clay soil under 150kPa surface load

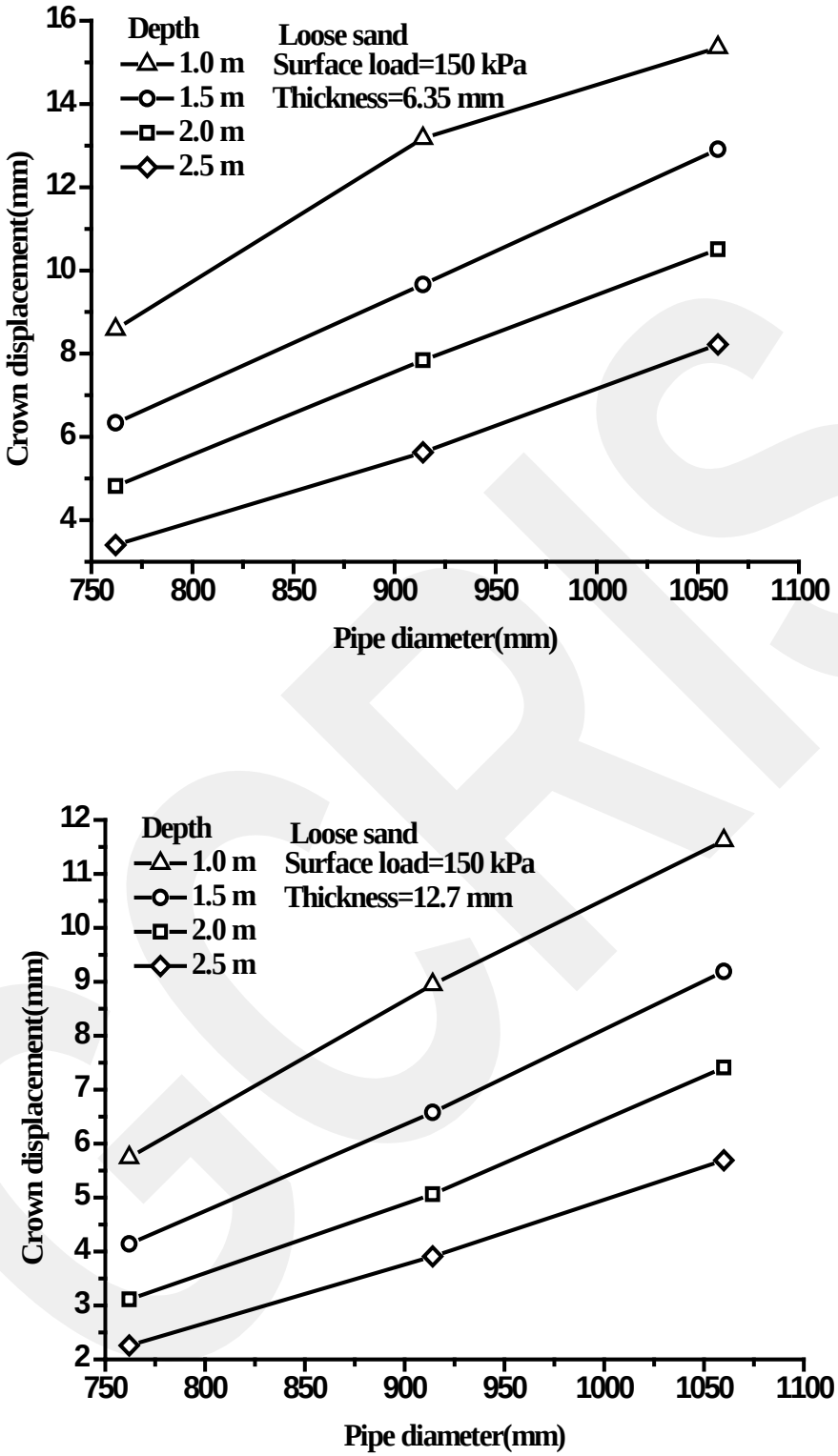
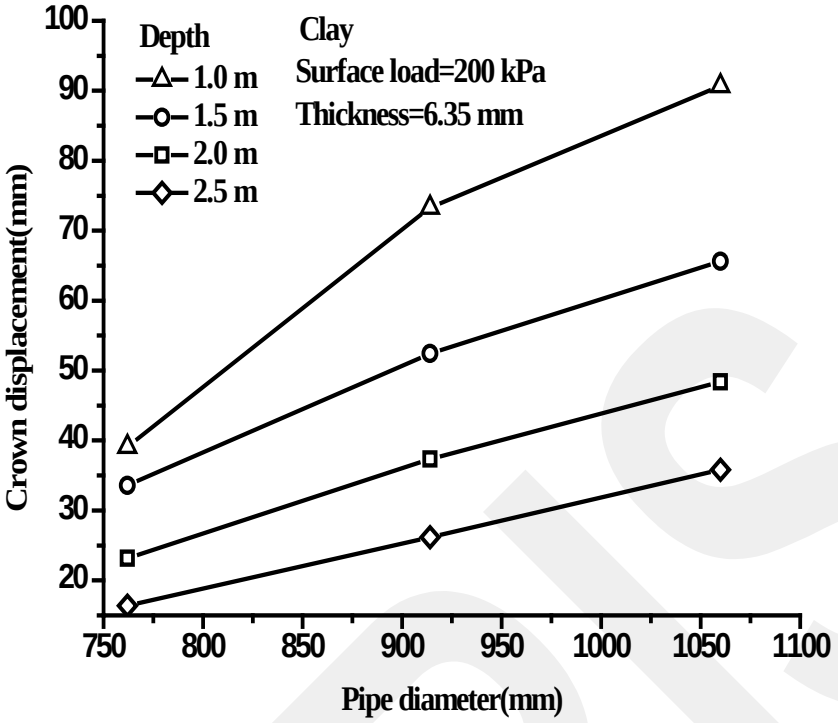


Figure 5.17 Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for loose sand soil under 150kPa surface loads



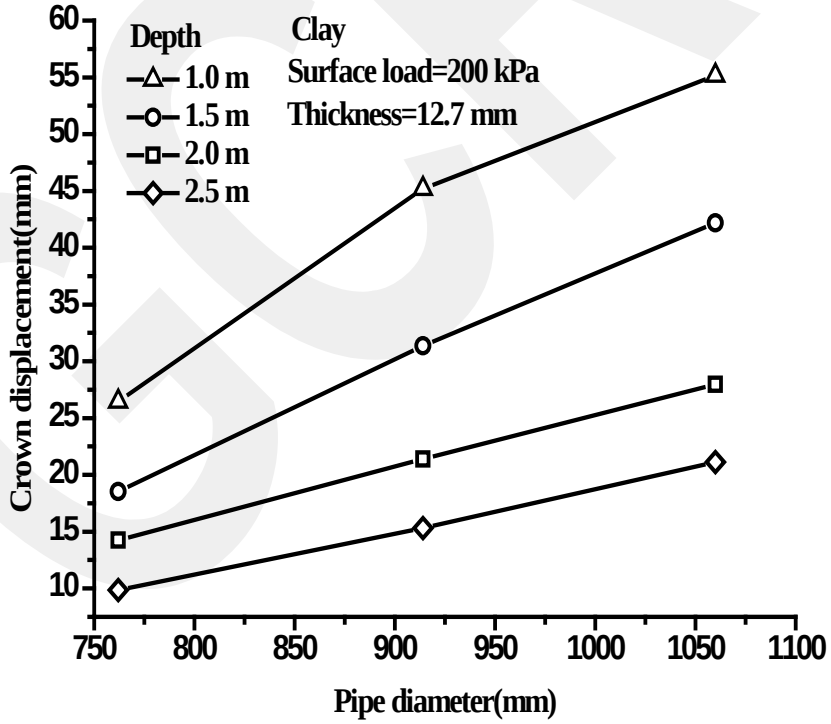


Figure 5.18 Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for clay soil under 200kPa surface load

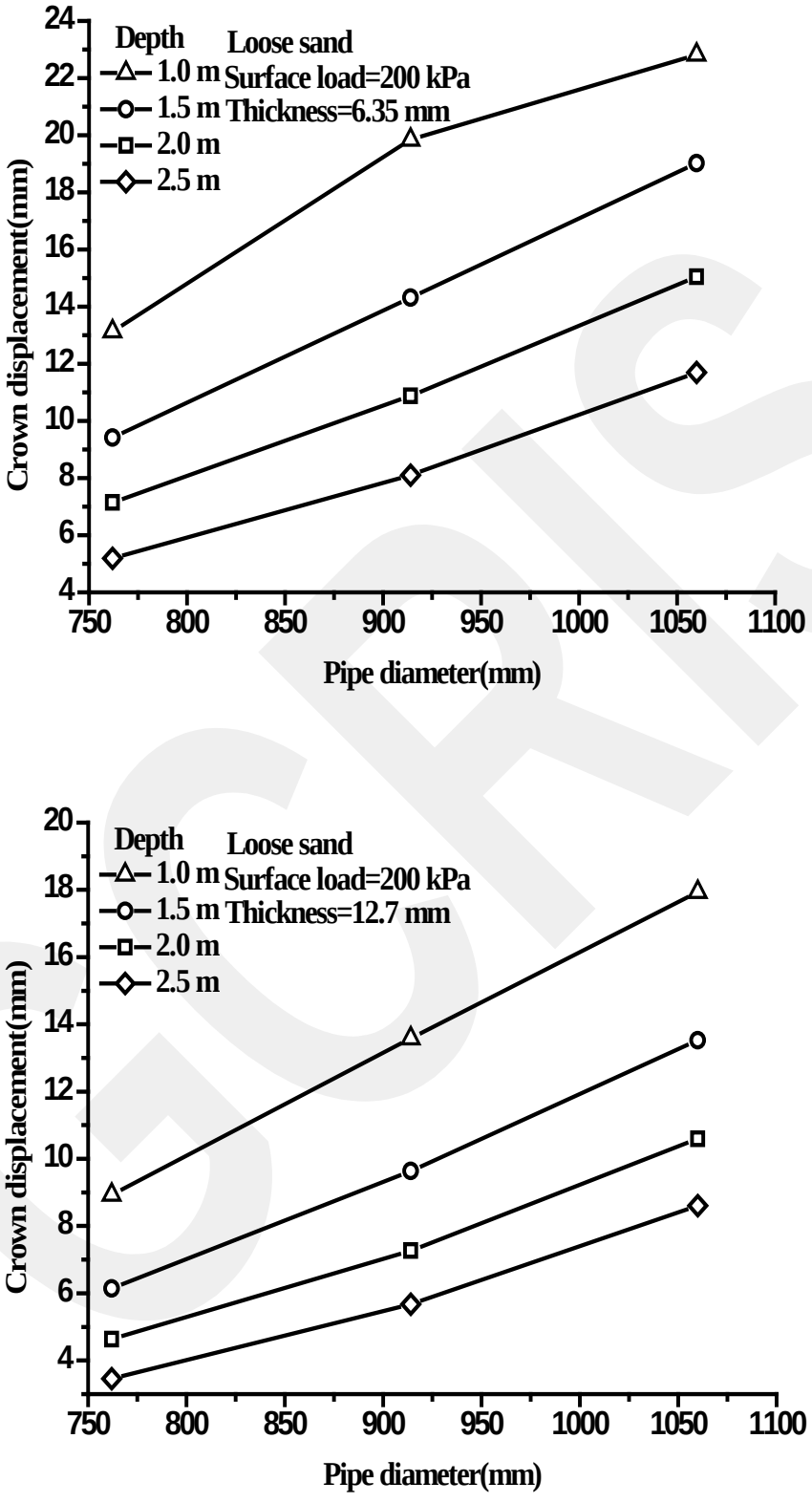
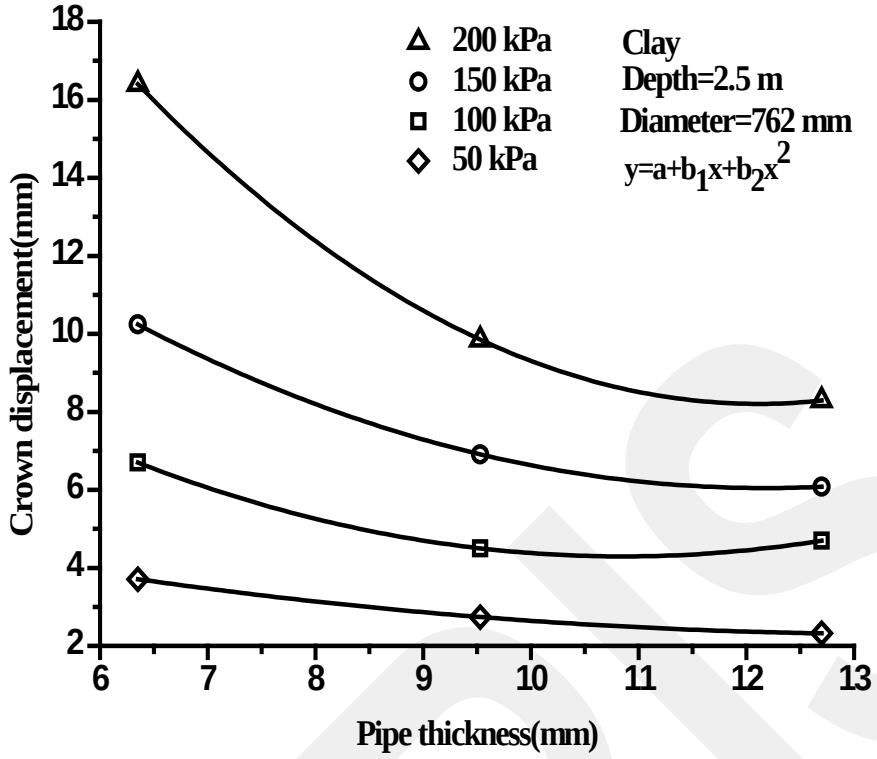


Figure 5.19Crown displacement for a given pipe diameter with t=6.35 and 12.7mm for loose sand soil under 200kPa surface load



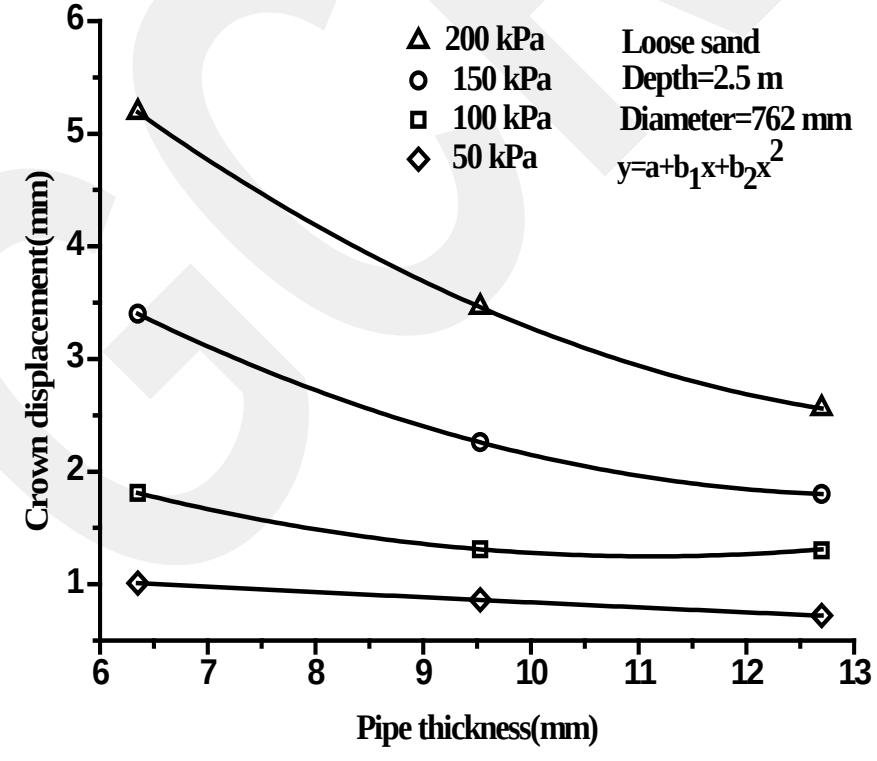


Figure 5.20 Crown displacement for a given pipe thicknessof D=762mm Inclay and loose sand soil under surface loads

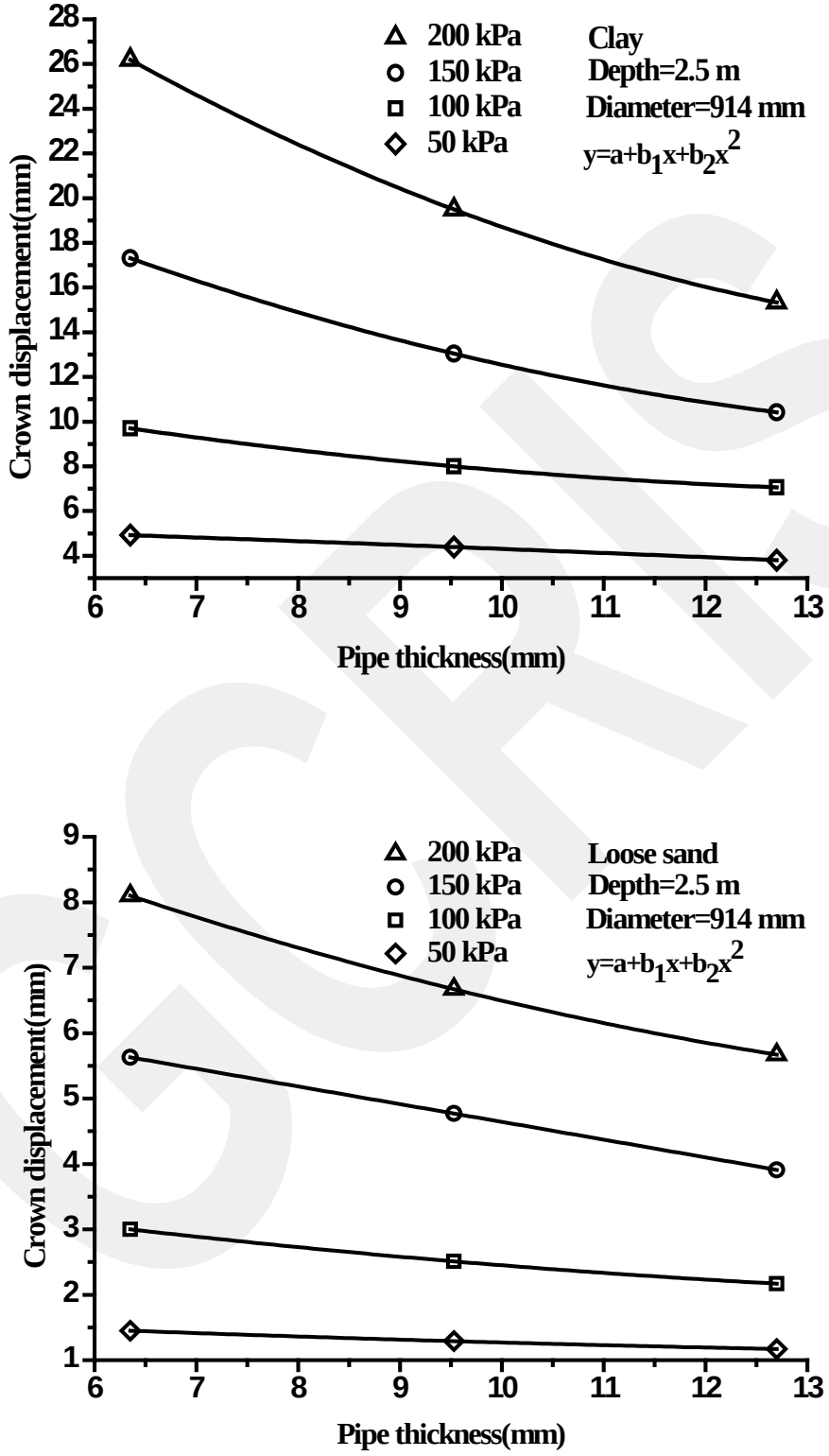


Figure 5.21Crown displacement for a given pipe thicknessof D=914mm inclay and loose sand soil under surface loads

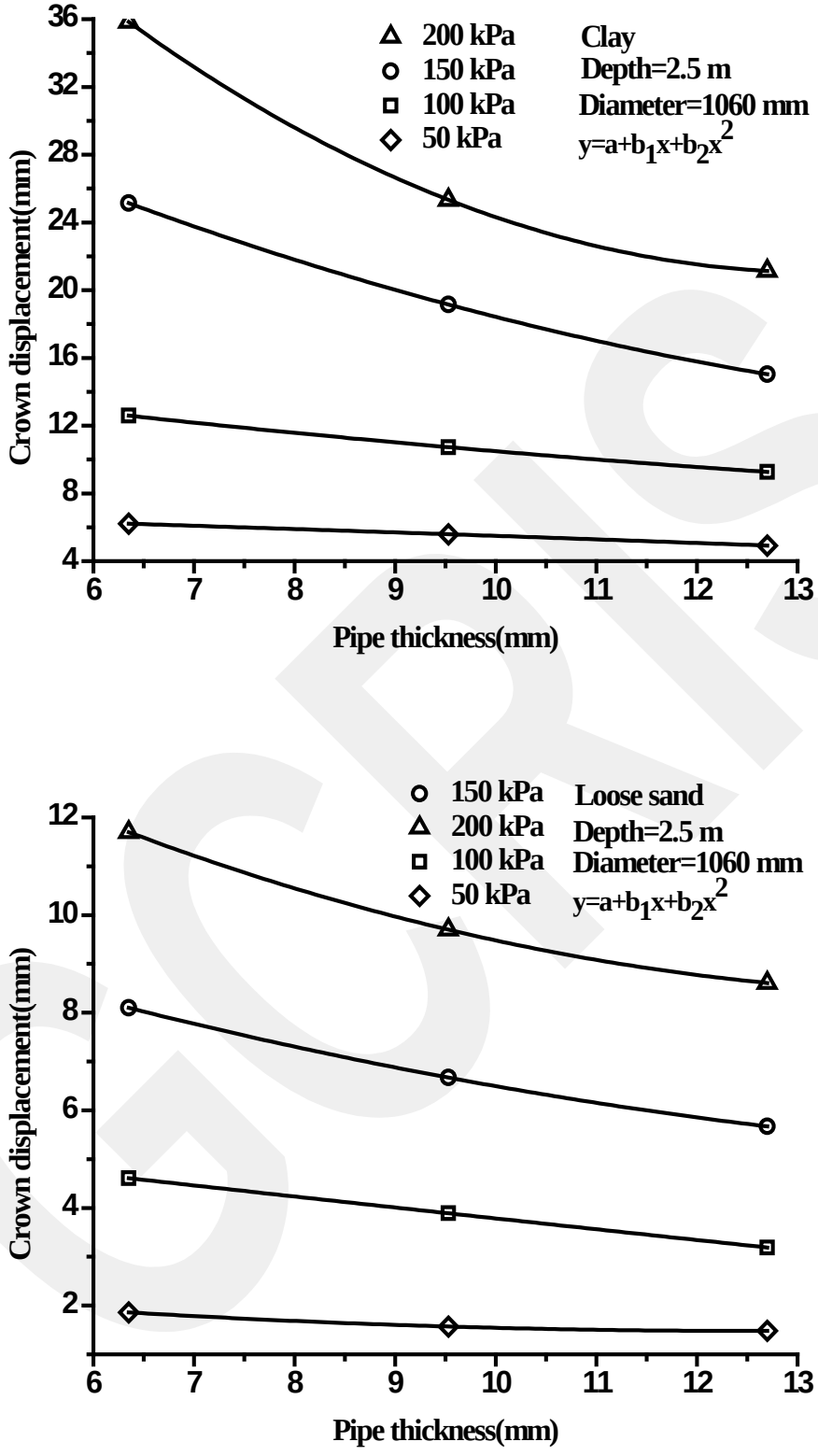


Figure 5.22Crown displacement for a given pipe thicknessof D=1060mm in clay and loose sand soil under surface loads

Table 5.3Polynomial coefficients of displacement – pipe thickness curve fitting

Diameter	Soil	Polynomial coefficients	Surface load			
			50kPa	100kPa	150kPa	200kPa
762 mm	Loose sand	a	1.3411	4.3068	7.7099	11.1234
		b_1	-0.0554	-0.5504	-0.8921	-1.1945
		b_2	5.2302	0.0247	0.0336	0.0409
	Clay	a	7.2912	18.2874	24.3738	44.4189
		b_1	-0.7365	-2.5797	-3.0111	-5.9800
		b_2	0.0271	0.1188	0.1236	0.2468
914 mm	Loose sand	a	1.8882	4.4247	7.3391	12.2347
		b_1	-0.08147	-0.2712	-0.2683	-0.7853
		b_2	0.0019	0.0073	-1.34E-4	0.02114
	Clay	a	5.7929	15.3633	30.756	47.1416
		b_1	-0.1180	-1.1299	-2.6338	-4.0940
		b_2	-0.0030	0.0374	0.0813	0.1251
1060 mm	Loose sand	a	3.0376	6.1010	12.2347	18.4105
		b_1	-0.2482	-0.2404	-0.7853	-1.3418
		b_2	0.0098	8.810E-4	0.0211	0.0448
	Clay	a	7.2918	17.4890	42.6663	75.6974
		b_1	-0.1539	-0.8958	-3.3440	-8.2568
		b_2	-0.0025	0.0195	0.0919	0.3118

As can be seen from Figures 5.12 – 5.22, the crown displacement increase with the increase of pipe diameter, while decreased with the increase of wall pipe thickness. The increase of pipe diameter simulates the maximum soil resistance. More recently, Wu et al. (2013) achieved the same results for the pipe diameter and wall thickness effectiveness (Figures B-6 and B-7).

CHAPTER 6

MULTI SOIL LAYERS

6.1 Preface

The current study is to estimate the effect of multi soil layers on the behavior of soil-pipe interaction. Finite element simulation (PLAXIS 2D program) isperformed to calculate the crown displacement of buried X65 steel pipeline subjected to surface loads of 200kPa.Multi soil layers means more characterization of soilstrength, to consider steel pipeline crossing two and three soils layers respectively, where crown pipe displacement varies with burying depth and diameter . The soil properties of soil layers and X65 steel pipeline are presented in Tables 6.1and 4.2, respectively. The FE geometry for two and three soil layers are shown in Figures 6.1, 6.2, respectively.

Table 6.1 Parameters of the soil medium around the pipe

Number of soil layers	**Type of soil**	**Properties**					
		Unit weight (kN/m^3)	Young modulus (kPa)	Poisson ratio	Cohesion (kPa)	Friction angel(°)	Dilatancy angle(°)
Two soil layers	Dense sand (Lin et al., 2012)	19.6	65000	0.35	5	30	0
	Clay (Jeon,2013)	15	5000	0.35	10	20	0
Three soil layers	Dense sand (Lin et al., 2012)	19.6	65000	0.35	5	30	0
	Medium sand (Jeon,2013)	19	25000	0.3	0	28	0
	Clay (Jeon,2013)	15	5000	0.35	10	20	0

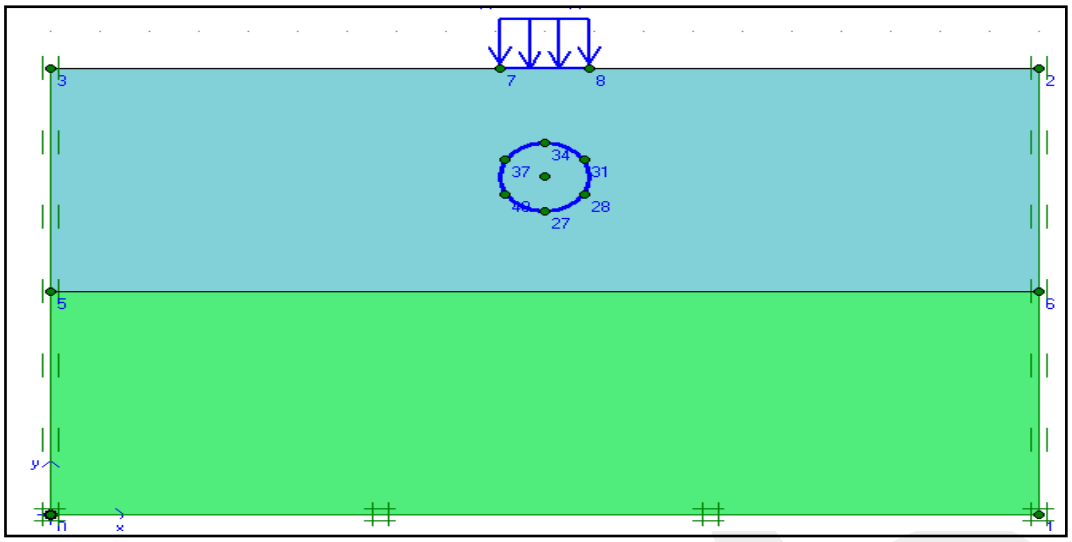


Figure 6.1Geometric models for two soil layers

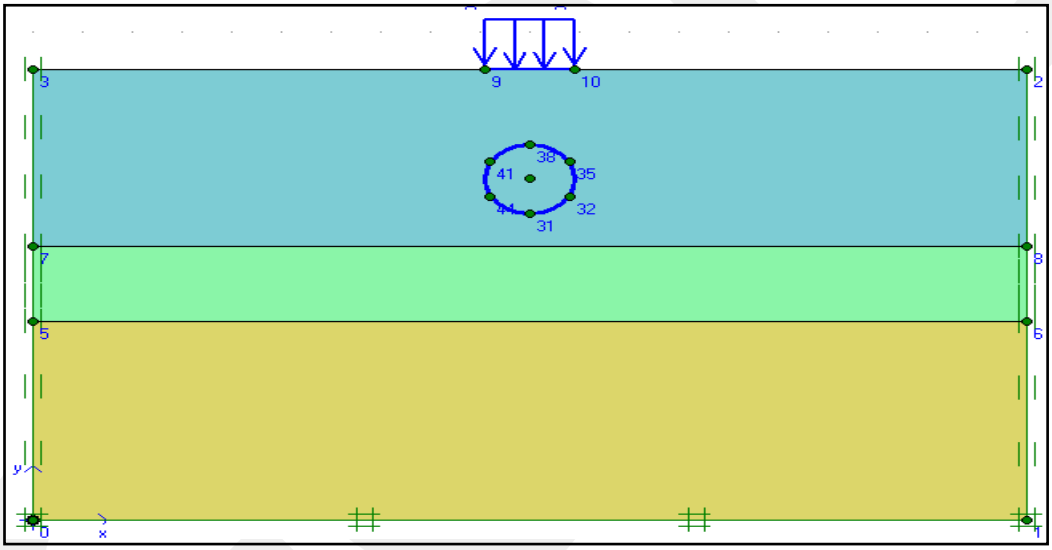


Figure 6.2Geometric modelsfor three soil layers

6.2 Two soil layers

6.2.1 Effect of pipe burial depth on crown displacement

Figure 6.3 shows the typical geometry of the pipeline in two soil layers. Under surface static load, the influence of burying depth on crown displacement of X65 steel pipeline is considered (Figure C-1); results obtained are summarized in Figures 6.4 - 6.6 for the diameter under study(762-1060 mm). Both ﻟay soil and dense sand are considered, where each of them having a height of 3m. Different depths of embedment (1,1.5,2, 2.5 and 3.5m) were considered. Surface static pressure load of

200kPa is applied to the surface of the soil. Table 6.2 lists out the polynomial coefficients ofthe curve fitting.

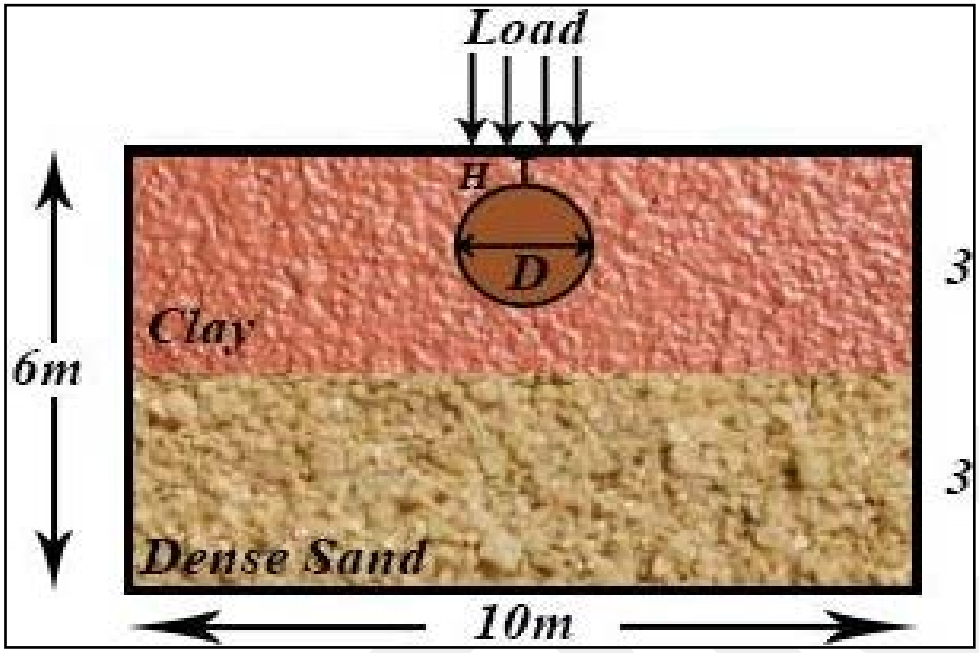


Figure 6.3Typical geometry of pipeline in two soil layers

Table 6.2 Polynomial coefficients of displacement- burial depthcurvesin two soil layers

Thickness	Polynomial parameters	Diameter(mm)		
		1060	914	762
6.35 mm	a	135.132	124.579	94.345
	b_1	-66.832	-82.733	-58.890
	b_2	2.682	16.392	9.5036
	b_3	1.588	-0.798	-0.08138
9.52 mm	a	113.084	-	-
	b_1	-69.073	-	-
	b_2	10.396	-	-
	b_3	0.0779	-	-
9.53 mm	a	-	96.061	-
	b_1	-	-69.927	-
	b_2	-	16.238	-
	b_3	-	-1.138	
12.7 mm	a	66.650	77.684	77.705
	b_1	-34.493	-61.330	-70.415
	b_2	2.1789	16.087	21.848
	b_3	0.6826	-1.372	-2.285
17.5 mm	a	-	-	79.554
	b_1	-	-	-79.665
	b_2	-	-	27.131
	b_3	-	-	-3.086

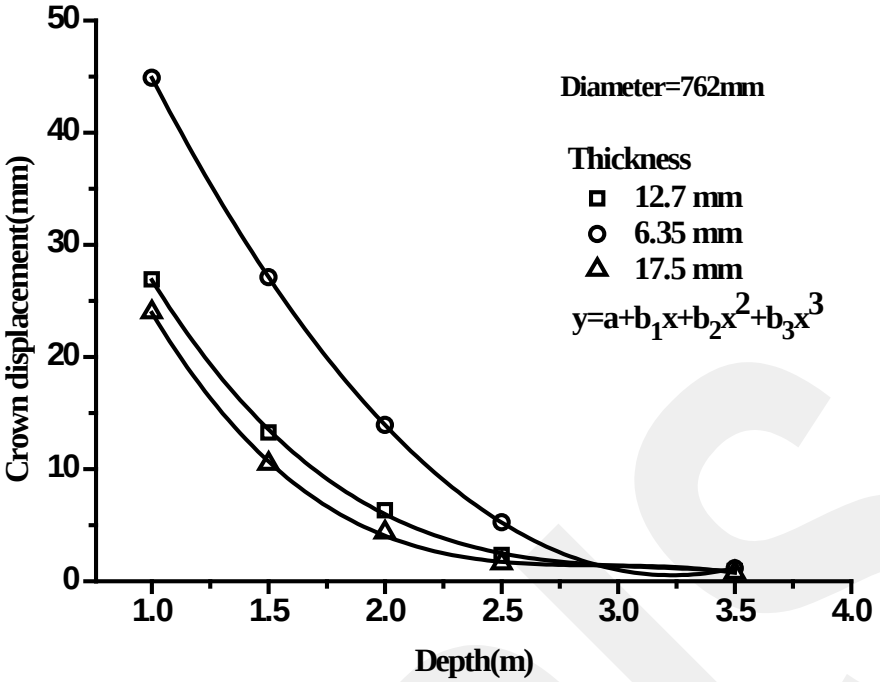


Figure 6.4Displacement versus burial depth in two soil layers for D=762mm

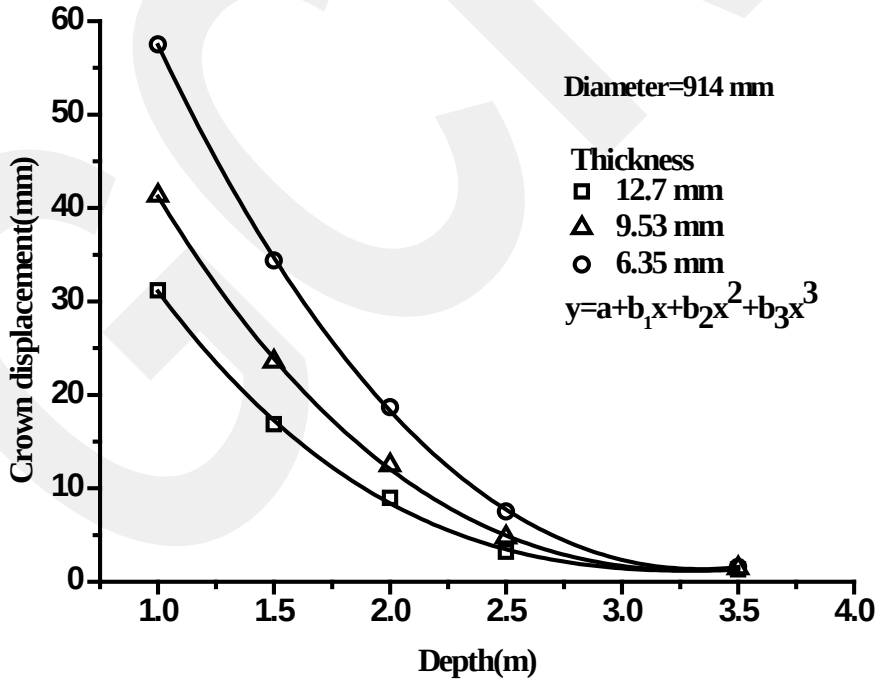


Figure 6.5Displacement versus burial depth in two soil layers forD=914mm

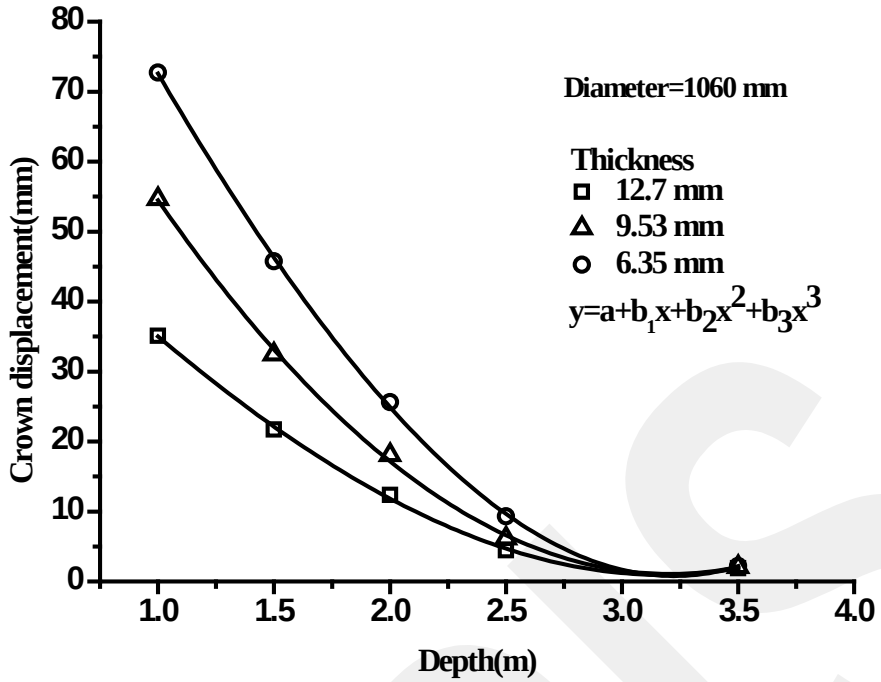


Figure 6.6Displacement versus burial depth in two soil layers forD=1060mm

The crown displacement reduces as the burying depth increases. This is due to the effects of overburden pressure. This means that the shallow buried depth, the poorer performance of the pipe, while great embedment can improve pipe performance. The results (less than 2.5m, within clay) compared with the finite element simulation of pipeline embedded in one soil layer (Figures 5.2 -5.10), in which the crown displacement of pipe embedded in two soil layers is less than that embedded in single layer. These results are common for all diameters and thicknesses under study. Another feature apparent in these figures at burial depth of more than 2.5m is the slow variation of crown displacement compared with those values of depth less than 2.5m.

6.2.2 Effect of pipe diameter on crown displacement

In this section, the prescribed diameters and depths in the previous section are used. With thicknesses 6.35 and 12.7mm, the role of X65 steel pipeline diameter in pipe crown displacement under 200 kPa are also analyzed (Figures 6.7 and 6.8).With

increase of diameter of pipes, the response displacement increases. Table 6.3 lists out the polynomial coefficients of fitting curves.

Table 6.3 Polynomial coefficients of displacement- diameter curves intwo soillayers

Depth(m)	Polynomial coefficients	Thickness (mm)	
		t=6.35	t=12.7
1.0	a	-222.516	30.476
	b_1	0.4741	-0.066
	b_2	-1.902E-4	6.194E-5
1.5	a	-115.451	-0.1909
	b_1	0.2451	-0.0037
	b_2	-9.652E-5	1.936E-5
2.0	a	-47.246	-8.6038
	b_1	0.1000	0.01661
	b_2	-3.855E-5	-
2.5	a	-6.8921	-4.6201
	b_1	0.01408	0.00936
3.5	a	-1.5025	-1.4792
	b_1	0.00373	0.00332

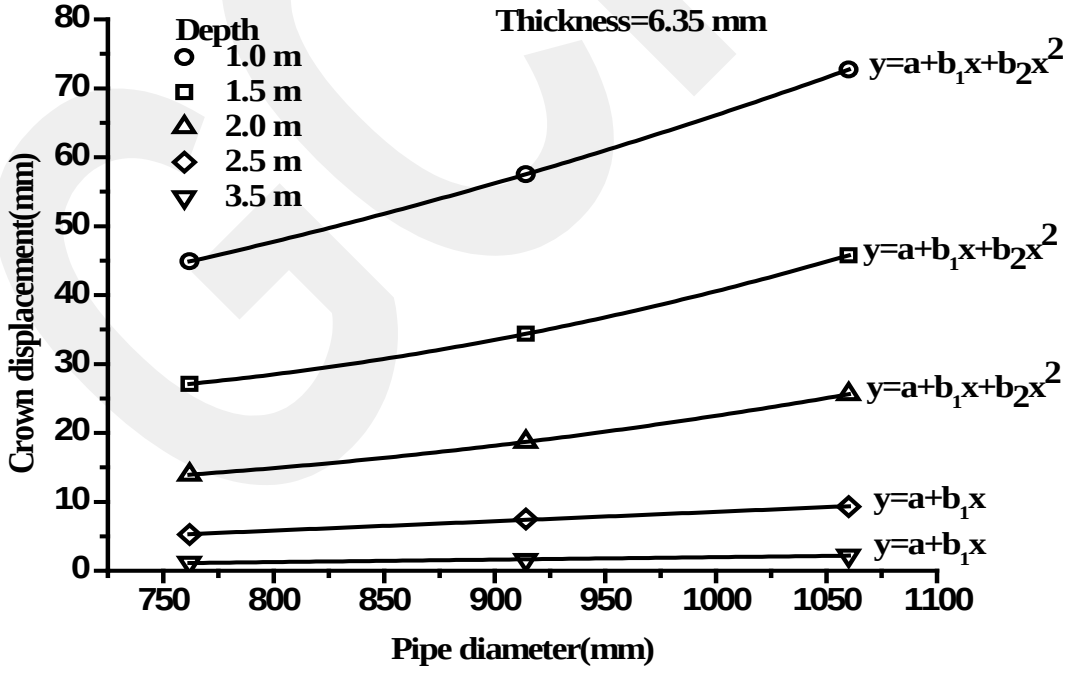


Figure 6.7Displacement versus pipe diameter for t=6.35mm in two soil layers

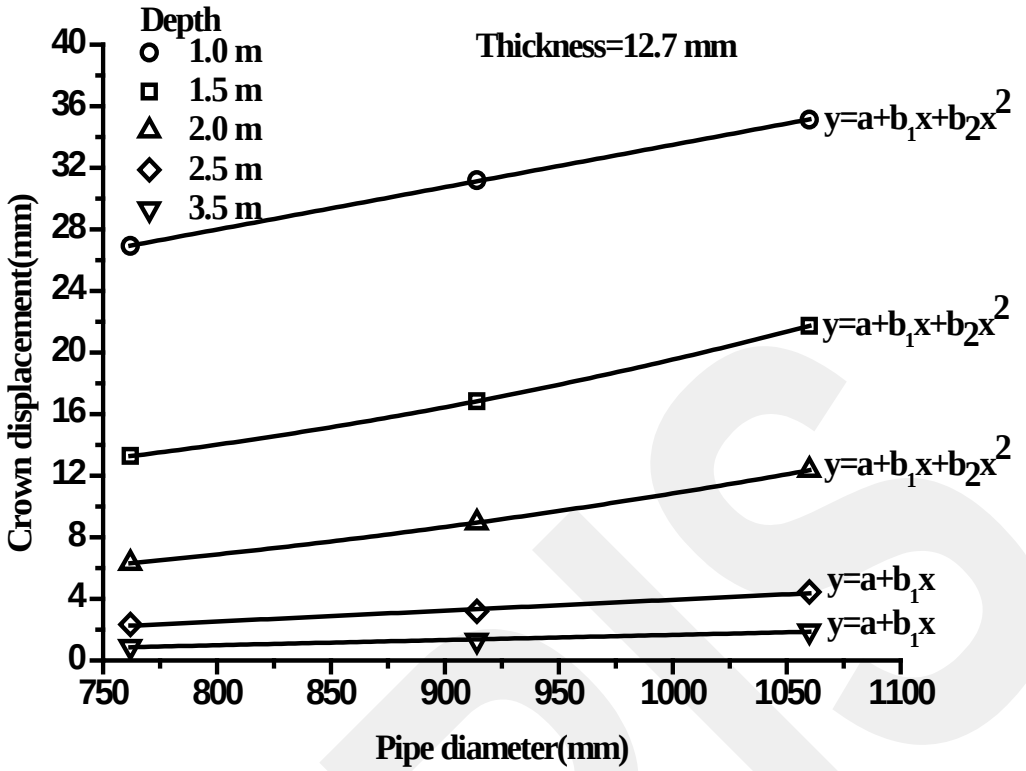


Figure 6.8Displacement versus pipe diameter for t=12.7mm in two soil layers

6.3Three soil layers

6.3.1 Effect of pipe burial depth on crown displacement

Under surface load of 200kPa, our finite element model consists of three soils such as clay, medium and dense sand with heights2.35m,1.0m and 2.65m, respectively(Figure 6.9). As adopted in the previous section, X65 steel pipes are laid horizontally with various burial depths with no slip assumption. The mechanical properties of soils are listed in Table 6.1.The coefficient of fitting curves is listed in Table 6.4.

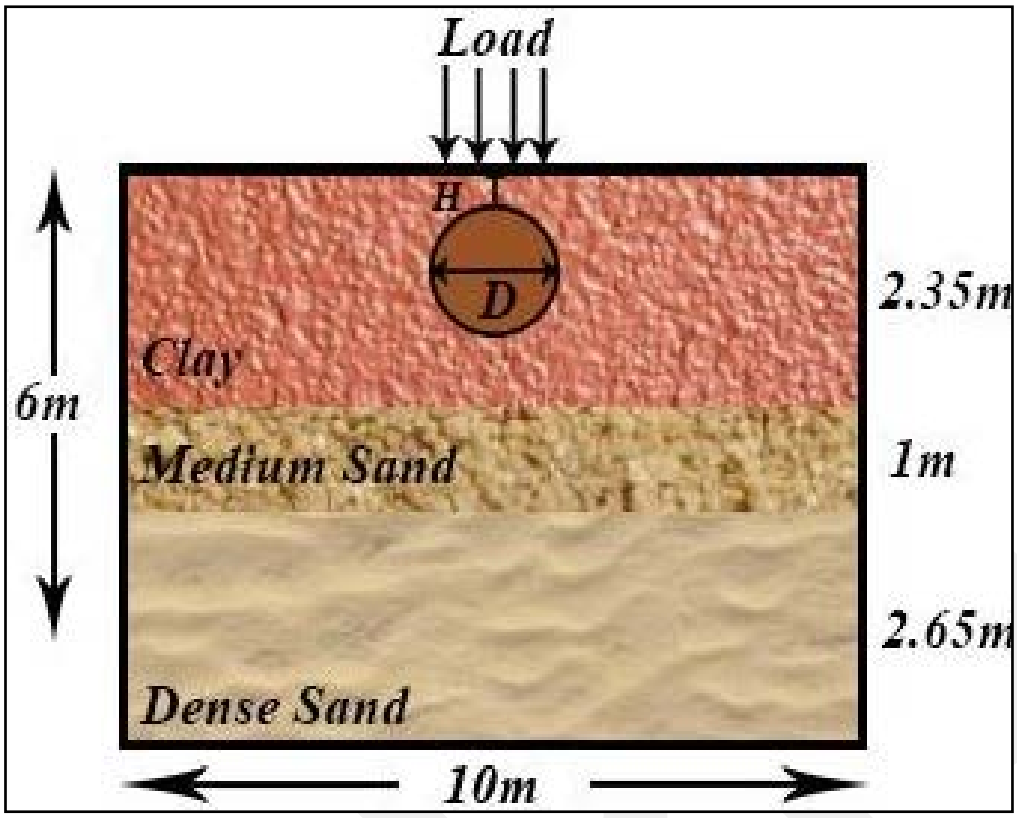
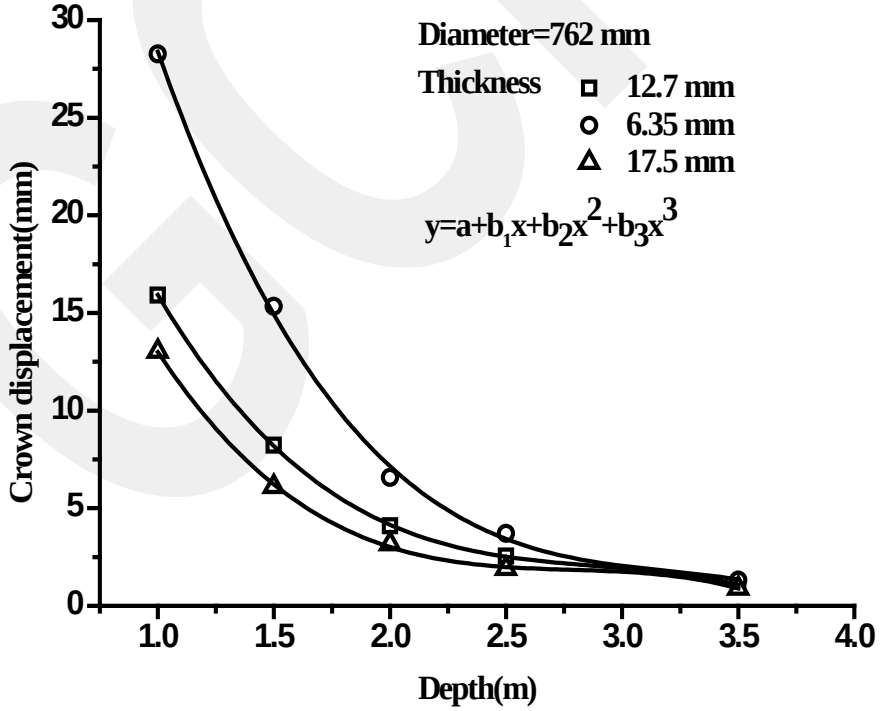
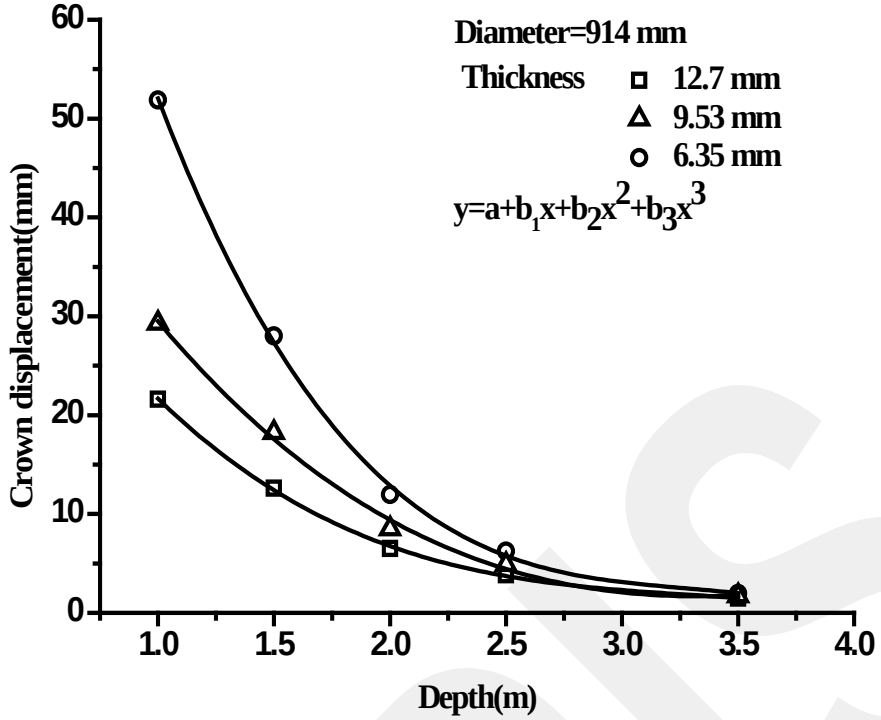


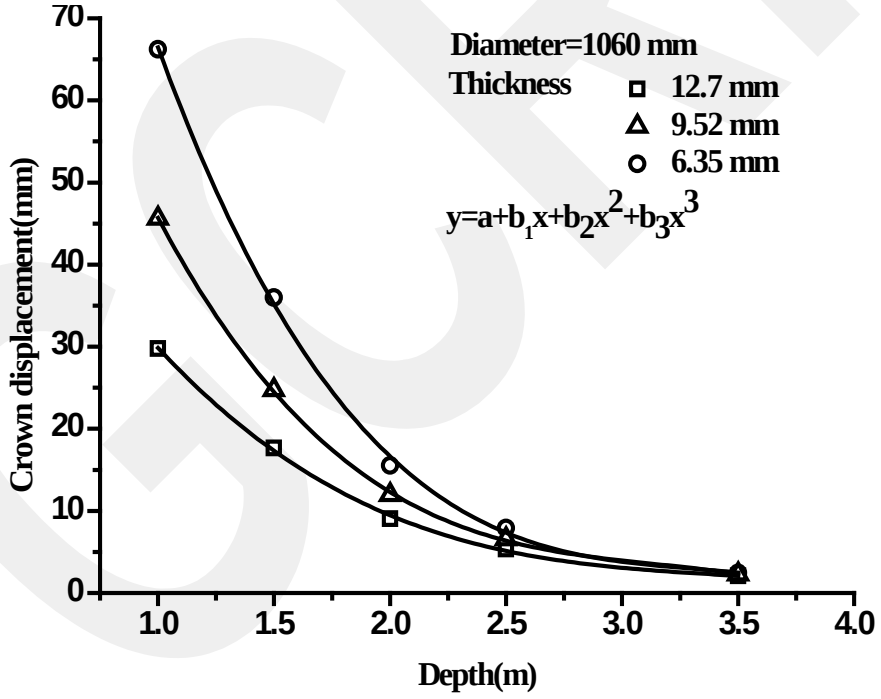
Figure 6.9Typical geometry of pipeline in three soil layers



Figures 6.10Displacement versus depth in three soil layersfor D=762mm



Figures 6.11Displacement versus depth in three soil layers for D=914mm



Figures 6.12Displacement versus depth in three soil layers for D=1060mm

Table 6.4 Polynomial coefficients of displacement- burial depth curves in three soil layers

Thickness(mm)	Polynomial parameters	Diameter(mm)		
		1060	914	762
6.35	a	181.3	143.857	79.188
	b_1	-156.696	-125.887	-70.07
	b_2	46.53	37.947	21.505
	b_3	-4.673	-3.874	-2.24
9.52	a	126.124	-	-
	b_1	-111.310	-	-
	b_2	34.536	-	-
	b_3	-3.669	-	-
9.53	a	-	66.829	-
	b_1	-	-47.501	-
	b_2	-	10.908	-
	b_3	-	-0.756	-
12.7	a	73.912	55.003	47.876
	b_1	-59.091	15-45.2	-45.592
	b_2	16.656	13.203	15.411
	b_3	-1.610	-1.329	-1.772
17.5	a	-	-	42.879
	b_1	-	-	-43.553
	b_2	-	-	15.535
	b_3	-	-	-1.862

Figures 6.10 - 6.12 show the effect of pipe burial depth on crown displacement at various depths (1, 1.5, 2, 2.5, and 3.5m), where crown displacement decreases as burial depth of pipe increased. These results were expected due to the fact that increasing the burial depth of pipe would limit pipe–soil friction force acting on unit length of the pipeline. Comparison with Figures 5.2 – 5.10shows that below 1.5m depth, the value of crown displacement obtained by three soil layer framework is smaller than those calculated in the frame of two or single soil layer.

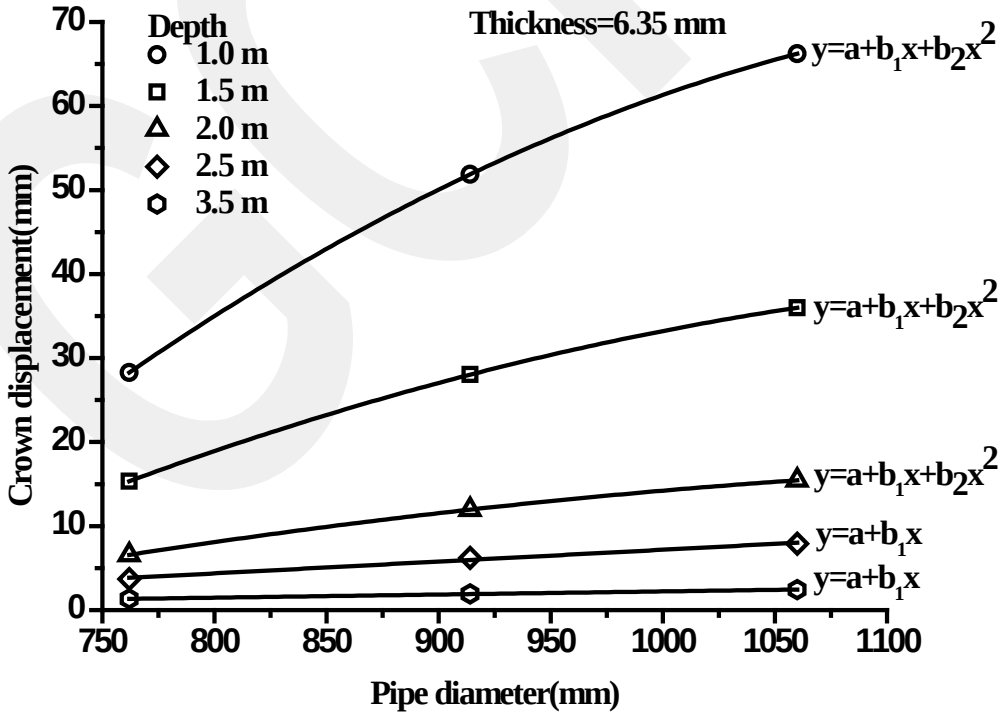
6.3.2 Effect of pipe diameter on crown displacement

In this section the effect of pipe diameter on crown displacement in 1-3.5m depths, three different soils and thicknesses of 6.35 and 12.7 mm have been investigated. As can be seen in Figures 6.13 and 6.14, when pipe diameter increases,

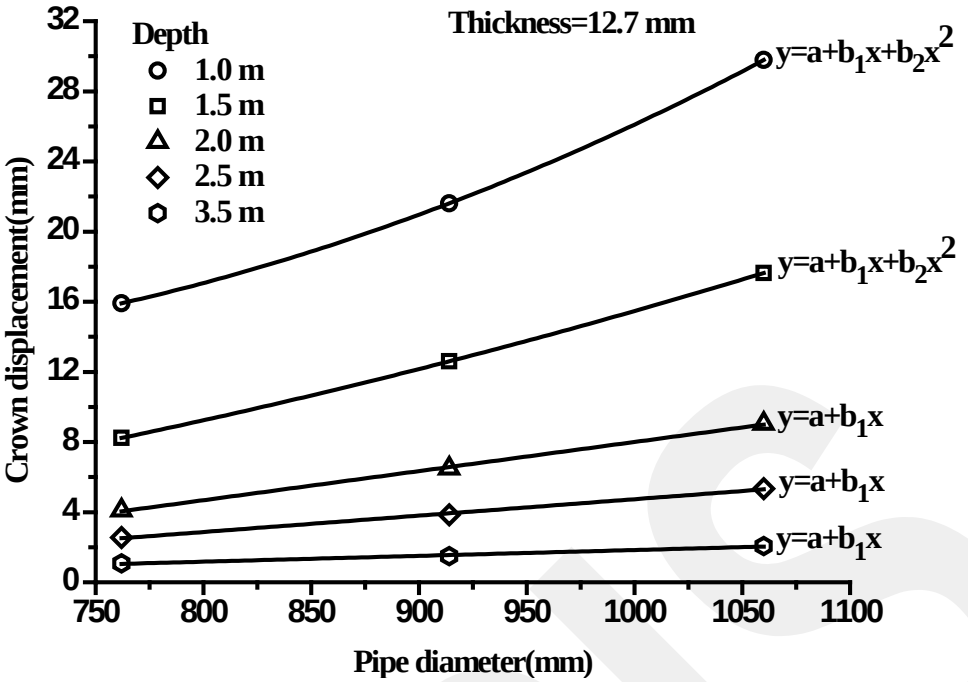
crown displacement increases. Results reveal that the contact between the overburden soil and pipe diameter increases.Table 6.5 lists out the polynomialcoefficients of fitting this relation.

Table 6.5 Polynomial coefficients of displacement- pipe diameter curves in three soil layers

Depth(m)	Polynomial coefficients	Thickness (mm)	
		t=6.35	t=12.7
1.0	a	-222.516	30.476
	b_1	0.4741	-0.066
	b_2	-1.902E-4	6.194E-5
1.5	a	-115.451	-0.1909
	b_1	0.2451	-0.0037
	b_2	-9.652E-5	1.936E-5
2.0	a	-47.246	-8.6038
	b_1	0.1000	0.01661
	b_2	-3.855E-5	-
2.5	a	-6.8921	-4.6201
	b_1	0.01408	0.00936
3.5	a	-1.5025	-1.4792
	b_1	0.00373	0.00332



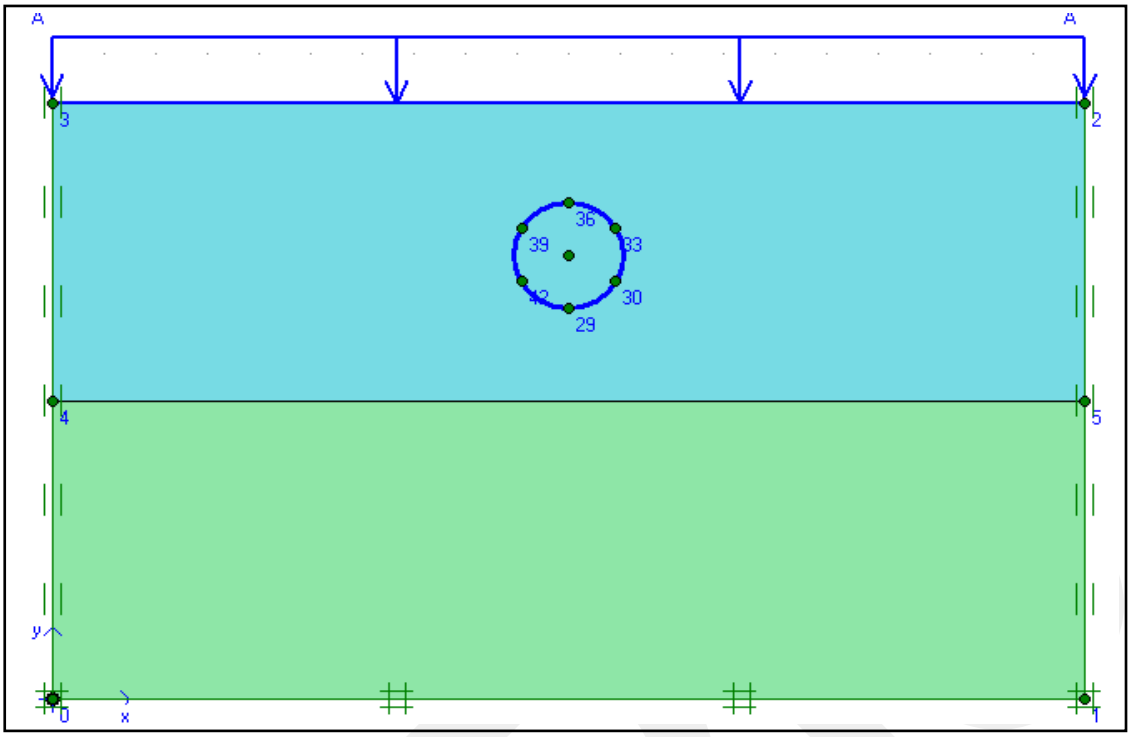
Figures 6.13Displacement versus pipe diameter in three soil layers for t=6.35 mm



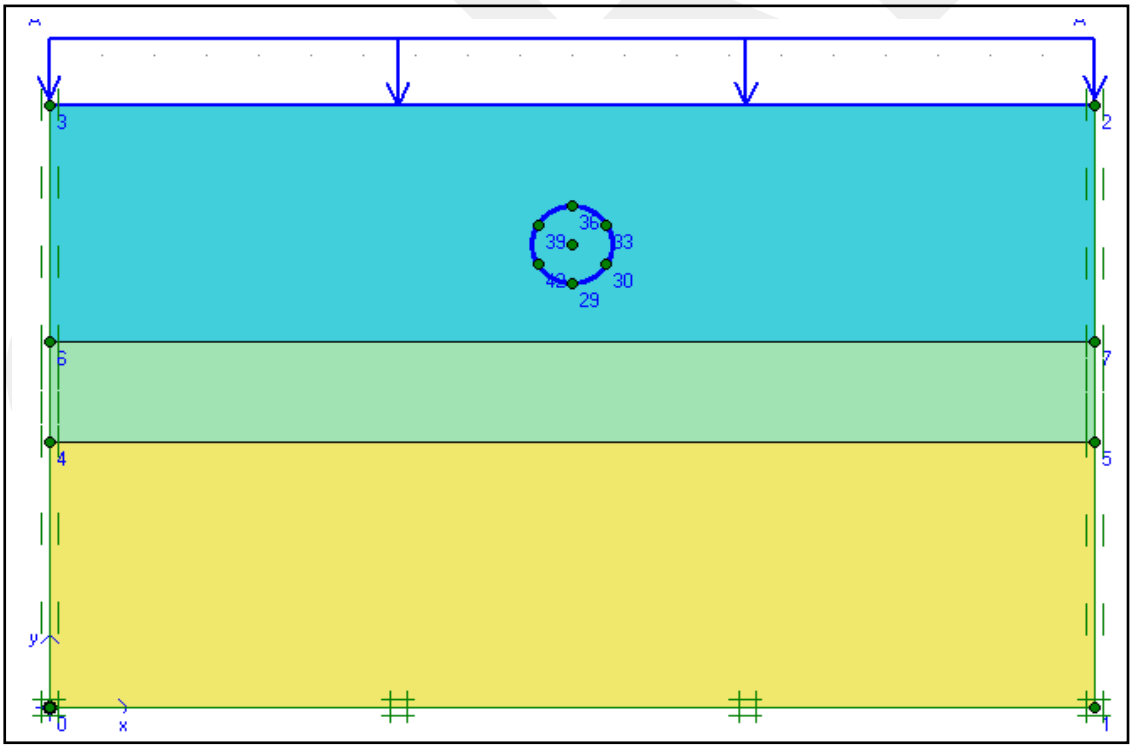
Figures 6.14Displacement versus pipe diameter
in three soil layers for t=12.7 mm

6.4 Pipes under static water load

To simulate the behavior of X65 buried pipeline under static water loads, where water layer of height 20m is above the soil,the effective water pressure on buried pipeline is calculated as water height multiply by its density ($10kN/m^3$). The properties of two and three soil layers for thickness of 6.35mm pipeline – is summarized in previous sections. The finite element geometry for two and three soil layers are shown in Figure 6.15. Figure 6.16 shows the typical geometry of the pipeline in two and three soil layers. Embedment depths (1, 1.5, 2, 2.5 and 3.5m) of two and three soil layers are plotted against pipe crown displacement in Figures 6.17 and 6.18, and the polynomial coefficients of curve fitting are listed in Table 6.6.The influence of pipe diameter on crown pipe displacement are investigated by Figures 6.19 and 6.20 for two soil layers and three soil layers respectively, and Table 6.7 shows the parameters of the curvefitting. Assuming that the case of sections 6.1 and 6.2 happened with limited load, where the applied load is restricted by the pipe diameter(limited load), while the present case is treated as extended load (extended load). A comparative study between these two cases has been illustrated in Figures 6.21 and 6.22 for two and three soil layers, respectively.



(a)



(b)

Figure 6.15Finite element geometric models for (a) two soil layers;

(b) three soil layers

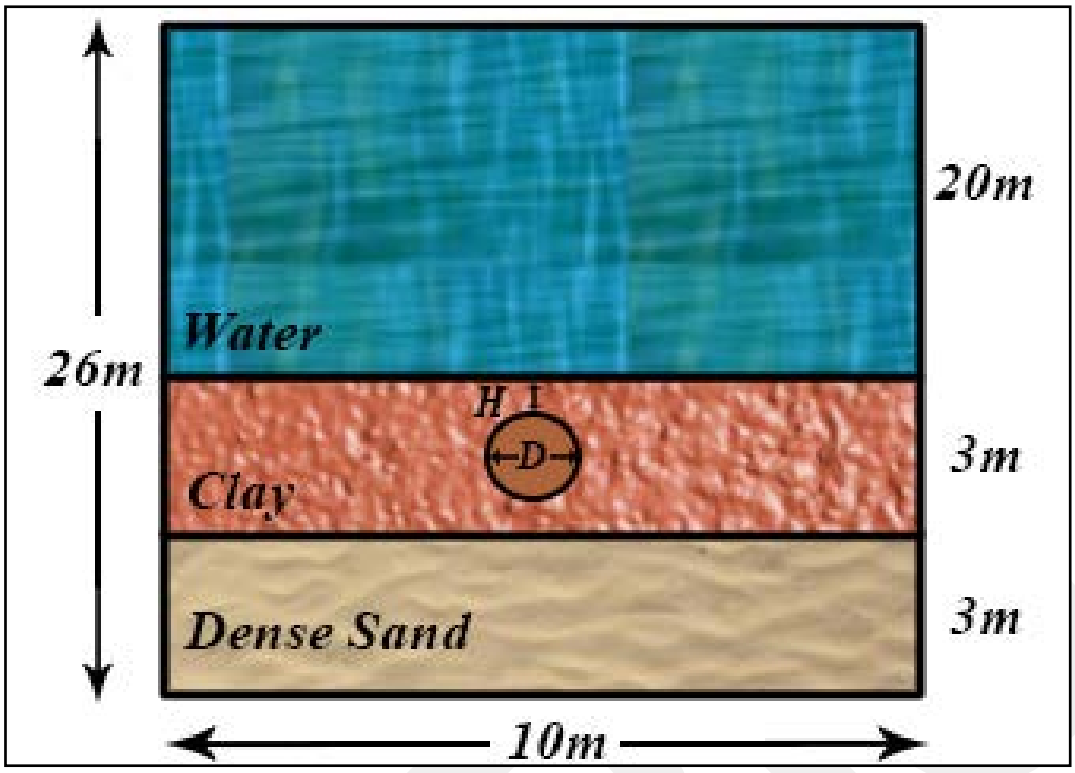


Figure 6.16Typical geometry of pipeline in two soil layers under water pressure

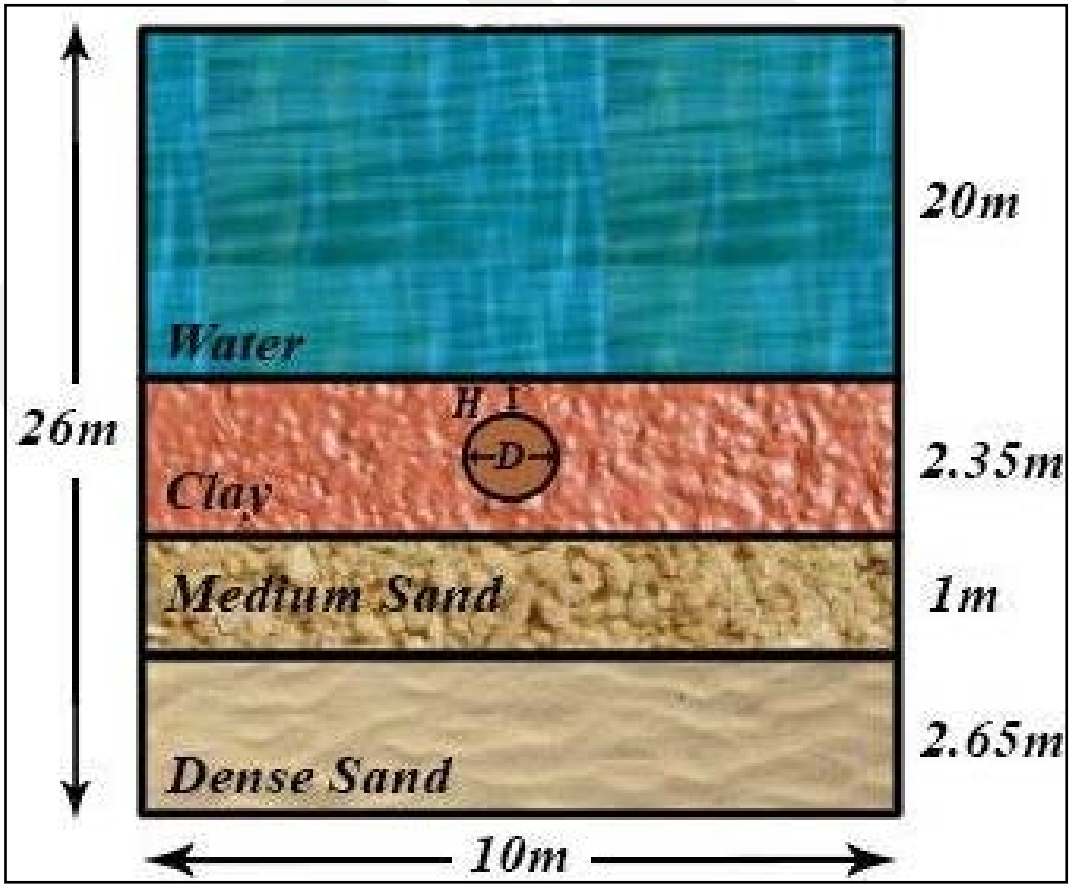


Figure 6.17Typical geometry of pipeline in three soil layers under water pressure

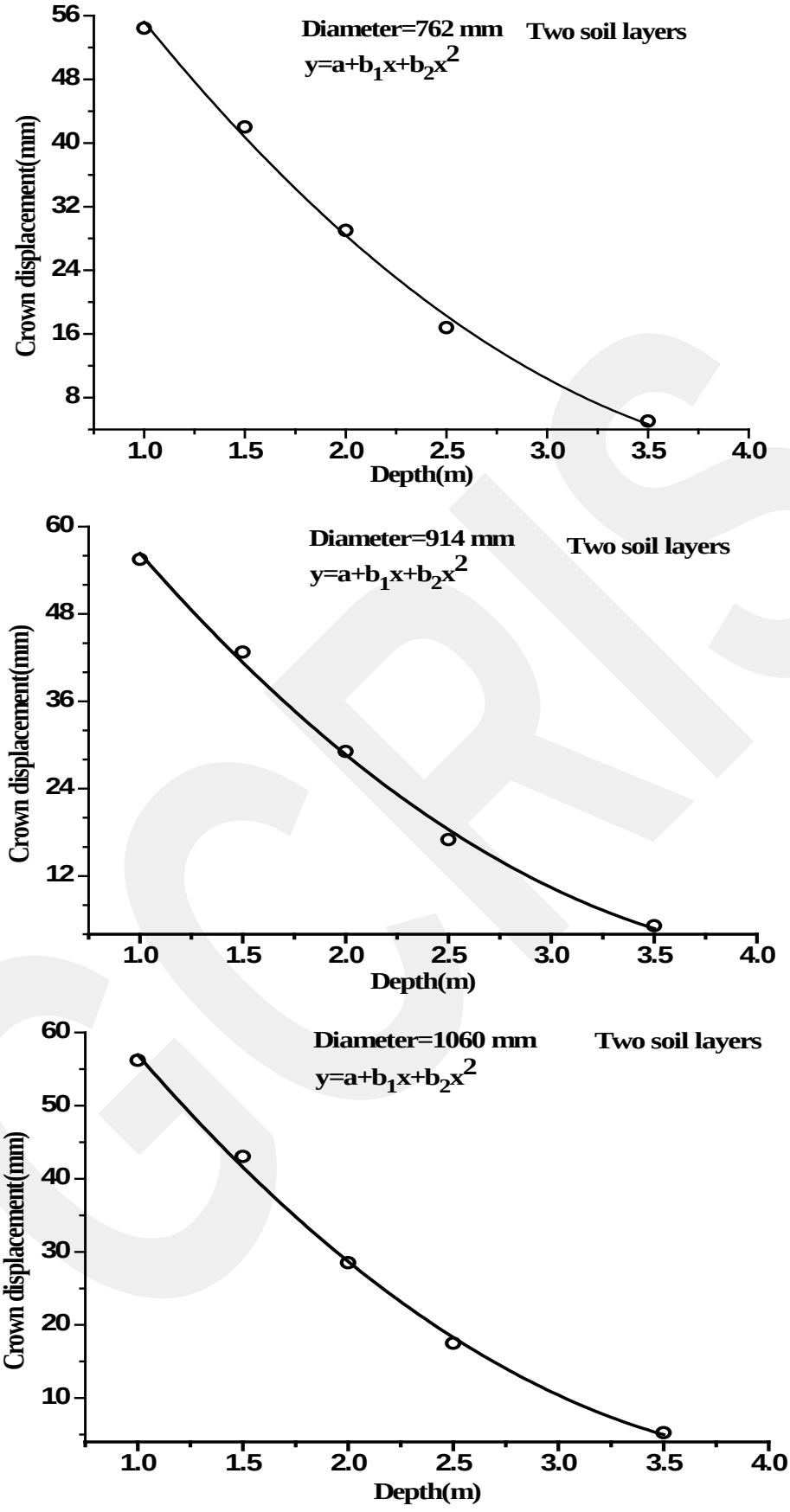


Figure 6.18Crown displacements versus depths in two soil layers

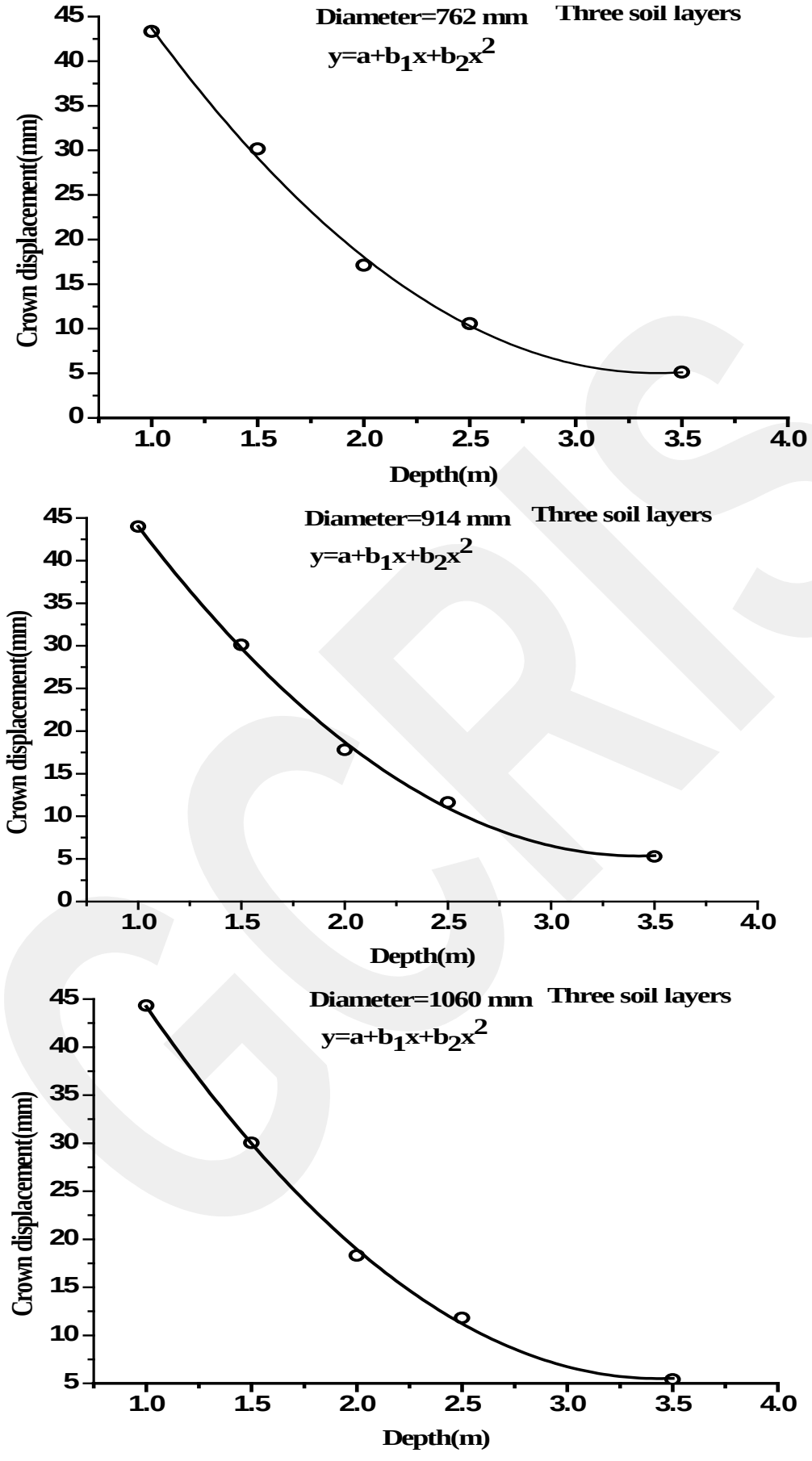


Figure 6.19Crown displacements versus depths in three soil layers

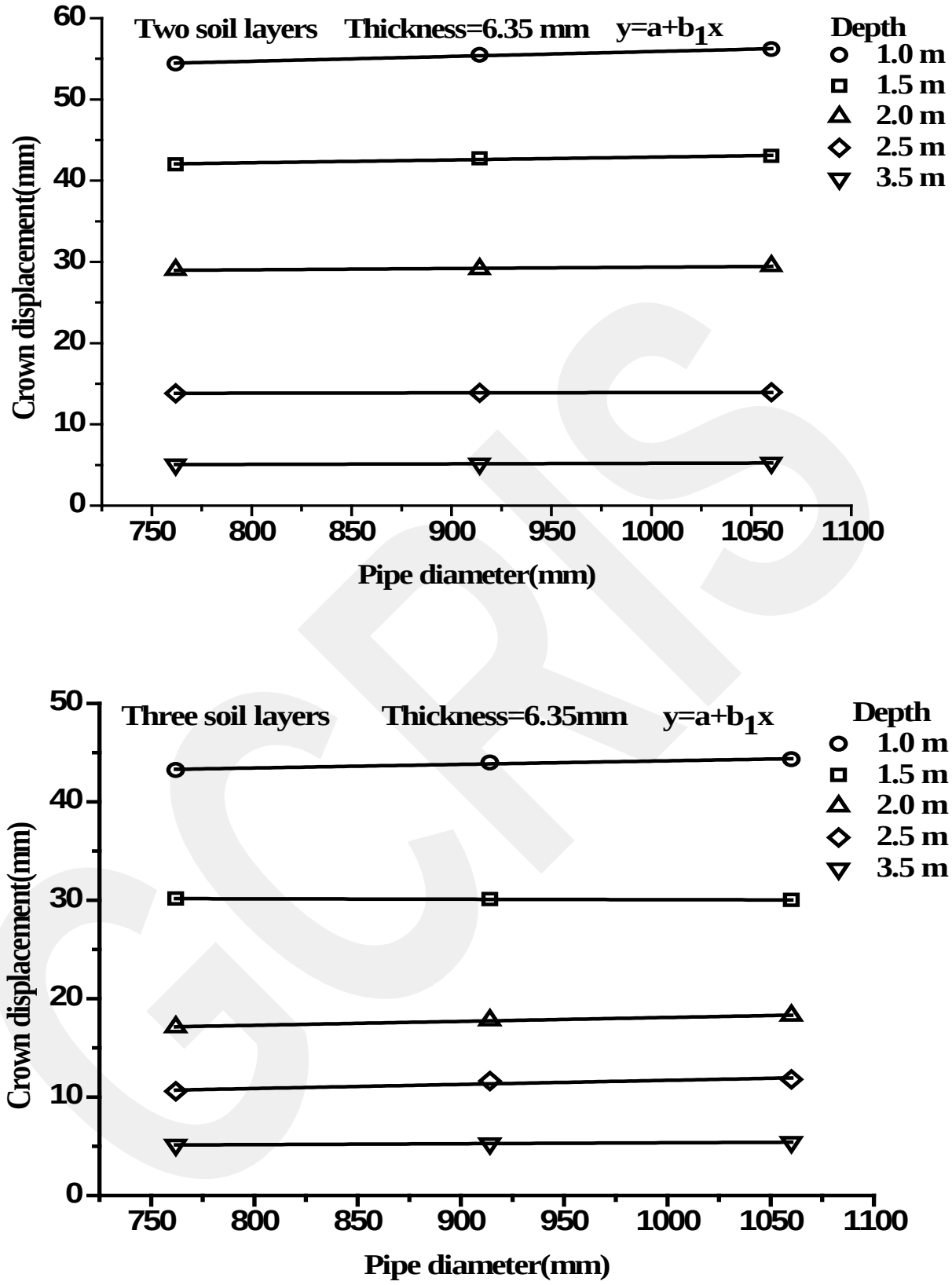


Figure 6.20Crown displacements versus pipe diameter in two andthree soil layers

Table 6.6Polynomial coefficients of displacement- burying depth curves in two and three soillayers

Soil	Polynomial coefficients	Diameter		
		762 mm	914 mm	1060 mm
Two soil layers	a	90.881	93.351	95.155
	b_1	-40.056	-41.707	-43.203
	b_2	4.4068	4.6860	4.9837
Three soil layers	a	82.912	82.476	82.572
	b_1	-46.045	-45.035	-44.874
	b_2	6.805	6.5738	6.5318

Table 6.7Polynomial coefficients of displacement- pipe diametercurves in two and three soil layers

Depth (m)	Polynomial coefficients	Two soil layers	Three soil layers
1.0	a	49.9428	40.5365
	b_1	0.00595	0.00363
1.5	a	39.4318	30.4942
	b_1	0.00347	-4.359E-5
2.0	a	27.7473	14.1255
	b_1	0.0016	0.00396
2.5	a	13.5469	7.5554
	b_1	3.688E-4	0.00415
3.5	a	4.538	4.4161
	b_1	6.710E-4	9.399E-4

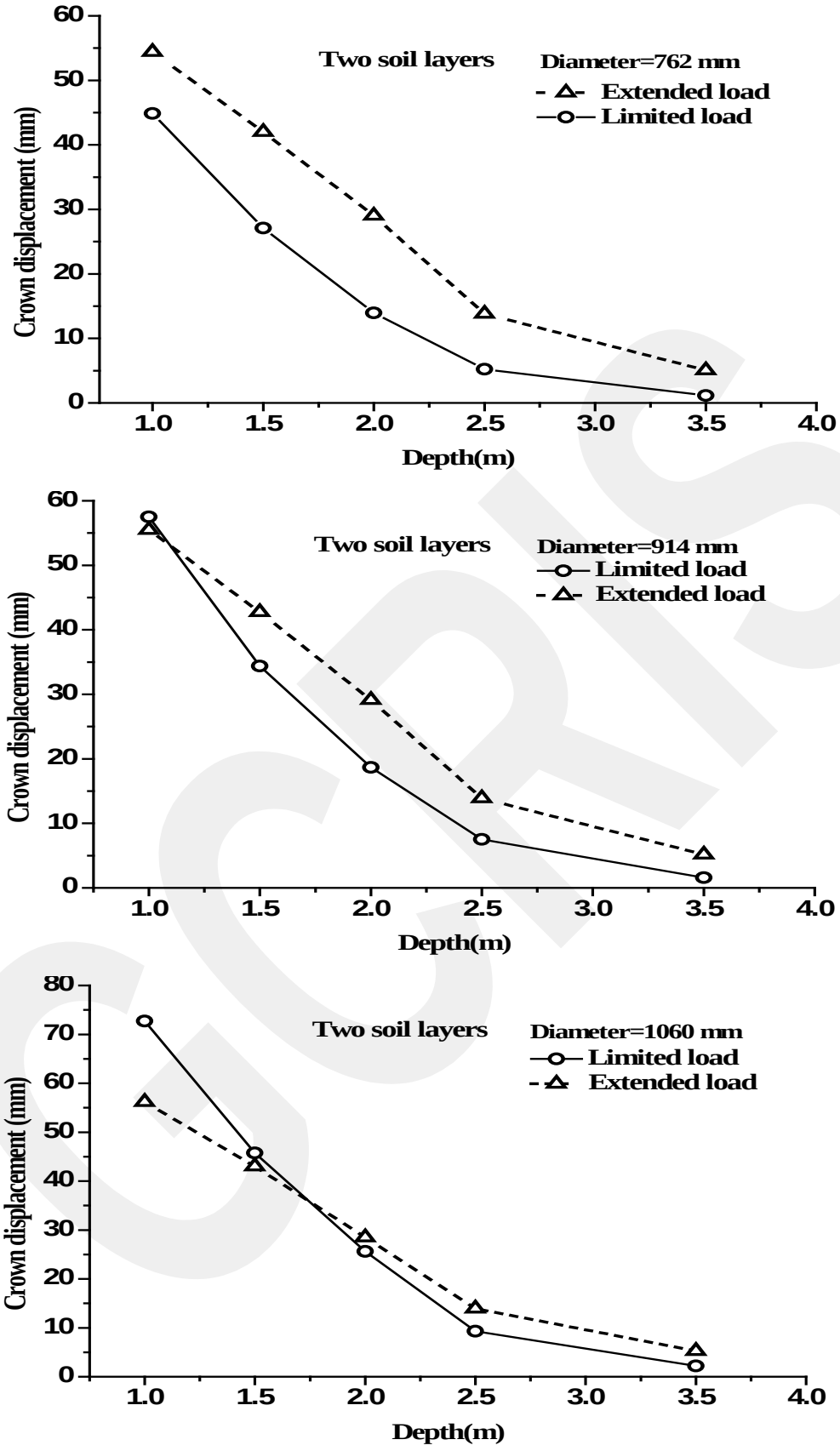
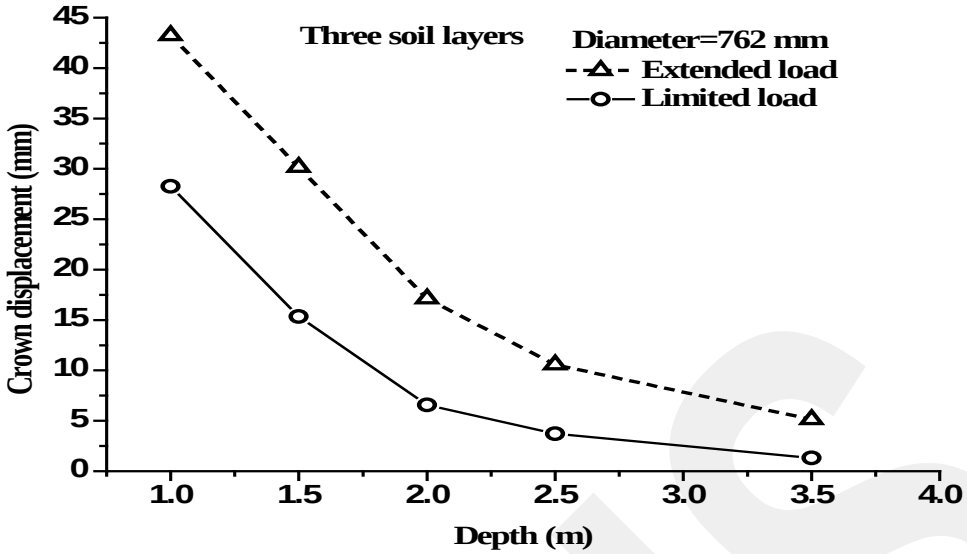
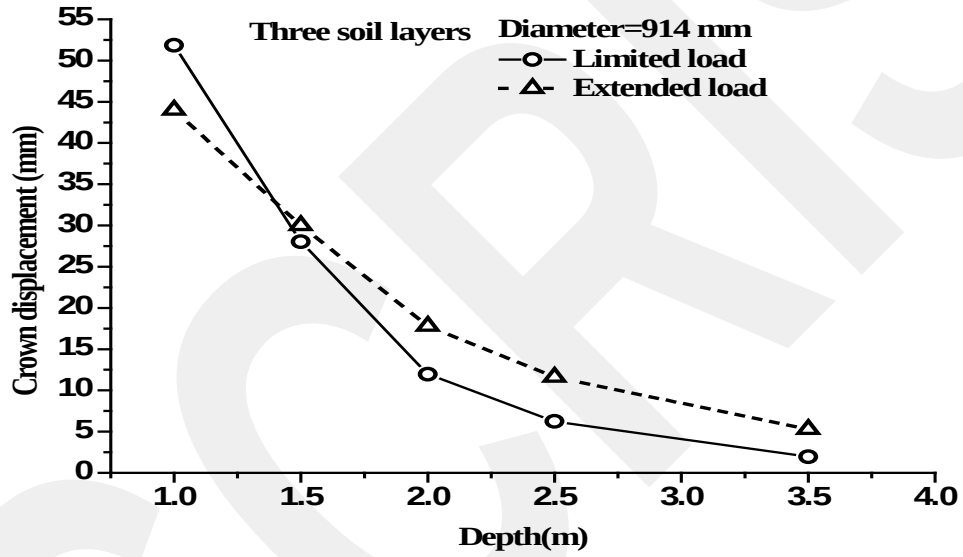


Figure 6.21 Comparative results for the variation of crown displacement with burying depth in two soil layers





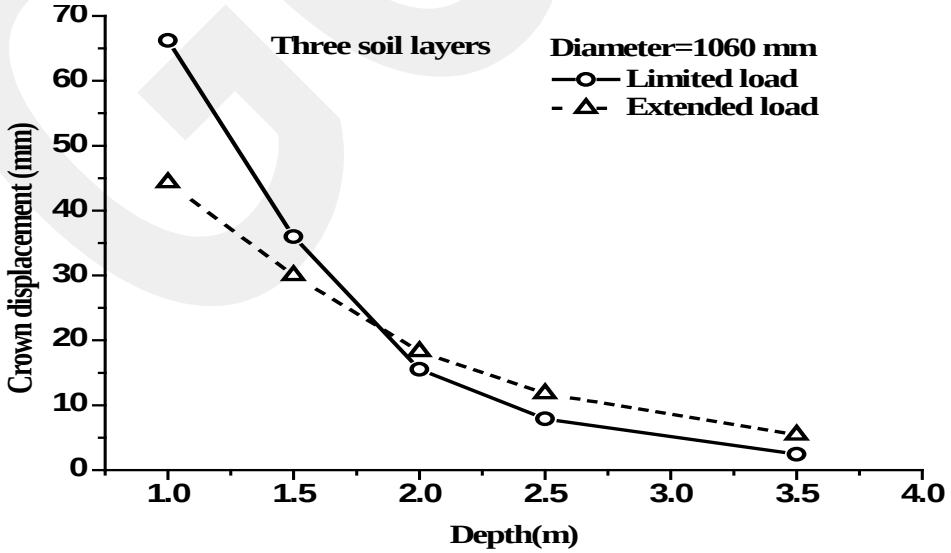


Figure 6.22 Comparative results for the variation of crown displacement with burying depth in three soil layers

For two and three soil layers framework, it is clear that the crown pipe displacement decreases as pipe burial depth increases and increases with the increasing of pipe diameter. These results are due to limiting soil –pipe friction in deeper depths more than in shallow depths. Higher displacements occur in shallow depths. It is also observed that pipe performance in three soil layers is better than in two soil layers, where crown pipe displacement is higher in two layer of soil than in three soil layers for the considered geometries. The variation of displacement with pipe diameter is very slow as compared with that variation in Figures 6.7, 6.8, 6.13 and 6.14.The comparative study in Figures 6.21 and 6.22 reveals remarkable differences between the cases under study, where the case of limited load gives more pipe displacement as the pipe diameter increases.

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CHAPTER 7

UNDERGROUND WATER TABLE

7.1 Preface

To determine the effect of underground water table on pipeline crown displacement,a buried steel pipeline of X65,which is typically used in oil and gas pipeline transmission, has been selected with applied surface load of 200kPa. PLAXIS 2D program has been used for numerical analysis. The ground water table against pipe crown displacement has been plotted. The soil and pipeline properties are shown in Tables 7.1 and 6.3, respectively.

Table7.1 Sand soil properties (Lin et al., 2012)

Properties	Dense sand	Loose sand
Unit weight(kN/m³)	19.6	18.9
Saturated unit weight (kN/m³)	21	20
Young modulus(kPa)	65000	25000
Poisson ratio	0.35	0.3
Cohesion (kPa)	5	5
Friction angle (°)	30	30
Dilatancy angle (°)	0	0

7.2 Effect of water levels

The response of pipeline under water table effect can be examined numerically. Both loose and dense sand properties are listed in Tables 7.1 and thepipeline material is characterized by Table 4.2. To perform the analysis, pipe buried in depth 1.0 m from ground surface and underground water levels are ranging from 1.0 m to 6.0 m.

Figures 7.1 – 7.6 illustrates the water table effect on pipe crown displacement for different soil and pipe conditions. Table 7.2 refers to polynomial coefficient of curve fitting.

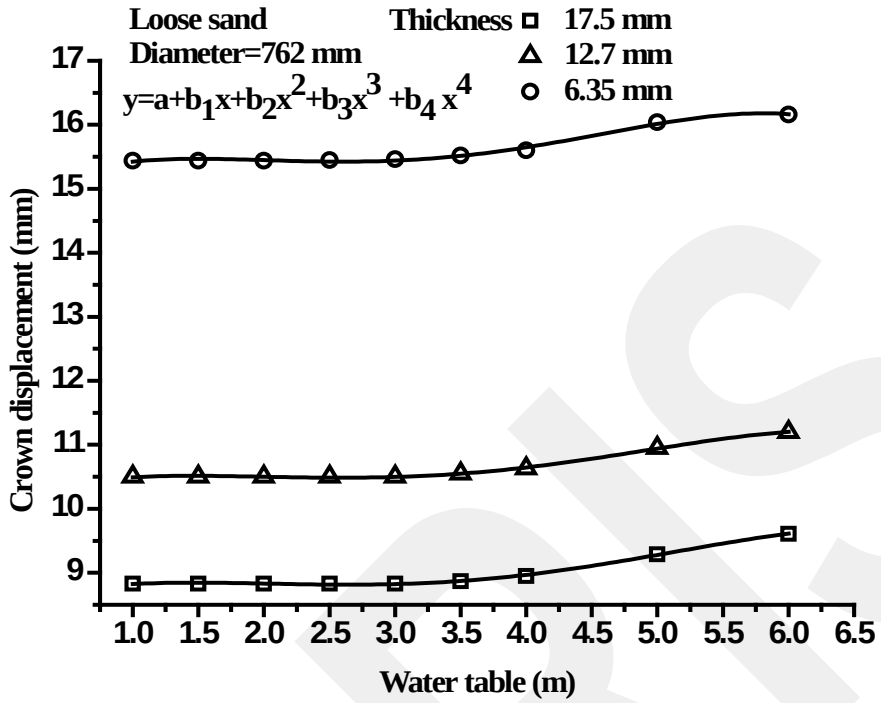


Figure 7.1Displacement versus water table of pipe having D=762mm embedded in loose sand

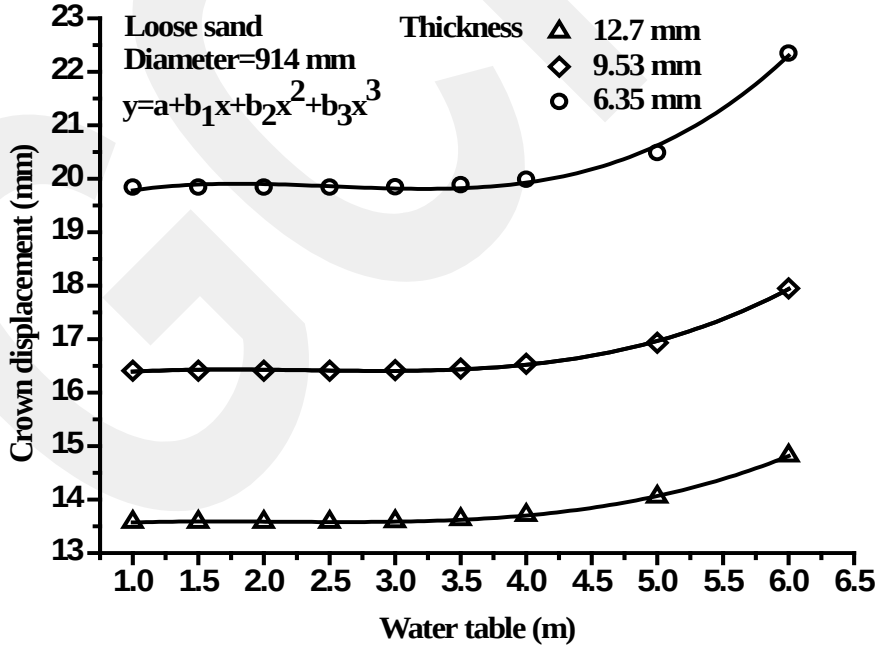


Figure 7.2 Displacement versus water table of pipe having D=914mm embedded in loose sand

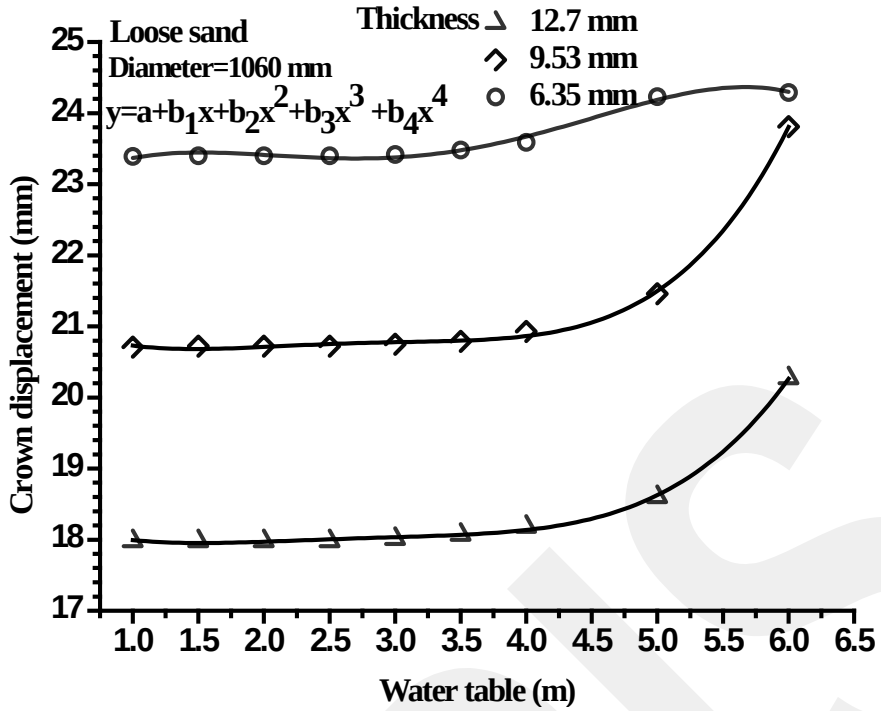


Figure 7.3 Displacement versus water table of pipe having 1060mm embedded in loose sand

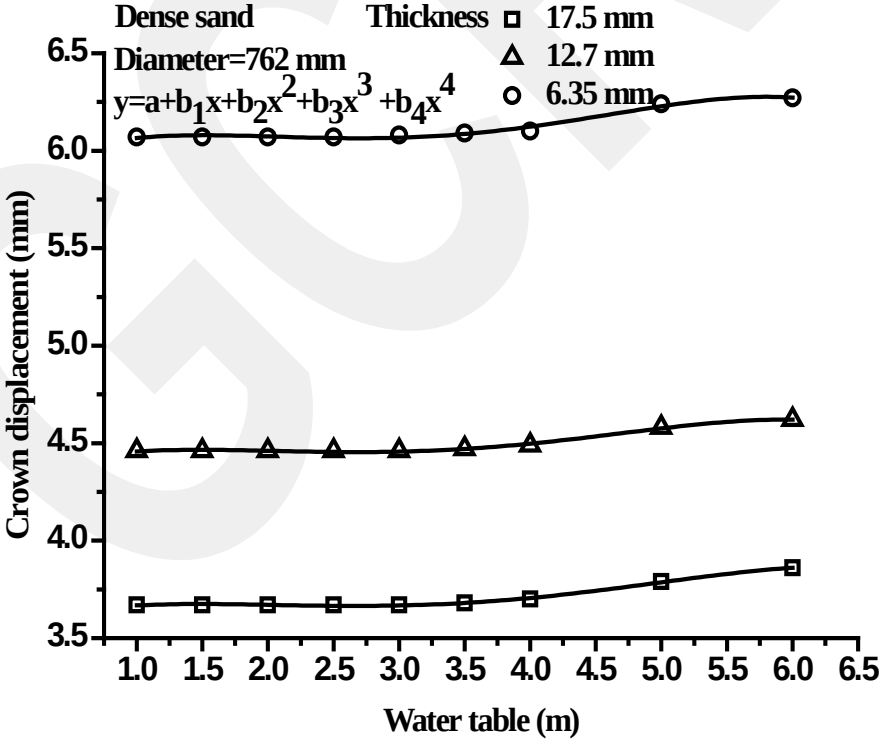


Figure 7.4 Displacement versus water table of pipe havingD=762mm embedded in dense sand

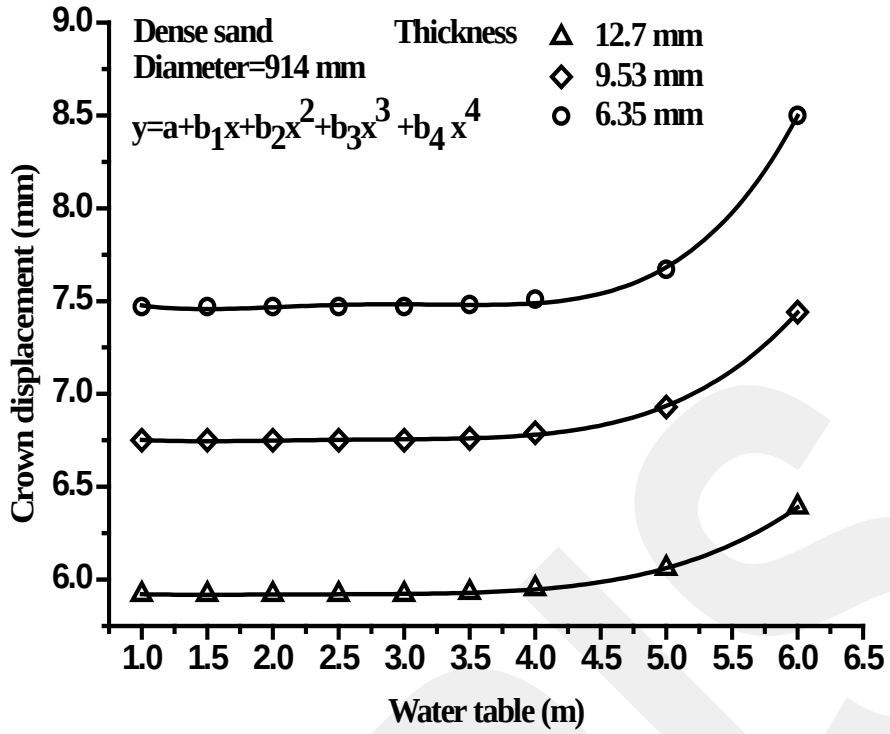


Figure 7.5Displacement versus water table of pipe havingD=914mm embedded in dense sand

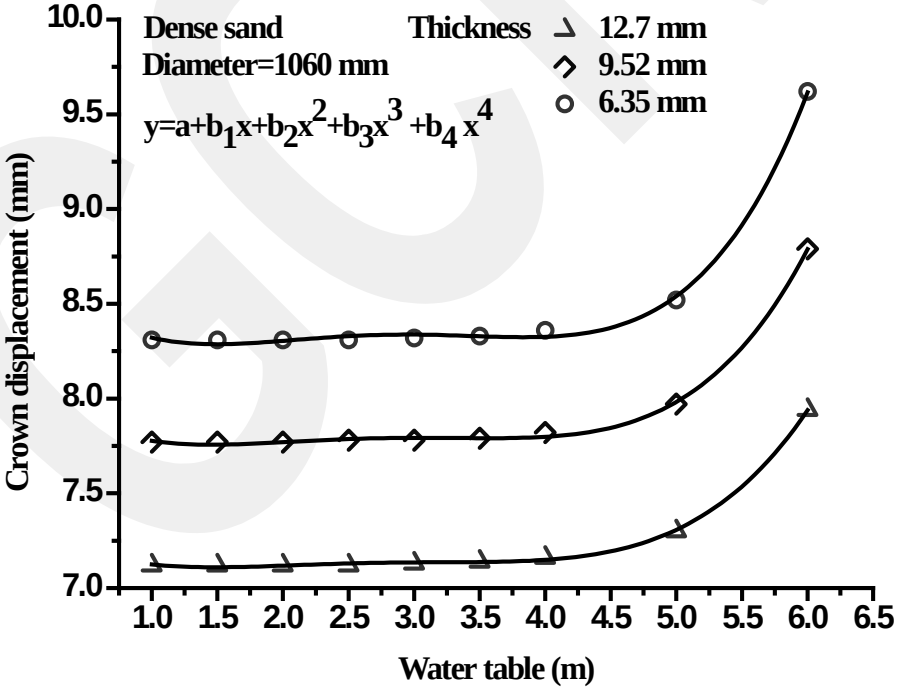


Figure 7.6 Displacement versus water table of pipe havingD=1060mm embedded in dense sand

Table 7.2 Coefficient of displacement – water table curve fitting

Thickness	Polynomial parameters	Loose sand			Dense sand		
		Diameter(mm)			Diameter(mm)		
		1060	914	762	1060	914	762
6.35 mm	a	22.3145	19.0647	14.8206	8.84631	7.7818	5.8694
	b_1	1.9940	1.1489	1.1578	-1.023	-0.6017	0.3692
	b_2	-1.2036	-0.4972	-0.7087	0.6505	0.3901	-0.2218
	b_3	0.2835	0.0659	0.1689	-0.1676	-0.1035	0.0519
	b_4	-0.0215	-	-0.0128	0.01519	0.0097	-0.00389
9.52 mm	a	21.496	-	-	8.1081	-	-
	b_1	-1.5107	-	-	-0.6535	-	-
	b_2	0.9784	-	-	0.4220	-	-
	b_3	-0.2594	-	-	-0.1104	-	-
	b_4	0.0248	-	-	0.01023	-	-
9.53 mm	a	-	16.1024	-	-	6.8661	-
	b_1	-	0.4797	-	-	-0.2281	-
	b_2	-	-0.2231	-	-	0.1529	-
	b_3	-	0.0323	-	-	-0.0429	-
	b_4	-	-	-	-	0.0044	-
12.7 mm	a	18.5604	13.4059	10.1423	7.3615	5.9645	4.3307
	b_1	-1.09074	0.2843	0.6761	-0.4646	-0.0907	0.2414
	b_2	0.68452	-0.1411	-0.4161	0.2993	0.0643	-0.1468
	b_3	-0.177	0.0221	0.0979	-0.0787	-0.0196	0.0344
	b_4	-0.01685	-	-0.0070	0.0074	0.0022	-0.00256
17.5 mm	a	-	-	8.4676	-	-	3.5626
	b_1	-	-	0.6762	-	-	0.1999
	b_2	-	-	-0.4088	-	-	-0.1208
	b_3	-	-	0.0939	-	-	0.0279
	b_4	-	-	-0.0065	-	-	-0.0019

The results depict the decreasing of pipe crown displacement by drop of water table. By examining above Figures, we find that above a certain water level (4.0 m), the slope of the curve changes rapidly, and itis also clear that there is an optimal level to the water table to be influenced on soil and floatation to be occurring.

CHAPTER 8

RESULTS AND DISCUSSION

In this study, finite element models of the buried steel oil and gas pipeline and soil are established to carry out the analysis of the static and dynamic loads. The study is limited to determination of the displacement and the response of empty underground pipes due to surface load and earthquake effects using a finite element package, PLAXIS-2D.Moreover, the influence of surface loads in different soil, diameter and burial depth of pipe as well as water table and the thickness of soil layer in pipeline displacement have been investigated. The response of buried pipelines in clay, dense and loose sand is also investigated in this study. The used materials properties (soils and pipelines) are tabulated in Tables 3.1, 4.1, 4.2, 6.1 and 7.1.

8.1Summary of results

A revision study of Rajkumar and Ilamparuthi work (2008) has been performed, where the behavior of PVC pipe embedded in dense sand and subjected to different surface loads was investigated in the frame of 2D Finite element code of PLAXIS. The numerically simulated model is illustrated in the Figures 3.3and 3.4 for pipeline without and with geogrid, respectively. In addition to the work of Rajkumar and Ilamparuthi, we have been appointed the modified experimental data and the parametric data which are obtained from the mechanical properties that presented by the authors (Table 3.1).

To analyze the response of buried X65steel pipeline subjected to earthquake events, the displacement has been calculated numerically. Using the soil and pipelines properties (Table 4.1and 4.2), the influence of pipe burial depth on crown pipe

displacement are computed and results are plotted in Figure 4.3under different burying depths for two different values of pipe thickness. The curves of these figures have been fitted and their polynomial coefficients are listed in Table 4.3.

Pipe diameter is one of the most effective parameters in pipeline analysis. Displacement of pipeline under earthquake events, are shown in Figures 4.3-4.7 for several burying depths (1, 1.5,2 and 2.5m), and the fitting values of polynomial coefficients are listed in Table 4.4. As shown in Figures 4.8-4.10 a constant diameter and soil type can investigated, which relates displacement in pipe to relative pipe wall thickness, and polynomial coefficients for the variable under study are found in Table 4.5.

The behavior of buried pipelines subjected to different surface loads (50,100,150 and 200 kPa) has also been studied numerically. To investigate the influence of soil types and burying depths, the study computes the relation of crown displacement with the surface load, and results obtained are presented in Figures 5.2- 5.10. Three different values of diameters with three values of thicknesses for each one are used,and thecoefficient of curve fitting islisted in Table 5.1. Figure 5.11 describes the variation of increment ratio of crown displacement with load variation, and the coefficients of curve fitting are listed in Table 5.2.The effect of pipe conditions, which includes both effects of pipe diameter and wall thickness on pipe crown displacement, where the numerical results are shown in Figures 5.12 – 5.19 and 5.20 – 5.22 respectively.

The study also estimates the effect of different soil layers on the behavior of soil-pipe interaction, where multi soil layers are taken into account. The study has been performed as a relationship between the crown displacement and burying depths for different diameters and wall thicknesses. Under 200kPa surface load, the study consists of twoframeworks: the first one treats the soil with two layers of clay and dense sand. The results obtained are demonstrated in Figures 6.4 - 6.6 for the effect of burial depth, and Figures 6.7 - 6.8 for the effect of pipe diameters. The second framework deals with the soil of tree layers(clay, medium and dense sand), where the computed crown displacement are illustrated in Figures 6.10-6.12 and 6.13- 6.14 for both kind of effects. The polynomial coefficients ofthe curve fitting are scaled in Tables 6.2 - 6.5.Figure 6.18 - 6.20 represent the behavior of pipeline under water pressure for two and three soil layers.

Chapter 7 discusses the effect of the underground water table on pipeline crown displacement, where theground water table against pipe crown displacement has been sketched in Figures 7.1 -7.6 for different soil and pipe conditions. Table 7.2 refers to polynomial coefficients of curve fitting.

8.2 Discussion

By examining the curves in Figures3.3 and 3.4, we found that the results ofRajkumar and IIamparuthi (2008) is incorrect, because the numerical values have a great deviation from scientific reality, where the experimental results should be multiplied by a factor of 1.4 to make it as close as to reality.This factor is related to the third dimension of theexperimental model (0.6 m) and PLAXIS-2D model (1m). In return,Rajkumar and IIamparuthihad multiplied the applied load in the FEM results by a reduction factor of 0.6.

Figures 4.2 – 4.7 clearly show that the pipe displacement increases as the pipe diameter and burial depth increases for different pipe wall thicknesses and soil type.These results are in accordance withSaeedzadeh and Hataf (2011) (Figure A-1) and Hongjing et al. (2008).Figures 4.4 – 4.7 also predict that for a given pipe diameter and wall thickness, pipes buried in loose sand have more response to the earthquake events, and the displacement in clay soil is less than that occurs in loose sand. These results are accordance with Feng et al.(2012). Roshan et al (2010)show that the pipeline embedded in soft clay is vulnerable response to earthquake excitation.It is worthy mentioned that the soil type is significant for the response of the pipeline (Do *et al*., 2009).The reverse holds for the relation of displacement with wall pipe thickness(Figures 4.8-4.10), where the predicted displacement decreases where pipe wall thickness increases or the rigidity of the pipe increases. This is due to the fact thatthe pipe ability to resist soil movement is proportional to the wall pipe thickness when the diameter is the same.

As can be seen from Figures 5.2 – 5.22, at different values of soil and pipe conditions, the crown pipe displacement increased with the increase of surface load and pipe diameter, and also when buried depth is shallow. At the same time, the increasing of wall pipe thickness will reduce the pipe displacement. Moreover, the pipelines suffer lessdisplacement when they buried in loose sand than in clay soil.

These result are in agreement with the findings byRajkumar and Ilamparuthi (2008) (Figures B1and B2) andBildik et al. (2012) (Figures B3 and B4). Recently, Wu et al. (2013) achieved the same results for the pipe diameter and wall thickness effectiveness (Figures B5 and B6).Figure5.11 showthat theincrement ratio exhibits an increasing tendency with increasing surface load.

By examining the curves in Figures6.4 – 6.14, 6.18 – 6.20, we find that in two and three soil layers, the pipe burying depth and pipe diameter have greater influence in decreasing and increasing the crown displacement, respectively. Comparing with the results of one soil layer (Figures 5.2 -5.10), we find that pipe embedded in three soil layers (below 1.5m burying depth) shows less displacement than that embedded in single or two soil layers. Another feature apparent in these figures, where at burial depth more than 2.5m the relationship shows slow variation in crown displacement compared with that value of other range.

The data in Figures 7.1 – 7.6 clearly indicate that the decreasing in pipe displacement by the drop of water table, and above a certain water level (4m), the slope of the curves change very rapidly than other range.

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CHAPTER 9

CONCLUSION

The performance of buried natural oil and gas pipeline systems in areas subjected to earthquake and surface loads is an important engineering consideration for natural gas and oil utility owners such the public property and safety are affected by the failure of these systems. The present thesis investigates the behavior of X65 buried steel pipeline subjected to earthquake and surface loads using PLAXIS-2D program software, where the "displacement" values have been plotted against different parameters like diameters, thicknesses, depths, soil types, loads and water tables. From the results of figures the following conclusions have been made.

1. The verification study of the numerical results of Rajkumar and Ilamparuthi (2008) suggested that the authors overestimate the soil - pipeline interaction, and also the determination of YoungModulus values.
2. Under earthquake and surface loads, the pipe displacement increased with the increase of pipe diameter at different depths. This is due to the fact that the friction force between the pipe and soil is proportional with the pipe perimeter almost.
3. Increasing the burial depth will increases the pipe displacement for different diameter values and soil media. It reveals that the predicted interaction forces increases where burial depth increases where pipeline become easy to deform and absorb more energy under earthquake load, Whereas in surface load, the pipe displacement decreases as burial depth increases.
4. The results show that pipe rigidity is important item on pipe behavior, wherelarger thickness pipes undergo less displacement in surface and earthquake loads. This fact is due to increase in the pipe rigidity.
5. According to results, steel pipeline displacement is affected by the type of soil surrounding the pipe. For a given pipe diameter and burying depth, pipes buried in loose sand have more response to the earthquake load, and the displacement in clay

soil is less than that occurs in sand soil. On the other hand, the pipe displacement in clay soil is less than that occurs in loose sand.

6. Increase in the surface load on pipeline, increases the pipe crown displacement for different soils, diameters, thicknesses and depths. It is important to say thata pipe buried in clay has more displacement than in loose sand.
7. Increasing the burial depth of pipe lessens the crown displacement in two and three soil layers. As the pipe becomes deeper and sand becomes denser, deeper burying of pipe shows more effectiveness.
8. The comparison between one and two soil layers for clay soil, depths less than 2.5m and surface load of 200kPa, in term of pipe diameter plotted against crown displacement, indicate a noticeable decreasing in crown displacement in two soil layers for the same smaller and larger diameters more than in one soil media.
9. The numerical results are presented in figures for pipe crown displacement in term of pipe diameter for two and three soil layers. It is concluded that the increase in the pipe diameter leads to anincrease the crown pipe displacement for different depths.
10. As can be seen from Figures,the comparison, between one, two and three soils media at depth of 1.5m and surface load of 200kPa, show that pipe crown displacement increases in one soil media more than in two and three soil layers and also conclude that higher displacement occurs in two soils more than in three soil layers.
11. Numerical results are obtained for various values of soil types, diameters and thicknesses for X65 steel pipelines to determine the effect of water table on pipe crown displacement. In the majority of cases analyzed, it is shown that by increasing the depth of water table, pipe crown displacement is increased. Also, there is an optimum level of water table that the most influence on floatation reduction take place.

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APPENDIXS

Appendix A

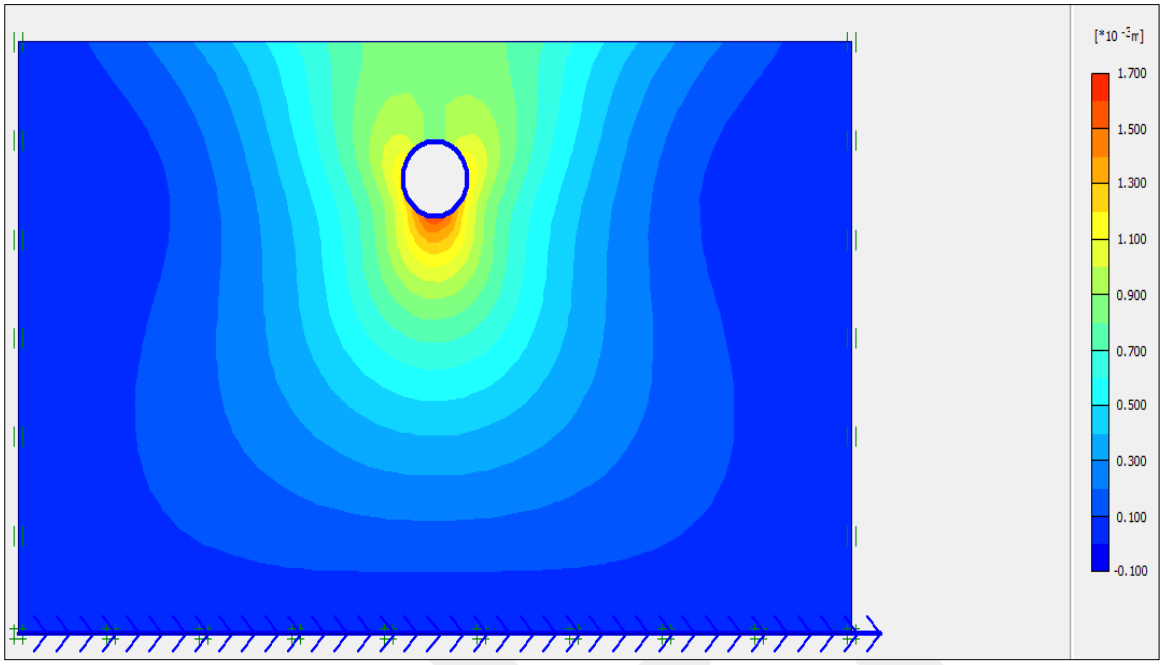


Figure A-1 pipe-soil displacements before earthquake

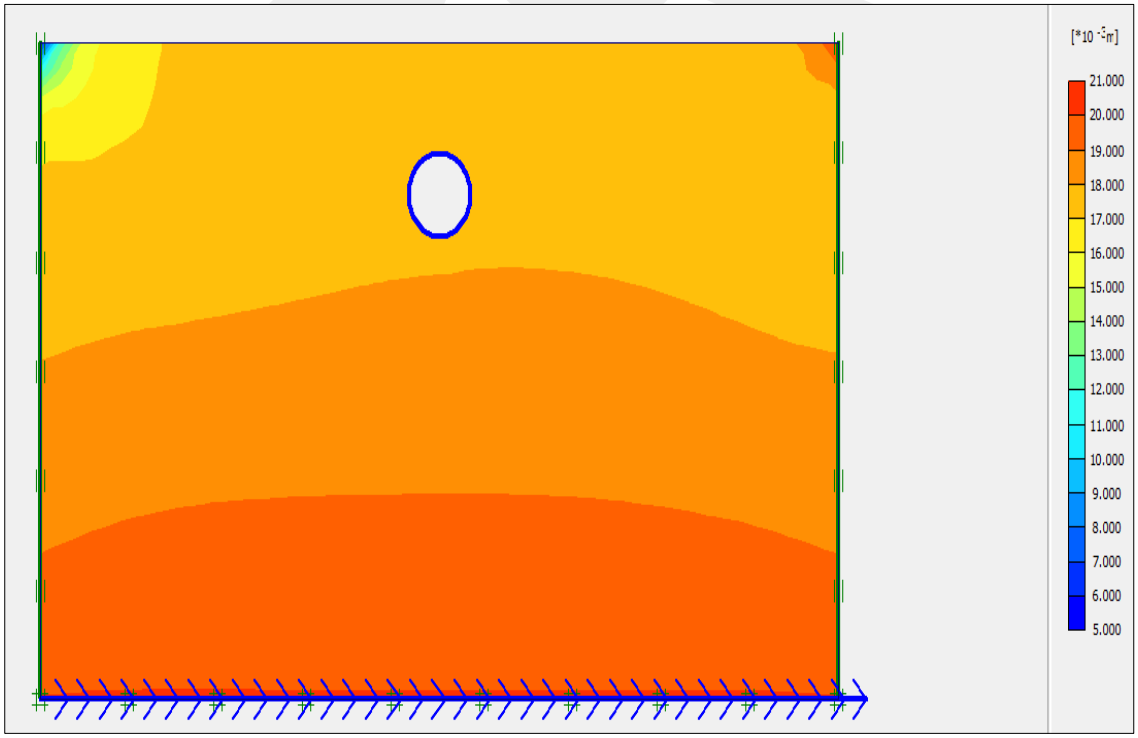


Figure A-2 pipe-soil displacements after earthquake

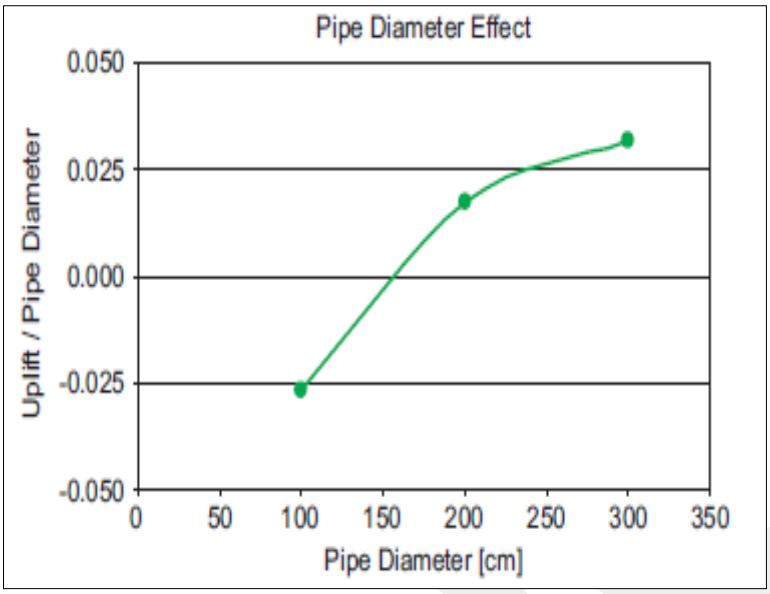


Figure A-3Effect of pipe diameter on uplift (Saeedzadeh and Hataf, 2011)

Appendix B

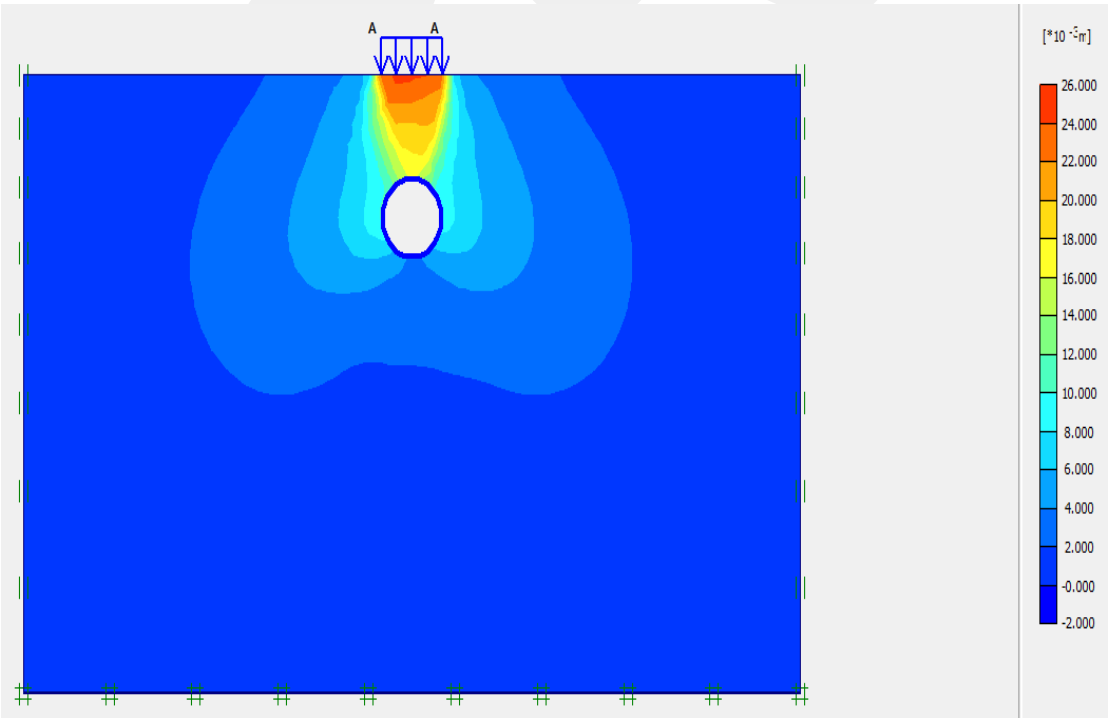


Figure B-1 values of limited loaddisplacements over the pipe

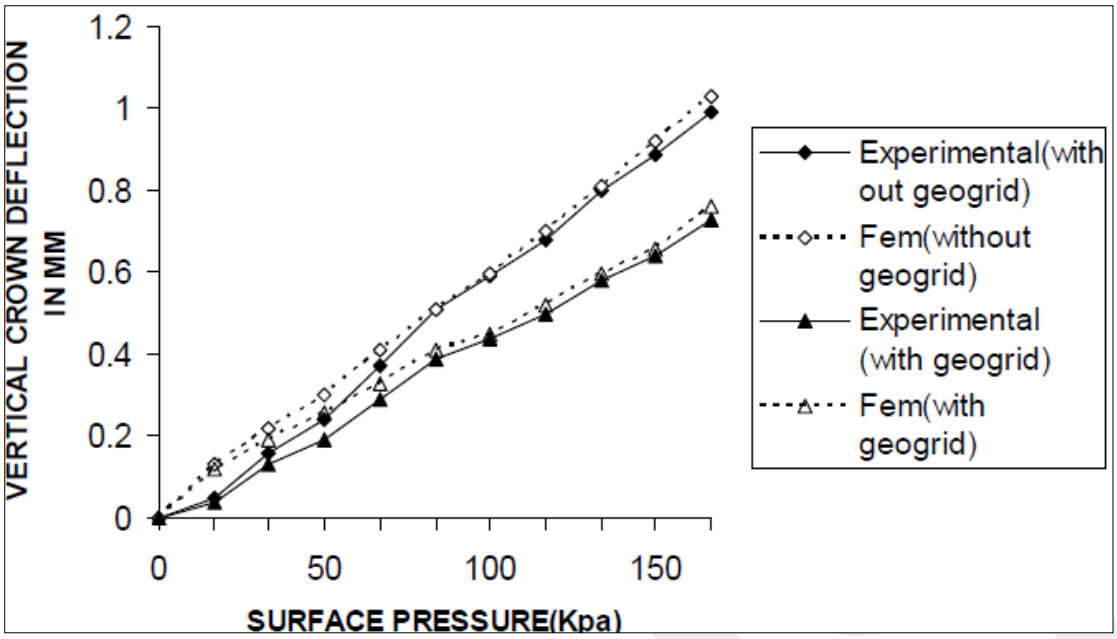


Figure B-2 Comparison of Experimental results with 2D finite element analyses for in dense sand (adapted fromRajkumar and Ilamparuthi, 2008)

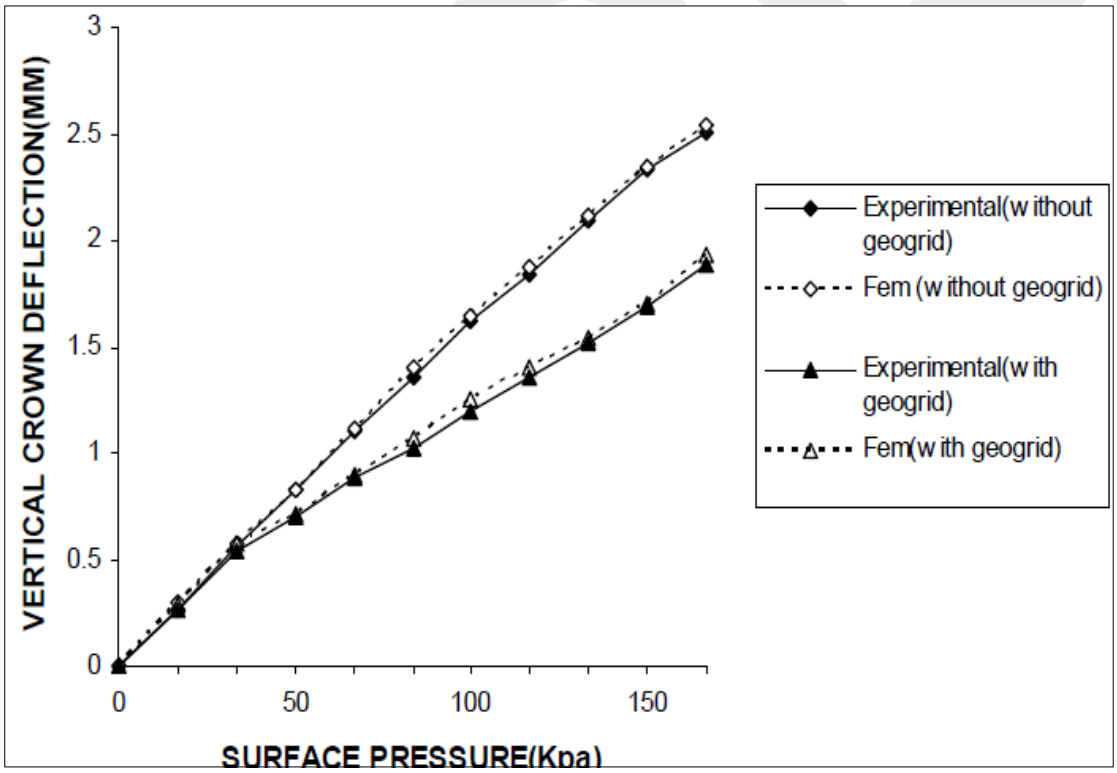


Figure B-3 Comparison of Experimental results with 2D finite element analyses for in loose sand (adapted fromRajkumar and Ilamparuthi, 2008)

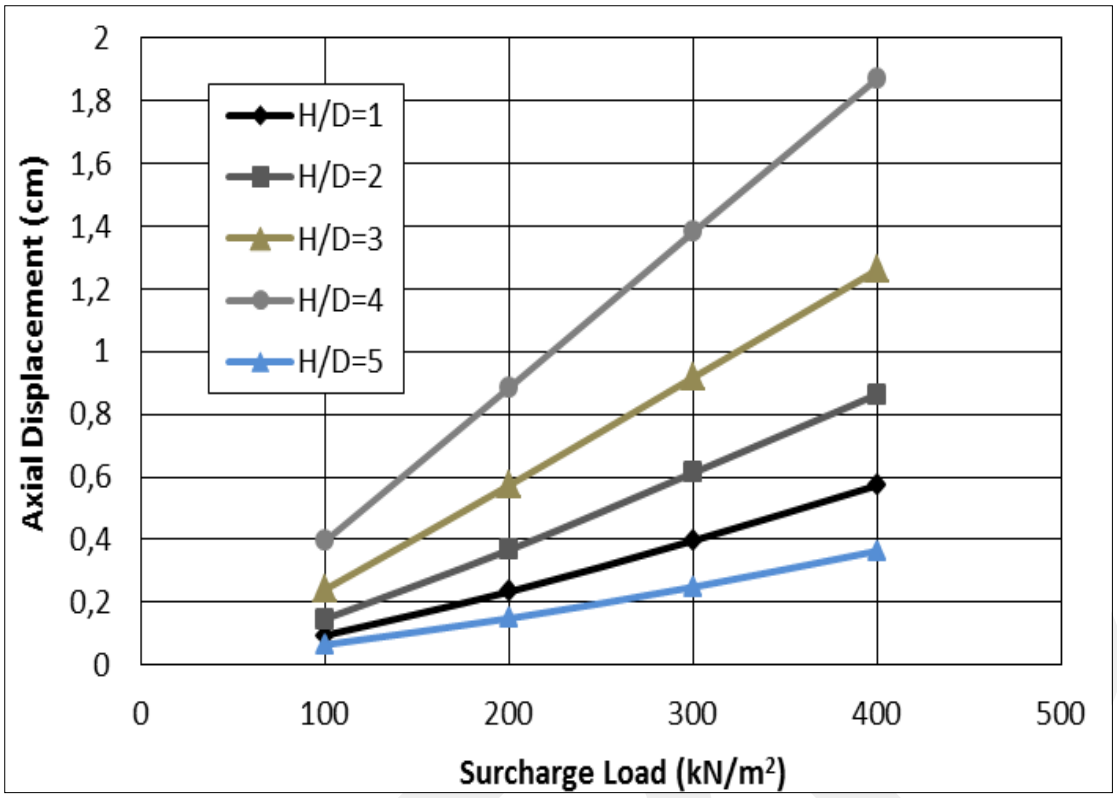


Figure B-4 Pipe displacement-surcharge load behavior in dense sand (adapted fromBildik et al., 2012)

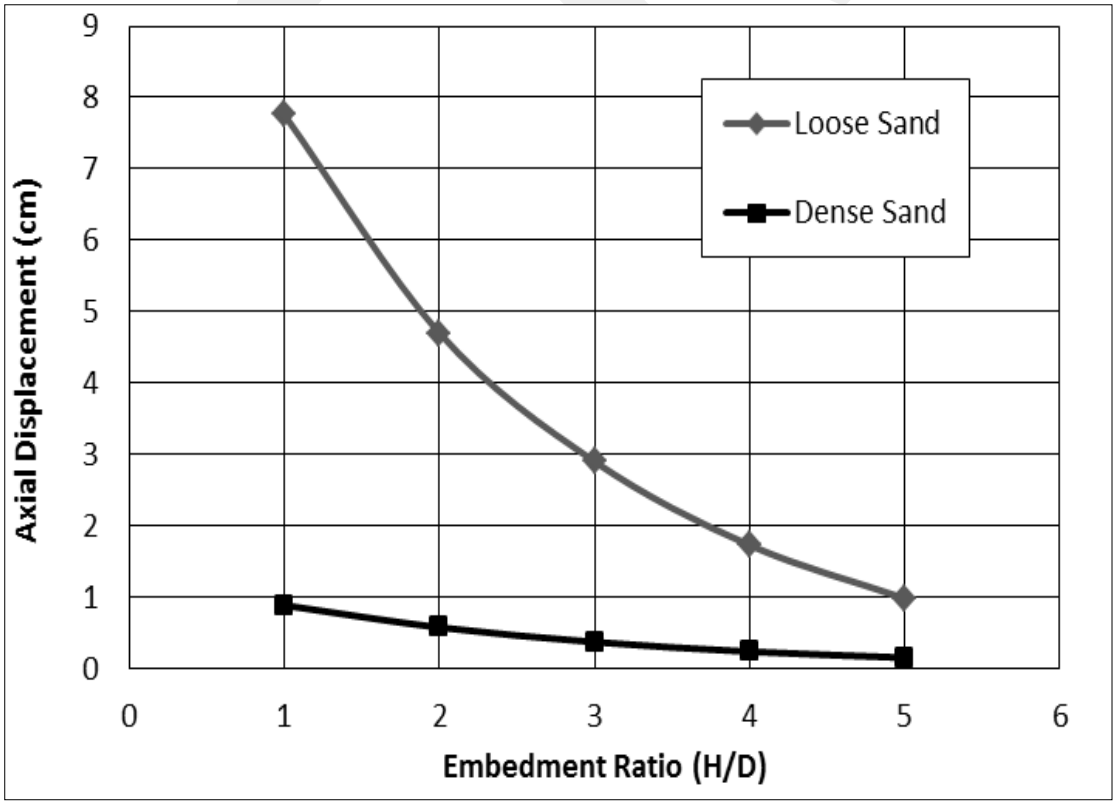


Figure B-5the effect of relative density of sand (adapted from Bildik et al., 2012)

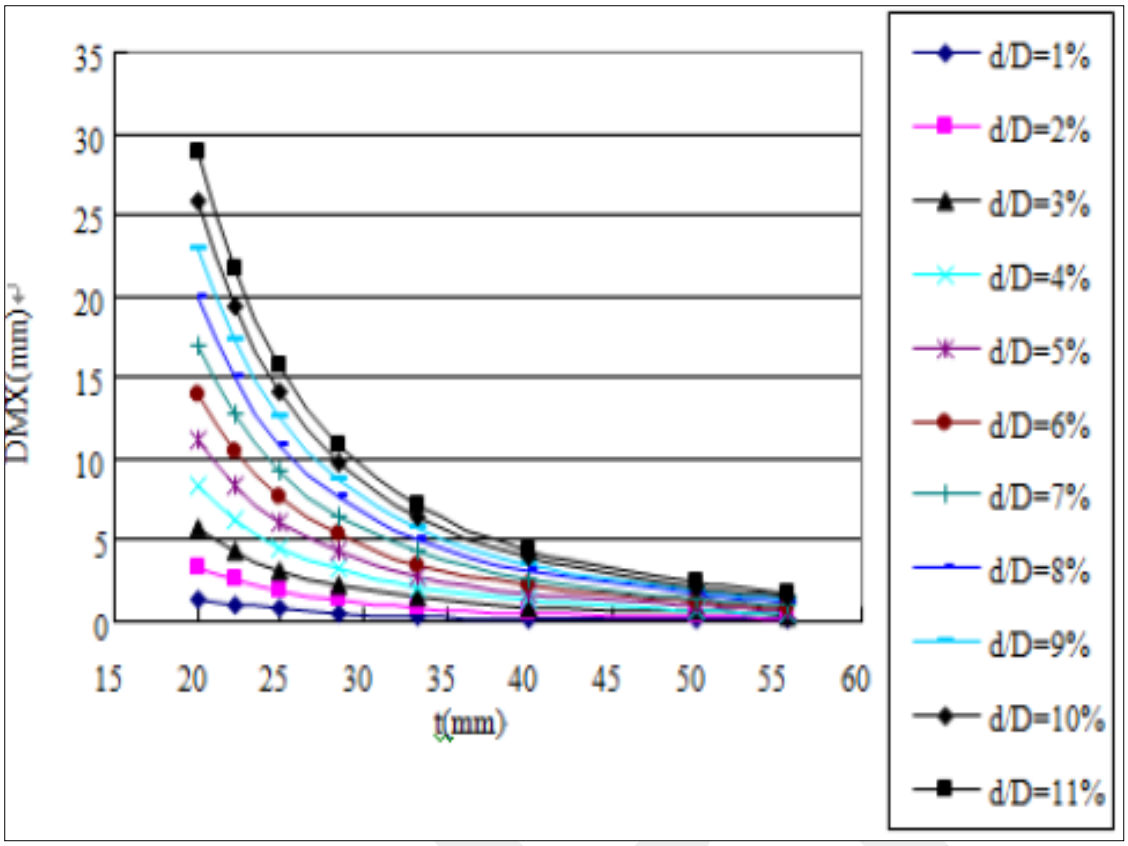


Figure B-6the relationship of the maximum displacement and pipe wall thickness(adapted from Wu et al.,)

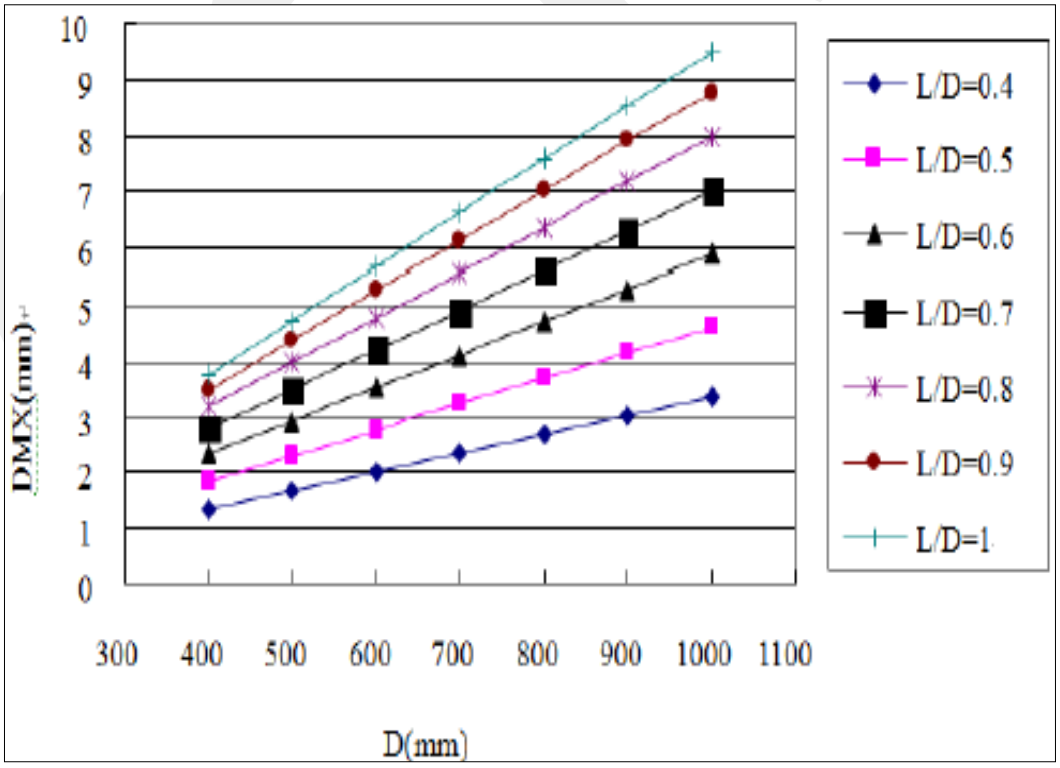


Figure B-7the relationship of the maximum displacement and pipe diameter (adapted from Wu et al., 2013)

Appendix C

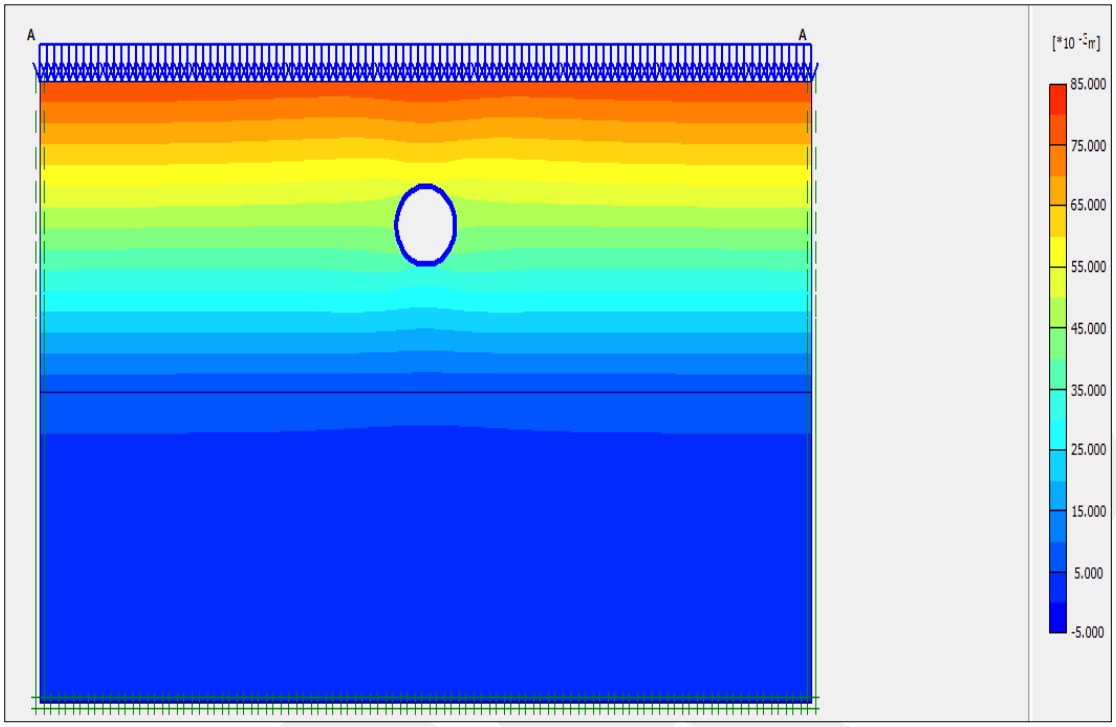


Figure C-1 values of water distributed load displacements over the soil