NUMERICAL MODELING OF BURIED DRAINAGE PIPES BY USING FINITE ELEMENT METHOD

by

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Dedicated to
My Beloved Brother Aykut Bul

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ABSTRACT

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With the increased use of pipelines for transporting water, gas, petroleum, and sewage, the importance of pipe is understood easily in life. As time goes on, pipe technology has been developing and present more facilities to humanity. It is a natural outgrowth of many years of study, testing and research in general areas of buried pipe performance. The objectives of this thesis are to investigate soil-pipe interaction and present the optimum alternatives of buried pipes subjected to the same loading conditions in various soil conditions by using finite element program. Also, this thesis aims to evaluate the soil pipe interaction problem by comparing experimental and numerical solutions.

In this study, various kinds and various sizes of buried drainage pipes were modeled in two different conditions. The behavior of a buried non-pressure High Density Polyethylene (HDPE), Fiber Reinforced Plastic (FRP) pipe and Poly Vinyl Chloride (PVC) pipe, with diameters of 300mm, 900mm, 1500mm, were analyzed through the PLAXIS finite element program. Regarding to these analyses, comparisons were performed between soil types and pipe types in order to evaluate soil-pipe behavior. In order to check the results of PLAXIS software, this study was compared with reference study. Modeling results were compared with the experimental study and CANDE program. As a result of finite element analysis, less displacement has been observed in trenches filled non-cohesive soil and the optimum trench condition has been observed for fiber reinforced (FRP) pipes in non-cohesive soil.

ÖZET

GÖMÜLÜ DRENAJ BORULARININ SONLU ELEMANLAR YÖNTEMİ İLE SAYISAL ANALİZİ

Su, gaz, atık ve petrol taşınmasında boru hatlarının kullanımının artmasıyla, borunun hayatımızdaki önemi kolaylıkla anlaşılır hale gelmiştir. Boru teknolojisi gün geçtikçe gelişmekte ve insanlığa daha fazla imkanlar sunmaktadır. Bu durum gömülü boru performansı hakkındaki araştırmaların, testlerin, çalışmaların doğal sonucudur. Bu tezin amacı zemin-boru etkileşimini incelemek, gömülü boruların terminolojisi hakkında bilgi vermek ve aynı yükleme altındaki gömülü boruların farklı zemin koşulları için sonlu elemanlar yöntemini kullanarak en elverişli hendek alternatiflerini sunmaktır. Ayrıca bu çalışma, deneysel ve nümerik çözümleri karşılaştırarak zemin-boru ilişkisini değerlendirmeyi amaçlamaktadır.

Bu çalışmada, iki farklı zemine gömülü farklı türdeki ve farklı çaptaki borular modellendi. 300mm, 900mm ve 1500mm çaplarındaki basınçsız High Density Polyethylene (HDPE), Fiber Reinforced Plastic (FRP) ve Poly Vinyl Chloride (PVC) malzemelerinden üretilen gömülü boruların PLAXIS sonlu elemanlar yöntemi ile analizleri yapılmıştır. Elde edilen analiz sonuçlarına göre, zemin tipleri ve boru tipleri arasında karşılaştırmalar yapılarak zemin-boru davranışı incelenmiştir. PLAXIS sonlu elemanlar programının doğruluğunu kontrol etmek için elde edilen sonuçlar, CANDE sonlu elemanlar analizi ve deneysel çalışmalardan oluşan referans çalışma ile karşılaştırıldı. Sonlu elemanlar analizinin sonucu olarak; kohezyonsuz zemin kullanılarak oluşturulan hendeklerin daha az yer değiştirme yaptığı ve en elverişli hendek çeşidinin kohezyonsuz zemine gömülü FRP borular olduğu gözlenmiştir.

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LIST OF SYMBOLS/ABBREVIATIONS

A	Cross section area
B	Trench width
B_t	Width of trench
C	Load factor
C_1	Pipe-soil interaction coefficient defined by Greenwood and Lang
C_i	Load coefficient
c	Cohesion
D	The mean diameter of the pipe
D_1	Deflection lag factor to take care of deflection which will develop over a period of time
d	Equivalent thickness
E	Young’s modulus
e	The modulus of passive resistance
E_p	Horizontal modulus of soil reaction
E_2	Soil modulus of the embedment
E_3	Soi1 modulus of the native soil
E’	The modulus of soil reaction
H	Height of the backfill above the pipe (m)
h_w	Height of water above top of pipe
I_p	Moment of inertia per unit length of cross section of the pipe wall
K	Modified bedding constant which is a function of α
K	Bedding factor defined by Greenwood-Lang
m	Exponent of power law for soil
m_c	Exponent of power law for pipe material
M_l	Relaxation modulus of soil
P_s	Pressure due to weight of soil at depth of h
q_o	Pressure at crown level without a pipe
R	The mean radius of pipe
R_w	Water buoyancy factor

S_r	Stiffness ratio
S	Stiffness of pipe
t	Time elapsed in minutes
T	Pipe wall thickness
T_{sl}	The spring line thrust in the pipe wall
T_c	The thrust in the pipe wall
w	The radial pressure on pipe from soil
W_S	Weight of the soil prism
W_c	Marston's load per unit length of pipe

υ	Poisson's Ratio
γ_s	Unit weight of soil
γ_s	Unit weight of the backfill
Δx	The horizontal deflection after load is applied above the pipe crown
Δx	Horizontal deformation (m)
γ	Unit weight of the backfill (kN/m3)
ς	Leonhardt relationship
δ_{vo}	Elongation due to compaction of the side fill
ρ	The radius of curvature
μ	Poisson ratio
Ø	Friction angle
ψ	Angle of dilatancy
Φ	Diameter of pipe
δ	Displacement on pipe section
Γ	Gamma function

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
FEA	Finite element analyses
FRP	Fiber reinforced plastic

LDPE	Low density polyethylene
MDPE	Medium density polyethylene
PE	Polyethylene
PVC	Polyvinyl chloride

1. INTRODUCTION

An important part of the infrastructure systems in urban areas is buried underground. Network systems such as water, gas, sewage, electricity, telephone, and communication are routinely routed through underground conduits. The significance of network system is required that they are properly protected and designed to resist the imposed stresses and loads.

Since the early 1900s steel pipes of rolled steel plate for water mains and corrugated steel pipes for drainage culverts have been in widespread use. Spangler developed the Iowa deflection equation in 1941 as a result of his work on flexible pipes, and today the most used methods for calculating deflections are based on this equation. With the increasing use of plastics as pipeline materials in the 1970s and 1980s were introduced covering the design of buried polyvinyl chloride (PVC) and polyethylene (PE) pipes. (Nixey,P.,1998) Today with improvements in material technology, the range of available pipes has increased significantly. In this thesis, various types of pipes including polyethylene (PE), polyvinyl chloride (PVC), and fiber reinforced plastic (FRP), embedded in soil with varying properties, was investigated analytically. The result of experimental studies and the result of CANDE finite element analysis were quoted from reference study which is performed by Reddy DV, Gazagnaire C and Ataoglu S. In the reference study, Φ 300 HDPE pipe designed in CANDE finite element program and performed experimental study. This experimental study of interaction between soil and high density polyethylene plastic pipe was performed in a laboratory soil box. The loading of 5600 lb (2.536,8 kg) was applied as a uniform pressure of magnitude 170 kPa spread over the pipeline. By taking into account reference study, in this thesis, experimental and numerical solutions were compared in order to evaluate the soil pipe interaction problem.

This study points out soil-pipe interaction and present the optimum alternatives of buried pipes subjected to the same loading conditions in cohesive and non-cohesive soil conditions by using finite element program. Cohesive soils are used for comparison of the results. Under the light of finite element analysis and experimental study, this thesis presents behaviors of various pipes and soils under the same trench conditions.

In this study, the effect of pipe size, material, stiffness, and soil-pipe behavior were investigated using the finite element method. A wide-ranging parametric study was conducted to investigate the effect of the different variables on the pipe to be used in the design of the conduit. Comparisons were made by using the results of finite element analyses. The results were presented in the form of design charts for conduits ranging in size 300mm, 900mm, and 1500mm, for various conduit material properties and section properties in non-cohesive and cohesive soil conditions. The stress distribution and the deflection ratios of different sizes of pipes produced by different kinds of raw material subjected to170 kPa dead load were obtained.

The work presented in this thesis is focused on the evaluation of pipe types buried in non-cohesive and cohesive soil conditions for trench-type installations. In this way, soil-pipe interaction can be more elucidated and thus ideal trench conditions can be obtained.

2. LITERATURE REVIEW

Pipes are important structural configurations of modern urban infrastructure. They serve civilization to distribute water, dispose wastewater, gas & petroleum transmission lines and manage storm water. In the last two decades, a lot of field studies were performed by Hurd (1986), Adams (1989), Webb (1996), Ataoğlu (2000), Masada (2002), Suleiman (2003), Kawabata (2004), Sargand (2005) in order to investigate soil-pipe interaction.

In the early years of the 20^{th} century in North America, the first attempts to design buried conduits were limited to rigid ones such as concrete and cast iron pipes. Concrete pipes were used to build sewer and drainage systems and cast iron pipes were extensively used to build water distribution systems. The high technology of today brought new material types providing good alternatives, often better products, facilities of easy installation, minimizing workmanship and transportation expanses. Today plastic pipes have wide range portion on the market. (Moser, M., 2000)

Plastics can be classified as two basic groups: thermosetting and thermoplastic. Thermosetting plastics form permanent shapes when cured by heat or chemicals. Thermoplastics soften upon heating and re-harden upon cooling. They can be formed and reformed repeatedly. Bjorkiund presented that the future use of plastic pipe, thermoplastic pipes account for 90% of the market for water distribution in the Nordic countries, and 75% for drains and sewers applications. (Björklund, I.,1996)

3. TECHNICAL PROPERTIES OF BURIED PIPES

A pipe can be defined by means of five technical parameters. These are given as below.

- E= Young's Modulus
- υ = Poisson's Ratio
- I = Moment of inertia
- A = Cross section area
- r = Radius

As can be seen Figure 3.1, the top and bottom of the pipe are called as crown and invert respectively. This spring line is a horizontal line divides the pipe as two parts. Shoulder is the upper part of the spring line and haunch is the bottom part of it. The A-A cross section represents wall types of the pipe in Figure 3.2. (See Page 5)

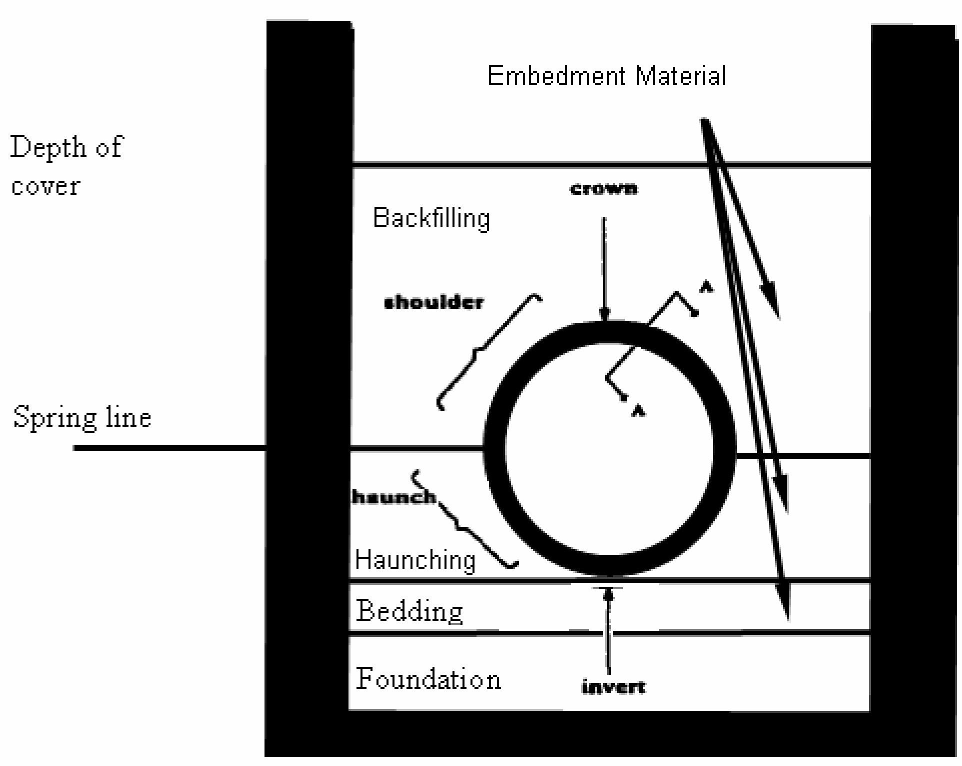


Figure 3.1. Trench cross section

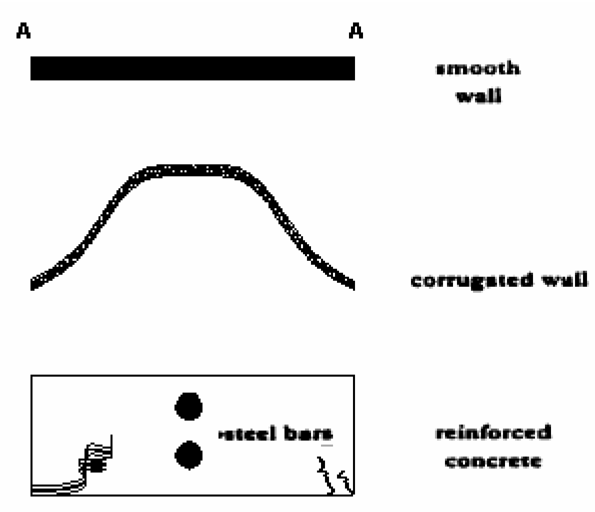


Figure 3.2. Wall types of pipes

According to ASTM D2321 (1995) specification, embedment material is divided three parts such as bedding, haunching and backfilling. The installation terminology is illustrated in Figure 3.1.

There are three main types of plastic pipes used in water-industry applications such as polyethylene (PE), polyvinyl chloride (PVC), and fiber reinforced plastic (FRP) pipes.

3.1. HDPE – High Density Polyethylene Pipe

Polyethylene is characterized by its density. High density (HDPE) is strong, the medium density (MDPE) gives good compromise of strength and toughness and low density (LDPE) is relatively weak but highly ductile. Their densities are 0,955 gr/cm^3, 0,940 gr/cm^3 and 0,920 gr/cm^3 respectively. LDPE is used for packaging like foils, trays and plastic bags both for food and non-food purposes, protective coating on paper, textiles and other plastics, for instance in milk cartons. MDPE is specially developed for the manufacture of high quality natural gas distribution systems. Drainage polyethylene pipes are non-pressure pipes produced by HDPE raw material are considerably used for collection and transmission of fluids.

Drainage HDPE pipes are lightweight and the corrugations provide wall stiffness and resistance to handling stresses, resulting in easy installation and lower transportation costs. Under constant deformation, PE pipe indicates stress relaxation and the ratio of relaxation is bigger than the decrease in strength in time. Because of longitudinal flexibility and rapid internal stress relaxation properties, bending stresses and compression are not decisive in the design of buried corrugated PE pipes provided sufficient soil envelope has been placed to take the load. As the pipe relaxes, the soil envelope limits the pipe strain and load is transferred to the envelope. The envelope takes shape a soil arch that supports the majority of the load. Ring deflection (defined as the ratio of change in pipe diameter to the original pipe diameter) governs the performance of PE pipes since excessive deflection may cause buckling as well as reduction in performance factors such as flow capacity.

PE pipes are thermoplastic which is defined as a material which becomes soft and pliable when heated without change in its other properties and hard and rigid when cooled again. PE resin has the properties have to resist environmental stresses from chemical and biological agents Thermoplastics are invulnerable to the corrosion process induced by electrolytes. This results in a negligible cost for maintenance and external protection such as painting, plastic coating, or cathodic protection.

3.2. PVC- Polyvinyl Chloride Pipe

Polyvinyl chloride pipes (PVC) are produced from ethylene and chlorine. The surfaces of the pipe are very smooth and resist any buildup of deposited minerals and other soils. It is totally corrosion resistant. PVC pipe is not subject to biological degradation. Abrasive resistance is excellent and no special care for cleaning is needed as compared to other pipe products. Dimensional control is excellent.

PVC is a thermoplastic and it is stronger than polyethylene, allowing thinner sections and reducing both weight and cost. However, it is more brittle and less tolerant of site handling.

PVC is the most widely used member of the vinyl family. It is most commonly used in pipe and fittings. PVC offers excellent corrosion and weather resistance. It has a high strength-to-weight ratio and is a good electrical and thermal insulator. PVC is also self-extinguishing per UL flammability tests. PVC may be used to temperatures of 140°F (60°C) and is readily available in sheets, rods, and tubing. PVC may be cemented, welded, machined, bent and shaped readily.

3.3. FRP – Fiber Reinforced Plastic Pipe

A fiber reinforced plastic pipe (FRP) comprising a cylindrical inner layer containing a thermosetting resin as a matrix and an outer layer formed by winding a thermoplastic resin sheet or tape around the inner layer, said inner and outer layers being heat cured and thermo-compression bonded in one united body; and a process for manufacturing the fiber reinforced plastic pipe. When the fiber reinforced plastic pipe is manufactured, the thermosetting resin is used for forming the inner layer and the thermoplastic resin is used for forming the outer layer. Moreover, a metal coat can be firmly bonded to the surface of the outer layer. Hence, a fiber reinforced plastic pipe prominently improved in impact resistance and abrasion resistance properties can be provided.

Fiber Reinforced Plastics pipes (FRP) are relatively lightweight, and can be easily tailored to specific applications. They are also relatively easy to handle. FRP pipes are flexible in design and construction, and highly corrosion resistant, offering the promise of new, highly cost effective and low maintenance process systems. The latent potential of FRP attributes has only been tapped. There are many areas of variation between FRP and other materials of construction, however, and they must be carefully considered in equipment design. Some of the characteristics of FRP will appear as liabilities, when, in fact, with the use of new design approaches, they become profound assets. One such characteristic is the variability of the product itself. Fiber Reinforced Plastic is actually produced as the equipment is being formed. This variability results in less well-defined physical properties for any particular composite. Also a wide range of physical properties are possible with different laminate constructions. In addition to this, Fiber Reinforced Plastic laminates have different physical properties in different directions, physical properties which also vary with exposure and time.

4. BEHAVIOR OF THE BURIED PLASTIC PIPES

The purpose of this chapter is to introduce the terminology and current philosophy of buried plastic pipes design in trenches. The review is constrained to soil-pipe interaction.

The parameters that affect pipe deflection are the following (Terzi N.,2007):

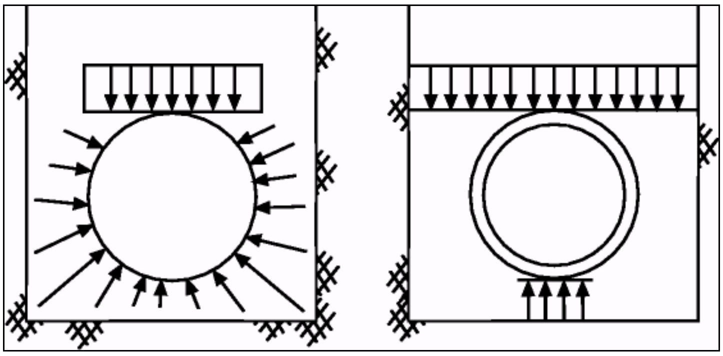
- Pipe stiffness
- Soil resistance
- Applied loads
- Trench configuration (geometry and embedment)
- Haunch support
- Construction stages
- Time
- Temperature
- Variability in construction procedures and in soil characteristics

4.1. Flexible and Rigid Pipe Concept

When installing rigid pipes made of materials like concrete, cohesive or ductile iron, the pipe is stiffer than the surrounding soil. The load is concentrated on the pipe. During the ground settlement after the installation, the soil moves past the pipe and the load remains on the pipe. Under overloading conditions, a rigid pipe does not deform adequately to produce an important amount of passive resistance at the sides in trench. In the event of loads are applied to rigid pipe, the load is transferred through the pipe wall into the bedding.

When installing a flexible pipe made of plastics material, it sheds the load by deformation. After ground settlement is completed, the surrounding soil carriers the load and not the pipe. Stresses in the pipe are reduced due to relaxation to almost zero after a few years. When the flexible pipe deflects against the backfill, the load is transferred and carried by the backfill. Flexible pipes evade the load and deform but do not break. A flexible pipe is able of forming oval shape by reducing in vertical direction and elongating in horizontal direction.

For both types of materials, proper backfill is very significant in allowing this load transfer to occur. Figure 4.1 shows the soil-pipe interaction and the corresponding load transfer.



Flexible Rigid

Figure 4.1. Soil-pipe interaction

It is possible to bury the flexible pipe much deeper than a similarly installed rigid pipe because of the flexible pipe-backfill interaction. A rigid pipe is stronger than the backfill material surrounding it, thus it must support earth loads well in excess of the prism load above the pipe. Conversely, a flexible pipe is not as strong as the surrounding backfill; this mobilizes the backfill envelope to carry the earth load.

4.2. Arching Concept

The ground soil carried by the pipe is not the same as the weight of the soil prism directly above the pipe due to soil arching. Arching is defined as the redistribution of free field soil normal stresses over a buried structure as a result of the difference in deformation properties of the structure and the soil. (Selig,1990)

According to Allgood (1971), arching (A) can be represented in terms of pressure on the buried pipe as :

$$A = 1 - \frac{P_{cr}}{P_v} \tag{4.1}$$

Where P_{cr} is the soil pressure acting on the crown of the buried structure and P_v is the vertical free field stress as shown in Figure 4.2. If the pressure on the buried structure is greater than the free field stress at the same depth, the value of A will be negative. If the pressure on the structure is less than the free field stress at the same depth, then the value of A will be positive. Zero arching occurs when the two pressures are equal. Hence, for a pipe which is rigid in bending this arching will be negative, while for a pipe which is flexible in bending this arching will be positive.

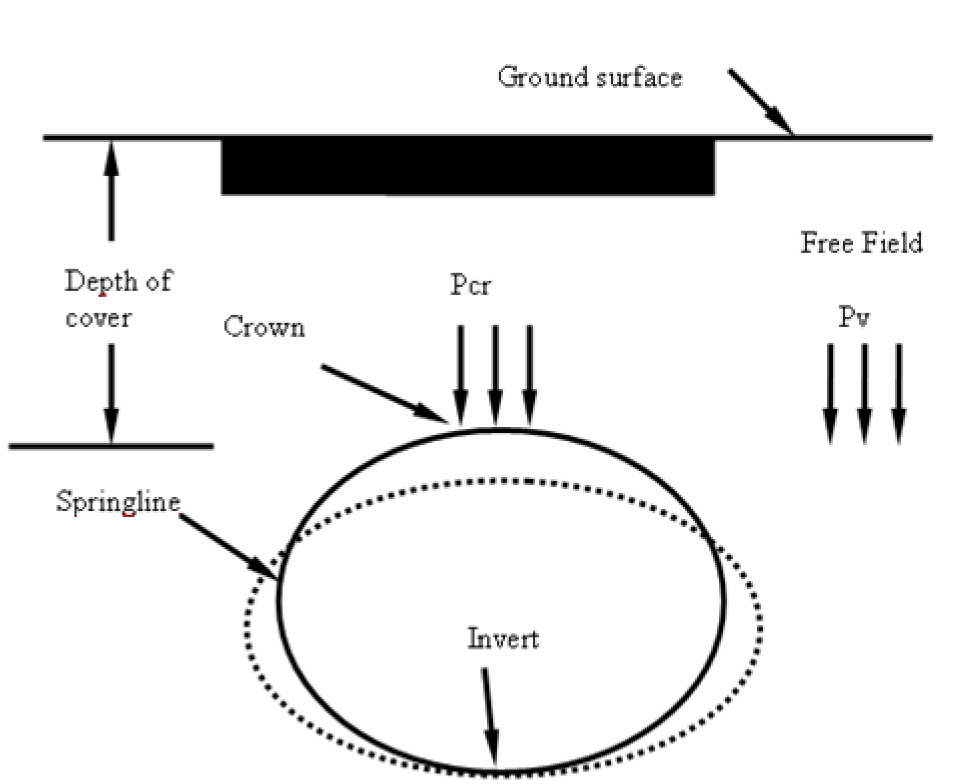


Figure 4.2. Arching in terms of soil pressures (Hashash, N.M.A.,1991)

Another definition of arching is related to spring line thrust in the buried pipe wall and can be formulated below. (Selig,1990)

$$A = 1 - (2x\frac{T_{sl}}{W_s}) \tag{4.2}$$

In given formula,

T_{sl}: the spring line thrust in the pipe wall

W_s: weight of the soil prism

The arching concept is illustrated in Figure 4.3

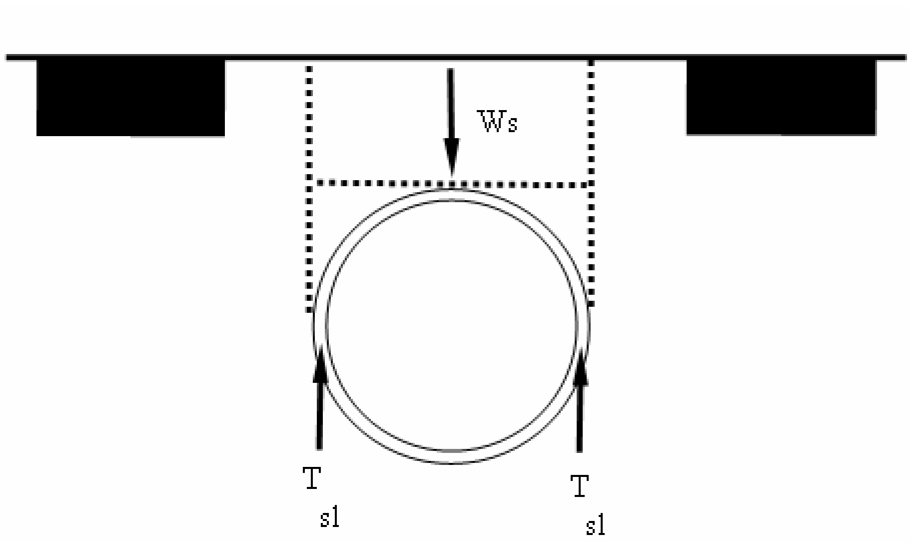


Figure 4.3. Arching in terms of Wall Thrust (Hashash, N.M.A.,1991)

Pipe-soil interaction addresses the mutual contributions of pipe and soil in a successful structural system, as soil supports much of the vertical pressure in arching action, over the pipe. The “bedding” condition has a very important effect on both circumferential and longitudinal bending moments. For instance, active lateral earth pressure can reduce the circumferential moment by 25%. The longitudinal bending moments can also be affected similarly. (Spangler, M.G.,1982)

The structural requirements for pressure and non-pressure installations are not the same. In the case of sewers and drains, internal pressure does not occur and therefore the pipes may be subjected to considerable backfill and surcharge compression loads, whereas pressure pipes such as potable water pipeline have to resist tensile stress.

For a buried pipe subjected to a deformation caused by ground movements, for example ground settlements in a mining area or earthquake regions, a high modulus of elasticity or high strength at break offers no protection because the forces of the ground will always be higher.

4.3. Soil Pressure and Soil Weight Concept

Stiffness properties of both the pipe and the surrounding soil are determinative parameters for conduits buried in the soil.

The soil pressure above flexible pipe is determined by the soil prism load theory as shown in Figure 4.4.

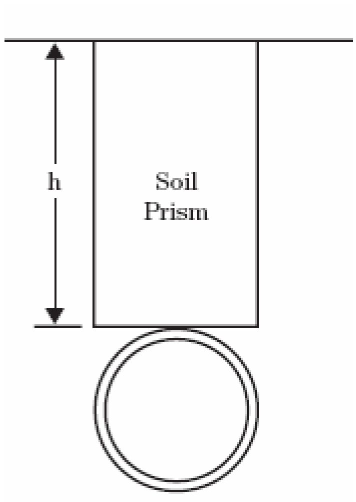


Figure 4.4. Soil prism

The soil pressure may be determined by the following equation:

$$P_s = \gamma_s \times h \tag{4.3}$$

where,

P_s: Pressure due to weight of soil at depth of h,

γ_s : Unit weight of soil

h : Height of ground surface top of pipe

When groundwater is above the top of the pipe, P_s may be reduced for buoyancy by the factor, R_w:

R_w : Water buoyancy factor

$$R_w = 1 - \frac{h_w}{3xh} \tag{4.4}$$

where,

h : Height of ground surface above top of pipe

h_w : Height of water above top of pipe

On the other hand, the weight of soil is calculated as below.

$$W_s = \gamma_s \times h \times D \tag{4.5}$$

where,

W_s= the weight of soil

D= the diameter of pipe

5. METHODS OF PIPE ANALYSIS

5.1. Marston Load Theory

The Marston Load Theory (1913) is the first study about buried pipes in literature. (Marston, A. Anderson,1913). It gives realistic results and it is still used in the current practice. The theory accounts for the shearing forces between the soil directly above the pipe and the side fill in an embankment installation. According to Marston Load Theory, soil prism above culvert is carried by shearing resistance of the soil on the vertical sides of the prism as shown in Figure 5.1.

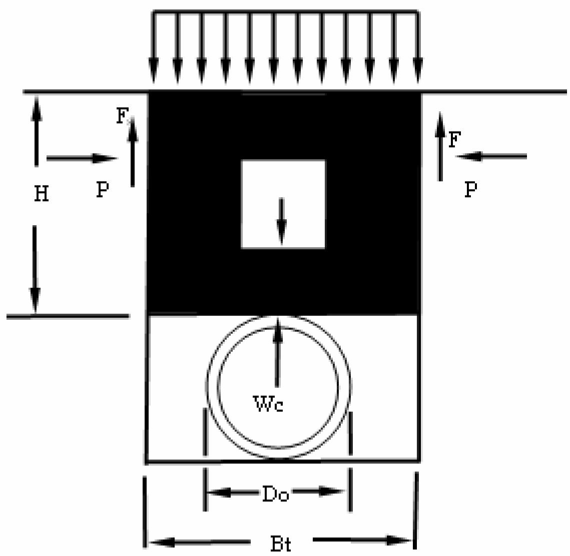


Figure 5.1. Marston Load Theory

The soil weight per unit length transmitted to the pipe is explained by,

$$W_c = C_i \times \gamma_s \times B_t^2 \quad (5.1)$$

In given formula,

C_i: Load coefficient

γ_s: Unit weight of the backfill

B_t: Width of trench

5.2. Iowa Deflection Formula

Iowa Deflection Formula is the most widespread method for anticipating pipe deflections. Spangler, a graduate student of Anson Marston, generated this method in 1941. This is the first study establishing flexible pipe behavior. This formula is an expression for the horizontal deflection of a flexible pipe due to the addition of fill on top of the pipe. Spangler concluded that as a fill is built over a flexible culvert, the ratio of the horizontal pressure on the pipe at any point to the horizontal movement at that point is constant based on experimental study carried on corrugated-metal pipe culverts. (Spangler, M. G.,1941)

Spangler proposed that both pipe stiffness and soil stiffness are effective parameters for determining side fill deflection. According to Spangler (1941) deflection can be defined as:

$$\text{Deflection}=\frac{\text{load}}{\text{pipe stiffness + soil stiffness}} \tag{5.2}$$

The Iowa deflection formula is based on five major limiting assumptions:

1. The vertical deflection is equivalent to the horizontal deflection for less than five per cent of pipe diameter
2. The deformation of the pipe is elliptical
3. The horizontal modulus of soil reaction is constant for the backfill material
4. The pipes are buried deeply
5. The horizontal pressure is distributed parabolically over the middle 100°.

As can be shown in Figure 5.2, the maximum unit pressure, P_{sl} is equal to one half of the horizontal deflection of the pipe multiplied by the modulus of passive pressure of the side fill material.

$$P_{sl} = ex\frac{\Delta x}{2} \tag{5.3}$$

where,

e: The modulus of passive resistance

Δx : The horizontal deflection after load is applied above the pipe crown

$$\Delta x = \frac{D_1 \times K \times W_c \times R^3}{E_p \times I_p + 0,061 \times e \times R^4} \tag{5.4}$$

In given formula,

K : modified bedding constant which is a function of α, given in Table 5.1.

W_c : Marston's load per unit length of pipe

E_p: horizontal modulus of soil reaction (MPa)

R : the mean radius of pipe

I_p: moment of inertia per unit length of cross section of the pipe wall

D_1 : deflection lag factor to take care of deflection which will develop over a period of time

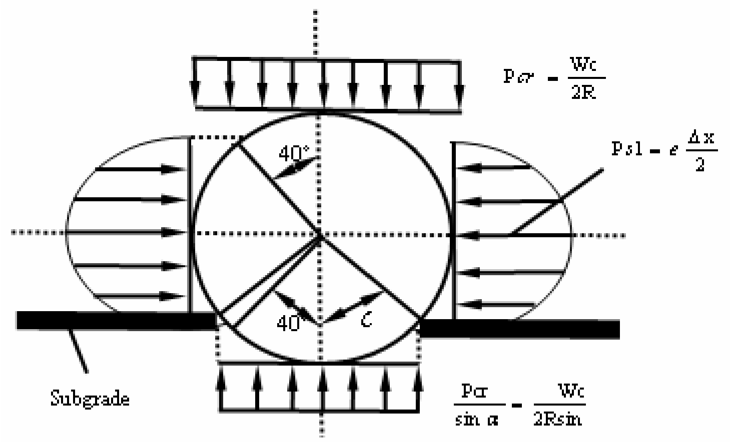


Figure 5.2. Pressure Distribution Around Buried Flexible Pipe (Spangler,1941)

Table 5.1. Value of Bedding Constant, K (Moser,2000)

Bedding Angle (^{o})	K
0	0,110
30	0.108
45	0.105
60	0.102
90	0.096
120	0.090
180	0.083

Watkins (1958) examined the modulus of passive resistance through a lot of studies and defined another soil parameter. This was called as the modulus of soil reaction, E'.

$$E' = e x R \tag{5.5}$$

By using the modulus of soil reaction, E', The Modified Iowa Formula was generated as below,

$$\Delta x = \frac{D_1 \times K \times W_c \times R^3}{E_p \times I_p + 0,061 \times E' \times R^3} \tag{5.6}$$

Howard (1977) composed a table of soil reaction modulus for various soil types by using laboratory and field tests, as shown below Table 5.2.

Table 5.2. Howard Soil Reaction Modulus, E' (Howard,1977)

Soil Class	Soil Type	Proctor Compaction (%)			
	Soil type-pipe bedding material	Dumped	< % 85	% 85-%95	> % 95
V	Fine Grained Soil (LL > 50) Soils with medium to high plastic CH, MH,CH-MH	No data available, consult a competent soils engineer, otherwise use E' = 0 (kPa)			
IV	Fine Grained Soils (LL< 50) Soils with medium to no plasticity CL, ML,ML-CL with less than 25% coarse grained particles	350	1400	2800	7000
III	Fine Grained Soils (LL< 50) Soils with medium to no plasticity CL,ML,ML-CL with more than 25% coarse grained particles Coarse grained soils with fines GM,GC,SM,SC contains more than 12% fines	700	2800	7000	14000
II	Coarse grained soil with little or no fines GW,GP,SW,SP contains less than 12% fines.	1400	7000	14000	21000
I	Crushed Rock	7000	21000	21000	21000

5.3. Greenwood-Lang Modified Iowa Deflection Formula

Greenwood-Lang observed that the pipes of low circumferential stiffness elongate in vertical direction by side fill compaction (Greenwood, M.E., Lang, D.C.1990). The modified Iowa formula of Greenwood and Lang (1990) is presented below.

$$\Delta x = \frac{K(\gamma H)}{EI/r^3 + 0.061\varsigma C_1 E'} - \delta_{vo} \tag{5.7}$$

In given formula;

Δx ; Horizontal deformation (m)

K ; Bedding factor (From Table 5.3.)

γ ; Unit weight of the backfill (kN/m^3)

H ; Height of the backfill above the pipe (m)

I ; Moment of inertia of the pipe per unit length of pipe (m^4/m)

r ; Mean radius of the pipe (m)

ς ; Leonhardt relationship

δ_{vo} ; Elongation due to compaction of the side fiils (m)

C_1 ; Pipe-soi1 interaction coefficient defined by Greenwood and Lang (1990)

$$C_1 = a\left(\frac{EI}{1250.D^3}\right)^b \tag{5.8}$$

$$\varsigma = \frac{1.662 + 0.639(B/D - 1)}{(B/D - 1) + [1.662 - 0.361(B/D) - 1]E_2/E_3} \tag{5.9}$$

E_2 ; Soil modulus of the embedment

E_3 ; Soi1 modulus of the native soil

B ; Trench width

Table 5.3. Bedding Factor Values, K (Greenwood-Lang 1990)

Soil	Range of fines (per cent)	Backfill Standard Proctor Density (per cent)			
		> 95	85-95	70-84	< 70
Clean Gravel	< 5 (5-12)	0.083 0.096	0.083 0.096	0.083 0.083	0.083 0.083
Dirty Gravel	12-50	0.103	0.103	0.096	0.083
Clean Non-cohesive	<5,(5-12)	0.103	0.103	0.096	0.083
Dirty Non-cohesive	12-50	0.103	0.103	0.096	0.083
Inorganic Cohesive /Silt	>50	0.103	0.103	0.096	0.083

The values of parameters a and b in equation 5.8 can be provided from Table 5.4.

Table 5.4. Values of parameters a and b (Greenwood and Lang 1990)

Backfill Standard Proctor Density (per cent)	a	b
> 95	1.24	0.180
85-95	0.983	0.245
70-84	0.643	0.353
< 70	0.456	0.436

5.4. Ring-Compression Theory

It assumes that the buried culvert behaves like a thin shell for which the structural bending stiffness and interface friction between the soil and culvert may be neglected. The soil pressure on the horizontal plane at the crown elevation, P_{cr}, is assumed to equal the vertical free field overburden stress, P_v , at that depth.(Figure 5.3) Thus the shearing stresses on the sides of the soil prism are neglected. The spring line thrust, T_{sl}, is determined by,

$$T_{s\,l} = P_v \times (\frac{D}{2}) \tag{5.10}$$

where,

D: the mean diameter of the pipe

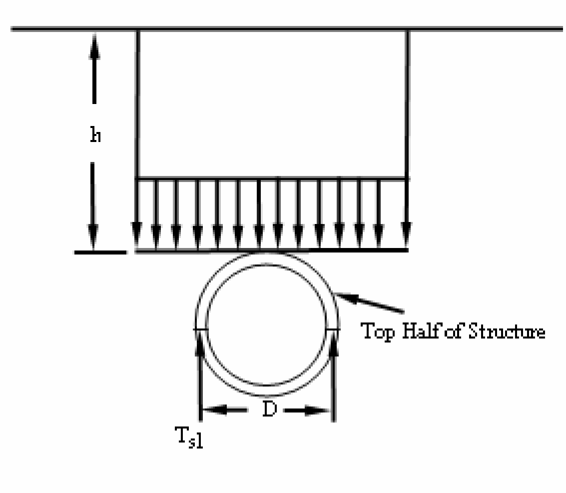


Figure 5.3. Soil-Structure Model

If bending moments and interface shear are neglected, a section of the shell maybe represented as shown in Figure 5.3. Principles of equilibrium show that the thrust in the pipe wall, T_c, can be calculated as:

$$T_c = \rho \times w \tag{5.11}$$

Where w is the radial pressure on pipe from soil, and ρ is the radius of curvature.

Assuming that $T_c = T_{sl}$ throughout the culvert, the soil pressure, w, can be calculated by equating equation (5.12). The thrust will actually vary around the culvert, but T_{sl} is usually its maximum value.

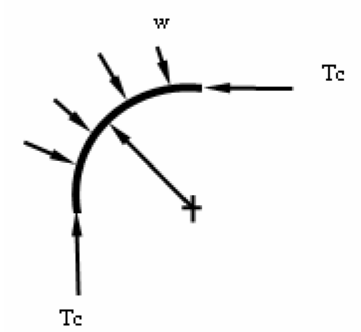


Figure 5.4. The equilibrium of a shell section

Molin (1981) found that the vertical soil pressure, w, above a pipe in an infinitely wide trench (e.g. under embankment fill) increased with the stiffness of the pipe and so proposed that the average pressure at crown level could be expressed by;

$$w = C \times q_o \tag{5.12}$$

where,

q_o: Pressure at crown level without a pipe

C: Load factor (minimum value of 1),

S_r: stiffness ratio = 8S/E′

S: stiffness of pipe = EI/D^3

E′: horizontal modulus of soil reaction as defined by the Iowa equation (MPa)

$$C = \frac{36 \times S_r \times (20 \times S_r + 1)}{(12 \times S_r + 1)(36 \times S_r + 1)} \tag{5.13}$$

This equation for C is a design approximation of the theoretical cases of full slip between the pipe and the soil and no slip. Full slip gives rise to maximum C values or the greatest pressures above pipes.

5.5. Elasticity Solution

An elasticity solution for an elastic pipe embedded in an infinite elastic medium and subjected to vertical and horizontal load is developed by Burns and Richard (1964). The solution was based on the condition of full-bond or free-slip at the soil-pipe interface. It was assumed that there is no gap at the soil-pipe interface and soil is homogeneous, isotropic, linear, elastic material. Figure 5.5 shows the elastic soil-pipe interaction considered by Burns and Richard. (Burns, J.Q. and Richard,1964)

The earth load pressure and live load at the depth of the pipe are represented by an equal pressure applied at the top surface of the medium.

Elastic Solution method is proper for rigid and flexible pipes. However, this method ignores arching effect by the trench.

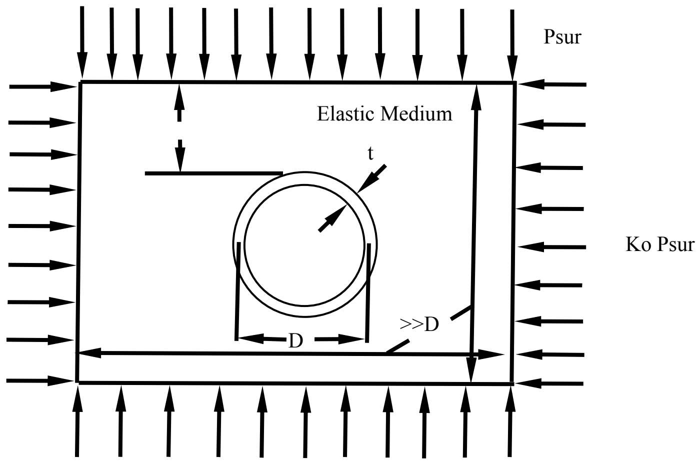


Figure 5.5. Elastic Plate Theory

Another elastic solution is developed by Hoeg (1968). Hoeg's method assumes that the soil behaves like an elastic material, which is isotropic and homogeneous. This is an unrealistic assumption because the soil behavior is always nonlinear. In addition, the Hoeg's method does not take into account the installation practice.

Contrary to Richard & Burns method, there is no relationship between the coefficient of side fill resistance (K) and Poisson ratio (ν) in Hoeg Elasticity method.

5.6. Chua and Lytton Viscoelastic Method

Chua and Lytton (1989) proposed a viscoelastic solution including the time dependence of the deflections, stresses and strains in the pipe-soil system.

$$C = \frac{1}{2}\frac{\left(\frac{1}{2t}\right)^{m} M_1\Gamma(1-m)\left(\frac{D}{T}\right)}{\left[\left(\frac{1}{2t}\right)^{m_c} E_{c1}\Gamma(1-m)\right]} \tag{5.14}$$

$$F = \frac{1}{4}\left(\frac{1-2\upsilon}{1-\upsilon}\right)\frac{\left(\frac{1}{2t}\right)^{m} M_1\Gamma(1-m)\left(\frac{D}{T}\right)^{3}}{\frac{\left[\left(\frac{1}{2t}\right)^{m_c} E_{c1}\Gamma(1-m)\right]}{(1-\upsilon_c{}^{2})}} \tag{5.15}$$

C: Compactibility ratio

F: Flexibility ratio

t: Time elapsed in minutes

m: Exponent of power law for soil

m_c: Exponent of power law for pipe material

M_l: Relaxation modulus of soil

T: Pipe wall thickness

Γ: Gamma function

$$\Gamma = \int_0^\infty e^{-x}.x^{n-1}.dx \quad (5.16)$$

$$\Gamma(n+1) = n.\Gamma(n) \quad (5.17)$$

5.7. Finite Element Method (FEM)

Finite element analysis has been developed by Hrennikoff (1941) and McHenry (1943). In literature, there are a lot of studies investigating buried soil-pipe behavior by using finite element method such as Bjeerrum, Clausen and Duncan (1972), Abel and Mark (1973), Katona Forest Odella and Allgood (1974), Chang, Espinoza ve Selig (1980), Mada (2005), Suleiman (2004), Terzi N.(2007).

Package programs in finite element method are enumerated following. PLAXIS, which is used in this thesis, PIPE5, CANDE (Culvert Analysis and Design) (Allgood, 1976) (Katona, 1980), which is the most widely used in the U.S., SPIDA (Heger, Liepins, Selig, 1985), ABAQUS (1998), LUSAS, ADINA, FEMAP, DIANA and SIGMA. (Terzi N.,2007).

6. DEFLECTIONS AND STRESS ANALYSIS OF BURIED PIPES

In this chapter, the problem is described with all details, the method of finite element modeling is explained step by step, stress and deflection values of trenches and load versus displacement diagrams are shown in figures.

6.1. Problem Description

In the different kinds of soil properties, the behavior of a buried non-pressure High Density Polyethylene (HDPE), Fiber Reinforced Plastic (FRP) pipe and Poly Vinyl Chloride (PVC) pipe, with diameters of 300mm, 900mm, 1500mm were analyzed with the PLAXIS finite element program. 18 analyses were performed to assess soil-pipe interaction (Table 6.1).

Table 6.1. Soil-pipe analysis list

SOIL	PIPE	DIAMETER(mm)
NON-COHESİVE	HDPE	Ø 300
		Ø 900
		Ø 1500
	PVC	Ø 300
		Ø 900
		Ø 1500
	FRP	Ø 300
		Ø 900
		Ø 1500
COHESİVE	HDPE	Ø 300
		Ø 900
		Ø 1500
	PVC	Ø 300
		Ø 900
		Ø 1500
	FRP	Ø 300
		Ø 900
		Ø 1500

The following types of soil can be differentiated below. The symbols in accordance with DIN 18 196 are given in brackets: (German ATV-DVWK-A 127E, 2000)

- Group 1 (G1): Non-cohesive soils
  (GE,GW,GI,SE,SW,SI)

- Group 2 (G2): Slightly cohesive soils
  (GU, GT, SU, ST)

- Group 3 (G3): Cohesive mixed soils, coarse clay
  (silty sand and gravel, cohesive stony residual soil)
  (GU, GT ,SU,ST ,UL,UM)

- Group 4 (G4): Cohesive soils (e.g. clay)
  (TL,TM,TA,OU,OT,OH,UA)

In this study, the behavior of buried pipes in both non-cohesive soil and cohesive soil were studied. Non-cohesive soils are the most convenient soils for burying pipes. The models with cohesive soils are for comparison of the results. On the other hand, the excavation and transportation of cohesive soil to the trench require extra workmanship, expanses and time.

Table 6.2. Types of soil (German ATV-DVWK-A 127E, 2000)

Group	Spec. gravity	Spec. Gravity under buoyancy	Internal friction angle	Elasticity modulus E_S in N/mm² with degrees of compaction D_{Pr} in %						Exponent in Eqn. (3.02) *[Amended]*	Reduction factor for creep
	γ_S kN/m³	γ_S kN/m³	φ' °	85	90	92	95	97	100	Z -	f_1 -
G1	20	11	35	2[2)]	6	9	16	23	40	0.4	1.0
G2	20	11	30	1.2	3	4	8	11	20	0.5	1.0
G3	20	10	25	0.8	2	3	5	8	13	0.6	0.8
G4	20	10	20	0.6	1.5	2	4	6	10	0.7	0.5

As can be stated in Table 6.2, elasticity modulus of soil located covering above the pipe crown and the side of the pipe can be differentiated. In this study, imperfect trench conditions were modeled by using one type non-compacted soil. It was observed that displacement ratios were below five per cent of pipe diameters.

Regarding to analyses, below comparisons were carried out.

1 The comparison of Φ 300 HDPE, Φ 900 HDPE, Φ 1500 HDPE pipes in non-cohesive soil
2 The comparison of Φ 300 PVC, Φ 900 PVC, Φ 1500 PVC pipes in non-cohesive soil
3 The comparison of Φ 300 FRP, Φ 900 FRP, Φ 1500 FRP pipes in non-cohesive soil
4 The comparison of Φ 300 HDPE, Φ 900 HDPE, Φ 1500 HDPE pipes in cohesive soil
5 The comparison of Φ 300 PVC, Φ 900 PVC, Φ 1500 PVC pipes in cohesive soil
6 The comparison of Φ 300 FRP, Φ 900 FRP, Φ 1500 FRP pipes in cohesive soil
7 The comparison of Φ 300 HDPE, Φ 300 PVC, Φ 300 FRP in non-cohesive soil
8 The comparison of Φ 900 HDPE, Φ 900 PVC, Φ 900 FRP in non-cohesive soil
9 The comparison of Φ 1500 HDPE, Φ 1500 PVC, Φ 1500 FRP in non-cohesive soil
10 The comparison of Φ 300 HDPE, Φ 300 PVC, Φ 300 FRP in cohesive soil
11 The comparison of Φ 900 HDPE, Φ 900 PVC, Φ 900 FRP in cohesive soil
12 The comparison of Φ 1500 HDPE, Φ 1500 PVC, Φ 1500 FRP in cohesive soil

The pipes have been buried in trench with the depth of 2,5m and the width of 2,5m.

In order to check the accuracy of PLAXIS analysis, the results have been compared with experimental study results and CANDE Finite Element Program of reference study. (Reddy DV, Gazagnaire C, Ataoglu S.,2007) Therefore, the first step was the comparison of the results of Φ 300 HDPE pipe designed in PLAXIS finite element program, with CANDE finite element program and experimental study. This experimental study of interaction between non-cohesive soil and high density polyethylene plastic pipe was performed in a 2,5m × 2,5m size laboratory soil box as illustrated in Figure 6.1. (Reddy DV, Gazagnaire C, Ataoglu S.,2007)

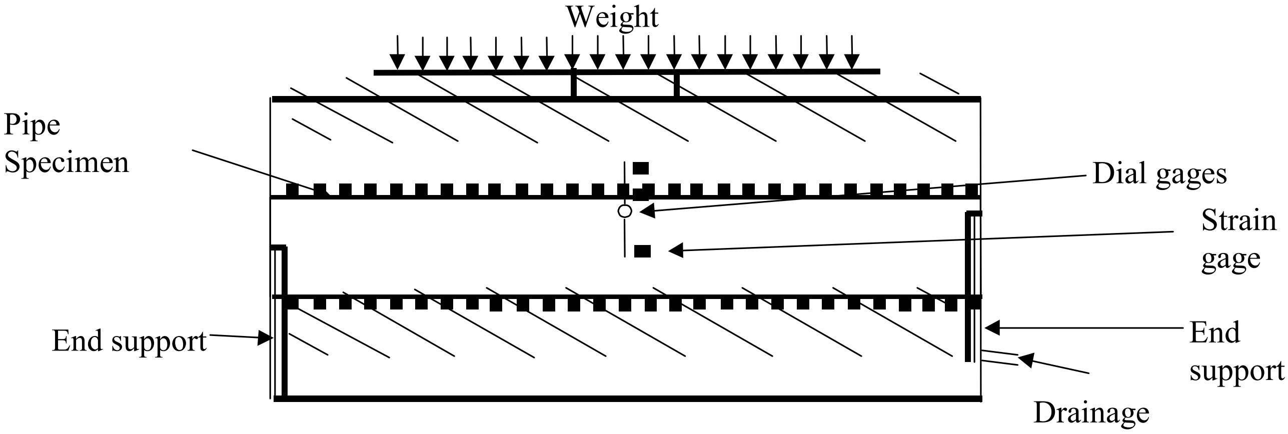


Figure 6.1. Schematic of the Test Setup of Reference Study

6.2. Finite Element Modeling

The study presented in this thesis focused on the trench-pipe installation subject by developing a finite element model including all the parameters of design. The numerical approach is a reasonable choice, considering the number of parameters concerned and the complex interaction between the response of the soil and the pipe. The final result of the work is based on a set of charts for pipe and soil properties.

6.2.1. CANDE Finite Element Analysis

The availability of Finite Element Analyses (FEA) has seen numerous recent attempts to understand the soil-pipe interaction model. Culvert ANalysis and DEsign (CANDE) a 2-D finite element program commonly used to analyze and design buried pipes that was developed by Katona (1990).

CANDE, verified software program for soil-structure interaction analyses of buried conduits, is used with established design criteria to achieve the design objective, which is the minimum cover requirement for corrugated plastic pipe.

The CANDE methodology incorporates the soil mass along with the structure into an incremental, static, plane-strain boundary value problem. Limiting aspects of CANDE were the assumption of a uniform soil envelope and the approximation of a 3D loading pattern in a 2D finite element analysis. Soil-pipe interaction in reference study has been solved by finite element modeling was undertaken using the computer program CANDE. (Katona, M.G., 1980)

6.2.2. PLAXIS Finite Element Analysis

PLAXIS 7.2 version is a two dimensional finite element package program for modeling of soil-structure interaction problems. PLAXIS represents PLAne strain and AXISymmetric analysis. PLAXIS contain various soil types, complicated geometry and different material types, boundary conditions and loadings. Five different soil models including the Mohr-Coulomb and linear elastic model are available. In this study, Mohr-Coulomb soil model was preferred. Structural elements are modeled using elastic beam elements, extension elements or spring elements. Boundary conditions, prescribed loads, displacements and fixities can also be specified. The structural model can be simulated in stages, according to the sequence of construction proposed in the field. Displacements at nodes and stresses at elemental stress points anywhere within the model can be obtained.

6.2.2.1. Review of the features

PLAXIS consists of four sub-programs such as Input, Calculations, Output and Curves.

6.2.2.2. High order continuum elements

In PLAXIS, two types of triangular elements are available. The standard quadratique 6-node element gives accurate results. However, the cubic 15-node element is even more accurate and gives a smooth distribution of stresses in the soil. 15-node element has been applied for this study.

6.2.2.3. Unit

The default units, as suggested by the program, are m (meter) for length, kN (kiloNewton) for force.

6.2.2.4. Model Geometry

The model geometry is created in the PLAXIS Input program contains all facilities to create and to modify a vertical cross-section model, to generate a 2D and 3D finite element mesh and initial conditions. The generation of the initial conditions is done in initial conditions mode. For this type of analysis the pipe will be subjected to loads that act only in the x and y direction, and that the cross-sectional area including the pipe and the backfill material is constant along an indefinite length in the z direction. These characteristics allow assuming the state of strain normal to the x-y plane ε_z, and the shear strains γ_{xz}, and γ_{yz}, to be zero. The description is first focused on the creation of a cross-section model and a finite element mesh (Geometry creation mode).

According to AASHTO (American Association of State Highway and Transportation Officials, 1994), the size of trench was determined as the depth of 2,5m and the width of 2,5m in this study.

A minimum amount of soil cover is needed to spread the surface loading and to create a more favorable soil pressure distribution around the pipe. Minimum cover requirements are listed in Table 6.3.

Table 6.3. Minimum cover requirements for corrugated polyethylene pipe (AASHTO,1994)

Inside Diameter In. (mm)	Minimum Cover ft (m)	Inside Diameter In. (mm)	Minimum Cover ft (m)
3 (75)	1 (0.3)	18 (450)	1 (0.3)
4 (100)	1 (0.3)	21 (525)	1 (0.3)
6 (150)	1 (0.3)	24 (600)	1 (0.3)
8 (200)	1 (0.3)	30 (750)	1 (0.3)
10 (250)	1 (0.3)	36 (900)	1 (0.3)
12 (300)	1 (0.3)	42 (1050)	1 (0.3)
15 (375)	1 (0.3)	48 (1200)	1 (0.3)

The minimum cover specified is mostly between 300mm and 600mm. This is comparable to the minimum cover of 300mm specified in AASHTO (American Association of State Highway and Transportation Officials (1994), Section 18. The maximum fill heights specified from 3 to 18.3m.

In order to generate pipe geometry, tunnel menu is selected. Φ300mm, Φ 900mm and Φ 1500mm pipes are designed regarding to their radius parameters.

6.2.2.5. Definition of Soil Model

PLAXIS comprises some advanced constitutive models, as well as some simple models. The simplest model is the well-known Mohr-Coulomb model. This model gives a good approximation of the ultimate load for simple problems. For more complex problems, involving time-dependent behavior or unloading-reloading residual strain, more advanced models are necessary. The Soft-Soil model, which is based on the Cam-Cohesive model (Schofield and Wroth, 1968), is efficient to analysis the behavior of normally consolidated soft soils. Secondary compression can also be modeled. For stiffer soils, the Hardening Soil model of Schanz (PLAXIS, 1998), which .is based on the

Hyperbolic model (Duncan and Chang, 1970), gives good results.

The modeling of the soil materials present in the trench installation is performed using the Mohr-Coulomb constitutive model. The soil material properties required as input in the constitutive model are: Young's modulus (E), Poisson's ratio (ν), cohesion (c), friction angle (Ø) and angle of dilatancy (ψ). The respective values for various soil materials modeled in the trench installation in the current study are listed in Table 6.4.

Table 6.4. Soil material properties

Soil Type	γ_{dry} (kN/m^3)	γ_{wet} (kN/m^3)	k_x (m/day)	k_y (m/day)	E_{ref} (kN/m^2)	ν	c_{ref} (kN/m^2)	Ø	Ψ
Non-cohesive	18	18	0,05	0,05	30.000	0,30	5	35	0,02
Cohesive	16	18	5×10^{-7}	5×10^{-7}	18.000	0,32	30	5	0,001

The load transfer analyses of buried pipes are influenced by the type of backfill material used. The related material types and properties reported in Table 6.4 (ASTM D 2321, 1993). With this provision, the bedding is placed in two different kinds of soils, indicated by their properties.

6.2.2.6. Definition of Pipe Model

After model parameters and the material properties for soil clusters are entered in material data sets, the next step is defining the beam elements. Each type of material has unique properties and reactions differently to the surrounding soil. As a result, material-specific design criteria have been developed. Many factors are involved in the choice of the structural material to be used. These factors include strength, toughness, stiffness, corrosion resistance, weight, compatibility with foundation movements, required quality control during construction, method of installation, and local availability.

In this work, three kinds of beam materials representing HDPE, PVC, FRP pipes have been entered to numerical analyzing model (IPEX product catalogue).

The material and section properties namely, the Young's modulus (E), Poisson's ratio (ν), moment of inertia and cross section area for the various types are given in Table 6.5 and Table 6.6.

Table 6.5. Pipe material properties

Pipe Type	Elasticity Modulus (kPa)	ν
HDPE	758×10^{3}	0,40
PVC	2760×10^{3}	0,38
FRP	28100×10^{3}	0,30

Table 6.6. Pipe section properties

Pipe Diameter (mm)	Moment of Inertia (m^4/m)	Area (m^2 /m)
Φ 300	$5,74\times10^{-7}$	$4,78\times10^{-3}$
Φ 900	$49,05\times10^{-7}$	$38,9\times10^{-3}$
Φ 1500	$310,32\times10^{-9}$	$15,5\times10^{-3}$

The input parameters for the beam elements are:

EA: The ability of the pipe to take circumferential thrust
EI: The flexural stiffness of the pipe in ring bending
d : Equivalent thickness
w: Weight
ν : Poisson's ratio

6.2.2.7. Standard Fixities

Standard fixities impose a set of general boundary conditions to the actual geometry model. These boundary conditions are generated according to the following rules:

- Vertical geometry lines for which the x-coordinate is equal to the lowest or highest x-coordinate in the model obtain a horizontal fixity ($u_x = 0$).

- Horizontal geometry lines for which the y-coordinate is equal to the lowest y-coordinate in the model obtain a full fixity ($u_x = u_y = 0$).
- Beams that extend to the boundary of the geometry model obtain a fixed rotation in the point at the boundary ($\Phi_z = 0$) if at least one of the displacement directions of that point is fixed. (PLAXIS 7.2 MANUAL,1998).

6.2.2.8. Load

The load is quoted from previous study because PLAXIS results are compared with the experimental results and CANDE results in reference study. In the reference work, dead loading was used to determine the maximum allowable loading of the specimens. A steel plate is used to distribute the load evenly.

The loading of 5600 lb (2.536,8 kg) was applied as a uniform pressure of magnitude 170 kPa spread over the pipeline. (Reddy DV, Gazagnaire C, Ataoglu S.,2007)

6.2.2.9. Mesh Generation

This feature enables the automatic generation of a random mesh of triangular elements. In the case of a buried pipe analysis, the mesh is refined in the trench, where most of the stress change and deformation occur.

6.2.2.10. Staged Construction

In order to get the most realistic results, staged construction generates. By entering the properties of soil types and materials during the calculation, the staged construction aspect is able to simulate the construction, excavation, and backfill processes.

6.3. Numerical Results

The various pipe and soil characteristic properties are described in this thesis. Three pipe material types – polyethylene (PE), polyvinyl chloride (PVC), and fiber reinforced plastic (FRP) – with significantly different modulus of elasticity, E, were considered in this study. Three conduit diameters, D (300mm, 900mm, 1500mm), were analyzed for each material type by using finite element program.

The finite element analysis and analyses methodology have been detailed in the previous section. The deflections of the pipe section and embedment for all the loading and installation cases have been modeled.

The Φ 300 HDPE pipe behavior which was adopted in reference experimental study and CANDE finite element program was very close to the deflection values of Φ 300 HDPE pipes that obtained using by PLAXIS finite element analysis program solutions have been summarized in Table 6.7. This means that the results of PLAXIS finite element analysis are accurate. In the light of this fact, other diameters of pipes in non-cohesive soil and cohesive soil have been solved by using PLAXIS program and obtained deflection and stress distribution.

Table 6.7. Vertical displacements of HDPE Φ 300 pipe buried in 2.5m×2.5m trench (Reddy DV, Gazagnaire C, Ataoglu S.,2007)

Vertical Displacement	HDPE Φ 300 PIPE		
	PLAXIS (This study)	CANDE	Experimental study
	4,85 mm	5,1 mm	4,9 mm

The results in PLAXIS are presented graphically various format such as a view of the deformed mesh by vectors, contour lines, or shaded areas, point displacement graphic and effective stress graphic.

Total displacement, deformed mesh and effective stress figures have been presented below.

The analysis outputs of HDPE Φ300 mm pipe in non-cohesive soil are given in Figure 6.2 and Figure 6.3.

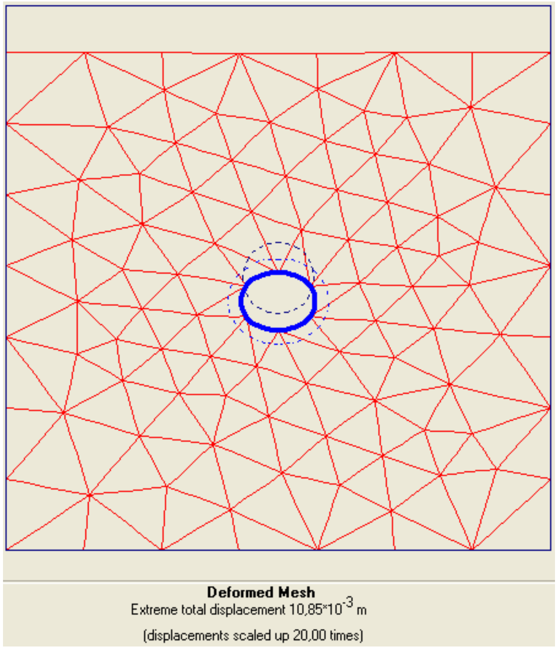


Figure 6.2. The deformed mesh of HDPE Φ300 mm pipe in non-cohesive soil

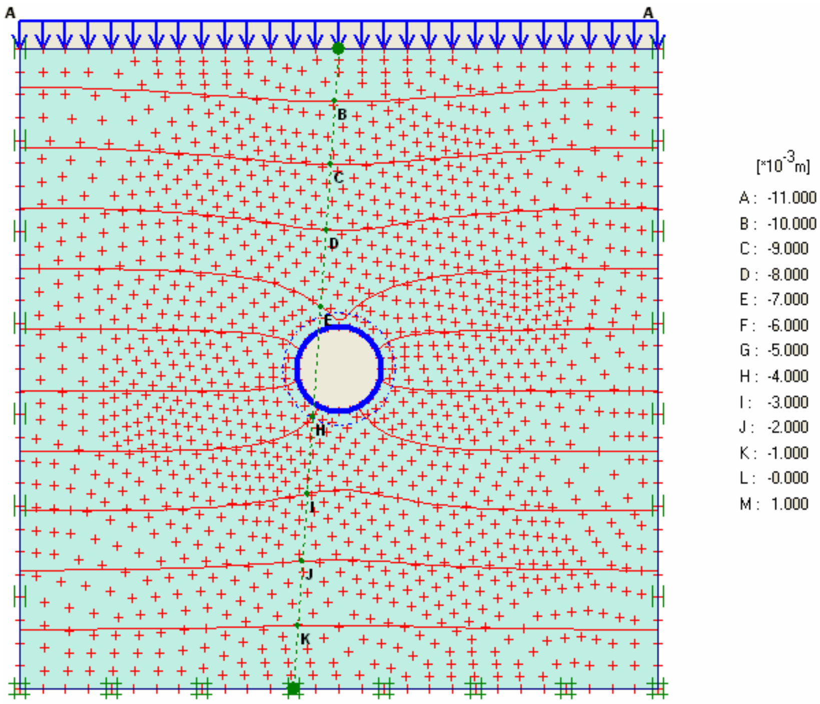


Figure 6.3. The vertical displacements of HDPE Φ300 mm pipe in non-cohesive soil

As can be seen in Figure 6.2 and Figure 6.3, maximum deflection is observed as 10,85mm in trench soil. HDPE 300 mm pipe which was placed between E point and H point and deflected 3,12 mm. Also, distribution of deflection is shown in Figure 6.4.

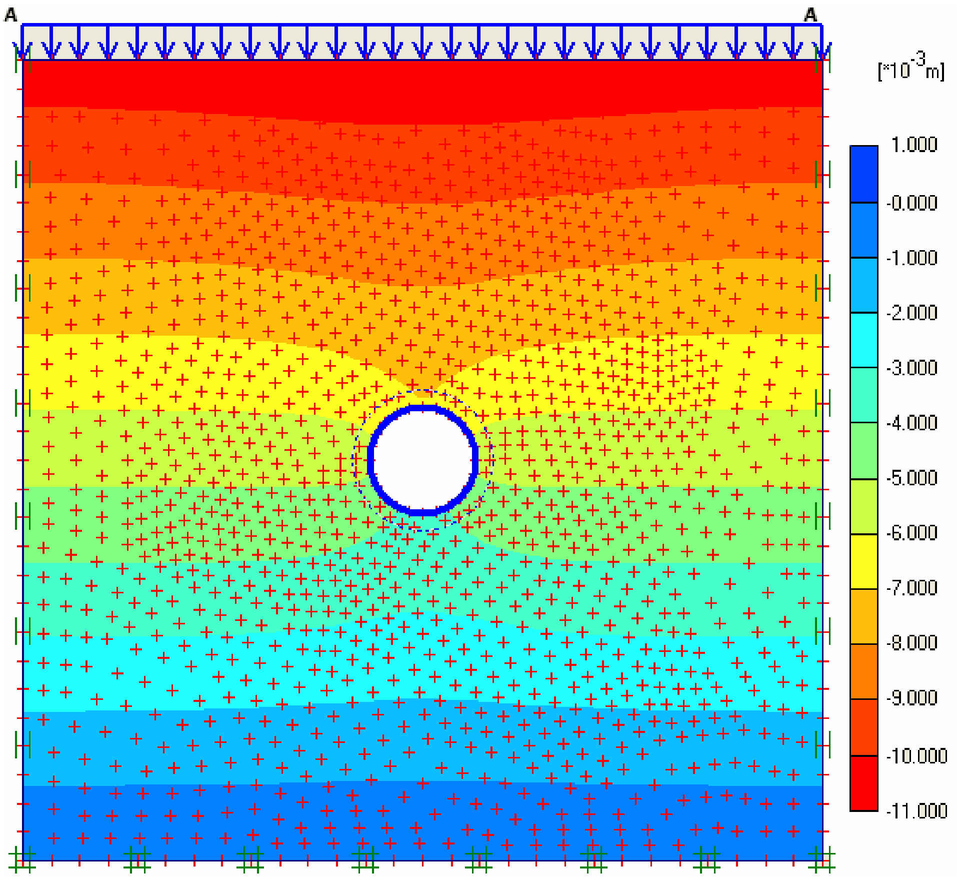


Figure 6.4. The vertical displacements of non-cohesive soil and HDPE Φ300 mm pipe

The distribution of effective stress is illustrated in Figure 6.5. In trench, the effective stress is getting increase around the pipe.

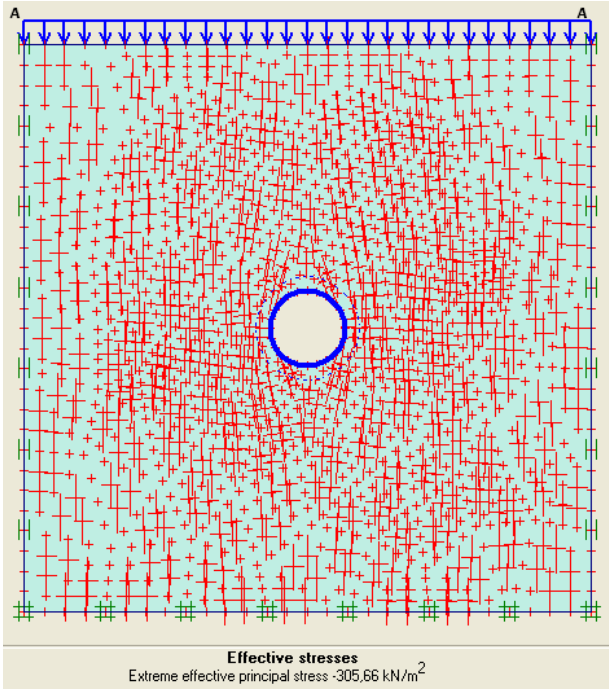


Figure 6.5. The effective stress of HDPE Φ300 mm pipe in non-cohesive soil

The rest outputs of 18 analyses are illustrated in Appendix.

6.4. Load versus Displacement Diagrams

When displacement figures and stress distribution figures are evaluated, load versus displacement diagrams can be stated as below.

1) As can be illustrated in Figure 6.6, Figure 6.7, Figure 6.8, Figure 6.9, Figure 6.10, Figure 6.11, in consideration of the different soil types, the same pipe materials and the same loading conditions, the maximum displacements have been observed on the pipes of the biggest diameters.

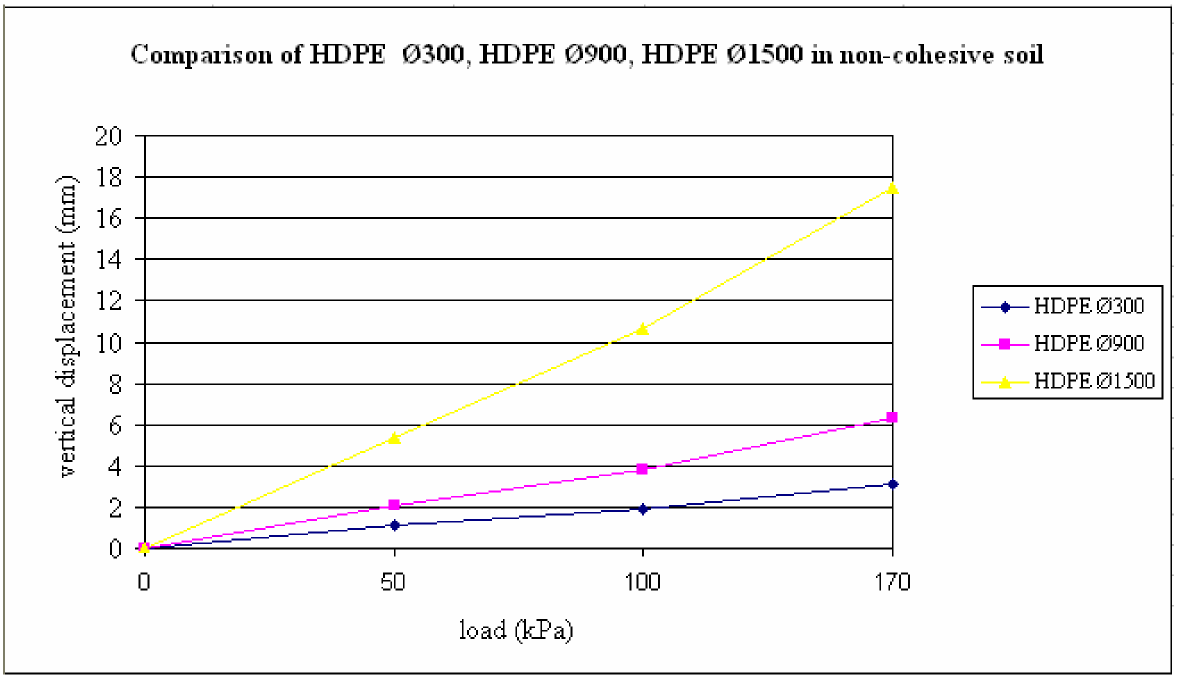


Figure 6.6. Comparison of HDPE Ø300 mm, HDPE Ø900 mm, HDPE Ø1500 mm pipe in non-cohesive soil

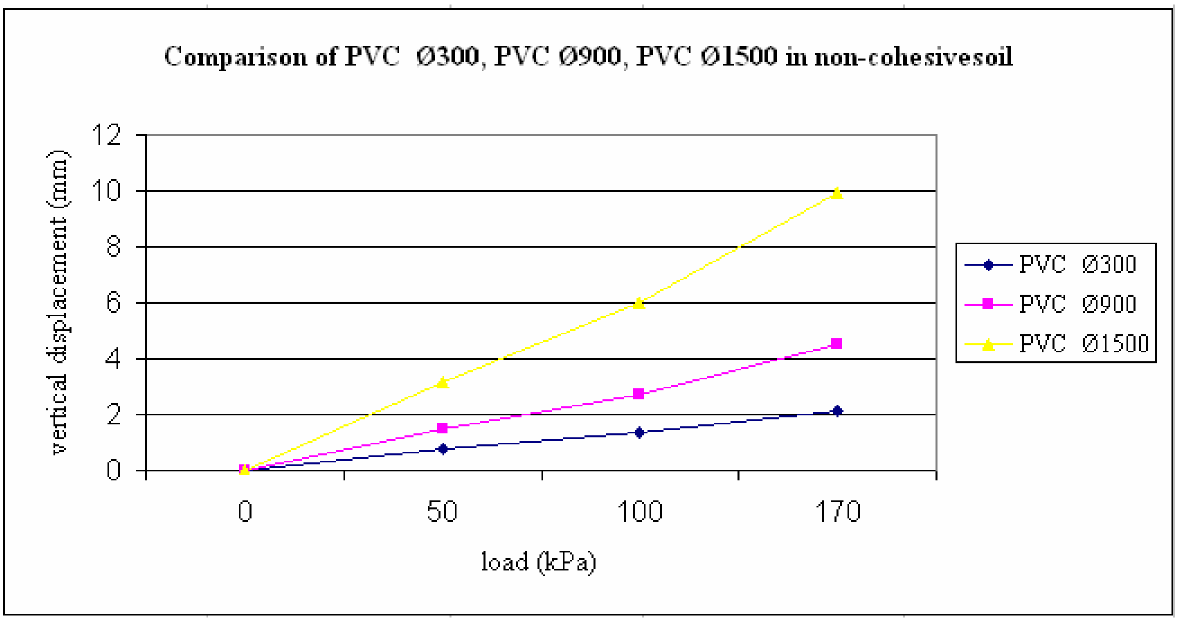


Figure 6.7. Comparison of PVC Ø300 mm, PVC Ø900 mm, PVC Ø1500 mm pipe in non-cohesive soil

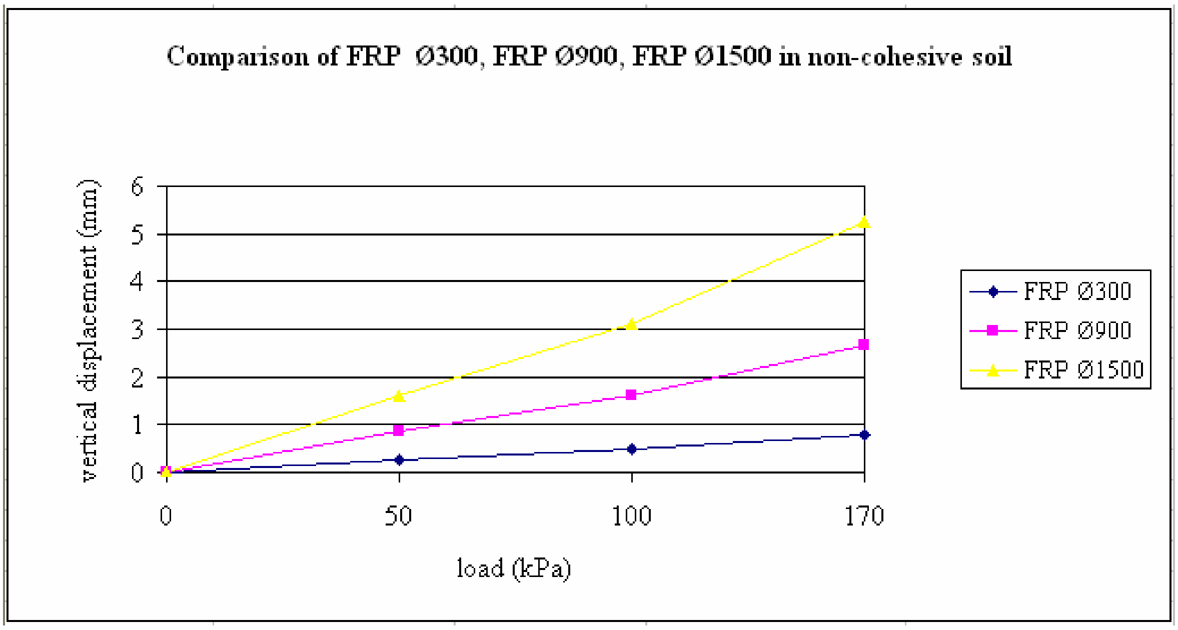


Figure 6.8. Comparison of FRP Ø300 mm, FRP Ø900 mm, FRP Ø1500 mm in non-cohesive soil

This situation can be explained like this: the circumferential stiffness of pipe is equal to (EI/D^3). This means that while the diameter of pipe (D) increases, the circumferential stiffness of pipe decreases and the deflection increases.

The displacements can be ranged as below.

$$\delta_{1500} > \delta_{900} > \delta_{300} \tag{6.2}$$

δ: the displacement on pipe section

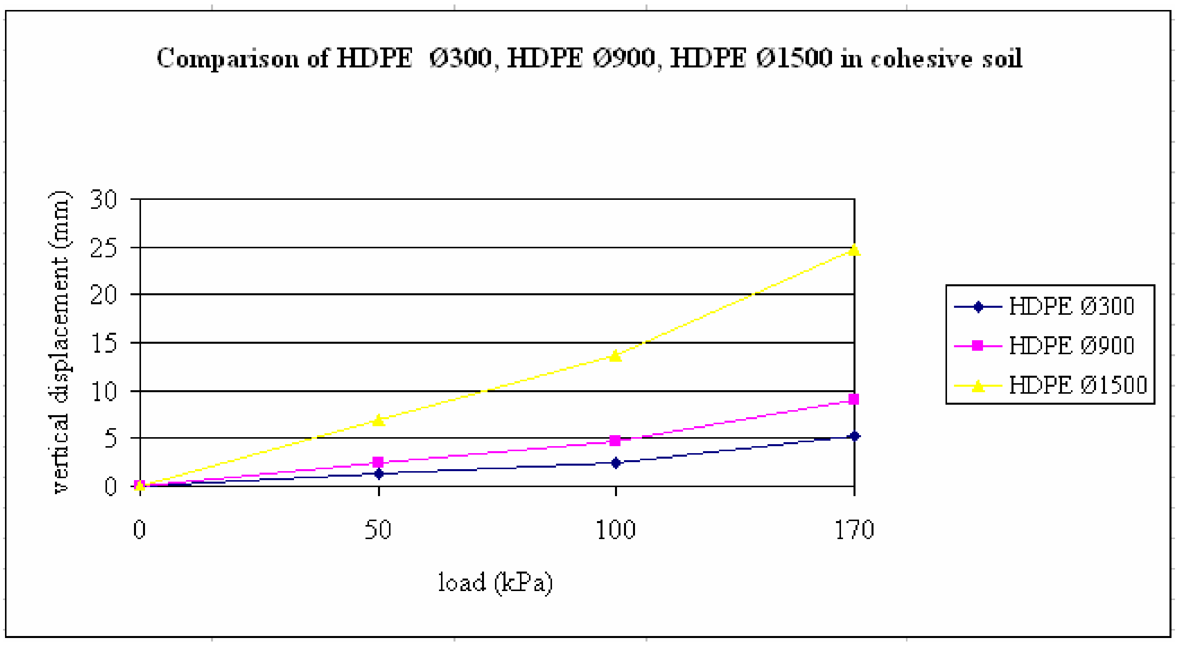


Figure 6.9. Comparison of HDPE Ø300 mm, HDPE Ø900 mm, HDPE Ø1500 mm in cohesive soil

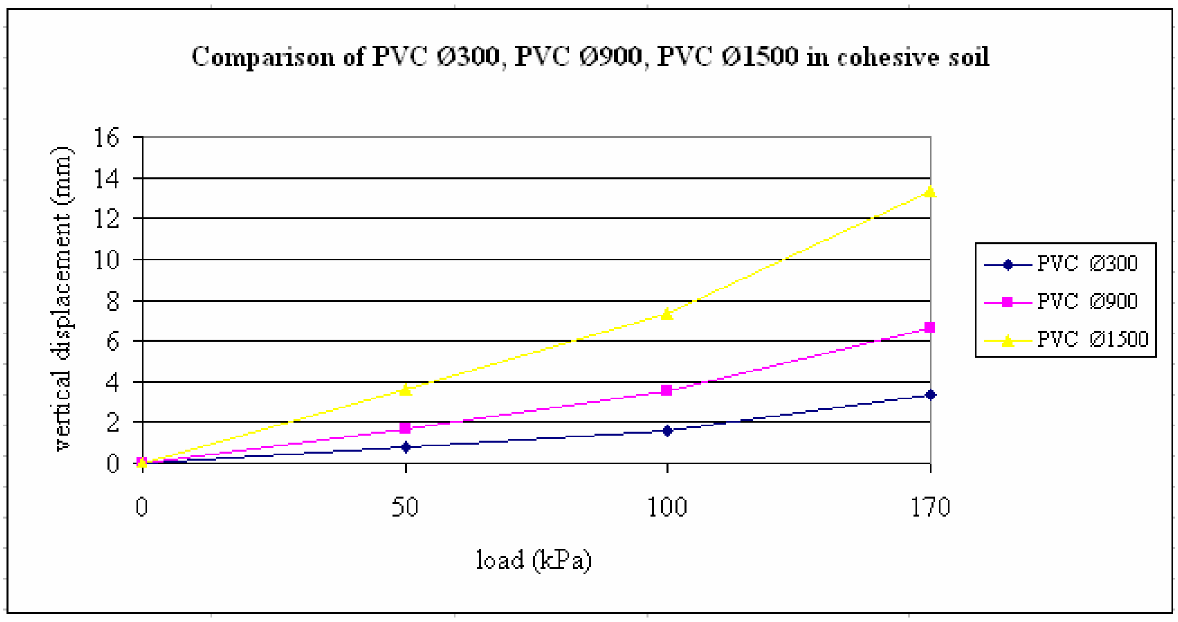


Figure 6.10. Comparison of PVC Ø300 mm, PVC Ø900 mm, PVC Ø1500 mm in cohesive soil

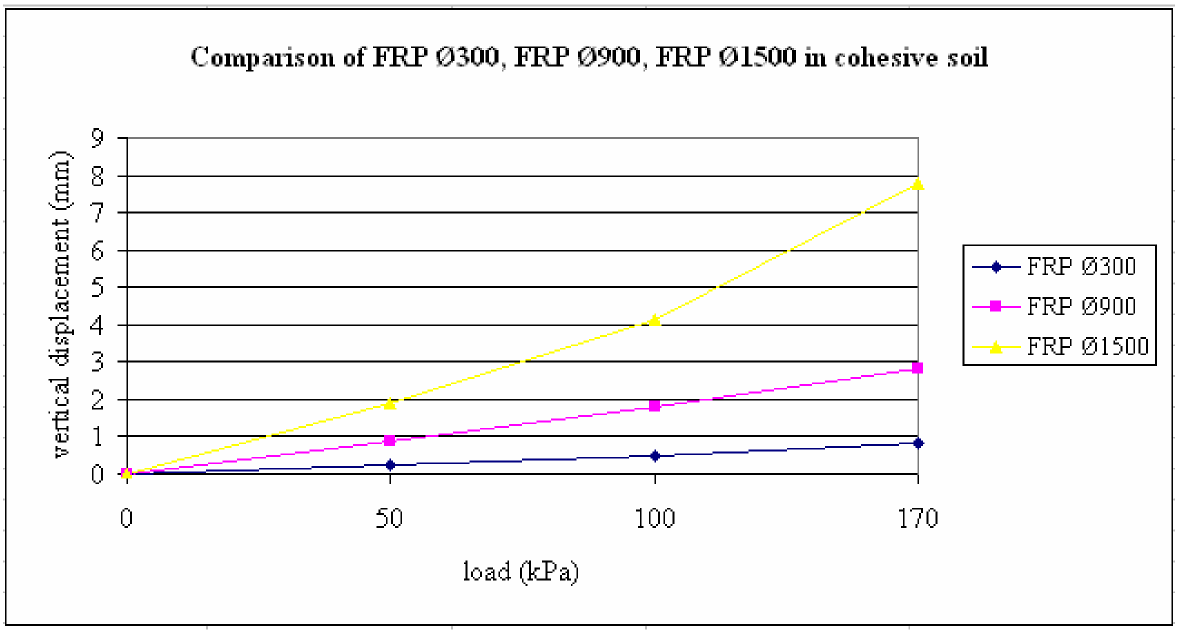


Figure 6.11. Comparison of FRP Ø300 mm, FRP Ø900 mm, FRP Ø1500 mm in cohesive soil

2) Even though the diameters of pipes are ranging the same increment, the displacement curves of 300mm pipes and 900mm pipes are closer to each other whereas the displacement curve of 1500mm pipe grows away from them in both soil conditions as can be shown in above Figure 6.6, Figure 6.7, Figure 6.8, Figure 6.9, Figure 6.10, Figure 6.11.

3) Since the elastic modulus are as follows:

$$E_{FRP} > E_{PVC} > E_{HDPE} \tag{6.3}$$

The maximum displacements have been observed on HDPE pipes, the minimum displacements have been observed on FRP pipes in consideration of the different soil types, the different pipe materials and the same loading conditions. PVC pipes represent an intermediate displacement between FRP and HDPE pipes by means of elastic modulus as shown in Figure 6.12, Figure 6.13, Figure 6.14.

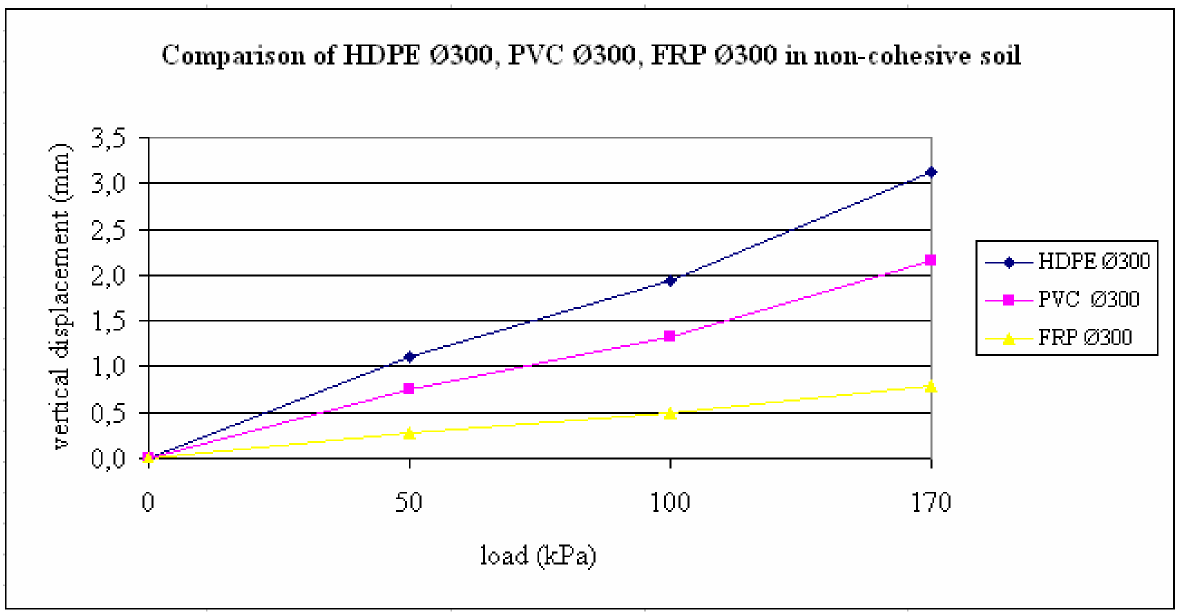


Figure 6.12. Comparison of HDPE Ø300 mm, PVC Ø300 mm, FRP Ø300 mm in non-cohesive soil

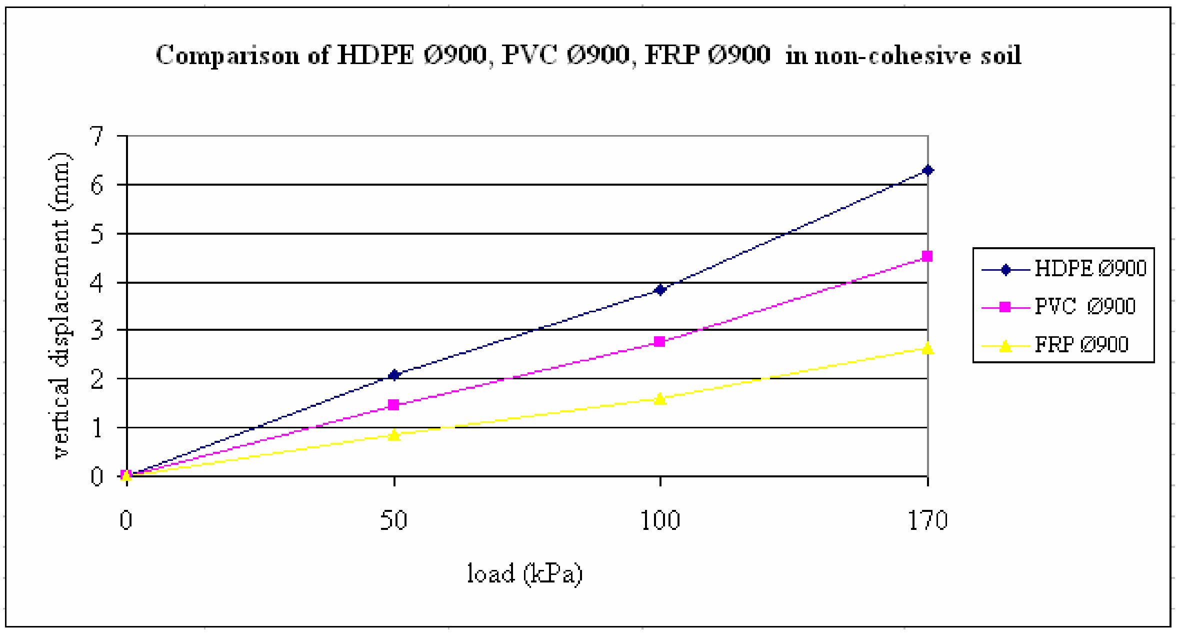


Figure 6.13. Comparison of HDPE Ø900 mm, PVC Ø900 mm, FRP Ø900 mm in non-cohesive soil

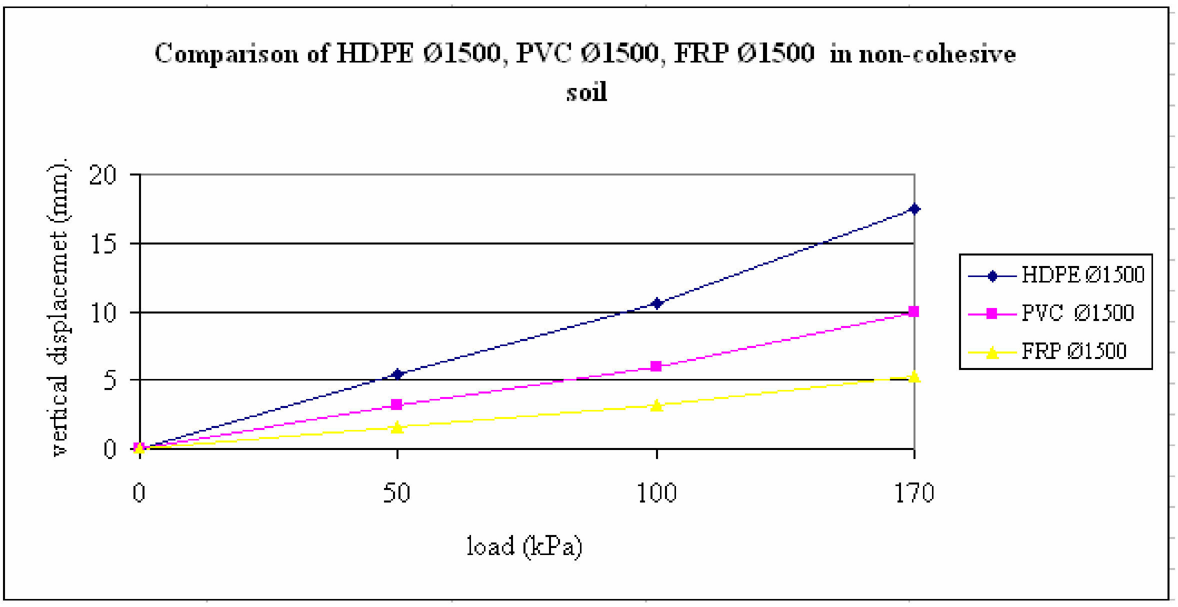


Figure 6.14. Comparison of HDPE Ø1500 mm, PVC Ø1500 mm, FRP Ø1500 mm in non-cohesive soil

For cohesive soil, comparison diagrams illustrated in Figure 6.15, Figure 6.16, Figure 6.17 below.

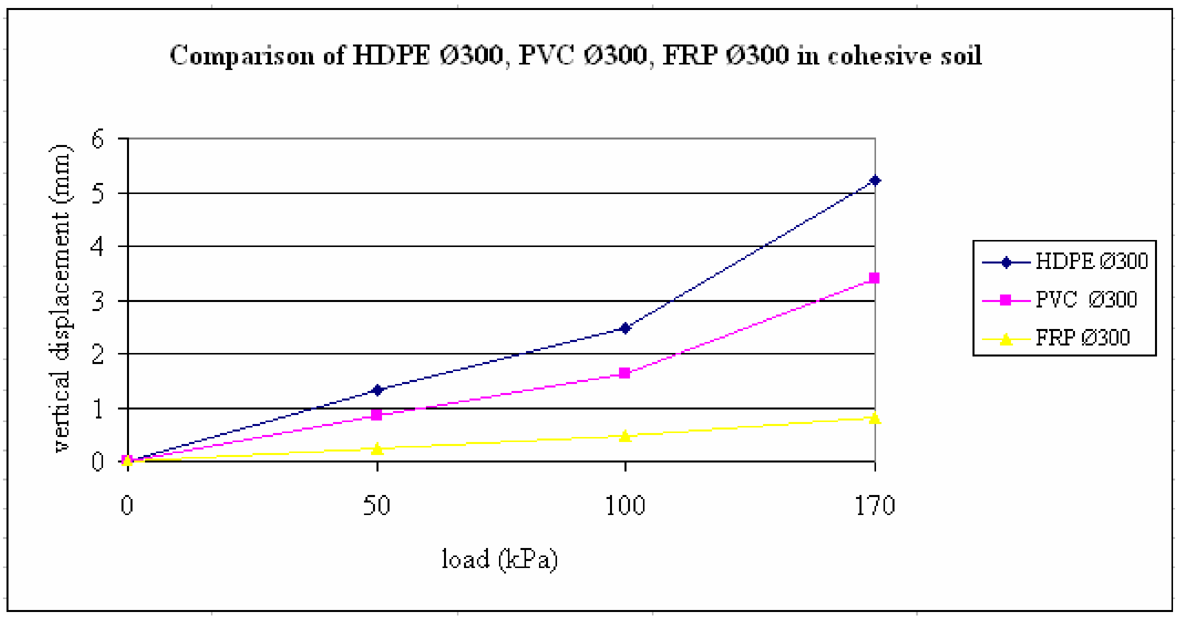


Figure 6.15. Comparison of HDPE Ø300 mm, PVC Ø300 mm, FRP Ø300 mm in cohesive soil

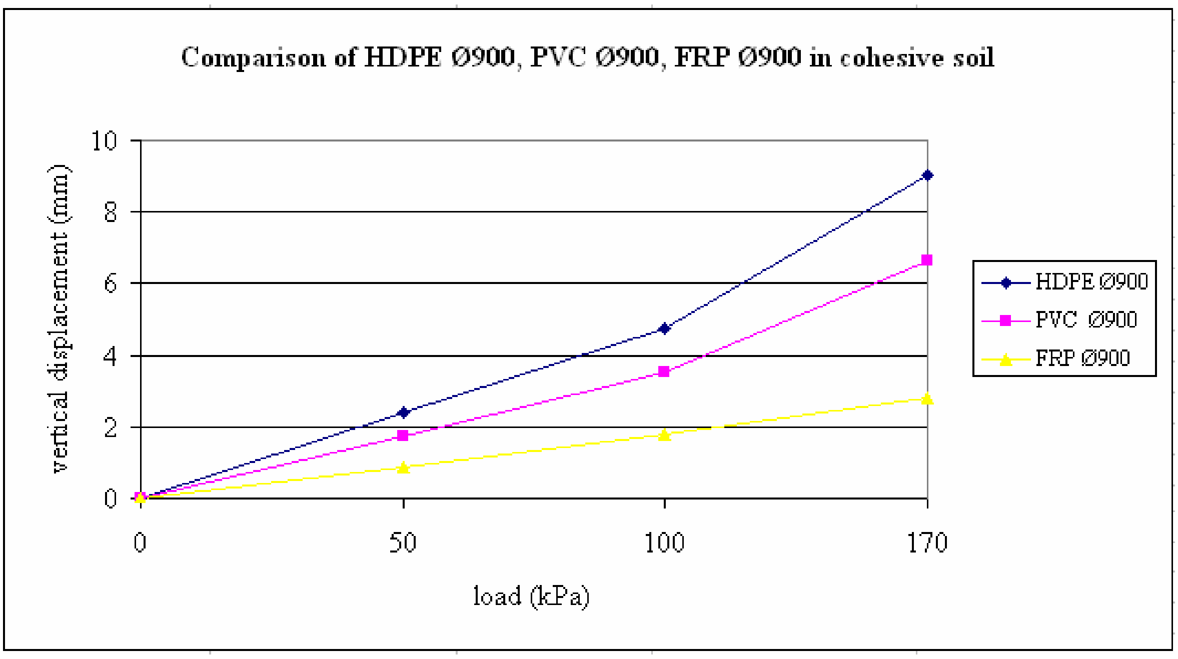


Figure 6.16. Comparison of HDPE Ø900 mm, PVC Ø900 mm, FRP Ø900 mm in cohesive soil

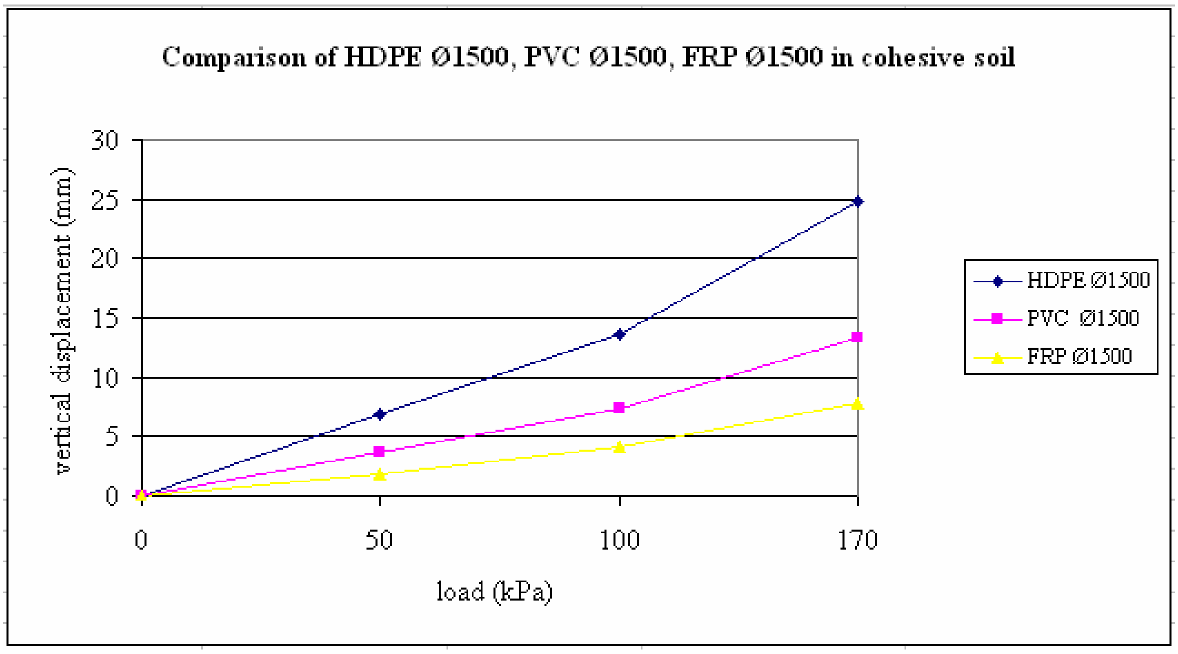


Figure 6.17. Comparison of HDPE Ø1500 mm, PVC Ø1500 mm, FRP Ø1500 mm in cohesive soil

4) The Young Modulus, E is a material property that describes its stiffness and is therefore one of the most important properties in engineering design. Elastic modulus is a determinative characteristic which extremely affects the results. While

elastic modulus increases, displacement decreases.

$$E_{non\text{-}cohesive} > E_{cohesive} \tag{6.1}$$

In the light of this fact, the conduits in cohesive soil are deformed more than the conduits in non-cohesive soil.

5) As can be illustrated in Figure 6.6, Figure 6.7, Figure 6.8, Figure 6.9, Figure 6.10, Figure 6.11, in consideration of the different soil types, the same pipe materials and the same loading conditions, the maximum displacements have been observed on the pipes of the biggest diameters.

This situation can be explained like this: the circumferential stiffness of pipe is equal to (EI/D^3). This means that while the diameter of pipe (D) increases, the circumferential stiffness of pipe decreases and the deflection increases.

The displacements can be ranged as below.

$$\delta_{1500} > \delta_{900} > \delta_{300} \tag{6.2}$$

δ: the displacement on pipe section

6) Since the elastic modulus are as follows:

$$E_{FRP} > E_{PVC} > E_{HDPE} \tag{6.3}$$

The maximum displacements have been observed on HDPE pipes, the minimum displacements have been observed on FRP pipes in consideration of the different soil types, the different pipe materials and the same loading conditions. PVC pipes represent an intermediate displacement between FRP and HDPE pipes by means of elastic modulus as shown in Figure 6.12, Figure 6.13, Figure 6.14, Figure 6.15, Figure 6.16, Figure 6.17.

7) Even though the diameters of pipes are ranging the same increment, the displacement curves of 300mm pipes and 900mm pipes are nearer to each other whereas the displacement curve of 1500mm pipe grows away from them in both soil conditions as can be shown in Figure 6.6, Figure 6.7, Figure 6.8, Figure 6.9, Figure 6.10, Figure 6.11.

8) Under the conditions of both non-cohesive and cohesive soils, the results of finite element analysis showed the displacements are conformable with ASTM D-2321 (1995) and AWWA M 45 (1997) (American Water Works Association) specifications. According to ASTM D-2321, the allowable maximum displacement limit is five per cent of the pipe diameter. As can be seen from Table 6.8., AWWA M 45 (1997) specification allows the displacement of flexible pipes more than three per cent of pipe diameter.

Table 6.8. AWWA M.45 (1997) Allowable displacement ratio

Type of Pipe	Displacement (per cent)
Rigid	0.1 (per cent of pipe diameter)
Semi- Rigid	< 3.0 (per cent of pipe diameter)
Flexible	> 3.0 (per cent of pipe diameter)

All the vertical displacement results of the finite element analyses conducted for two kinds of soil types as a combination for polyethylene, poly vinyl and fiber reinforced plastic pipes for the case of 300mm, 900mm, 1500mm pipe diameters, are summarized in Table 6.9. (See Page 50)

Table 6.9. The maximum vertical displacements on pipe

SOIL	PIPE	DIAMETER (mm)	MAXIMUM VERTICAL DISPLACEMENT (mm)	MAXIMUM VERTICAL DISPLACEMENT (per cent)
NON-COHESIVE	HDPE	Ø 300	3,12	1,04
		Ø 900	6,28	0,70
		Ø 1500	17,48	1,17
	PVC	Ø 300	2,16	0,72
		Ø 900	4,52	0,50
		Ø 1500	9,92	0,66
	FRP	Ø 300	0,79	0,26
		Ø 900	2,65	0,29
		Ø 1500	5,24	0,35
COHESIVE	HDPE	Ø 300	5,21	1,74
		Ø 900	9,04	1,00
		Ø 1500	24,83	1,66
	PVC	Ø 300	3,38	1,13
		Ø 900	6,65	0,74
		Ø 1500	13,34	0,89
	FRP	Ø 300	0,82	0,27
		Ø 900	2,82	0,31
		Ø 1500	7,8	0,52

7. CONCLUSIONS

The behavior of a buried High Density Polyethylene (HDPE) pipes, Poly Vinyl Chloride (PVC) pipes and Fiber Reinforced Plastic (FRP) pipes, with diameters of 300mm, 900mm and 1500mm respectively in non-cohesive and cohesive soil subjected to 170 kPa dead load, were analyzed with the PLAXIS finite element program. 18 analyses were performed by using PLAXIS finite element program to model the soil-pipe interaction. The analyses were based on the numerical analysis of Mohr Coloumb Soil Model.

In this study, the data were taken from the experimental study performed by Reddy DV, Gazagnaire C and Ataoglu S. In their research, they used the CANDE software for modeling the experimental study. In this study, modeling results were compared with the experimental study and CANDE results. The maximum vertical displacements of HDPE Φ 300 pipe buried in trench is 4,85 mm, 5,1 mm and 4,9 mm for PLAXIS, CANDE and experimental study, respectively. It is seen that the result of PLAXIS software is 95 per cent similar to CANDE, 98 per cent similar to experimental study. After the check of accuracy of PLAXIS software, 12 comparisons were performed to evaluate the results of 18 analyses. As a result of finite element analysis, less displacement has been observed in trenches filled non-cohesive soil and the optimum trench condition has been observed for fiber reinforced (FRP) pipes in non-cohesive soil.

It is easy to state that non-cohesive soil is ideal backfill and fiber reinforced plastic (FRP) pipes are ideal pipe comparing high density polyethylene (HDPE) and polyvinyl chloride (PVC) pipes.

It is suggested to carry out experimental studies for all kinds of trench conditions and compare the numerical results. Numerical models can be used for understanding the behavior of buried drainage pipes. In addition to them, the numbers of pipe diameters, pipe types and soil types can be increased to get more realistic evaluation about soil-pipe interaction.

APPENDIX : THE OUTPUTS OF FINITE ELEMENT ANALYSIS

A.1. The analysis outputs of HDPE Φ900 mm pipe in non-cohesive soil

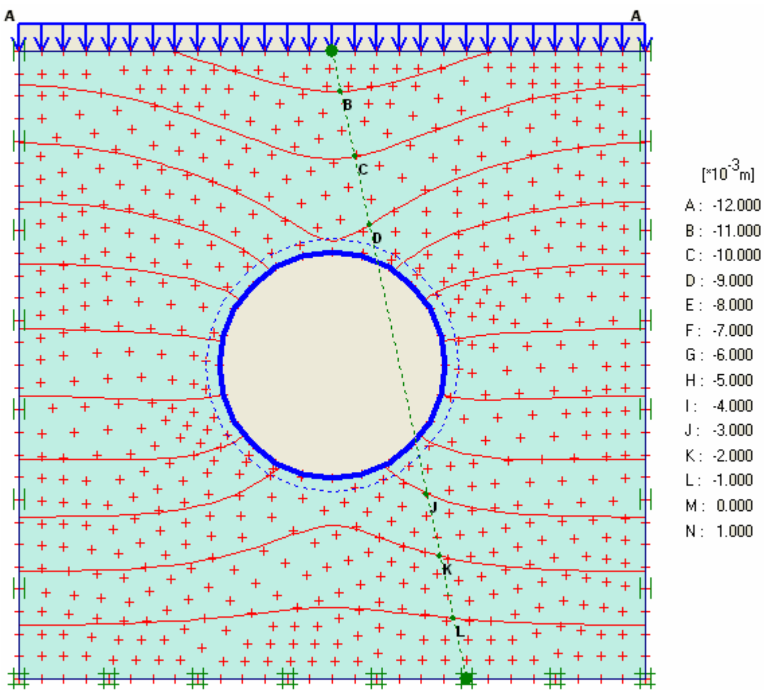


Figure A.1. The vertical displacement of HDPE Φ900 mm pipe in non-cohesive soil

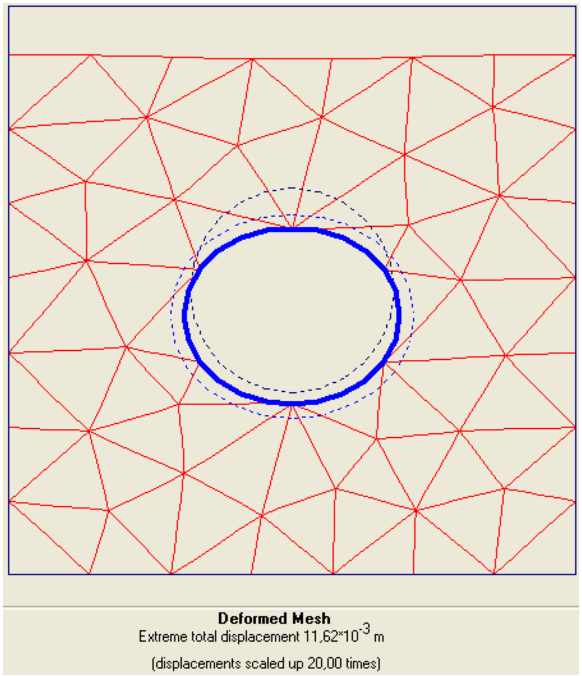


Figure A.2. The deformed mesh of HDPE Φ900 mm pipe in non-cohesive soil

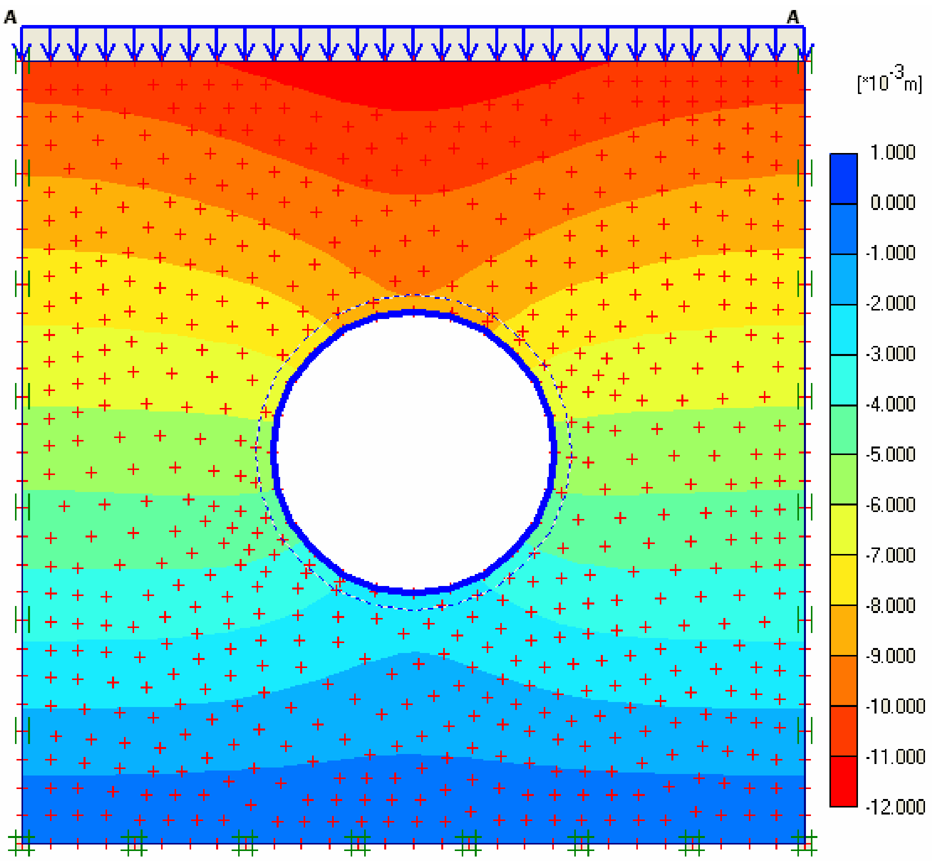


Figure A.3. The vertical displacement of non-cohesive soil and HDPE Φ900 mm pipe

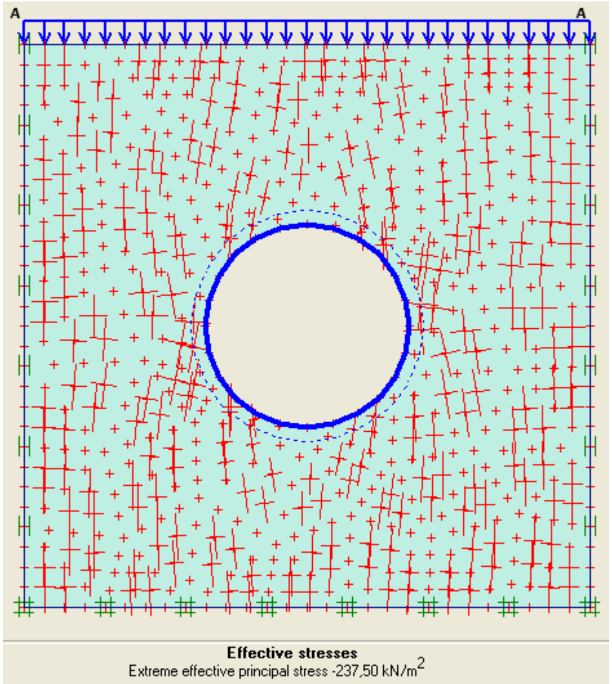


Figure A.4. The effective stress of HDPE Φ900 mm pipe in non-cohesive soil

A.2. The analysis outputs of HDPE Φ1500 mm pipe in non-cohesive soil

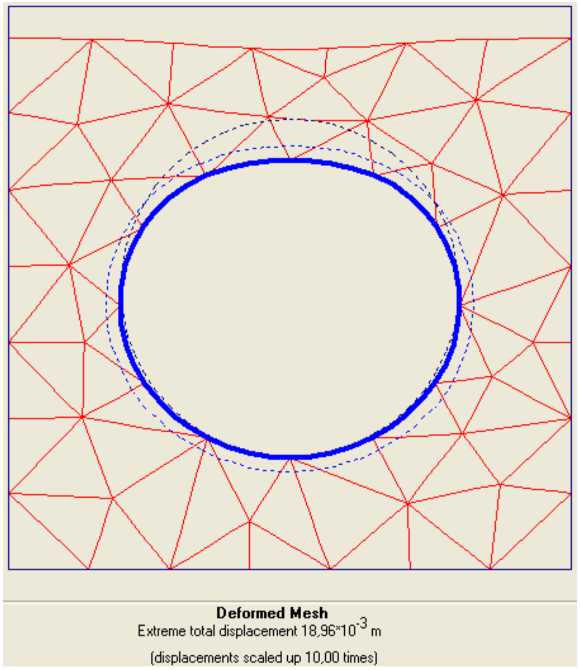


Figure A.5. The deformed mesh of HDPE Φ1500 mm pipe in non-cohesive soil

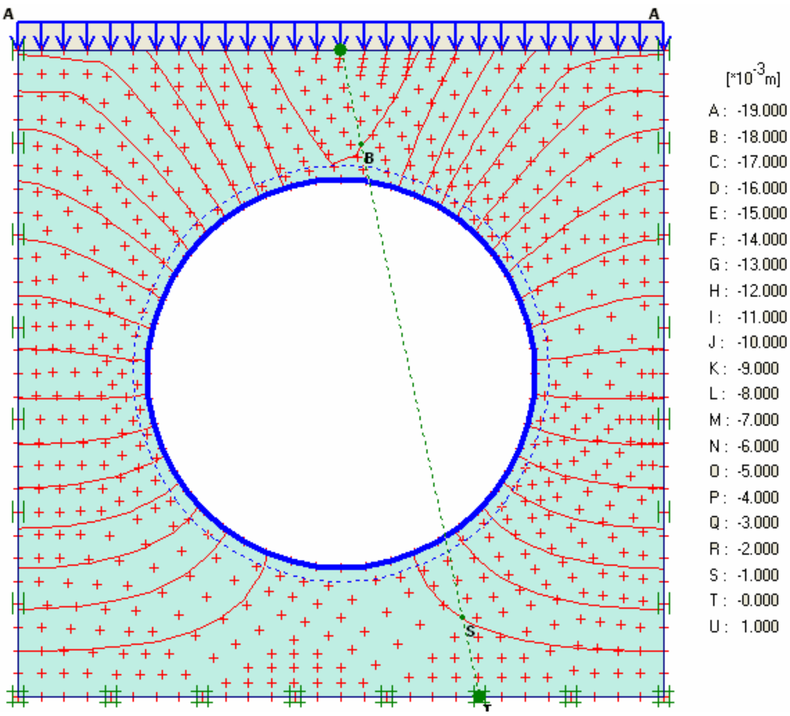


Figure A.6. The vertical displacement of HDPE Φ1500 mm pipe in non-cohesive soil

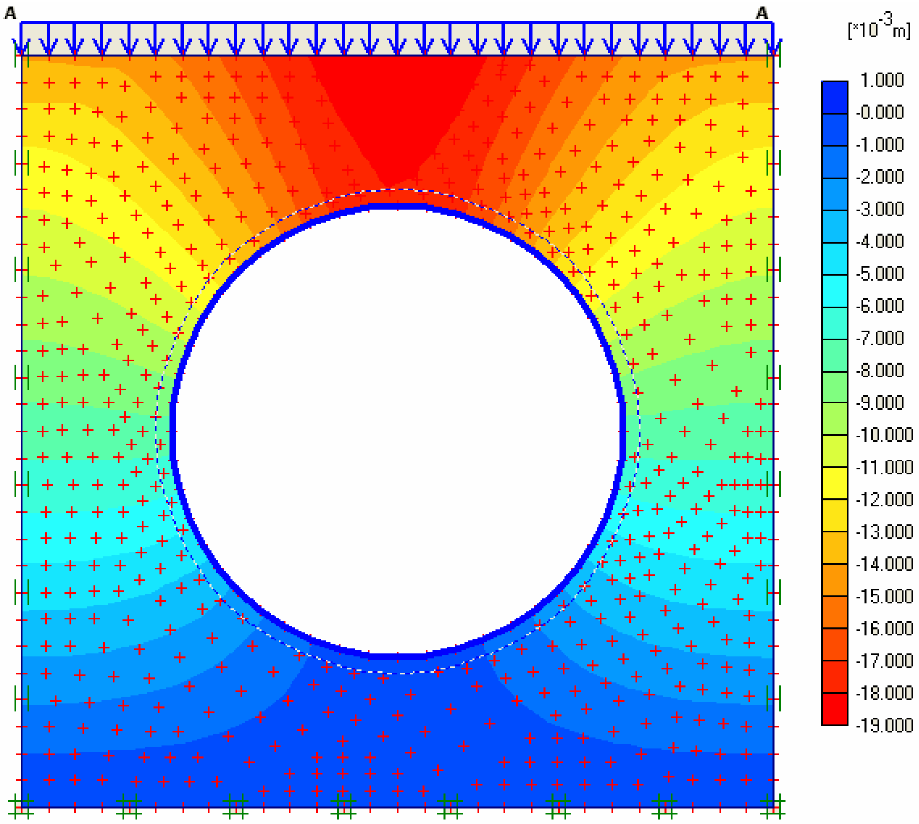


Figure A.7. The vertical displacement of non-cohesive soil and HDPE Φ1500 mm pipe

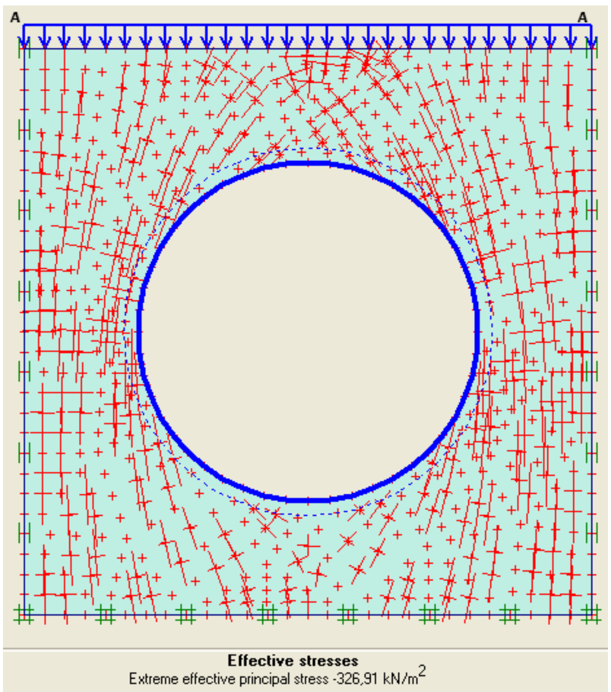


Figure A.8. The effective stress of HDPE Φ1500 mm pipe in non-cohesive soil

A.3. The analysis outputs of PVC Φ300 mm pipe in non-cohesive soil

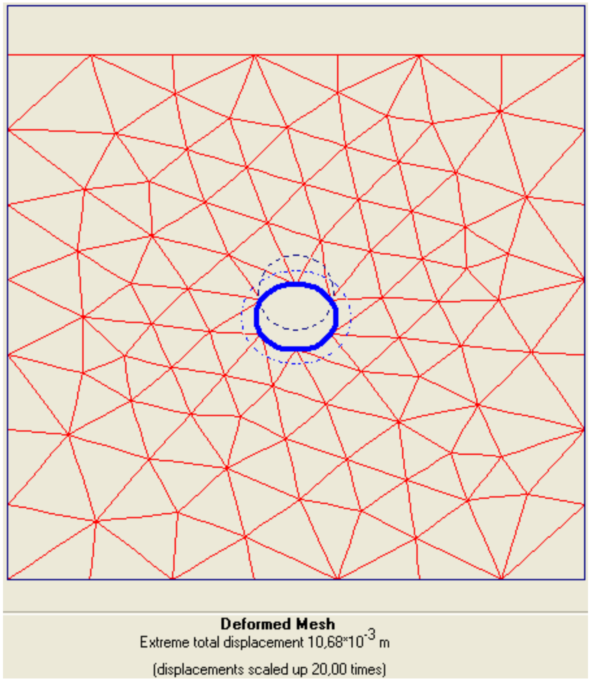


Figure A.9. The deformed mesh of PVC Φ300 mm pipe in non-cohesive soil

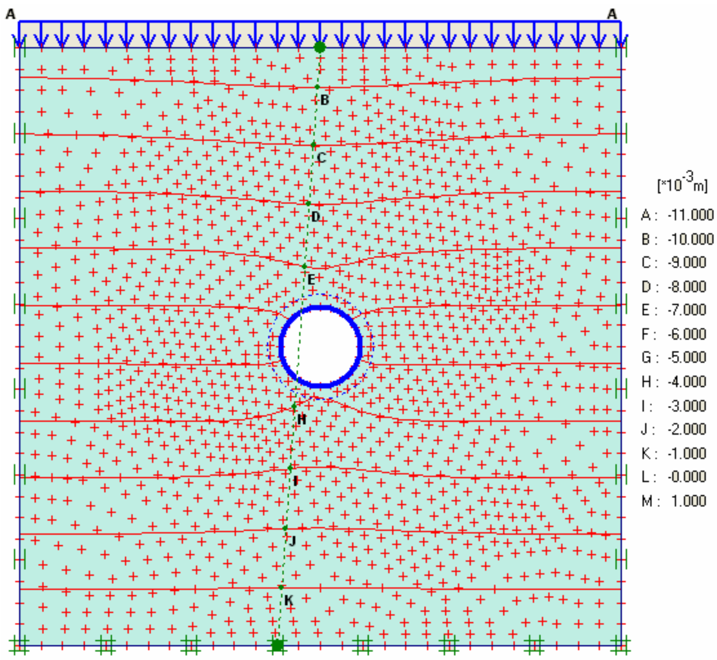


Figure A.10. The vertical displacement of PVC Φ300 mm pipe in non-cohesive soil

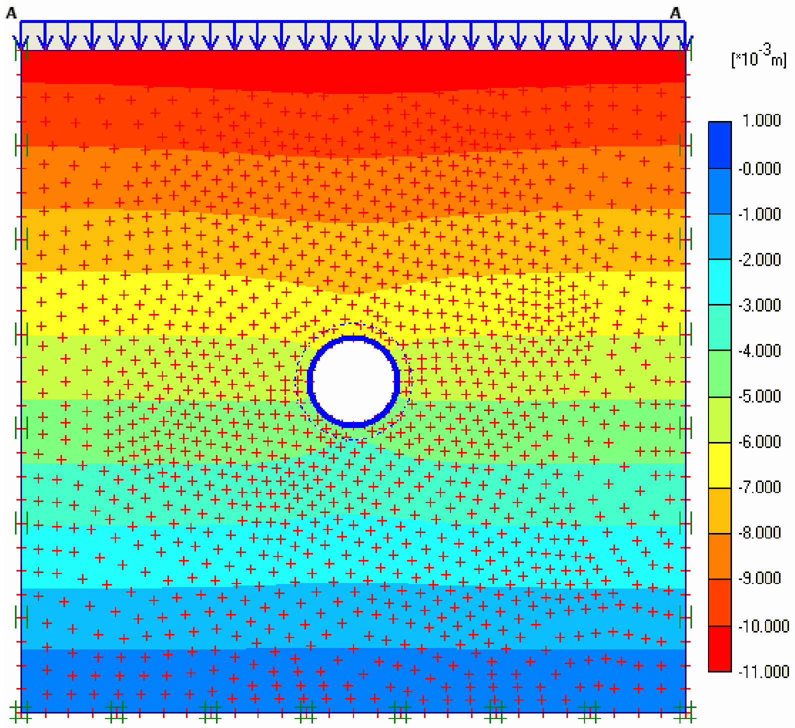


Figure A.11. The total displacement of non-cohesive soil and PVC Φ300 mm pipe

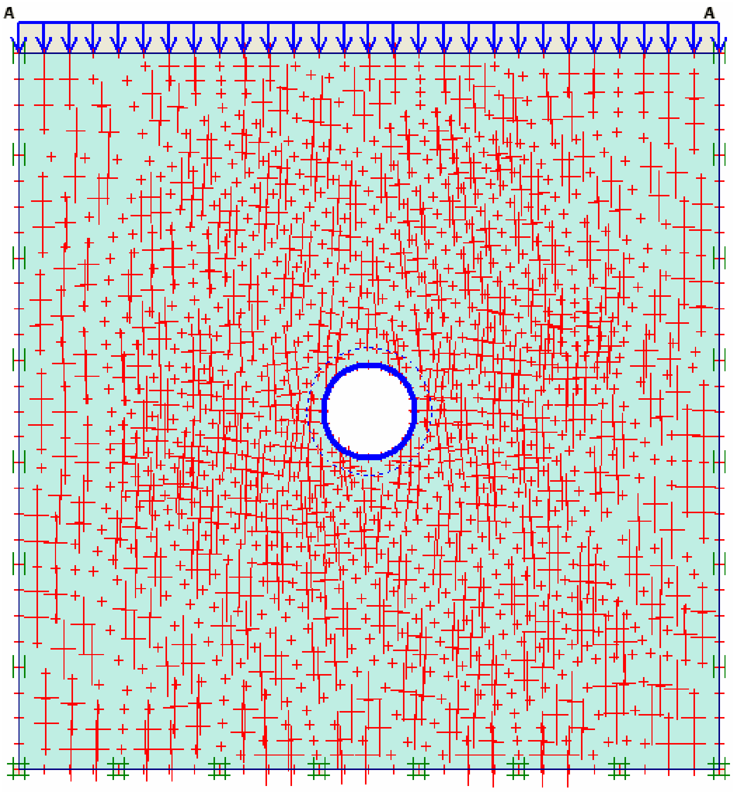


Figure A.12. The effective stress of PVC Φ300 mm pipe in non-cohesive soil

A.4. The analysis outputs of PVC Φ900 mm pipe in non-cohesive soil

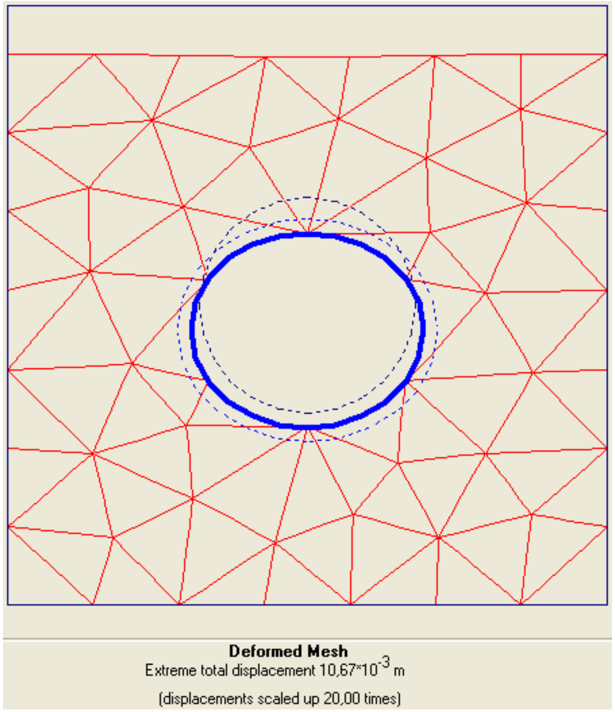


Figure A.13. The deformed mesh of PVC Φ900 mm pipe in non-cohesive soil

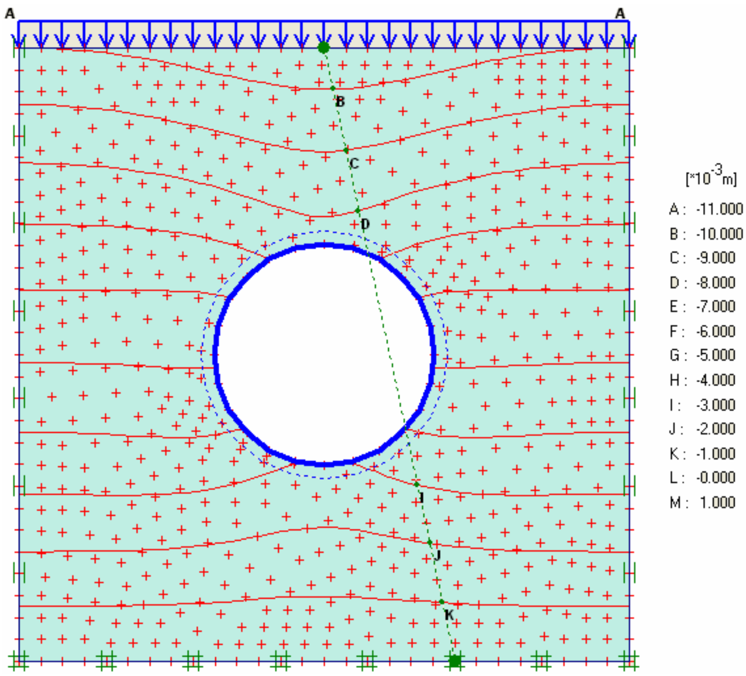


Figure A.14. The vertical displacement of PVC Φ900 mm pipe in non-cohesive soil

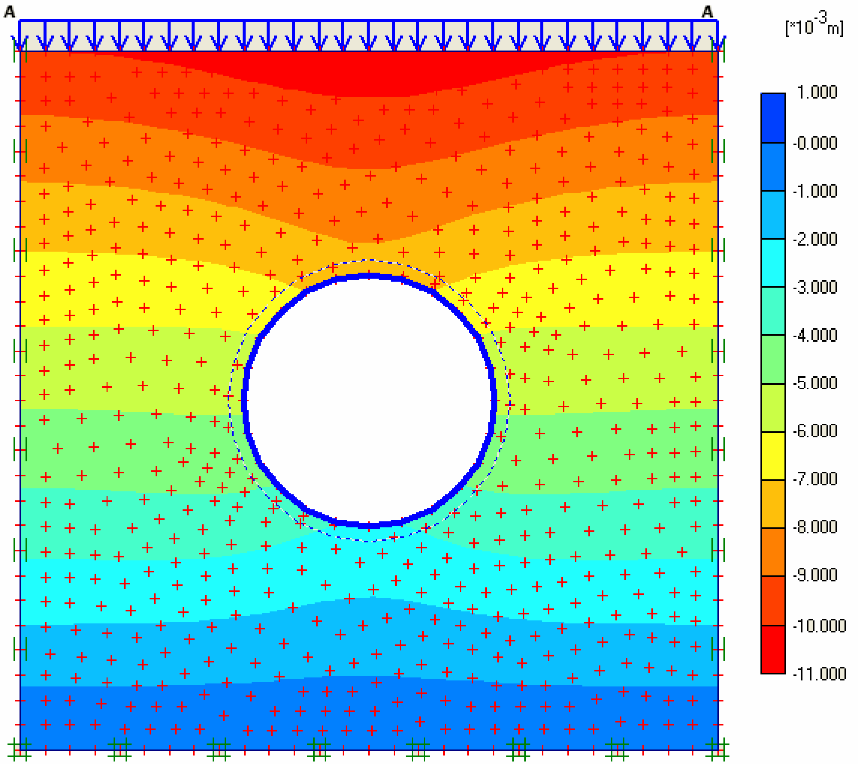


Figure A.15. The vertical displacement of non-cohesive soil and PVC Φ900 mm pipe

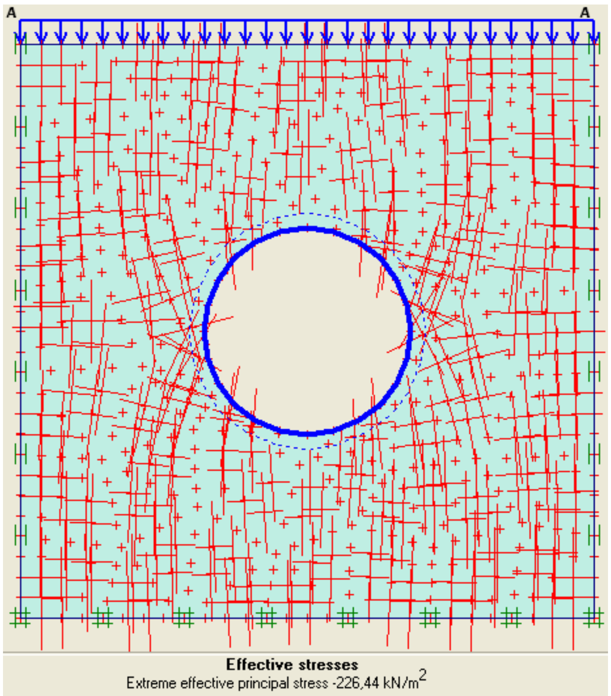


Figure A.16. The effective stress of PVC Φ900 mm pipe in non-cohesive soil

A.5. The analysis outputs of PVC Φ1500 mm pipe in non-cohesive soil

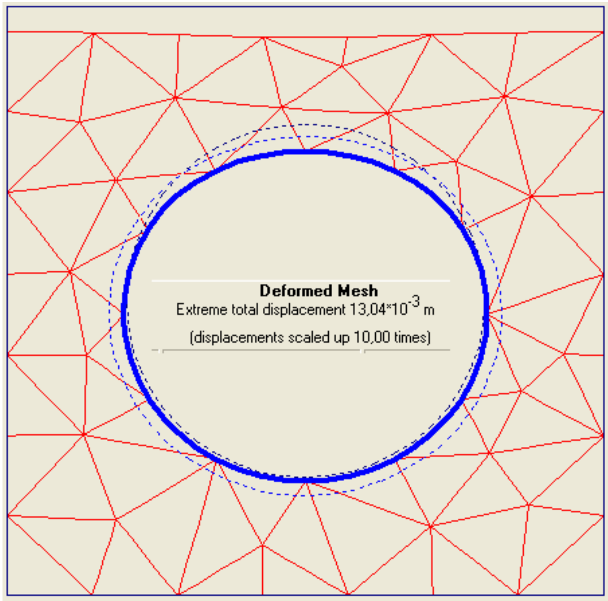


Figure A.17. The deformed mesh of PVC Φ1500 mm pipe in non-cohesive soil

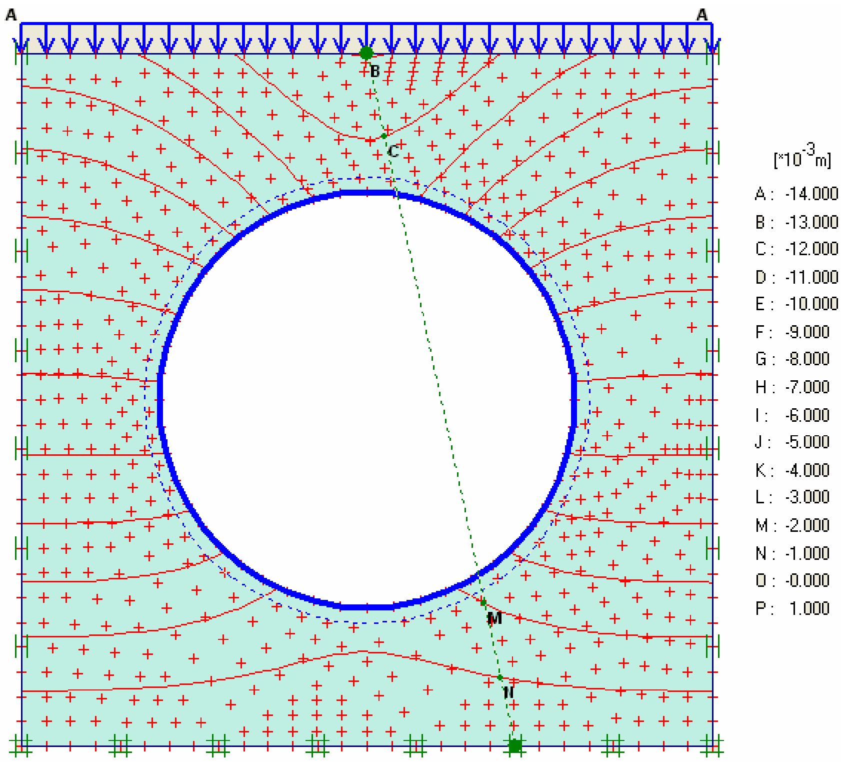


Figure A.18. The vertical displacement of PVC Φ1500 mm pipe in non-cohesive soil

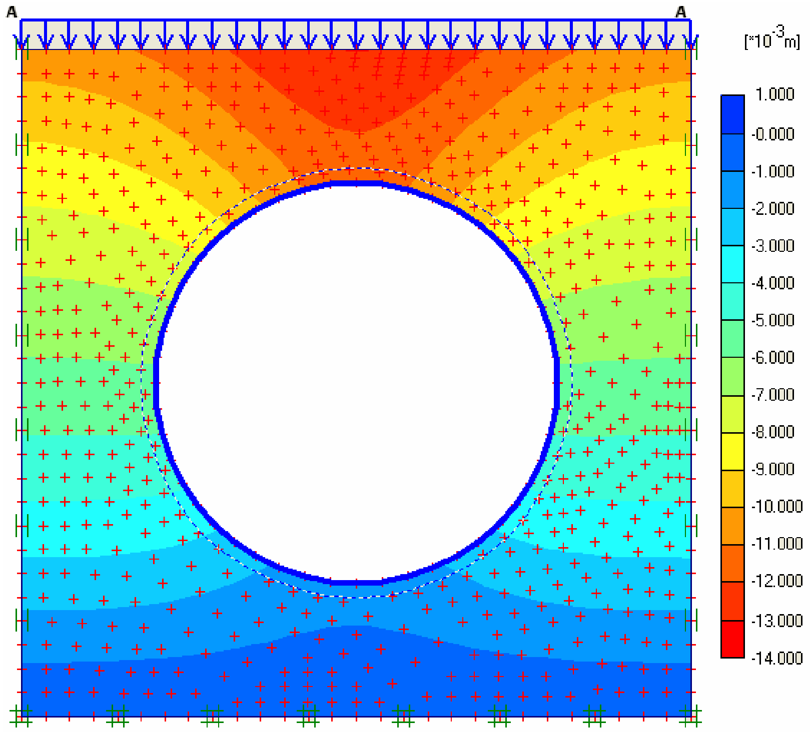


Figure A.19. The vertical displacement of non-cohesive soil and PVC Φ1500 mm pipe

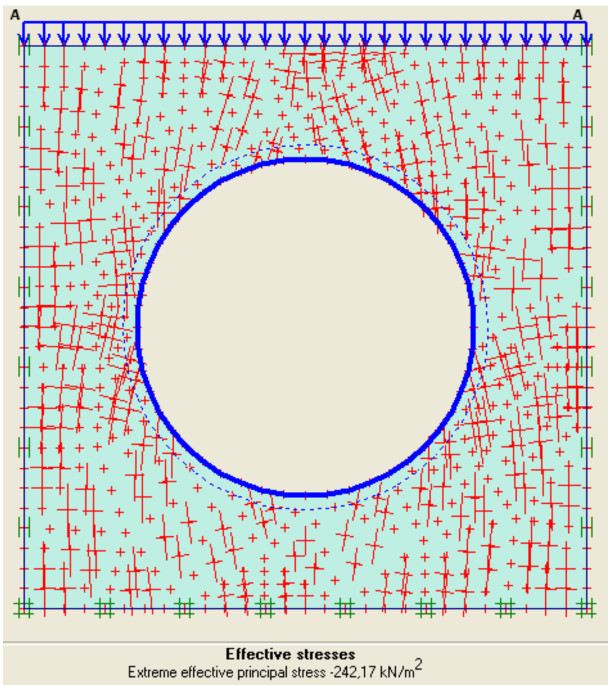


Figure A.20. The effective stress of PVC Φ1500 mm pipe in non-cohesive soil

A.6. The analysis outputs of FRP Φ300 mm pipe in non-cohesive soil

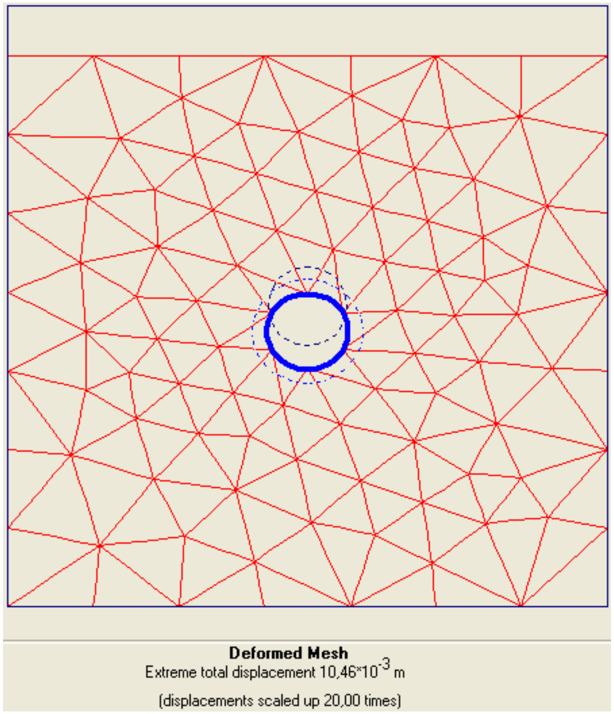


Figure A.21. The deformed mesh of FRP Φ300 mm pipe in non-cohesive soil

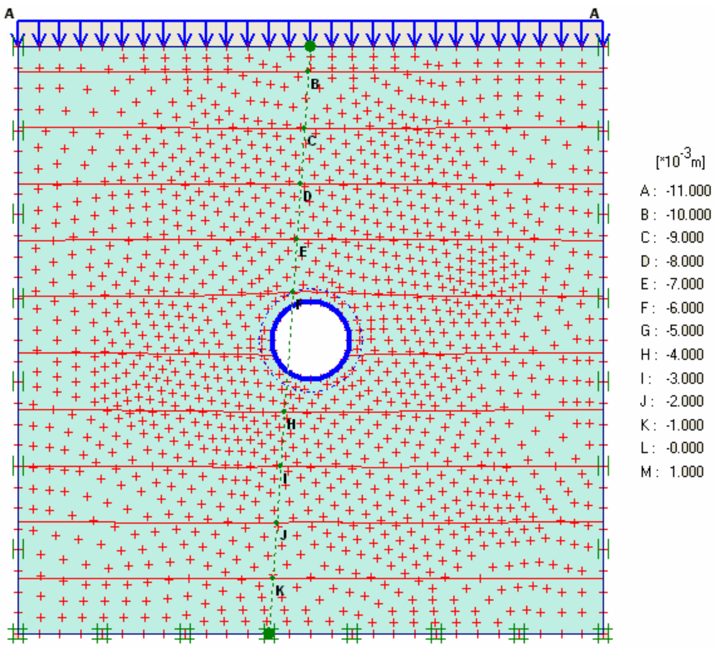


Figure A.22. The vertical displacement of FRP Φ300 mm pipe in non-cohesive soil

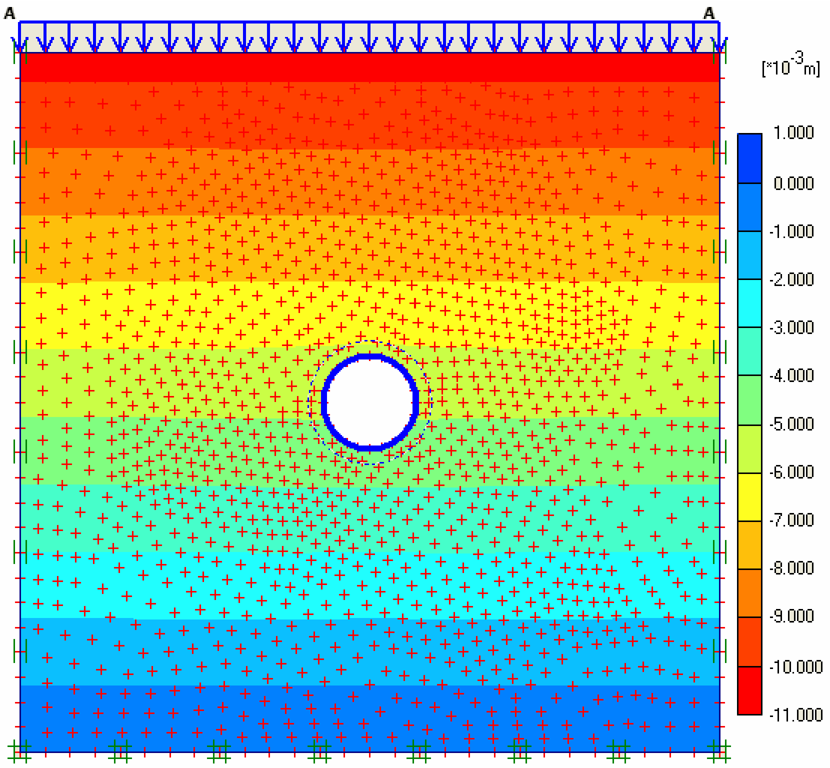


Figure A.23. The vertical displacement of non-cohesive soil and FRP Φ300 mm pipe

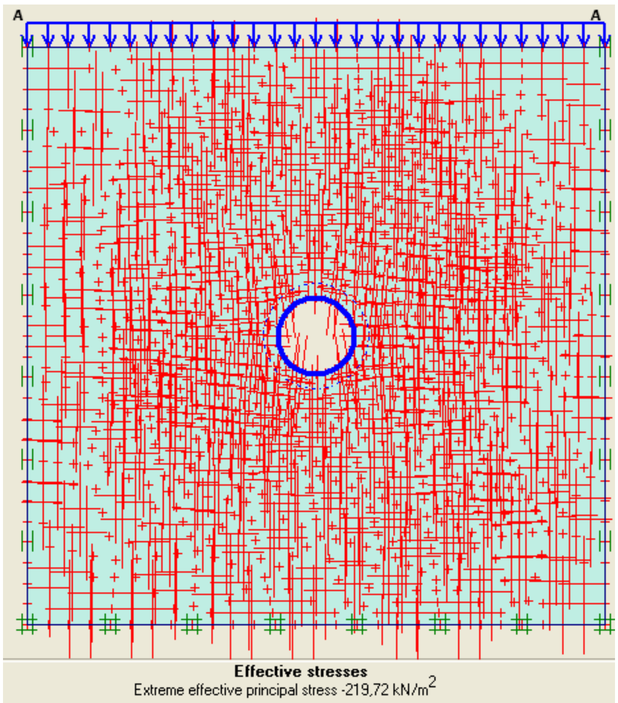


Figure A.24. The effective stress of FRP Φ300 mm pipe in non-cohesive soil

A.7. The analysis outputs of FRP Φ900 mm pipe in non-cohesive soil

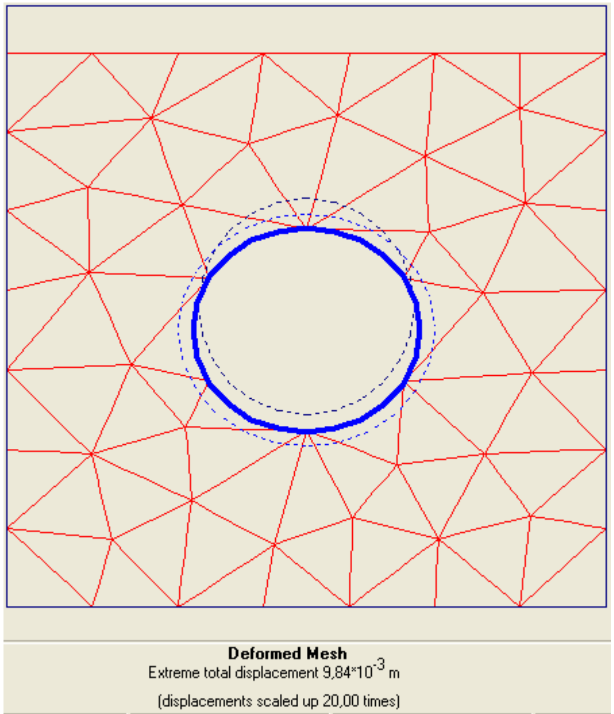


Figure A.25. The deformed mesh of FRP Φ900 mm pipe in non-cohesive soil

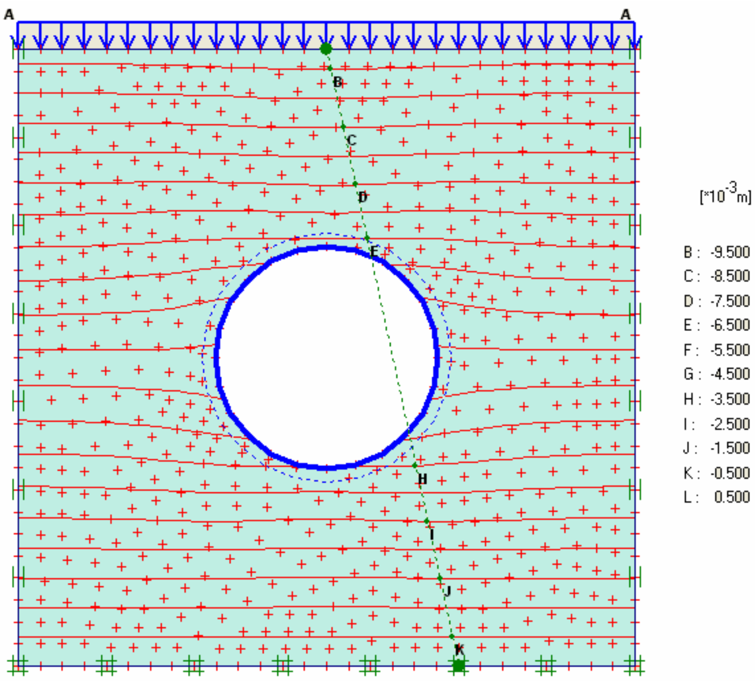


Figure A.26. The vertical displacement of FRP Φ900 mm pipe in non-cohesive soil

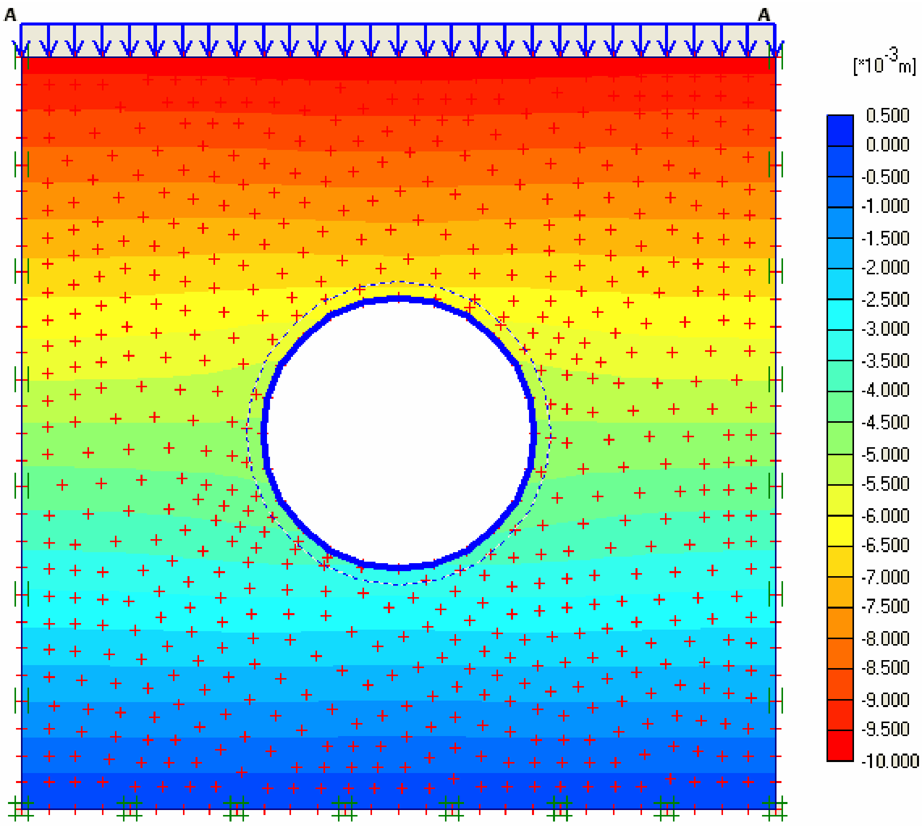


Figure A.27. The vertical displacements of non-cohesive soil and FRP Φ900 mm pipe

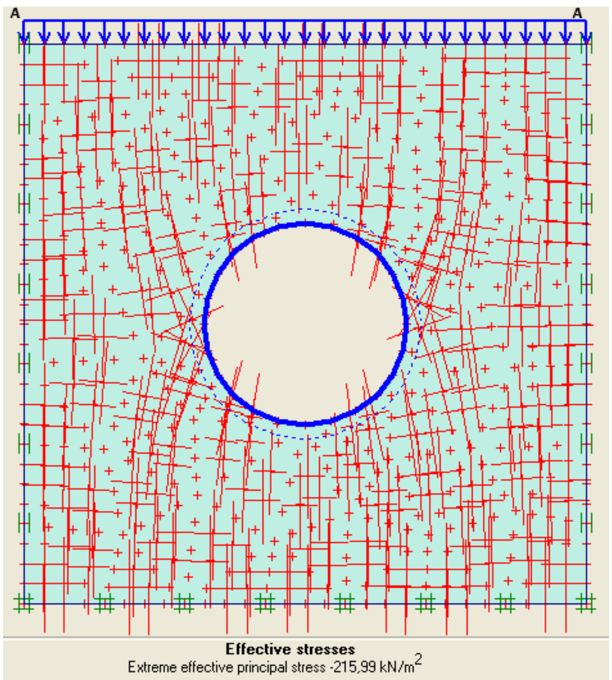


Figure A.28. The effective stresses of FRP Φ900 mm pipe in non-cohesive soil

A.8. The analysis outputs of FRP Φ1500 mm pipe in non-cohesive soil

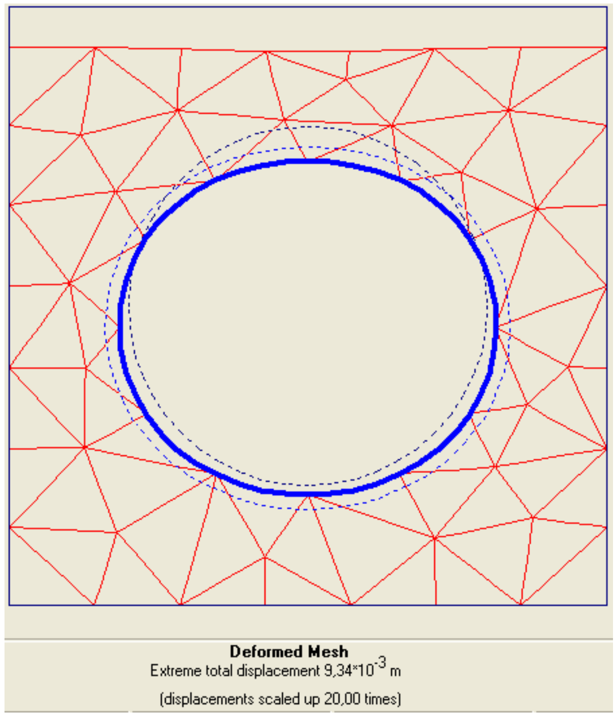


Figure A.29. The deformed mesh of FRP Φ1500 mm pipe in non-cohesive soil

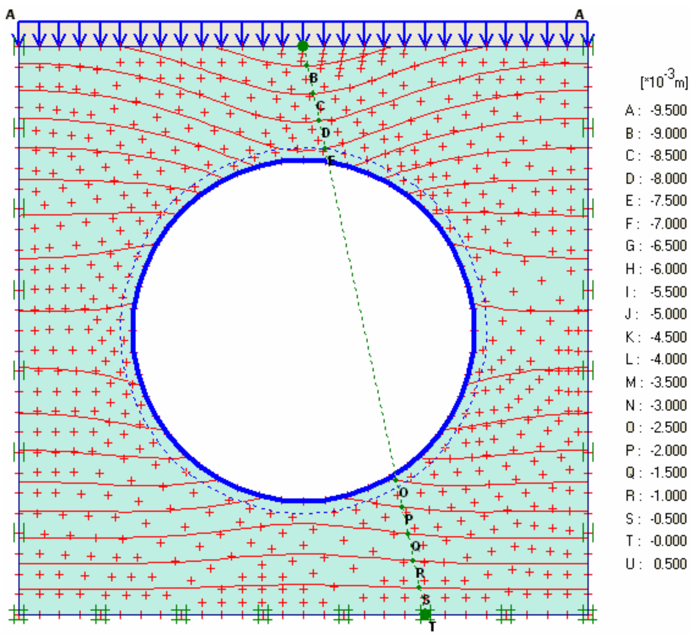


Figure A.30. The vertical displacement of FRP Φ1500 mm pipe in non-cohesive soil

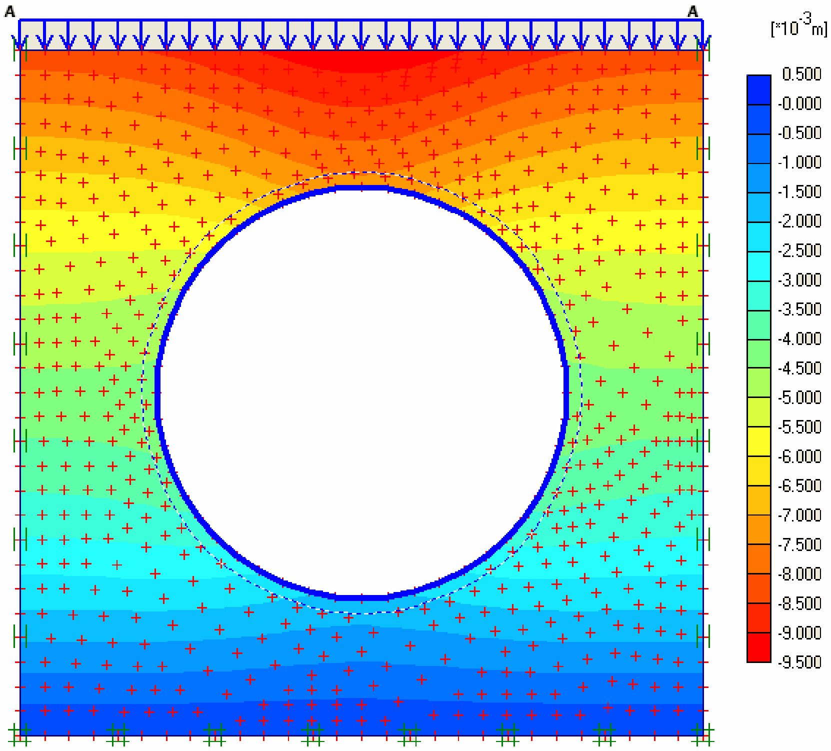


Figure A.31. The vertical displacement of non-cohesive soil and FRP Φ1500 mm pipe

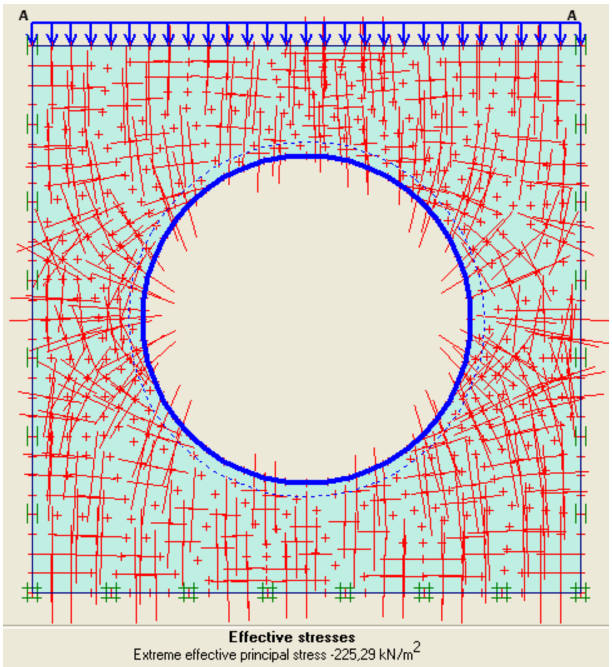


Figure A.32. The effective stress of FRP Φ1500 mm pipe in non-cohesive soil

A.9. The analysis outputs of HDPE Φ300 mm pipe in cohesive soil

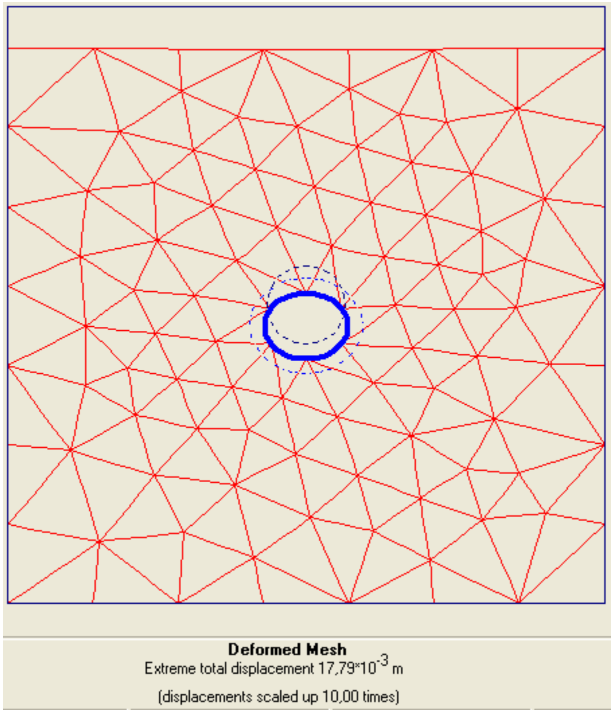


Figure A.33. The deformed mesh of HDPE Φ300 mm pipe in cohesive soil

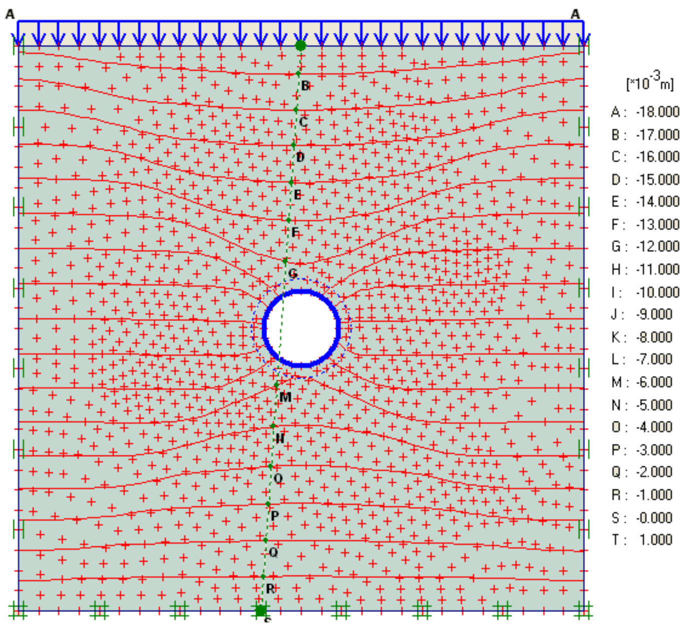


Figure A.34. The vertical displacement of HDPE Φ300 mm pipe in cohesive soil

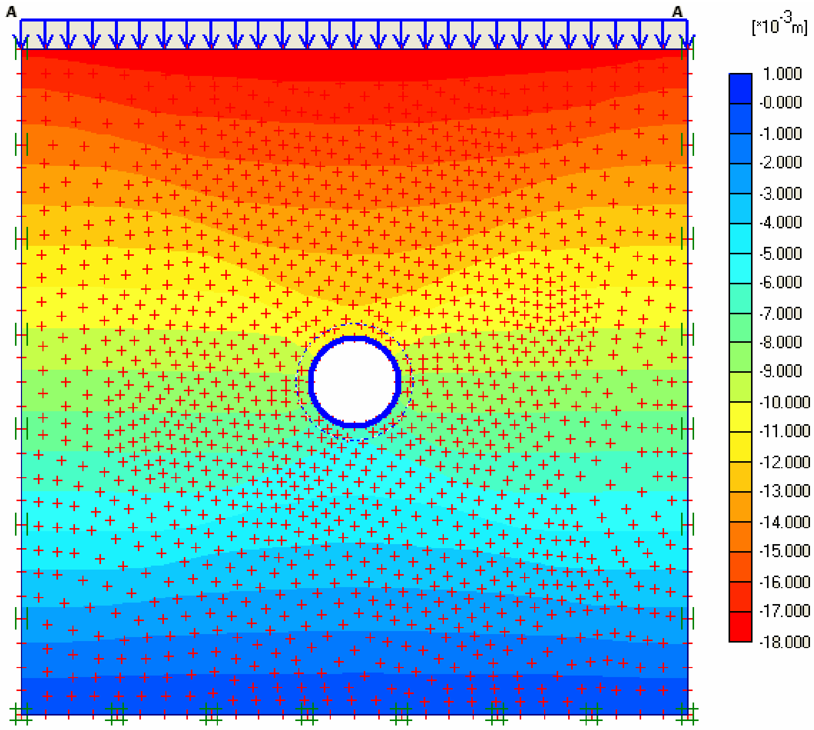


Figure A.35. The vertical displacements of cohesive soil and HDPE Φ300 mm pipe

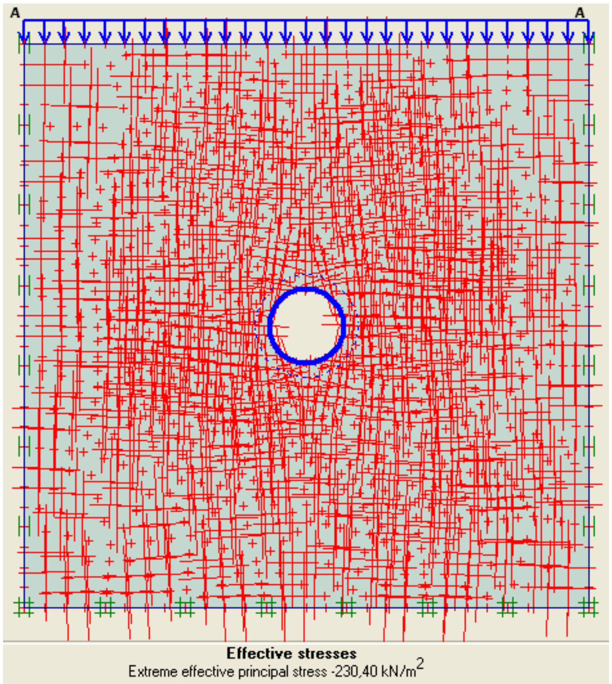


Figure A.36. The effective stresses of HDPE Φ300 mm pipe in cohesive soil

A.10. The deflection of HDPE Φ900 mm pipe in cohesive soil

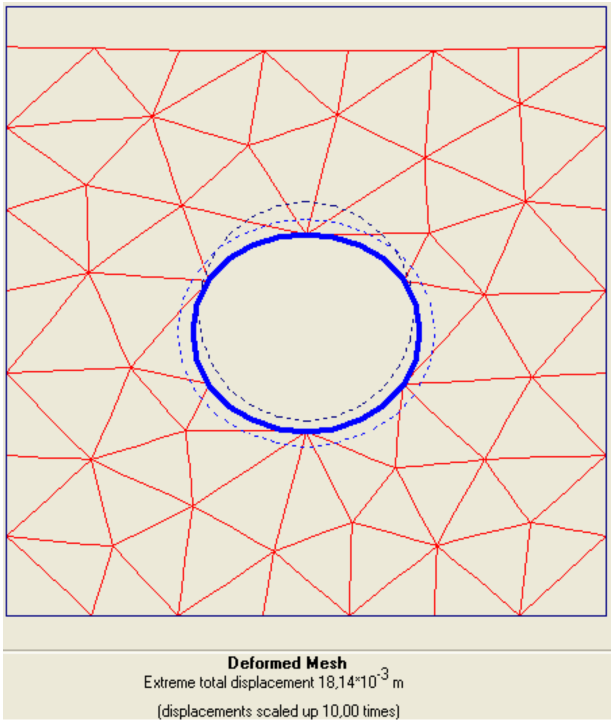


Figure A.37. The deformed mesh of HDPE Φ900 mm pipe in cohesive soil

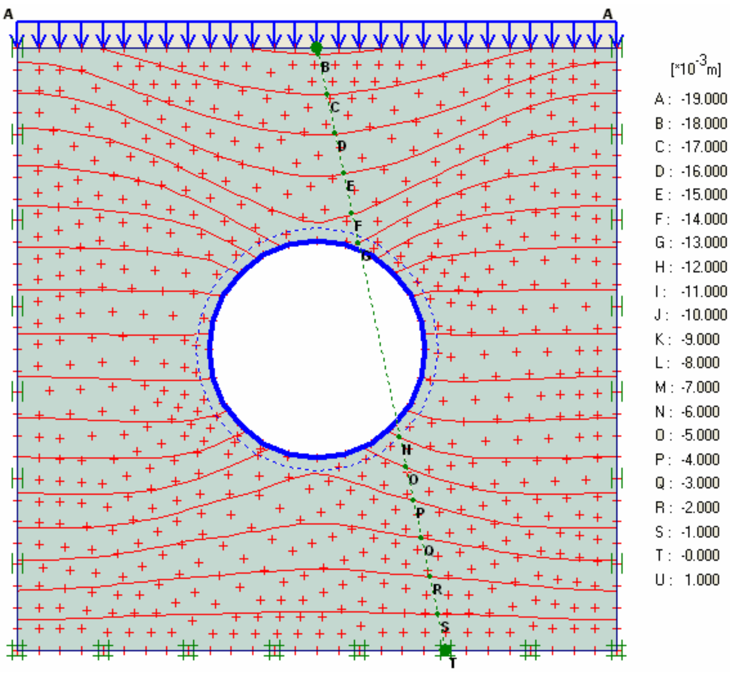


Figure A.38. The vertical displacement of HDPE Φ900 mm pipe in cohesive soil

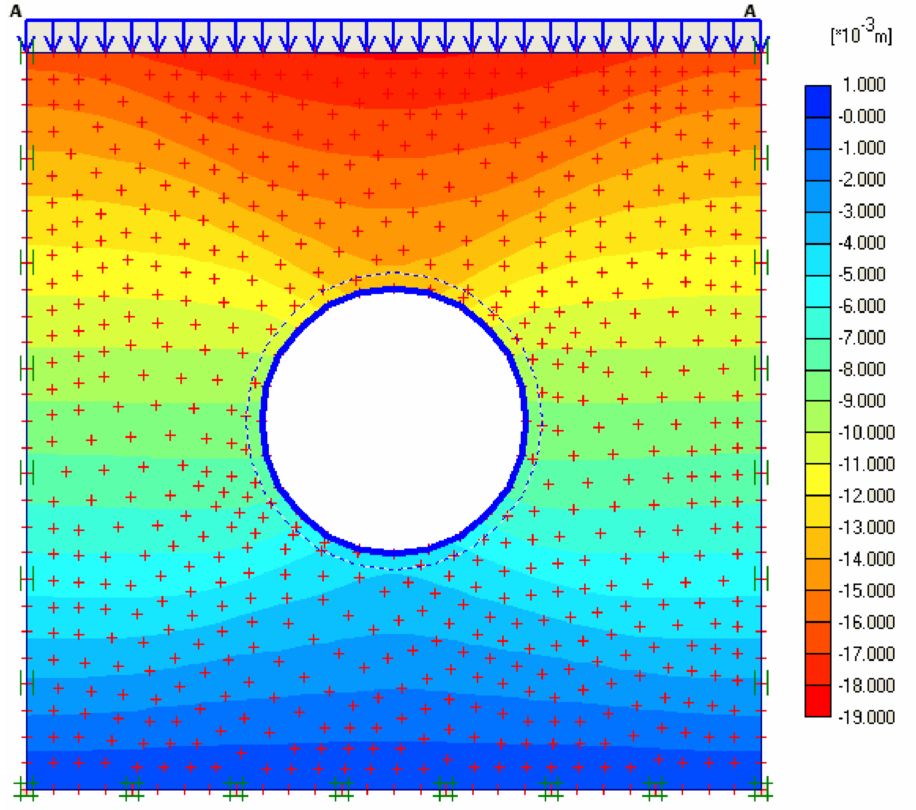


Figure A.39. The vertical displacement of cohesive soil and HDPE Φ900 mm pipe

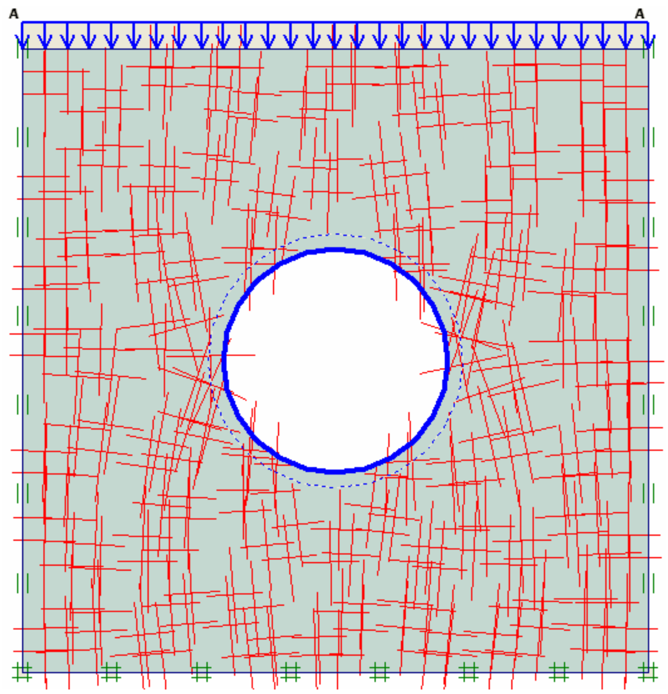


Figure A.40. The effective stress of HDPE Φ900 mm pipe in cohesive soil

A.11. The analysis outputs of HDPE Φ1500 mm pipe in cohesive soil

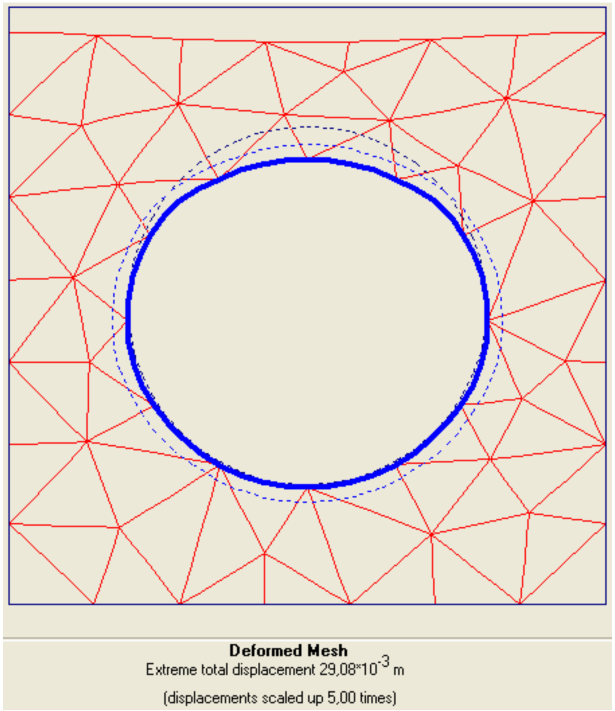


Figure A.41. The deformed mesh of HDPE Φ1500 mm pipe in cohesive soil

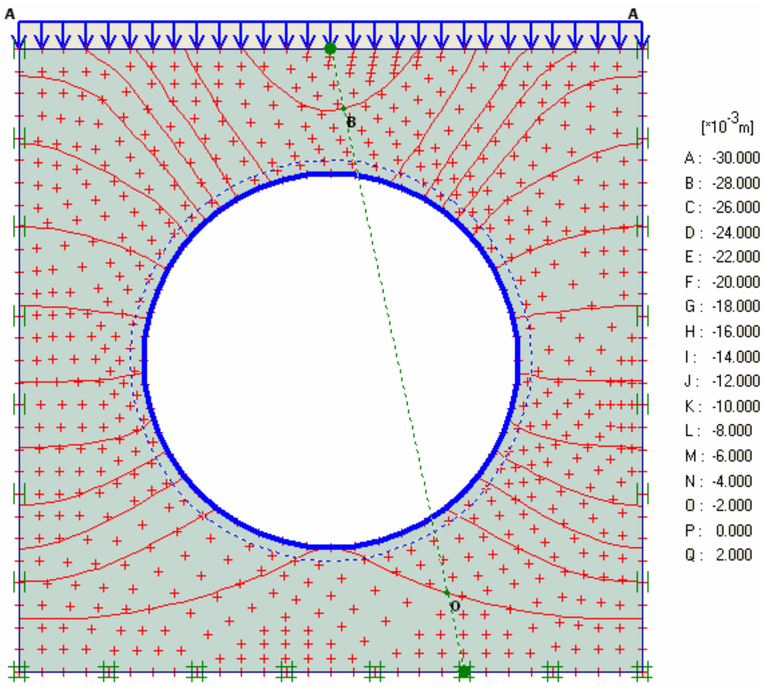


Figure A.42. The vertical displacement of HDPE Φ1500 mm pipe in cohesive soil

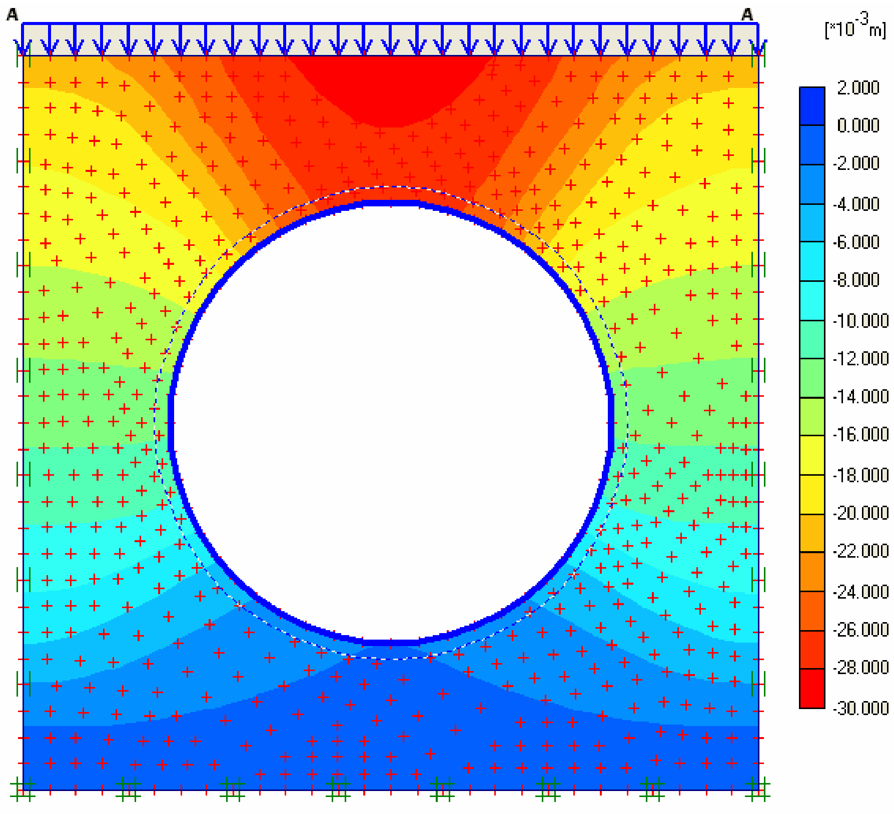


Figure A.43. The vertical displacement of cohesive soil and HDPE Φ1500 mm pipe

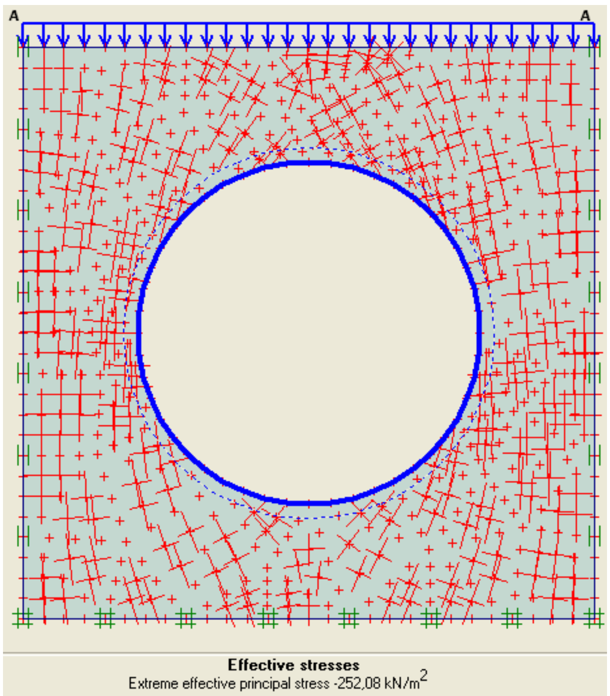


Figure A.44. The effective stress of HDPE Φ1500 mm pipe in cohesive soil

A.12. The deflection of PVC Φ300 mm pipe in cohesive soil

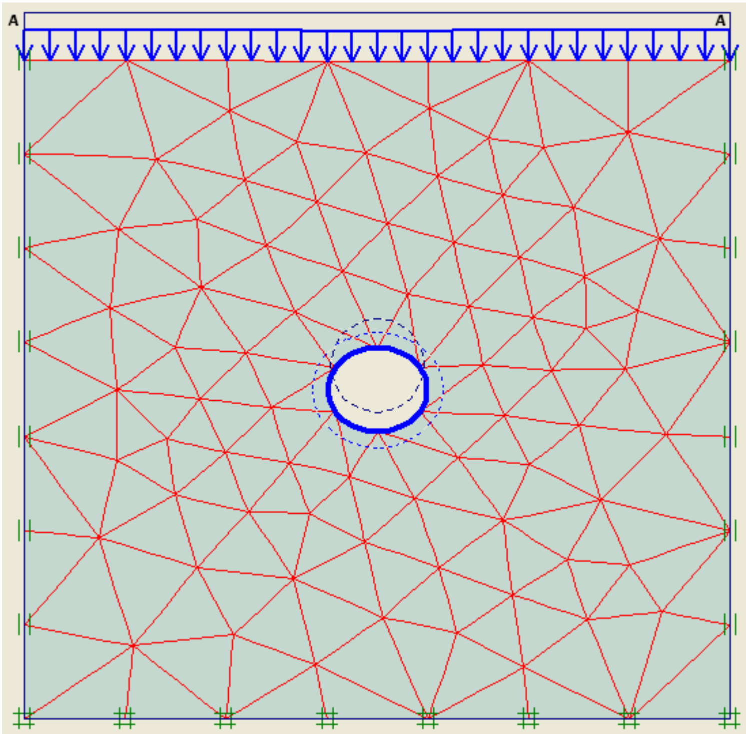


Figure A.45. The deformed mesh of PVC Φ300 mm pipe in cohesive soil

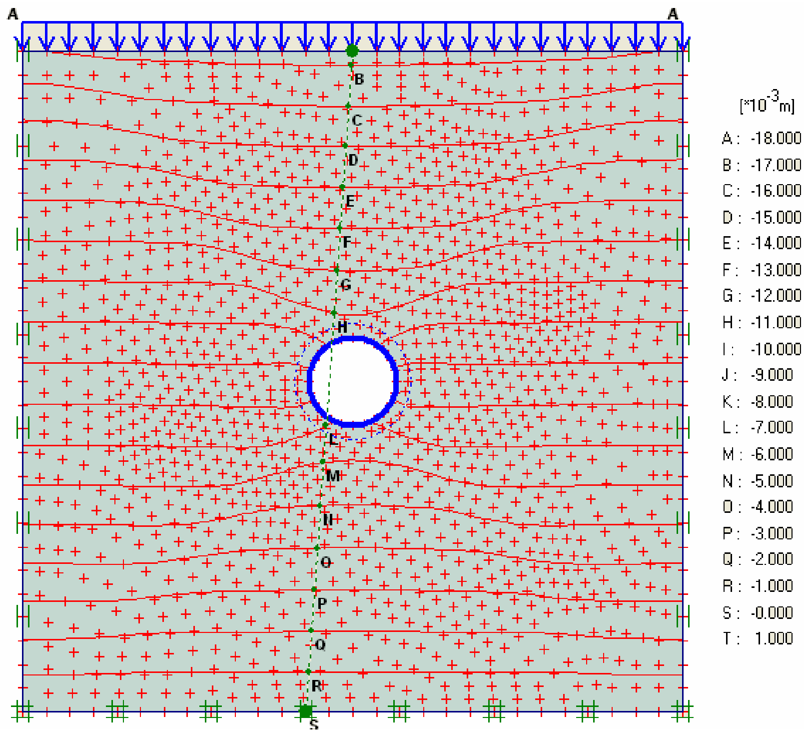


Figure A.46. The total displacement of PVC Φ300 mm pipe in cohesive soil

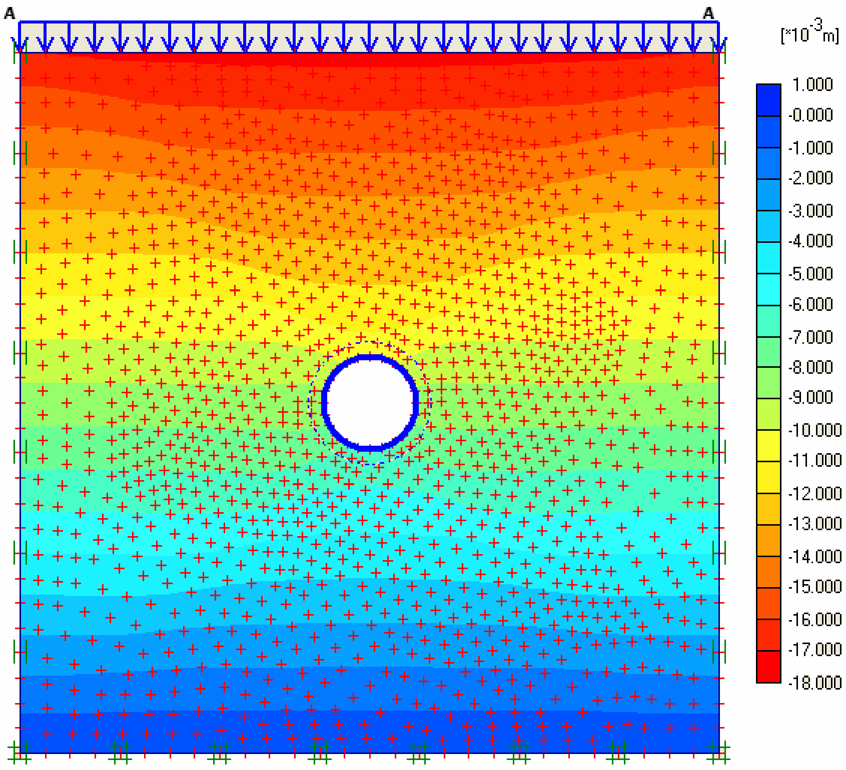


Figure A.47. The total displacement of cohesive soil and PVC Φ300 mm pipe

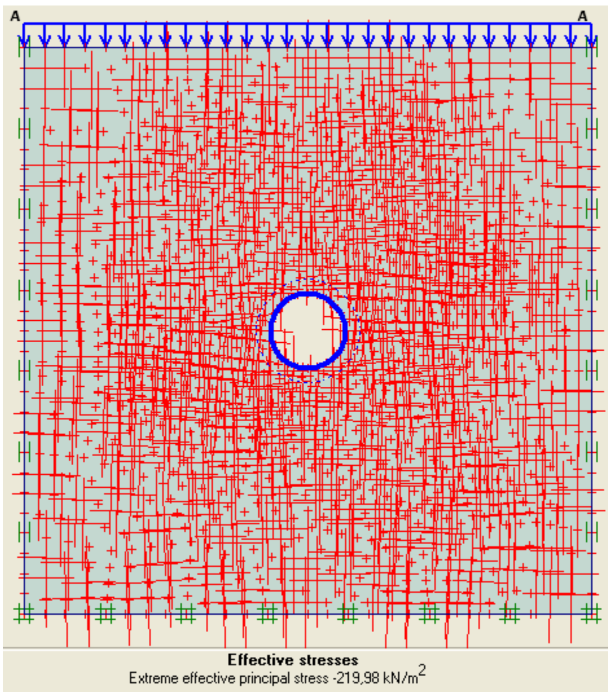


Figure A.48. The effective stress of PVC Φ300 mm pipe in cohesive soil

A.13. The analysis outputs of PVC Φ900 mm pipe in cohesive soil

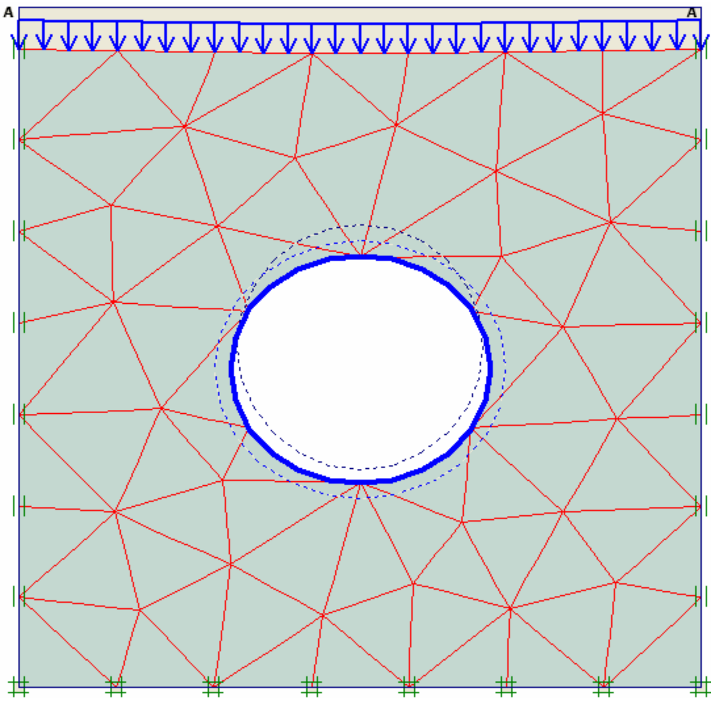


Figure A.49. The deformed mesh of PVC Φ900 mm pipe in cohesive soil

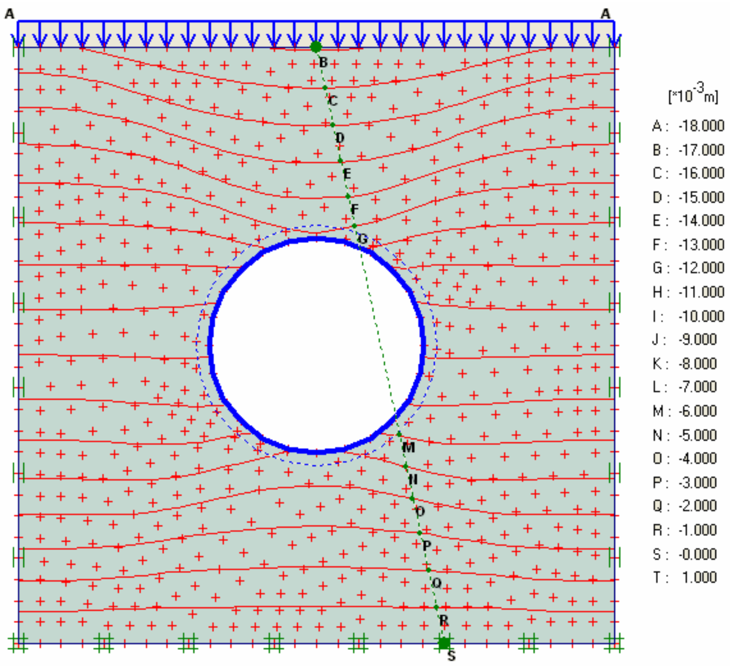


Figure A.50. The vertical displacement of PVC Φ900 mm pipe in cohesive soil

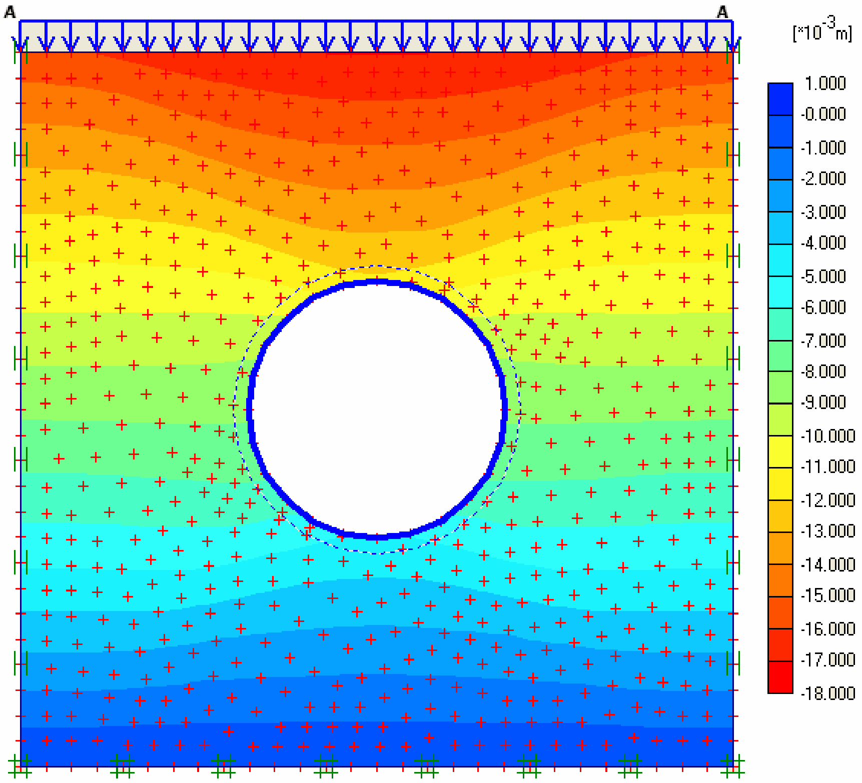


Figure A.51. The total displacement of cohesive soil and PVC Φ900 mm pipe

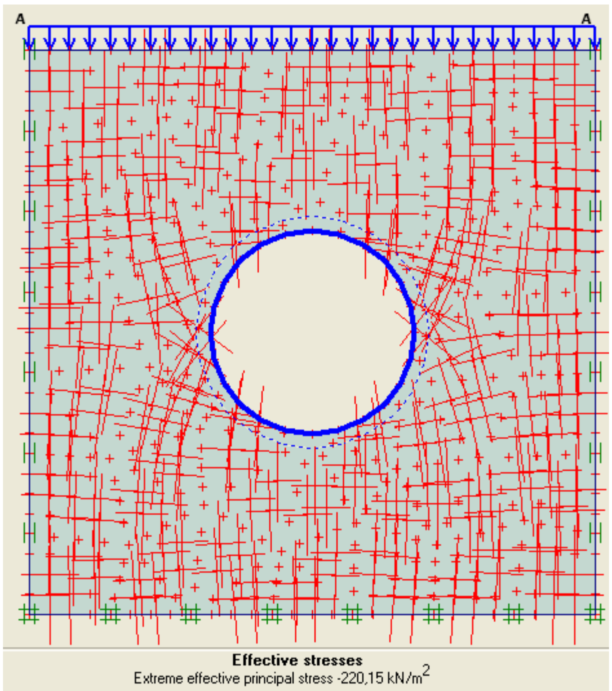


Figure A.52. The effective stress of PVC Φ900 mm pipe in cohesive soil

A.14. The analysis outputs of PVC Φ1500 mm pipe in cohesive soil

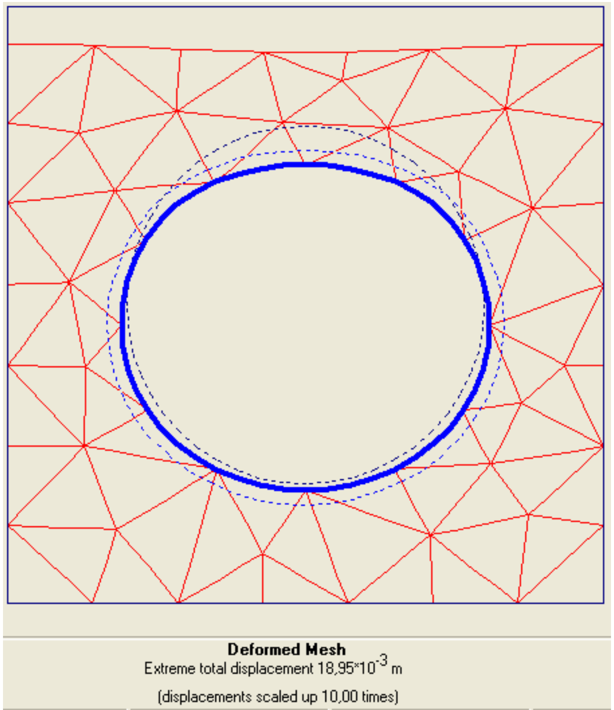


Figure A.53. The deformed mesh of PVC Φ1500 mm pipe in cohesive soil

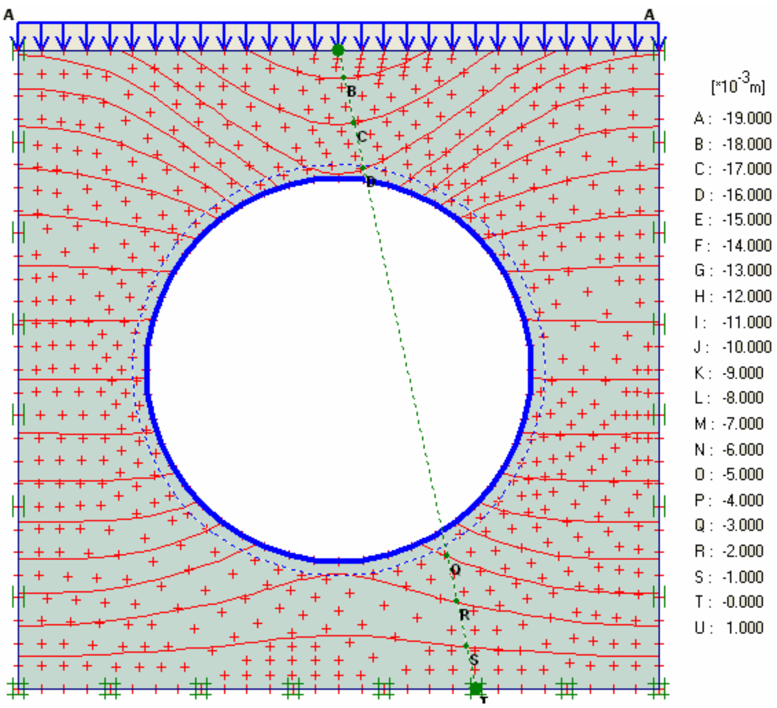


Figure A.54. The vertical displacement of PVC Φ1500 mm pipe in cohesive soil

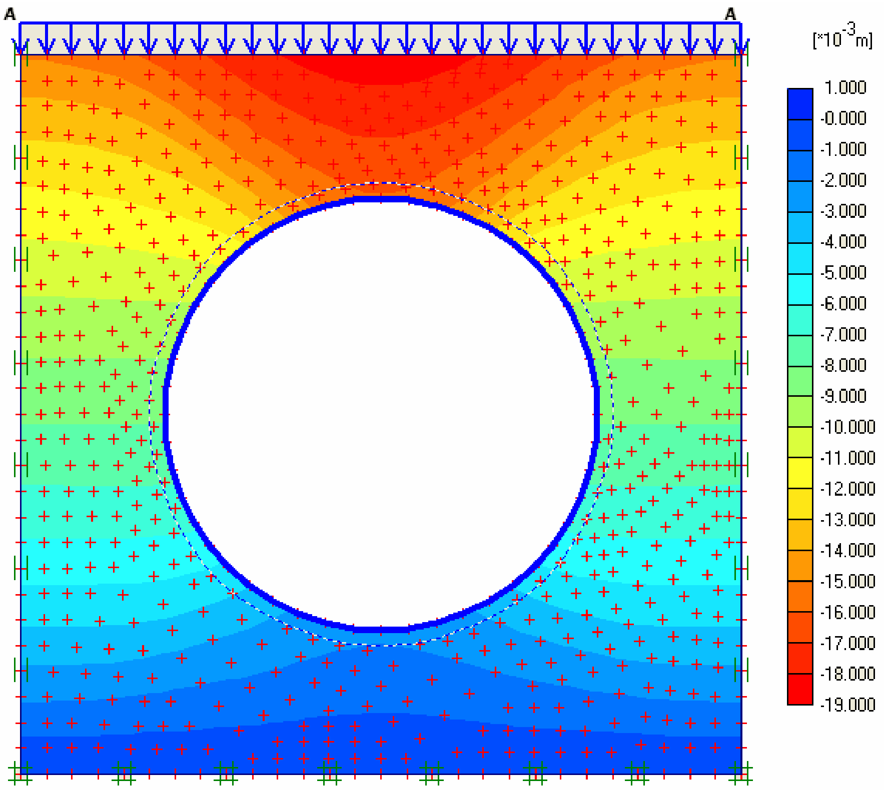


Figure A.55. The total displacement of cohesive soil and PVC Φ1500 mm pipe

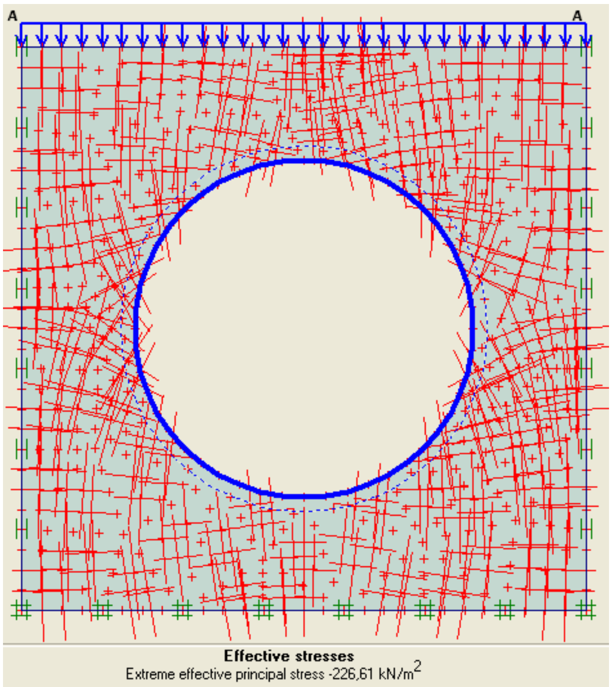


Figure A.56. The effective stress of PVC Φ1500 mm pipe in cohesive soil

A.15. The analysis outputs of FRP Φ300 mm pipe in cohesive soil

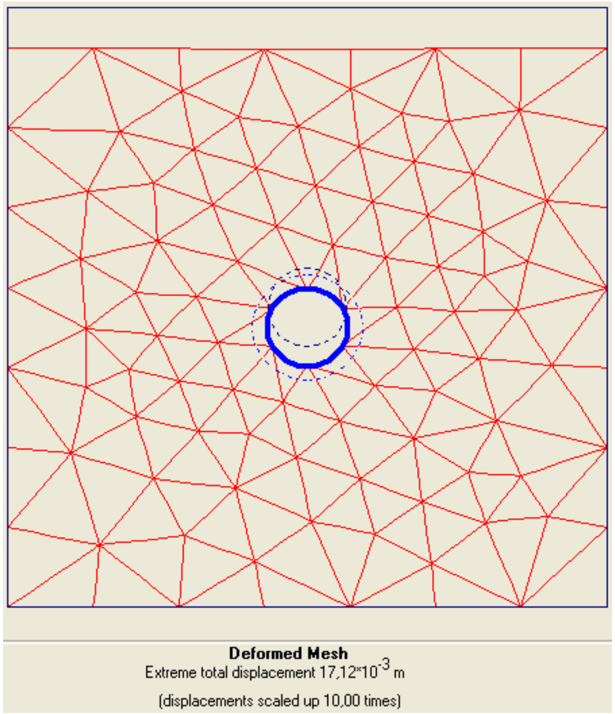


Figure A.57. The deformed mesh of FRP Φ300 mm pipe in cohesive soil

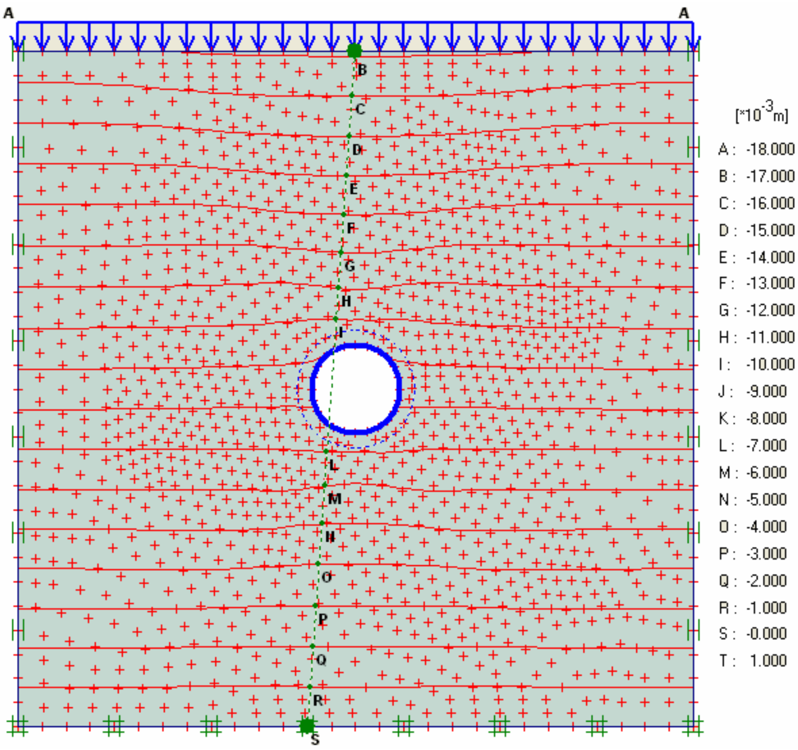


Figure A.58. The total displacement of FRP Φ300 mm pipe in cohesive soil

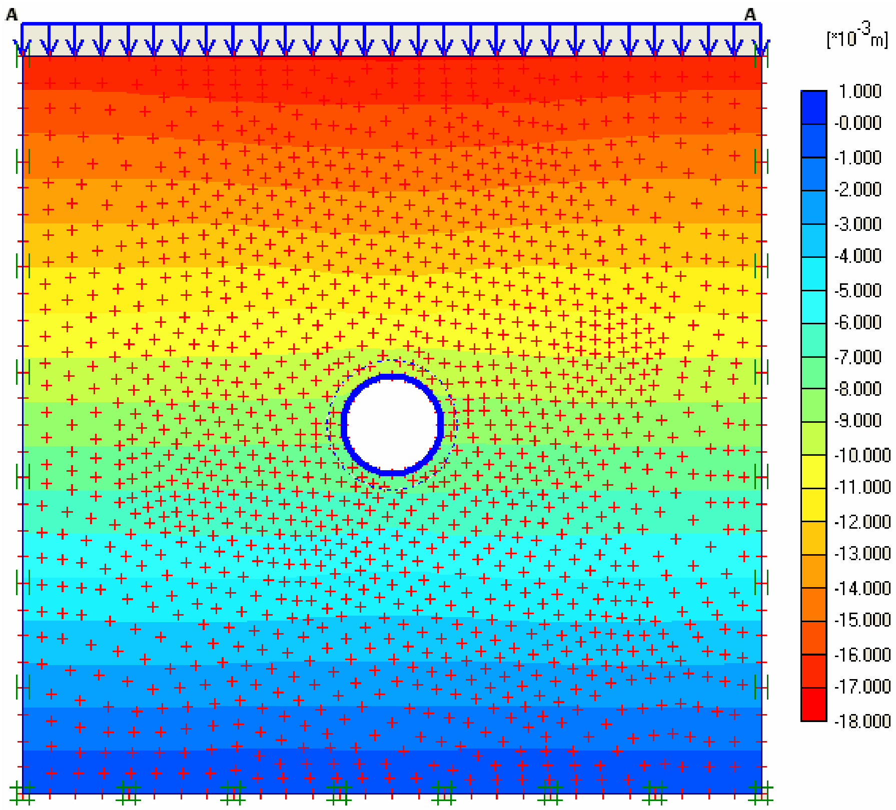


Figure A.59. The total displacement of cohesive soil and FRP Φ300 mm pipe

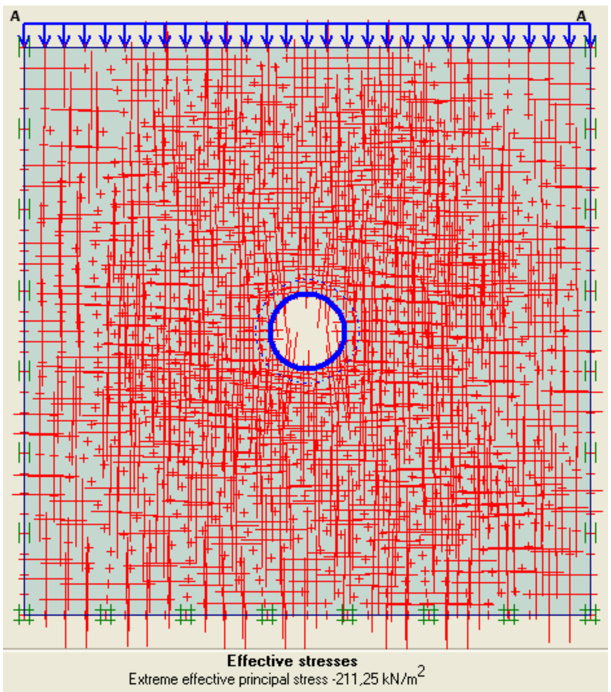


Figure A.60. The effective stress of FRP Φ300 mm pipe in cohesive soil

A.16. The analysis outputs of FRP Φ900 mm pipe in cohesive soil

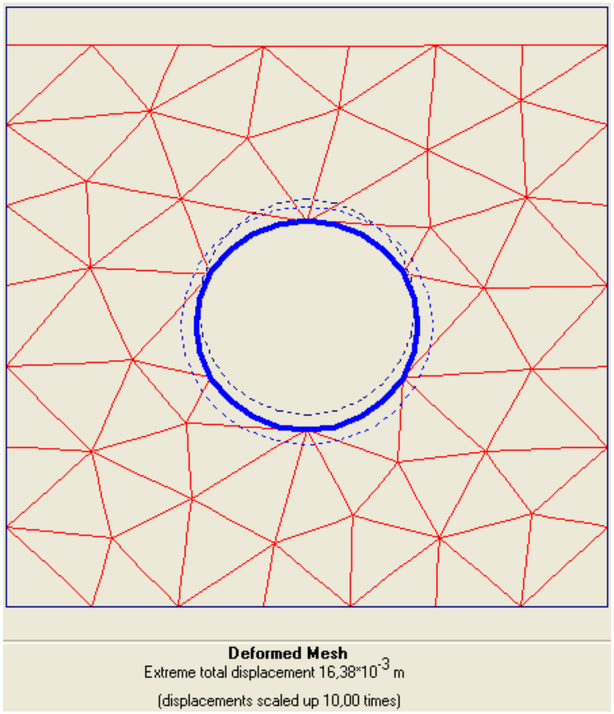


Figure A.61. The deformed mesh of FRP Φ900 mm pipe in cohesive soil

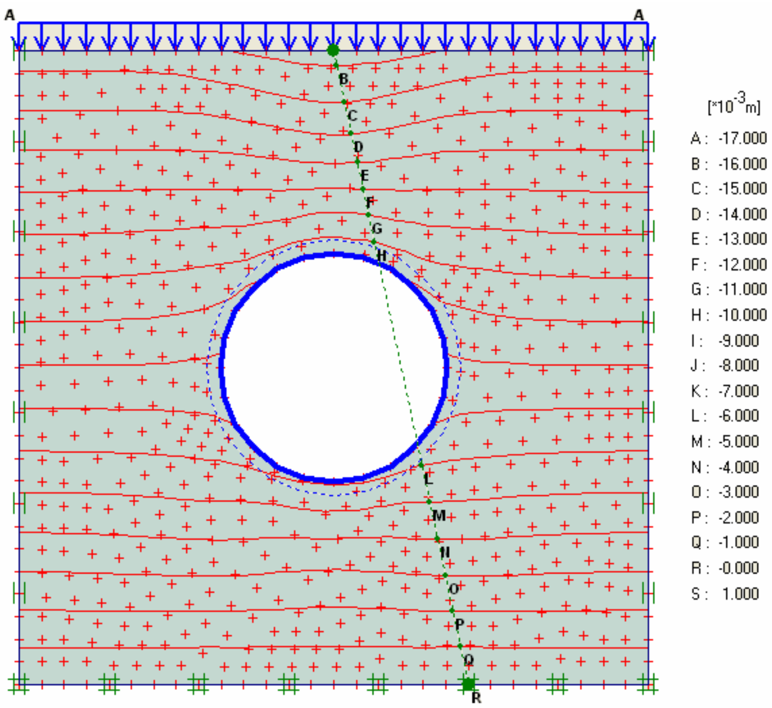


Figure A.62. The vertical displacement of FRP Φ900 mm pipe in cohesive soil

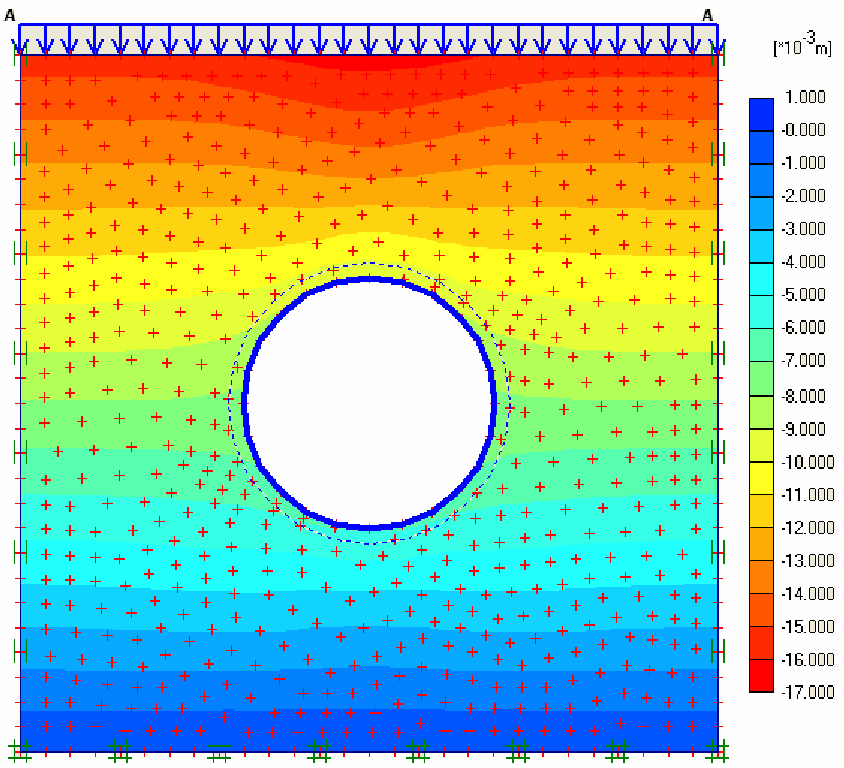


Figure A.63. The total displacement of cohesive soil and FRP Φ900 mm pipe

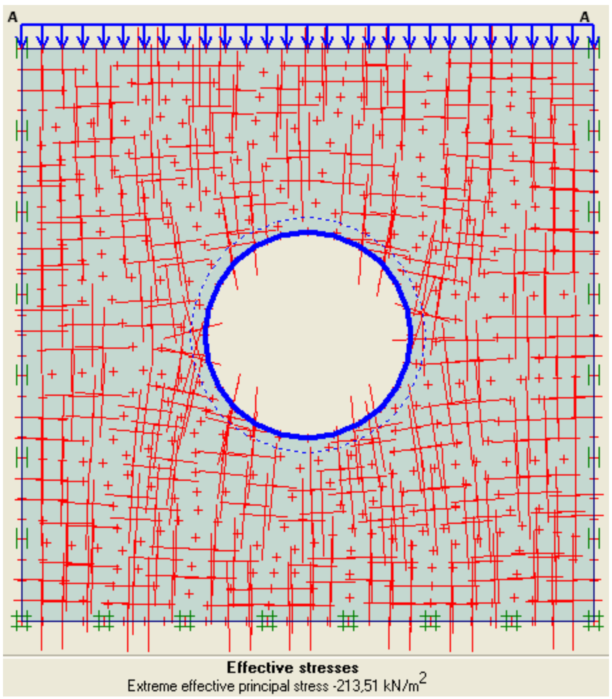


Figure A.64. The effective stress of FRP Φ900 mm pipe in cohesive soil

A.17. The analysis outputs of FRP Φ1500 mm pipe in cohesive soil

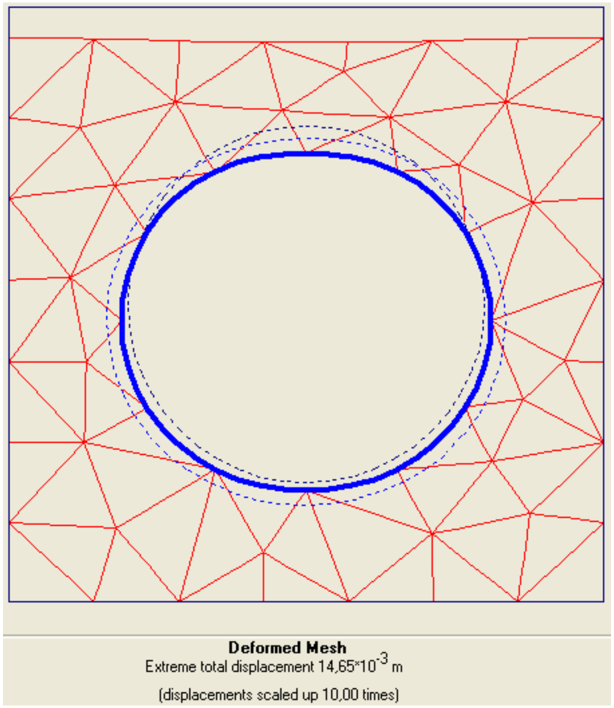


Figure A.65. The deformed mesh of FRP Φ1500 mm pipe in cohesive soil

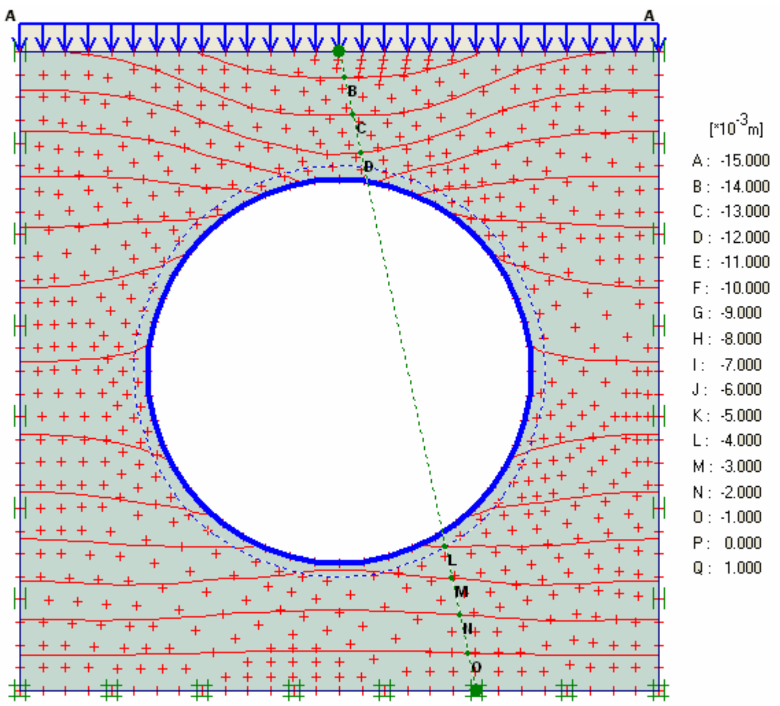


Figure A.66. The total displacement of FRP Φ1500 mm pipe in cohesive soil

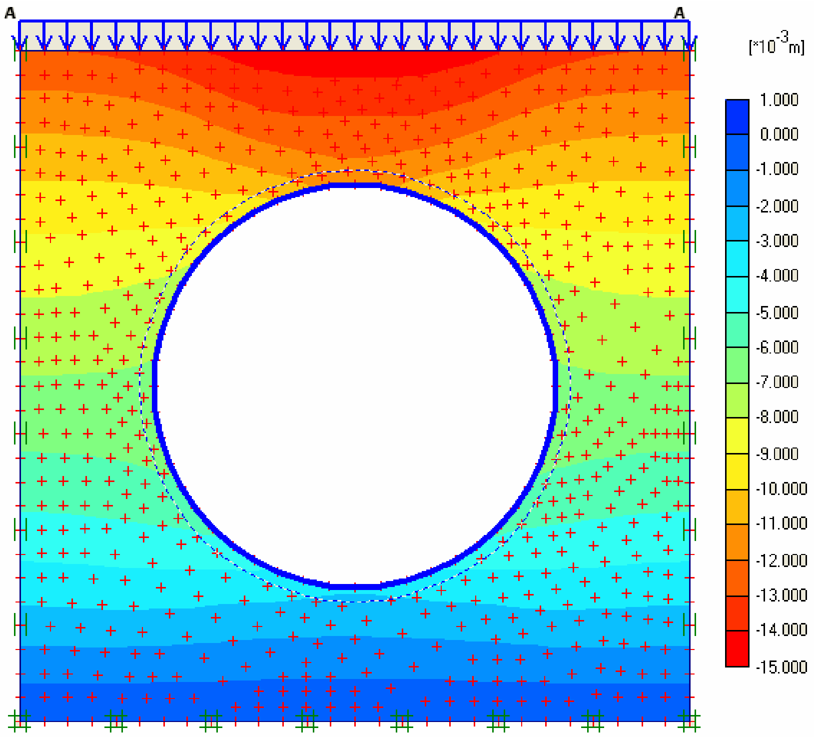


Figure A.67. The total displacement of cohesive soil and FRP Φ1500 mm pipe

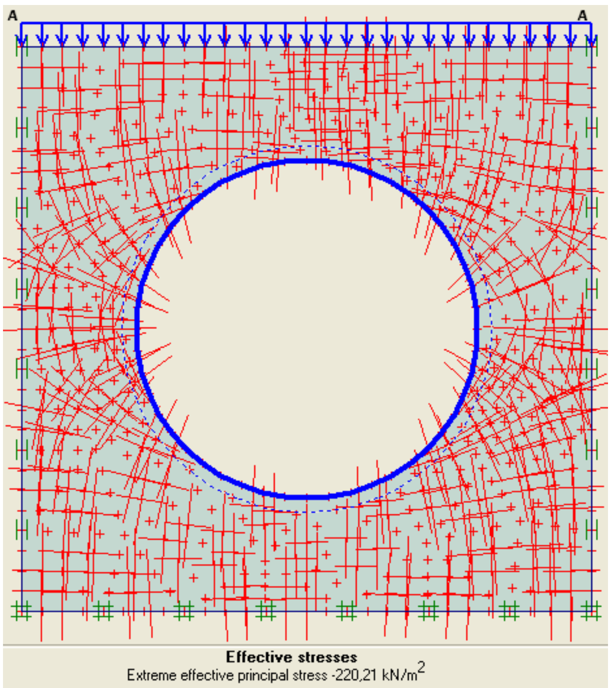


Figure A.68. The effective stress of FRP Φ1500 mm pipe in cohesive soil

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