Major Project-II On

# LOAD-DEFORMATION RESPONSE OF SINGLE CORRUGATED PILE IN SOIL MEDIA

Submitted In Partial Fulfillment For The Award Of The Degree Of

MASTER OF TECHNOLOGY

IN

CIVIL ENGINEERING

With Specialization In

**GEOTECHNICAL ENGINEERING**

By

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**2015-2016**

**DELHI TECHNOLOGICAL UNIVERSITY, DELHI**

**CERTIFICATE**

This is to certify that the major project report entitled "**LOAD-DEFORMATION RESPONSE OF SINGLE CORRUGATED PILE IN SOIL MEDIA**" is a bona fide record of work carried out by Archana Rawat (Roll No. 2K14/GTE/06) under my guidance and supervision, during the session 2015-2016 in partial fulfillment of the requirement for the degree of Master of Technology (Geotechnical Engineering) from Delhi Technological University, Delhi.

The work embodied in this major project has not been submitted for the award of any other degree to the best of our knowledge.

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## ACKNOWLEDGEMENT

As I write this acknowledgement, I must clarify that this is not just a formal acknowledgement but also a sincere note of thanks and regard from my side. From understanding the initial concepts to finally submitting the thesis, in some way this project also captures my journey at this institute. I surpass my expectations for the caliber and authenticity of this majestic university, and with this thesis I hope to reciprocate.

I express my heartfelt gratitude to Prof. A.Trivedi for his continued encouragement and precious time to time solicitations and suggestions which has greatly inspired me to shape the project and complete it within time.

Also, I express my gratitude to the Head-of-Department and other faculty members of the Department of Civil Engineering.

I am deeply thankful to all the laboratory assistants of Departments of Civil Engineering and Mechanical Engineering, Delhi Technological University, who has helped me in software laboratory work.

Upon ending this, I must mention this that I am also very thankful to my family and friends who continuously stimulated me to bring this work gradually to a successful closure.

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## DECLARATION

I hereby declare that the work being presented in this Project Report entitled "LOAD-DEFORMATION RESPONSE OF SINGLE CORRUGATED PILE IN SOIL MEDIA**"** is a bona fide record of work carried out by me as a part of major project in partial fulfillment of the requirement for the degree of Master of Technology in Geotechnical Engineering.

I have not submitted the matter presented in this report for the award of any degree.

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# ABSTRACT

In the work, 3D numerical modelling and analysis was performed on pile foundation. The numerical modelling and analysis of pile-soil system was accomplished in finite element based software ABAQUS/CAE6.10-1.

Also, the analysis was done for corrugated piles of different thicknesses and results were compared. The ratio of pile length to pile diameter was assumed to be 30.The diameter of the pile was taken 0.3 m and correspondingly the length was assumed as 9m.

The pile material was taken as steel and soil was assumed to be sandy. ABAQUS defines the contact conditions between two bodies using a master and slave algorithm. In the work, the pile was selected as the master surface and the sand as the slave surface. The meshing density of the pile-soil element contains 1808 nodes and 1162 elements. Vertical compressive loading was applied on the top surface of the pile and outer boundary of the soil was considered fixed.

The response of pile foundation was captured under static compressive loading and the vertical deflections were studied considering elastic models of soil and pile. For elastic models of the pile and soil, the Young's modulus of elasticity and poisson's ratio were defined in the material property section. The influence of loading on settlement was explored. All the pile models have been embellished assuming an elastic response for the stress-strain relationship within the pile and soil material.

# CHAPTER I-GENERAL

## 1.1INTRODUCTION

One of the important aspects of a Civil Engineering Project is the Foundation system design for a safe, efficient and economic project. Foundations are the substructure components which transmit the loads from the superstructure to the soils or rocks.

Depending upon the length to diameter ratio, foundations are classified as Shallow foundations and deep foundation. There are many reasons of using deep foundations over shallow foundations like heavy design loads, poor soil conditions at shallow depth, costing etc.

Pile foundations are deep foundations and are formed by long, slender, columnar elements made from timber, RCC or steel. Pile foundations are necessary where the bearing capacity of the surface soils are not sufficient enough to bear the loads imposed and so they are transferred to deeper layers with high bearing capacity.

Pile foundations are commonly used to resist vertical loads and lateral loads. The vertical loads comprise of the loads coming from the superstructure, i.e. combination of dead loads and live loads whereas lateral loads comprise of wind loads and earthquake loads.

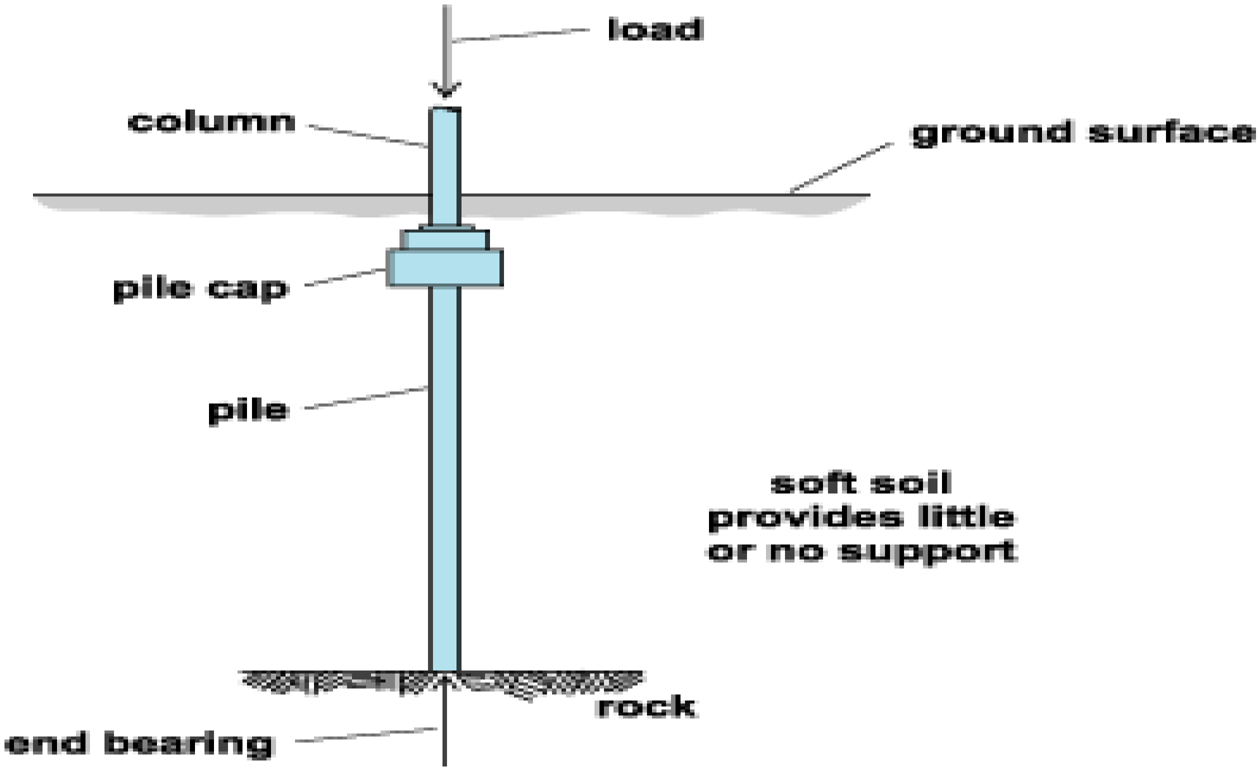


**Figure1 Pile foundation**

*Source:* http://indiavasthu.blogspot.in/2012/09/deep-foundation-pile-foundation.html

The load bearing mechanism of pile foundation is depicted here in the image.

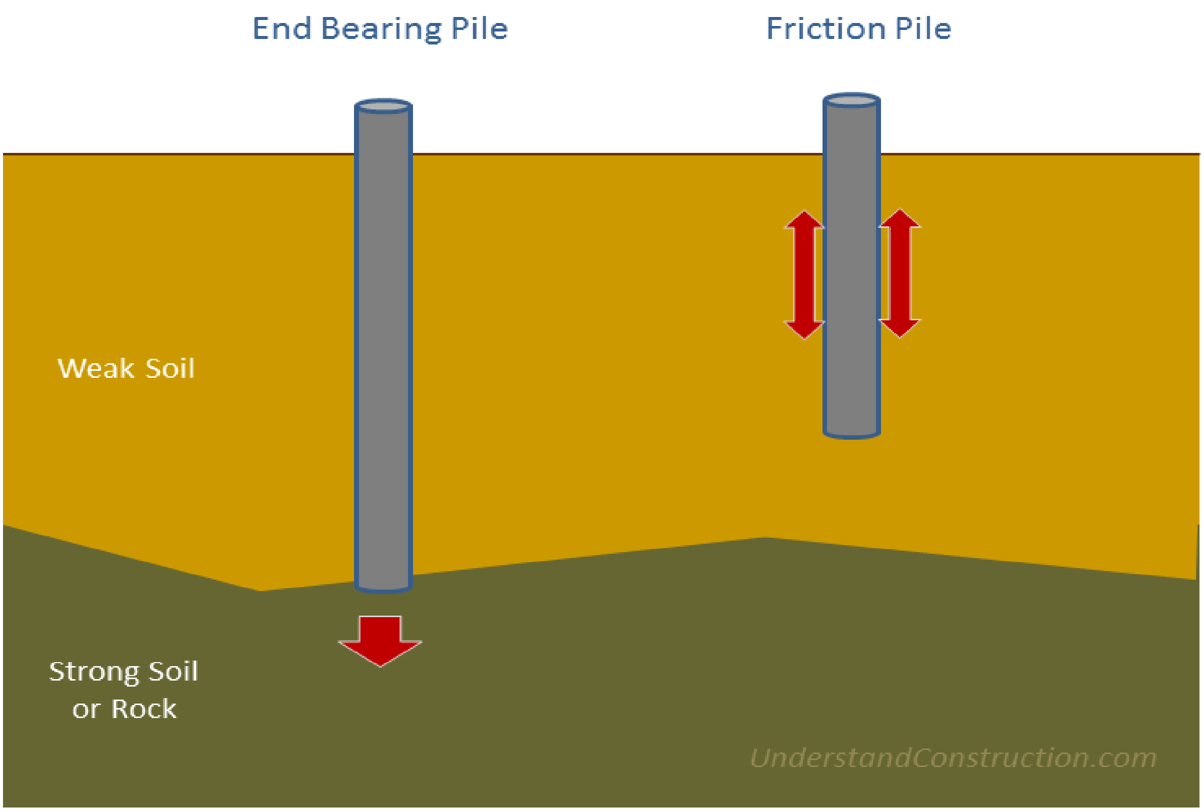


**Figure 2 Load Bearing Mechanism of Pile Foundation**

*Source:* http://www.understandconstruction.com/pile-foundations.html

The use of pile foundations can be traced back to Roman civilization and with the progress into the industrial age, new innovative approaches in pile design and analysis can be seen.

Finite Element Method (FEM) is a rational tool to analyse the complex nature of pile foundations under loading. However, the FEM computational method is limited by input data available and idealized algorithms, such as constitutive models that describe the behaviour of pile and soil once loaded.

In mathematics, the **finite element method** (**FEM**) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. There are various software packages available which are based on FEM technique like ABAQUS, PLAXIS 3D etc.

The thesis covers the modeling and analysis work of three-dimensional finite element analysis carried out in ABAQUS/CAE 6.10-1 to investigate the behaviour of piles embedded in soil subjected to vertical compressive loading.

Working with ABAQUS/CAE 6.10-1 involves mainly three steps:

- *Pre-processing or modelling:* This step involves the modelling of the geometry and creating an input file for a finite-element analyzer.
- *Processing or finite element analysis:* This step gives an output file.
- *Post*-processing: This step is a visual rendering stage and involves generation of image, animation, report etc from the output file.

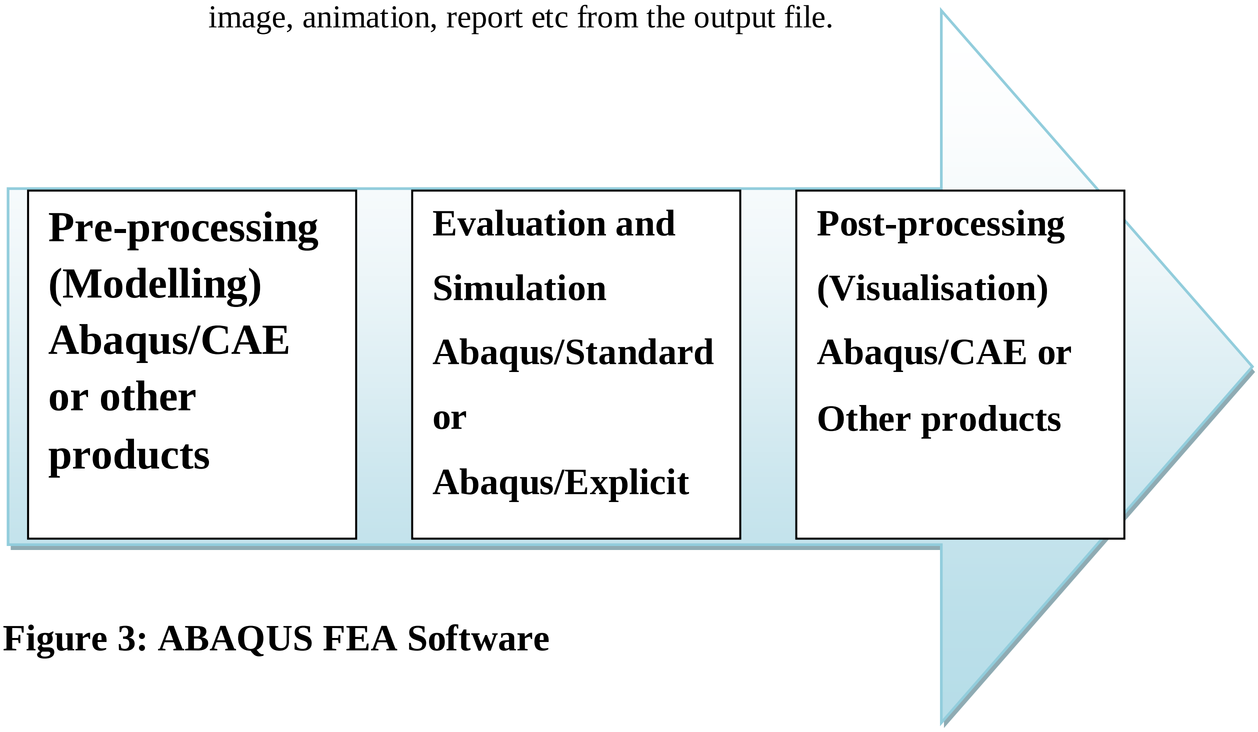


**Figure 3: ABAQUS FEA Software**

## 1.2Objectives of Study:

As a general rule, piles are used when the bearing capacity and settlement criteria cannot be satisfied with shallow foundations. Designers choose pile foundations over shallow foundations under the following conditions:

- Predicted settlement of a shallow foundation is expected to exceed serviceability limit state.
- Differential settlement under a structure is excessive.
- The bearing capacity of the soil is not sufficient to support shallow foundations.
- When faced with possible scour problems in rivers etc.

Some typical applications for pile foundations can be seen under large buildings, portal frames etc.These types of structures can place a range of loading combinations on the pile including axial (tension/compression) forces, lateral loads and moments. One such technique to predict the load-deformation behaviour and study the settlements is Finite element Analysis. The computational method like FEM requires work to verify output, and a realistic input for the constitutive properties and in situ stresses.

So, here the study covers the analysis of pile foundation under compressive vertical loading with the following objectives:

- To study the Load-deformation behaviour of pile foundation under vertical compressive loading opting for the elastic models for pile and soil.
- To study the Load-displacement plots for piles with corrugations of different thickness values.
- To compare the settlement values of pile with corrugated piles of different thickness.

# CHAPTER-2 Literature Review-Piles

Various researches have been conducted on numerical analysis of pile foundation for different soil conditions and different loading cases. Most of the researches have been done to simulate the response of pile foundation (single or group) embedded on the soils considering the elasto-plastic behaviour or plastic behaviour of soils.

For elasto-plastic behaviour of soil, Mohr-Coulomb model is adopted and for plastic behaviour of soil Drucker-Prager model is adopted. **Plaban Deb (2016)**, **Dr. Sujit Kumar Pal(2016**) have presented the work on effect of soil properties, pile length-to-diameter ratio and time-dependent load-settlement behaviour on the capacity of a pile using ABAQUS. **Kazimierz Jozefiak (2015)**, **Artur Zbiciak (2015**), **Maciej Maslakowski (2015)** and **Tomasz Piotrowski (2015)** have presented the work on modelling of a soil-pile system and bearing capacity analysis using FEM implemented in Abaqus software.

**Dr. Hussein A. Shaia (2015), Dr. Sarmad A. Abbas (2015)** have presented the result of three-dimensional finite element analysis carried out in ABAQUS to investigate the behaviour of vertical piles embedded in cohesion less soil under variable oblique loads. Two different diameters D= 0.5m and D= 1 m were chosen in order to study the effect of pile geometry. The pile is supposed to be elastic and the soil is modelled using Mohr-Coulomb constitutive relationship.

**Yasser Khodair (2014)** and **Ahmed Abdel-mohti (2014)** have presented the analysis of a numerical study of pile-soil interaction subjected to axial and lateral loads in software LPILE,ABAQUS/Cae and SAP2000.**Dr. Mosa Jawad Al-mosawe(2013)**, **Dr. A'amal Abdul Ghani Al-Saidi(2013)**, **Dr. Faris Waleed Jawad(2013)** have done their research on effect of (length of pile/diameter of pile) ratio on the load carrying capacity and settlement reduction behaviour of piled raft on loose sand. The work was conducted on small-scale models and the results were validated by using 3-D finite element in ABAQUS program.

**Yuan-gang Zhan (2012)**, **Hong Wang(2012)**, **Fu-chen Liu(2012)** have presented the result on numerical analysis of vertical loading pile in homogeneous soil by using software package ABAQUS(Abaqus, 2010).N.Kumar(2016) has formally presented his scientific studies upon the role of special features in side resistance of a model steel pile.These special features comprise of corrugated piles or screw/helical piles.

# CHAPTER-3 Numerical Pile Model Development

The use of numerical models to simulate complex engineering problems has become more famous due to advancement in computer speed and technologies. The numerical models allow for multiple simulations to be explored, and allow us to gain a thorough and better understanding of the entire mechanisms allowed.

The full-scale testing of piles can be a difficult task due to their size and cost. Researchers and analysts can explore the interaction of both soil and pile under various loading cases and soil properties by using numerical methods, such as finite element method or finite difference method. The analysis presented in this project uses the finite element computer package, ABAQUS 6.10-1.

ABAQUS is a multi-purpose computer package that allows users to investigate mechanical, structural and geotechnical problems under static and dynamic loadings. It is an ideal package due to its capability in modelling complex interactions between several bodies, and the available constitutive models for both structural and geotechnical materials. The package also allows for initial residual stress fields to be defined.

It is important to verify a numerical model to ensure its predictions are within an acceptable limit when compared to a real life situation. The following sections show the finite element model and algorithms used to achieve the aims of this work.

## 3.1 Numerical Model Algorithms and Behaviour Criteria

This section explores some of the available numerical model algorithms and constitutive behaviour models, which may be used to predict soil and pile behaviour.

### General Finite Element Algorithms

It is noted that the assembled matrix may be solved implicitly or explicitly and both have differences like: The implicit solution method requires matrix inversion of the structural stiffness matrix and the explicit solution does not.

The three dimensional elements that can be used to simulate the response of a pile under load include:

- Linear elements: these elements assume a linear shape function between adjoining nodes.
- Quadratic elements: these elements assume a quadratic shape function between two adjoining nodes.

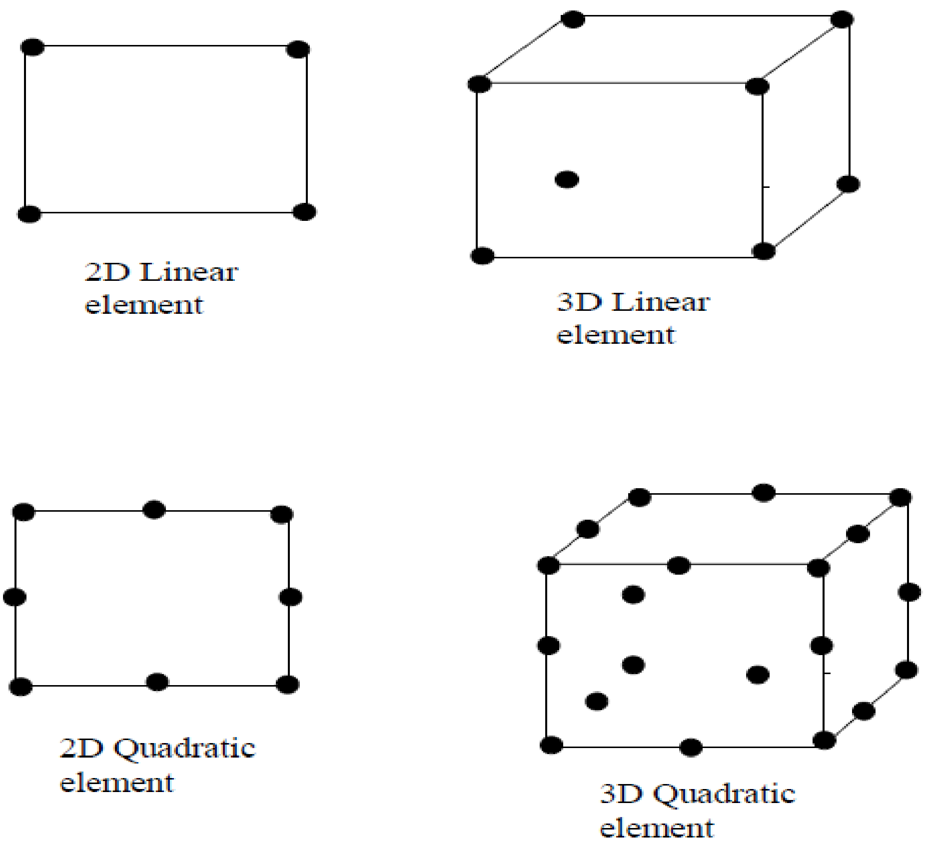


**Figure 4: Linear and quadratic elements**

Source: *Johnson, Kate(2005) Load-Deformation Behaviour of Foundations Under Vertical and Oblique Loads. PhD thesis, James Cook University*

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A linear elastic model to represent the elastic response was used.

Sometimes in geotechnical engineering problems it is necessary to simulate the interaction between two material types. A classical example of this is loaded pile in soil. Abaqus has a vast range of interaction models available. The models include:

1. Mechanical(E.g. Friction)
2. Thermal
3. Coupled thermal-mechanical

4. Coupled pore fluid-mechanical
5. Coupled thermal-electrical

In the case of modeling the pile-soil interaction surface-based contact allows for great versatility and control. Surface-based interactions are dependent on the master and slave concept. The nodes on the two contacting surfaces are grouped together to form master ad slave surfaces. This concept is an interaction model that governs the transfer of stresses from one surface to another. Some typical examples of surface-based interactions are:

1) Contact between two deformable bodies (e.g. pile-soil interaction).

2) Contact between rigid and deformable bodies

3) Self contact

4) Problems where two separate surfaces need to be tied together, so no relative motion occurs between the bodies.

5) Coupled-pore fluid-mechanical interaction between two bodies. For example, interfaces between layered soils materials at a waste disposal site.

ABAQUS imposes restraints and relationships onto master and slave surfaces. These conditions are listed below:

1) The slave nodes are not permitted to penetrate into the master surface. However, the master surface nodes can penetrate into the slave surface.
2) Contact direction is always normal to master surface.
3) Only the master surface is used as a surface, where its geometry and orientation are taken into consideration. The data retained from the slave surface is restricted to the slave node locations and the area associated with each node. Hence a slave surface can be defined as a group of nodes.

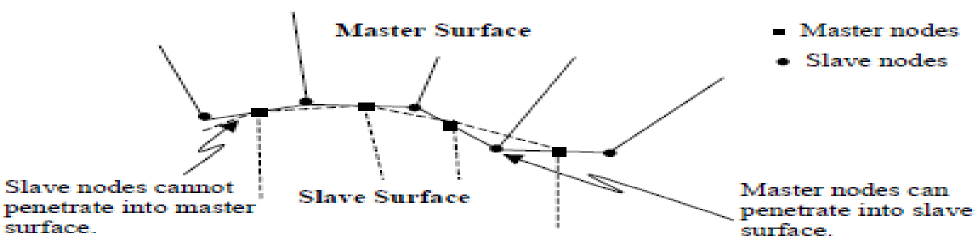


**Figure 5: Penetration restriction between slave and master surfaces**

*Source: Johnson, Kate(2005) Load-Deformation Behaviour of Foundations Under Vertical and Oblique Loads .PhD thesis, James Cook University*

## 3.2 Construction of Finite Element Model in ABAQUS

Some specifications for pile are as follows:

L/d = 30

Length of pile, L = 9m

Diameter of pile, d =0.3m

Area=0.071 $m^2$

| | CORRUGATION THICKNESS (mm) |
|---|---|
| PILE1 | 0 |
| PILE2 | 10 |
| PILE3 | 20 |
| PILE4 | 30 |
| PILE5 | 40 |

**Table 1: Pile Corrugation thickness**

## Problem Geometry and Boundary Conditions

A circular pile under pure axial loading (compression) was modelled as shown in figures below

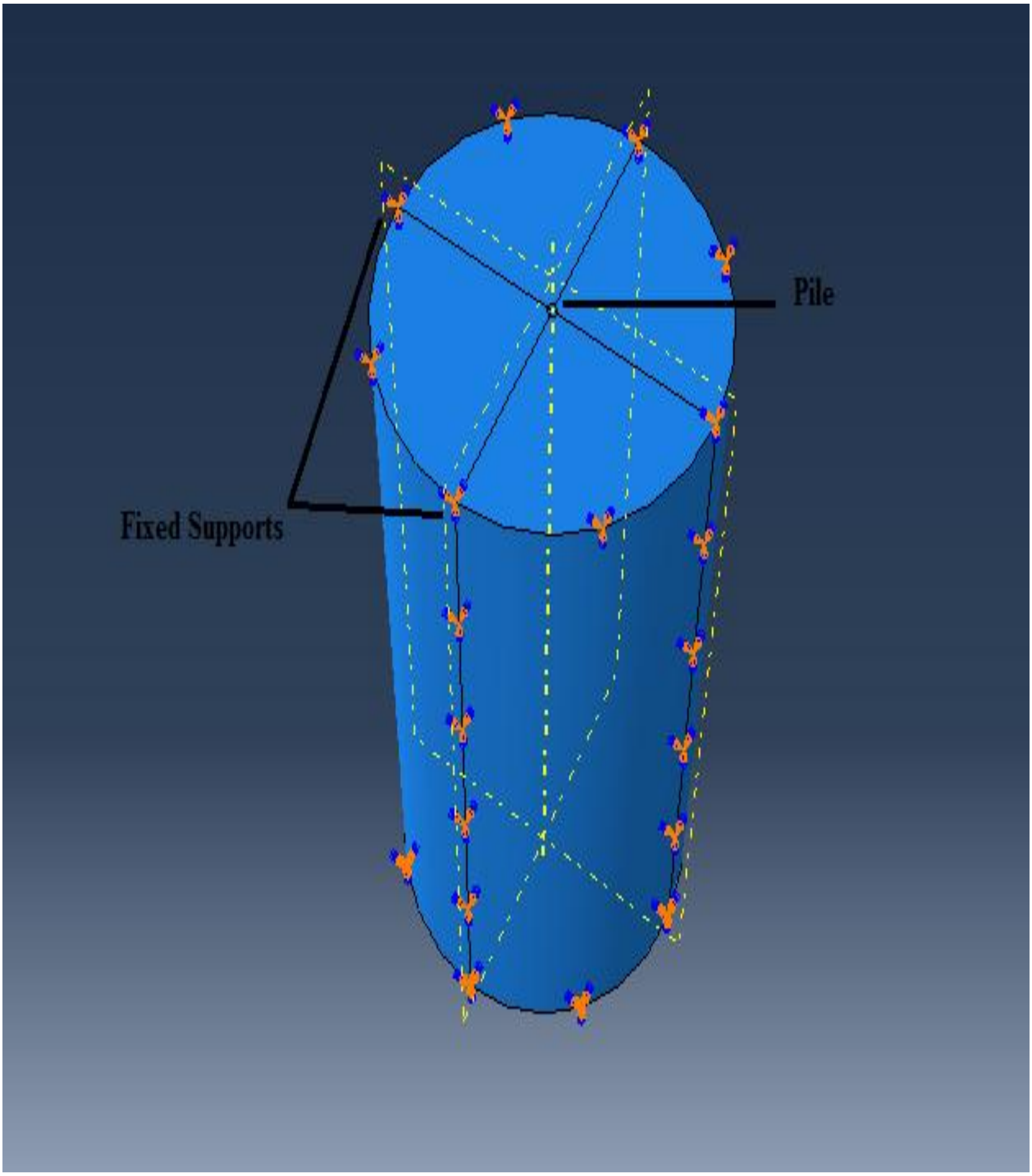


**Figure 6: Pile-soil model with fixed supports**

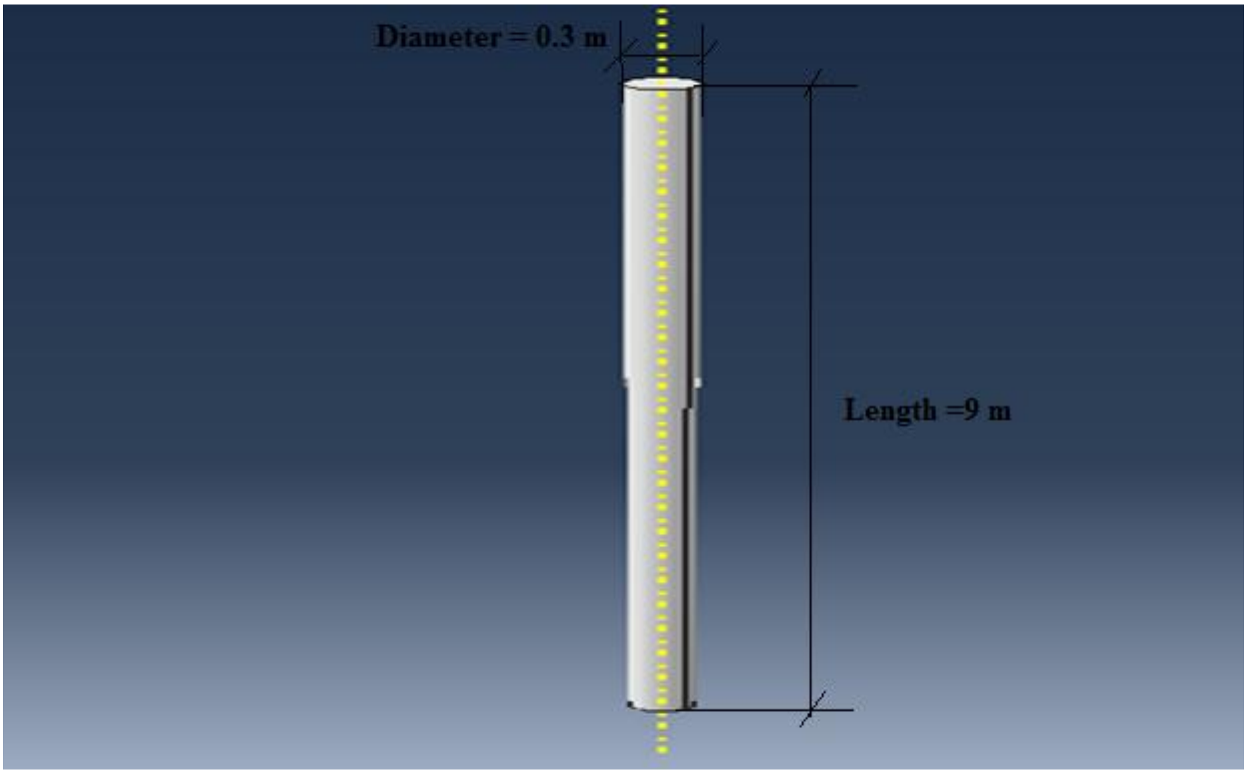


**Figure 7: Elevation view of the pile**

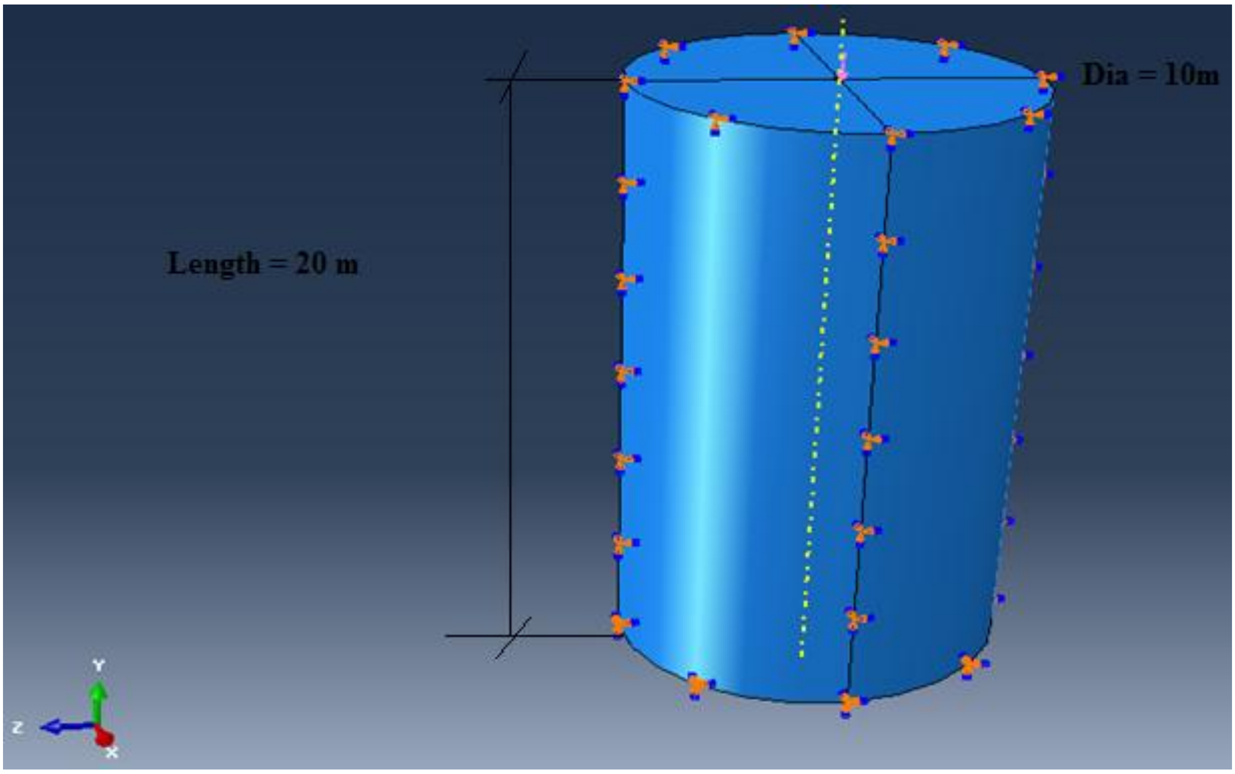


**Figure 8: Elevation View of the Pile-soil system**

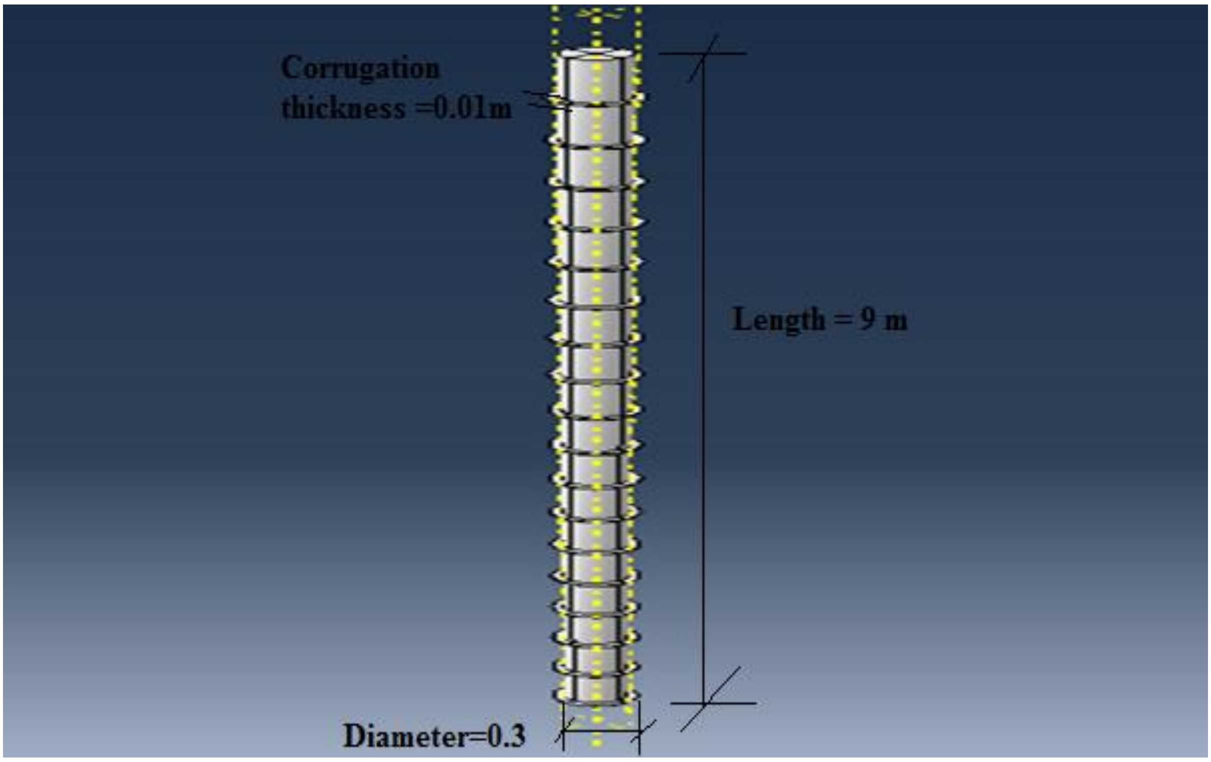


**Figure 9: Corrugated Pile 1 (Corrugation thickness=0.01m)**

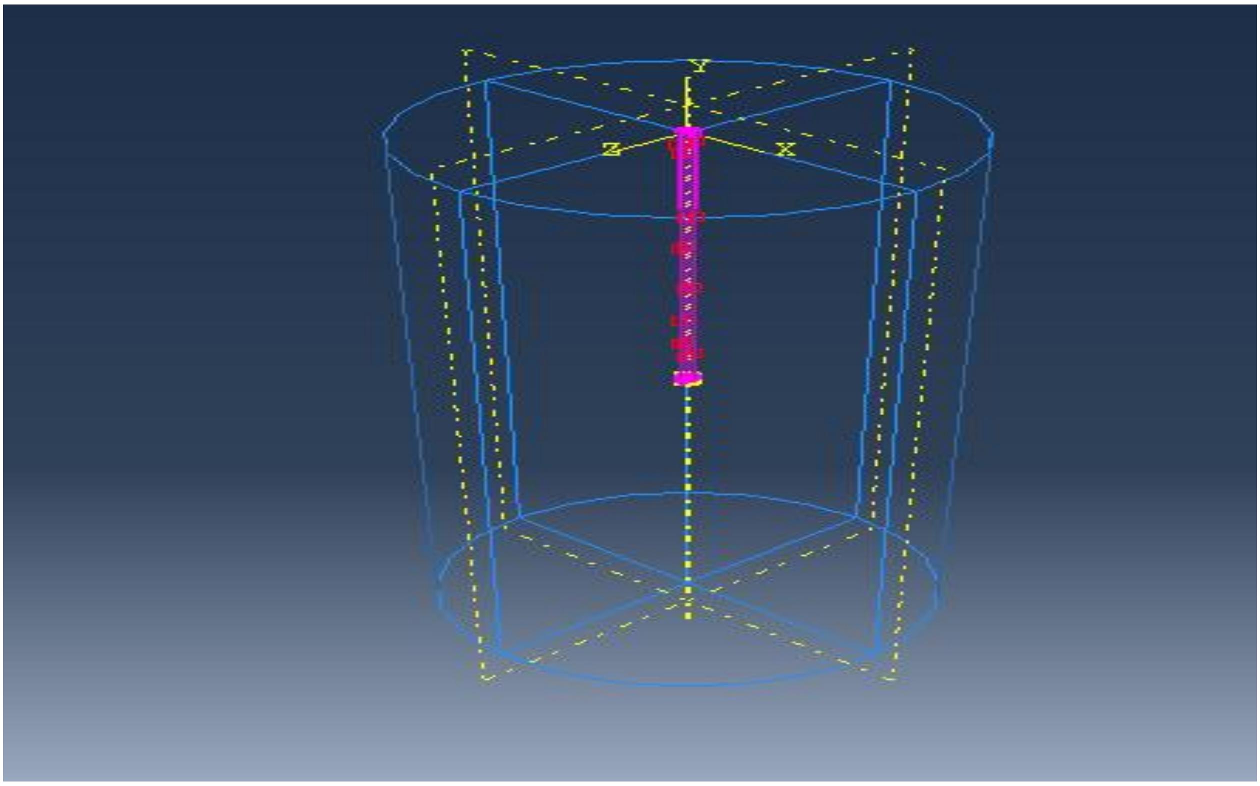


**Figure 10: Soil-pile Interaction for Pile 1(coefficient of friction =0.3)**

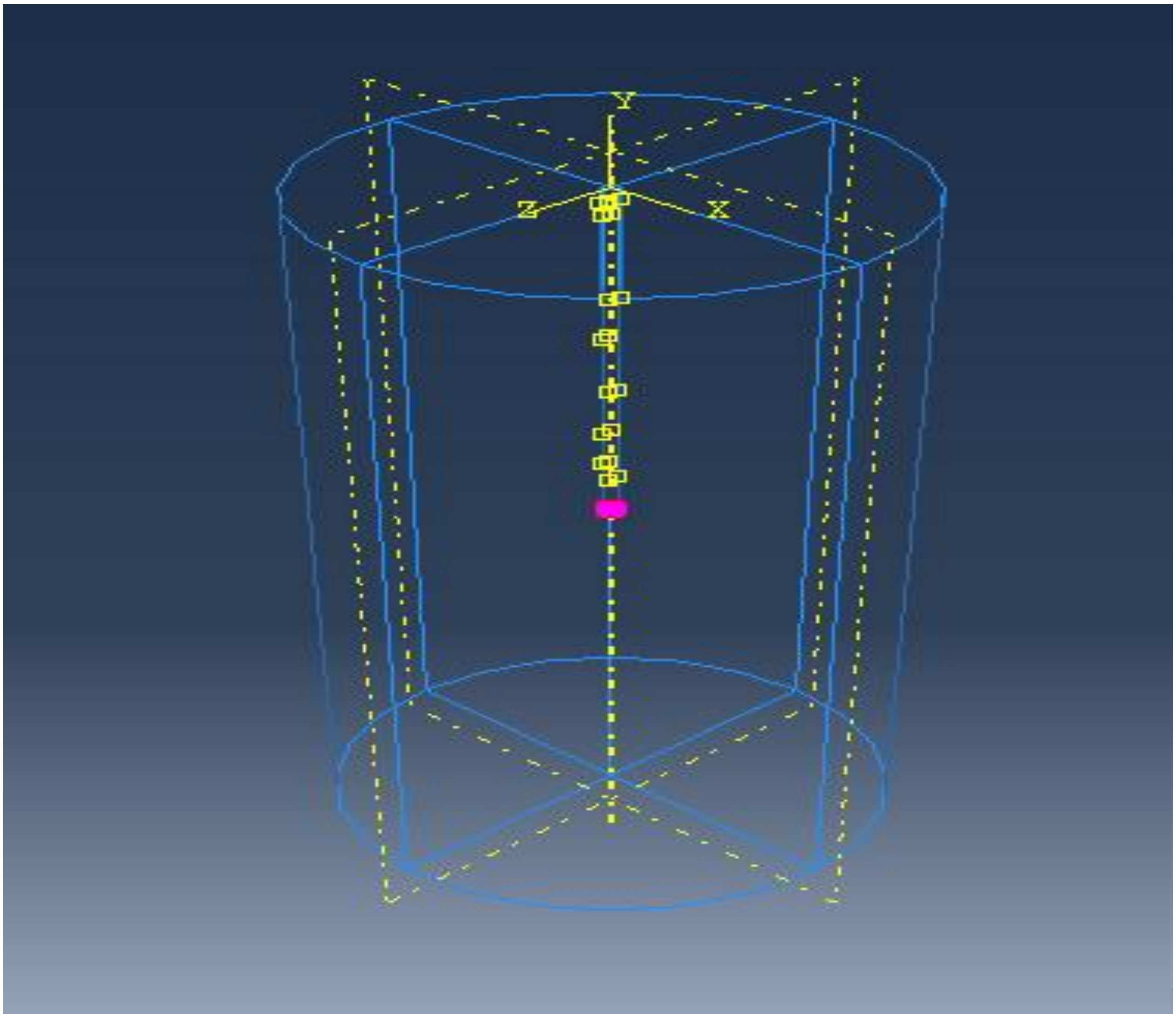


**Figure 11: Base Interaction for Pile 1(with no corrugation)**

## Finite Element Pile Mesh

Several models were developed during the course of the project. The models have linear elastic three-dimensional models with contact surfaces. Also, varying mesh densities and distances from the loading area to the outer edge of the model were investigated for accurate and sensitive analysis. Each variation required a new mesh to be prepared from the beginning in the software. The meshing density for pile1(zero corrugation thickness) was taken keeping the global size for soil as 2 and global size for pile as 0.5.The total number of nodes came out to be 1808 nodes with 1162 elements. Similarly, for other piles with different corrugation thicknesses, the global size for soil was taken as 2 and for pile it was taken as 0.5.

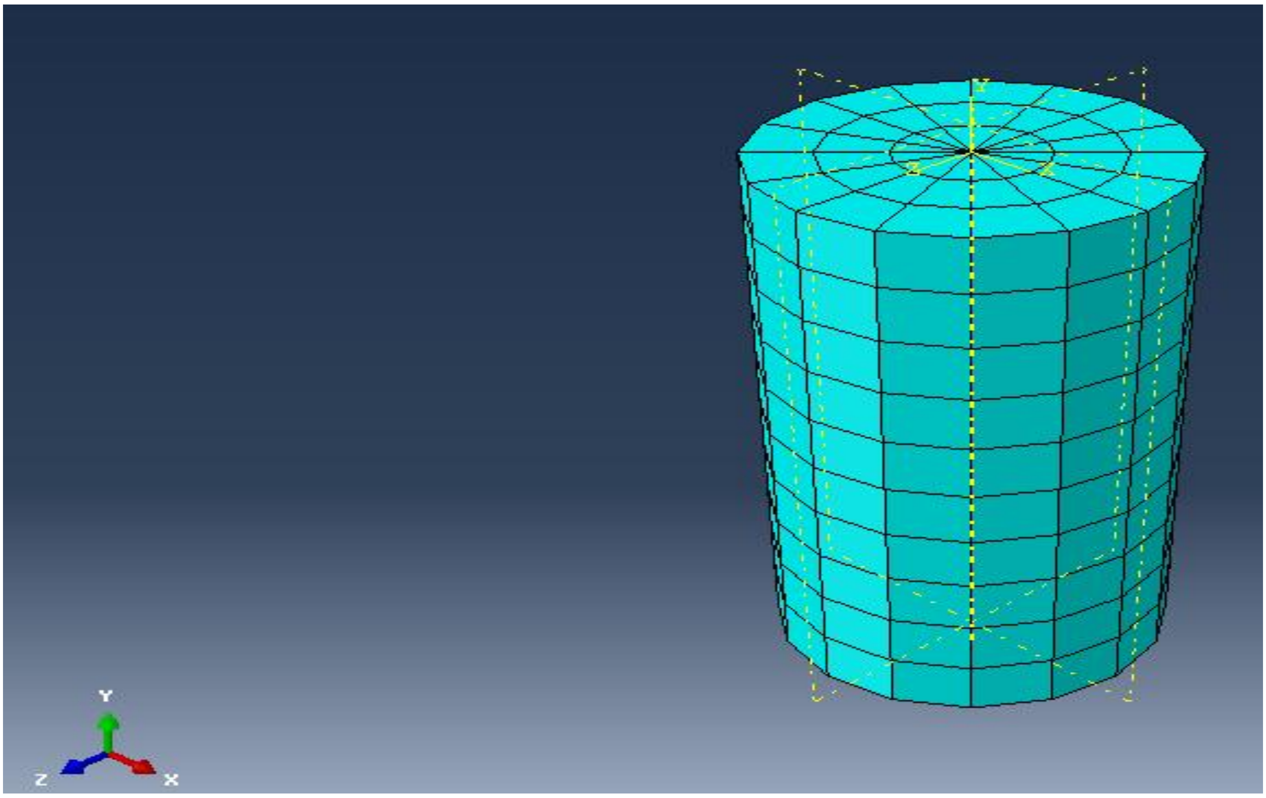


**Figure 12: Soil-Pile Meshing(Global size 2)**

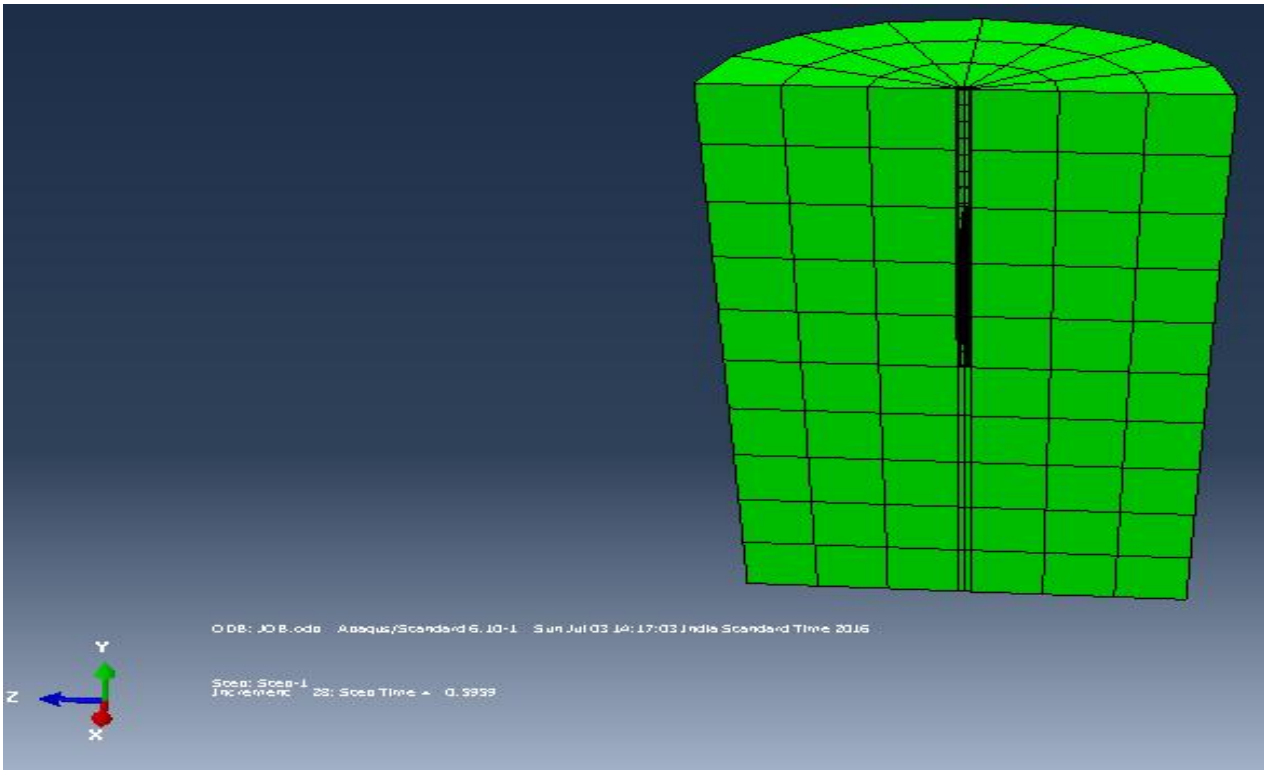


**Figure 13: Half View of Soil-pile meshing(Global size for soil =2, Global size for pile =1)**

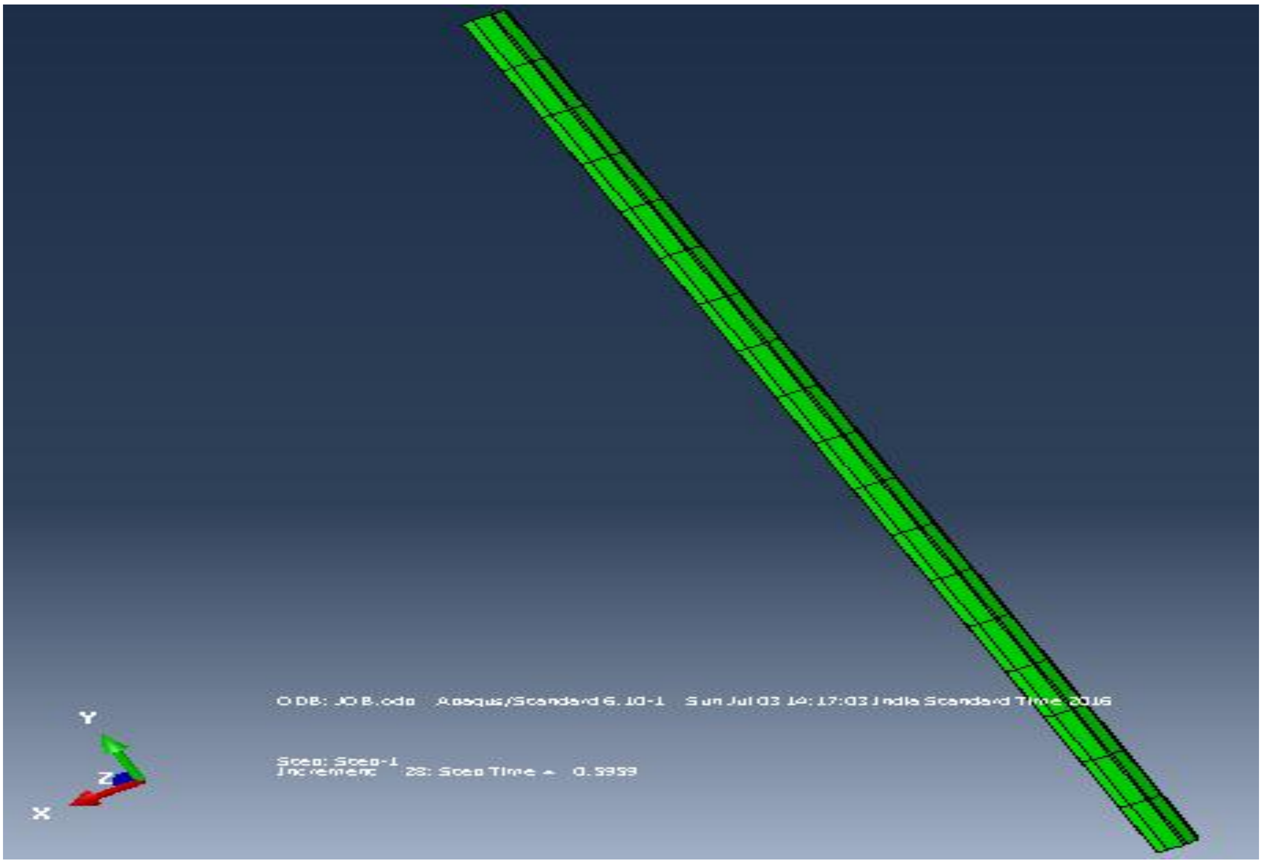


**Figure 14: Pile Meshing(Global size = 0.5)**

The final numerical model for simple pile in the analysis contained 1808 nodes and 1162 elements. The general characteristics of each mesh are as follows:

-Element type: The problem was discretized using 3-D finite elements due to the pile shape. Eight noded linear bricks were utilized. These rectangular bricks have linear shape functions to approximate the displacement pattern between nodes.

-Boundary Conditions: The nodes at the base of the mesh and far bounds are fixed against all displacements.

-Contact Interface: the interaction at the pile-soil interface was modeled by using surface based contact. The coefficient of friction used is equal to 0.3*( between sand and steel pile).The interface allows for relative motion between the pile and soil to occur.

*Reference for value-http://www.finesoftware.eu/help/geo5/en/table-of-ultimate-friction-factors-for-dissimilar-materials-01/

-Input Data: The steel pile and sand properties are used as given below. It was assumed that the sand behaved linear elastically. Once the stress state at any location reaches the failure surface it will undergo plastic deformation. But, here in analysis only elastic deformation was performed.

| Material | Young's Modulus of elasticity($N/m^2$) | Poisson's Ratio |
|---|---|---|
| Steel Pile | $210 \times 10^9$ | 0.3 |
| Sand | $30 \times 10^6$ | 0.4 |

Table 2: Material Property

## 3.3 POST PROCESSING RESULTS

**The following images show the post processing results of the analyses.**

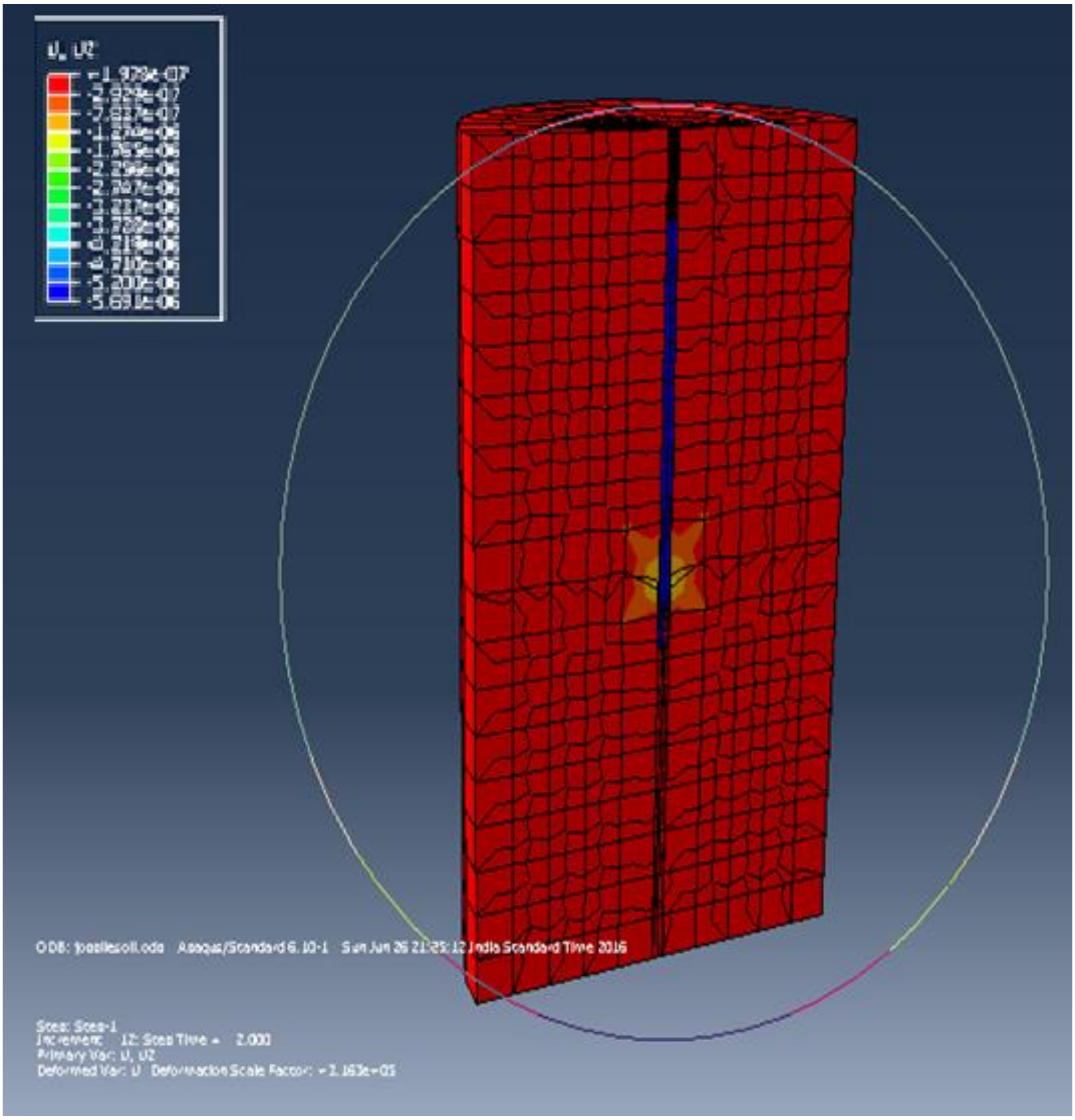


**Figure 15 Displacement Contours for Pile 1(with no corrugation)**

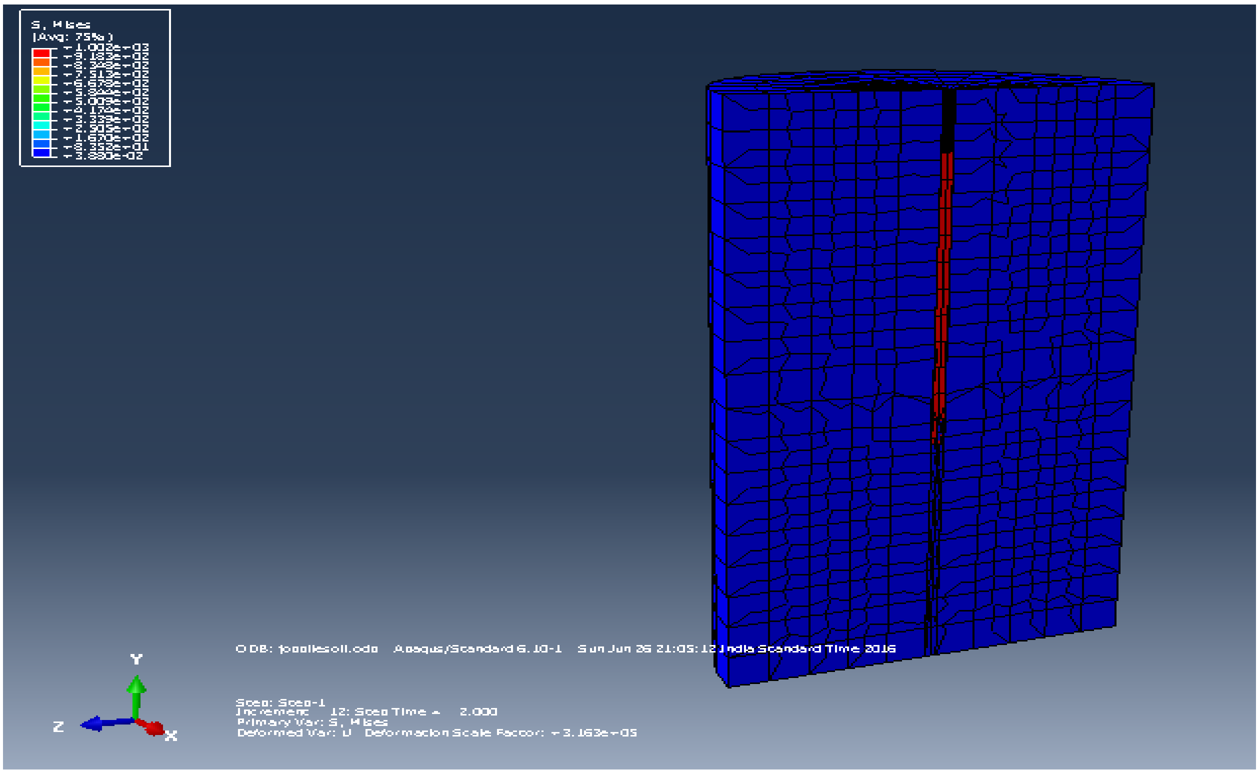


**Figure 16 Stress Contours for Pile 1(with no corrugation)**

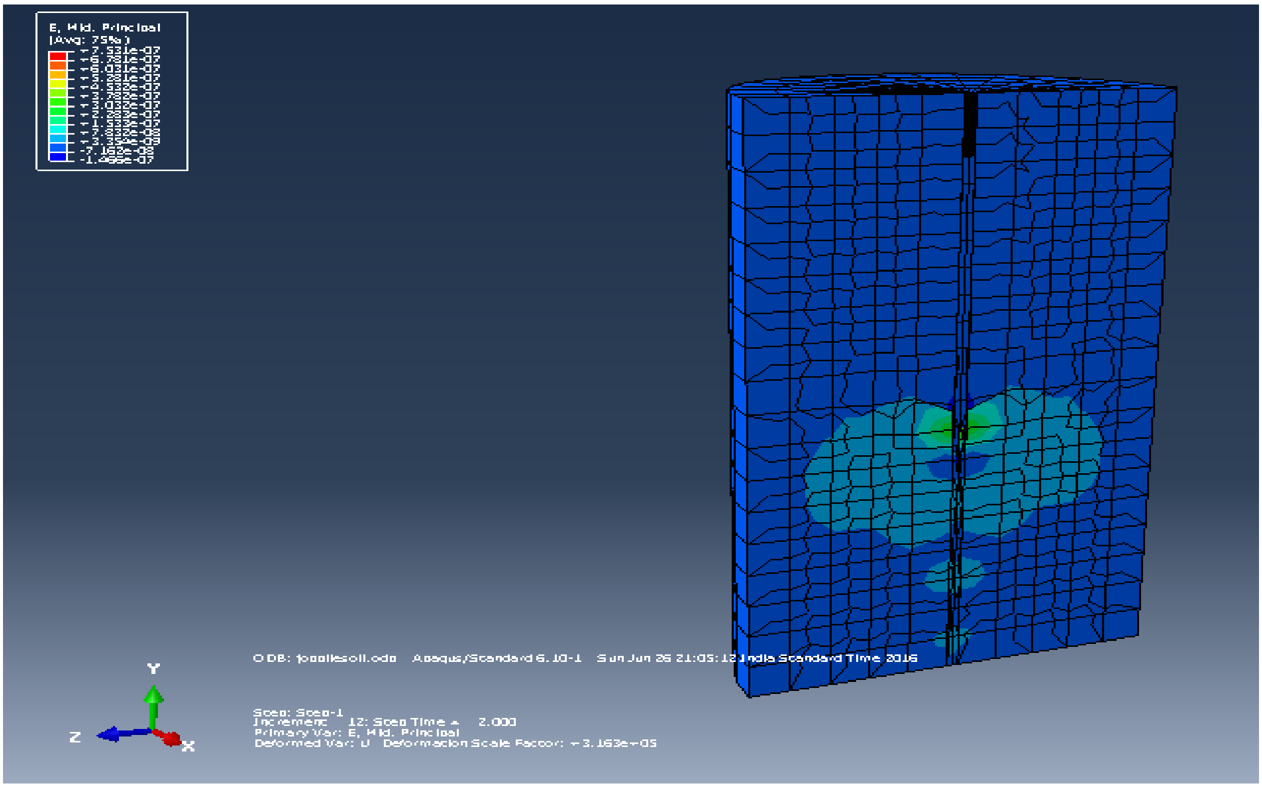


**Figure 17 Strain Contours for Pile 1(with no corrugation)**

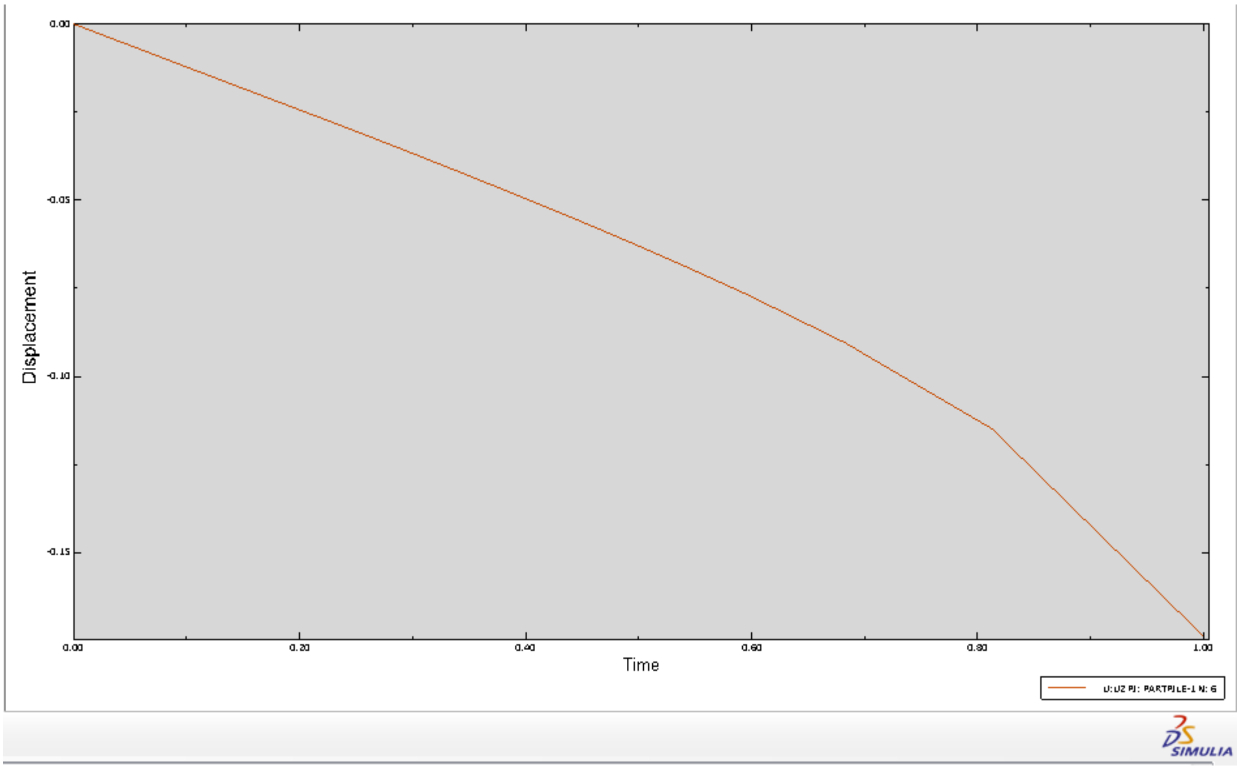


**Figure 18 Displacement (at pile head) Plot for Pile 1(with no corrugation)**

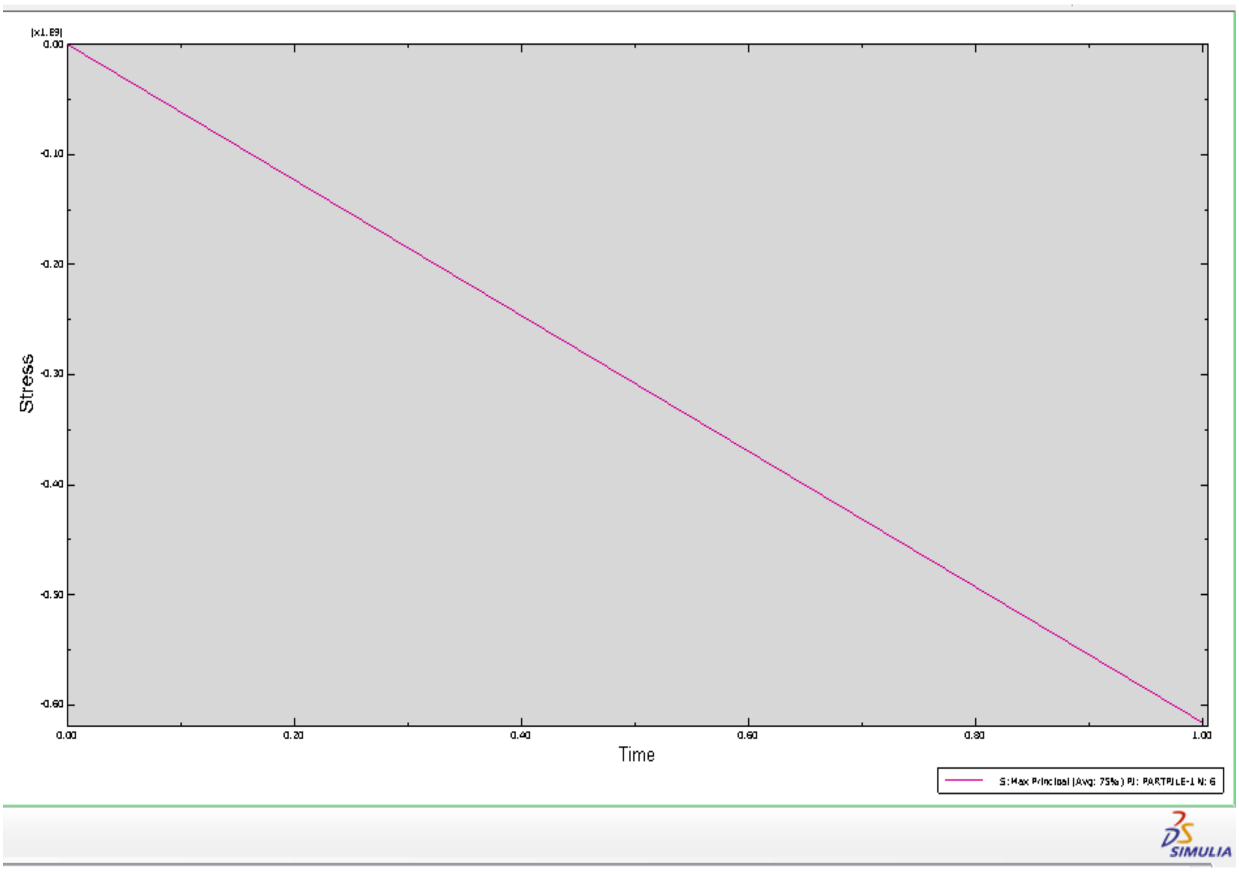


**Figure 19 Stress (at pile head) Plot for Pile 1(with no corrugation)**

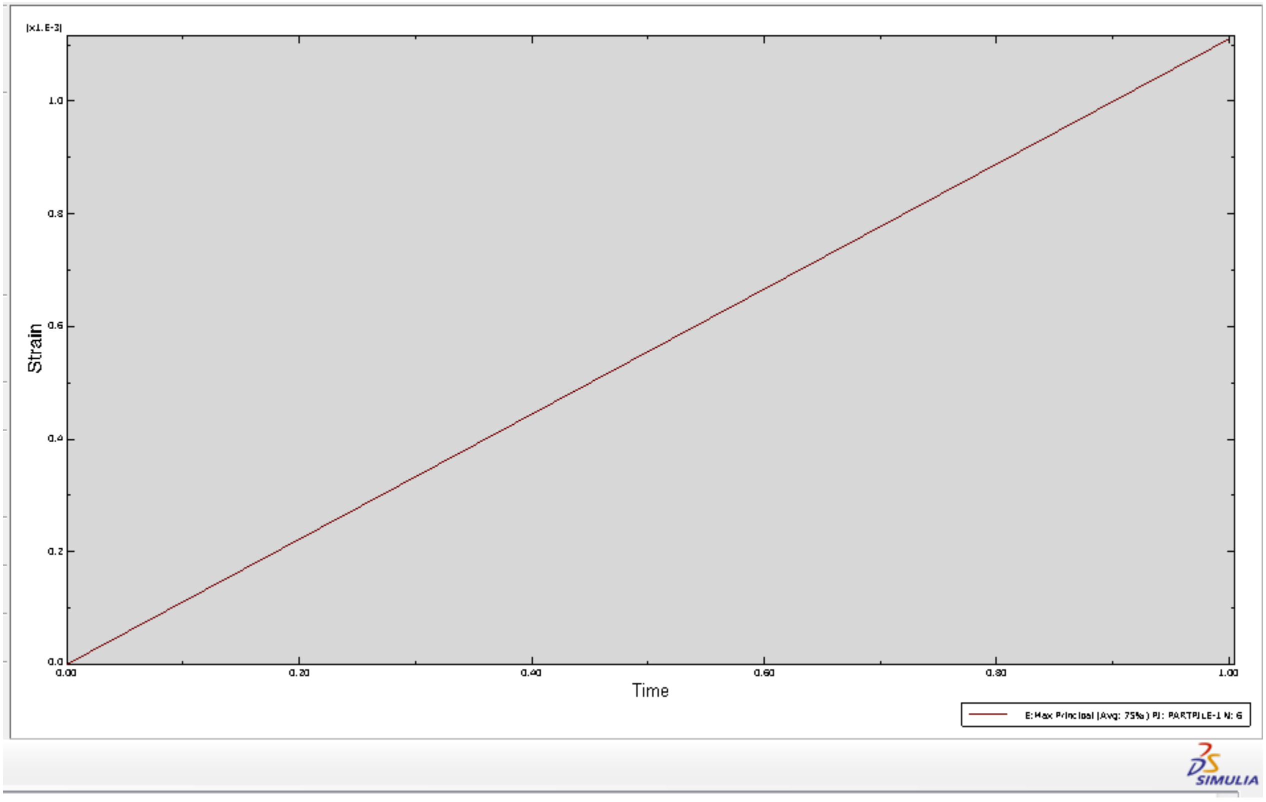


**Figure 20 Strain (at pile head) Plot for Pile 1(with no corrugation)**

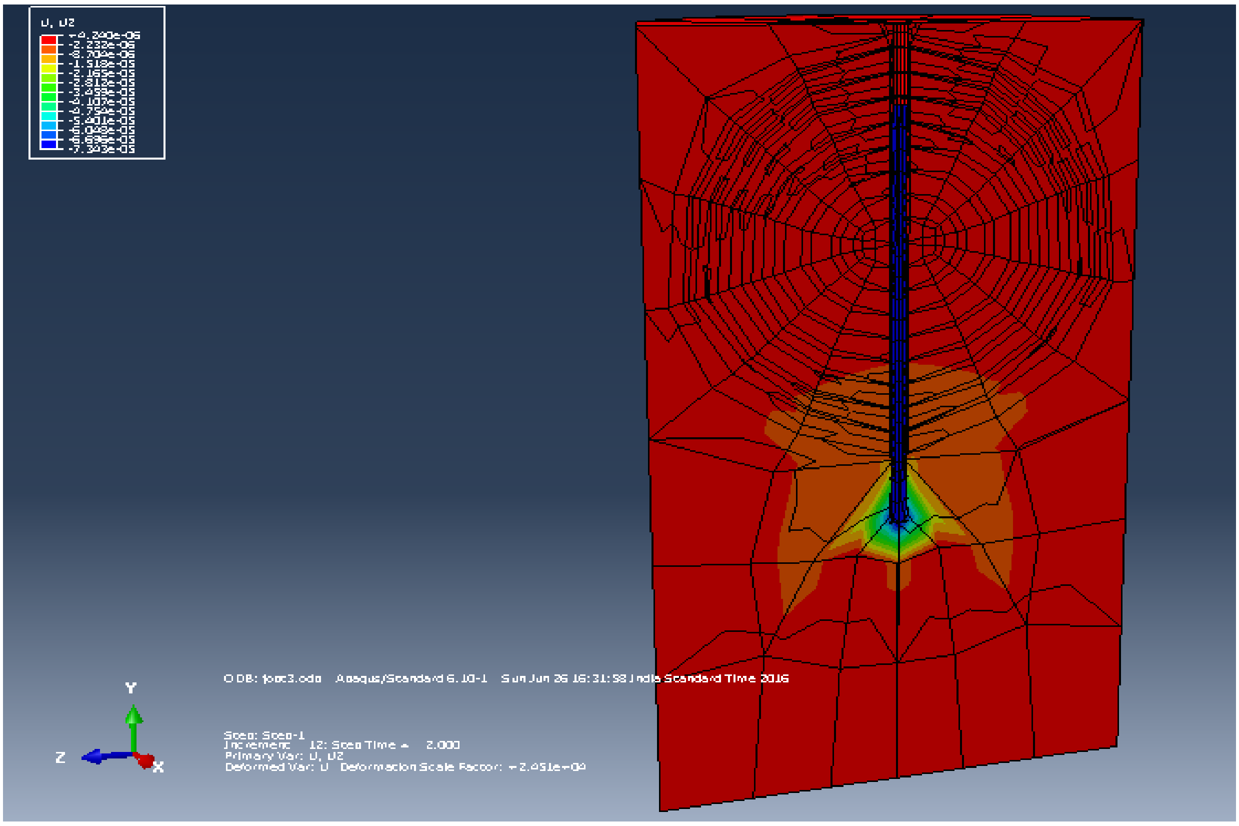


**Figure 21 Displacement Contours for Pile 2(corrugation thickness = 0.01m)**

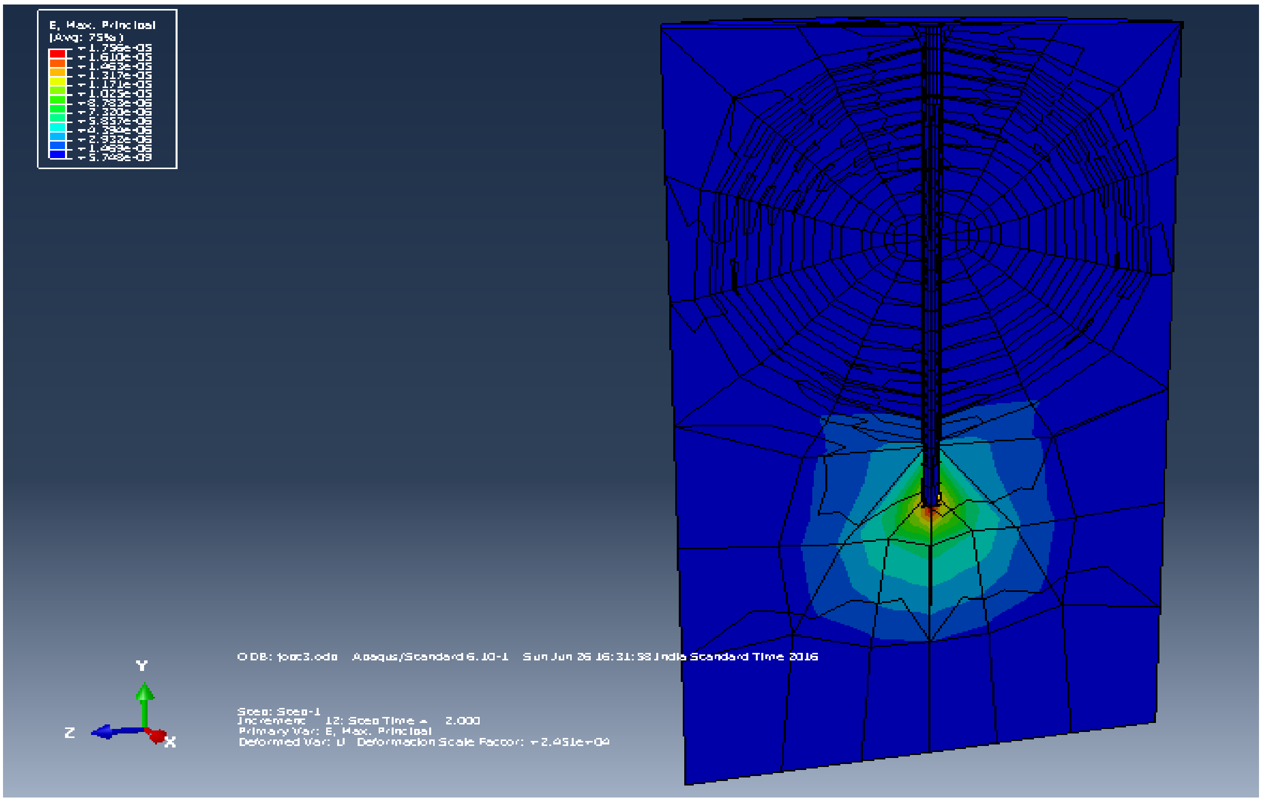


**Figure 22 Strain Contours for Pile 2(corrugation thickness = 0.01m)**

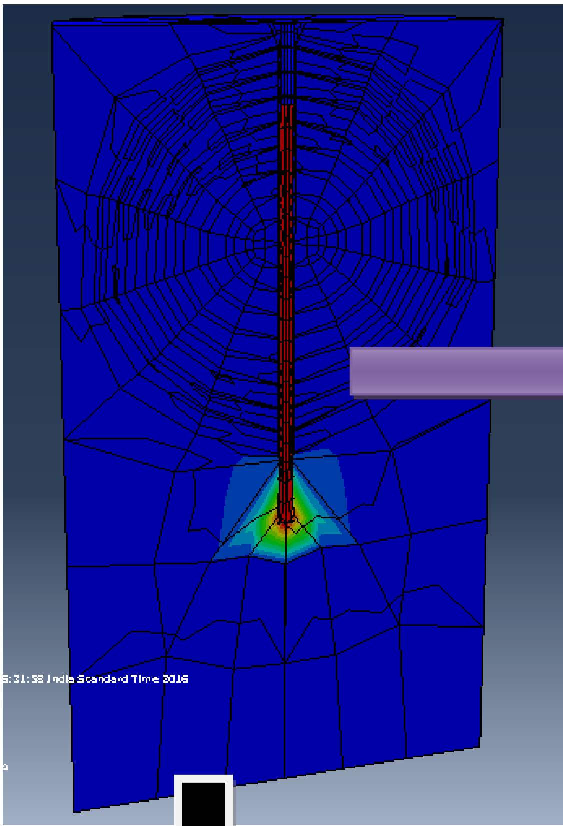

**Figure 23 C rugated Piles**

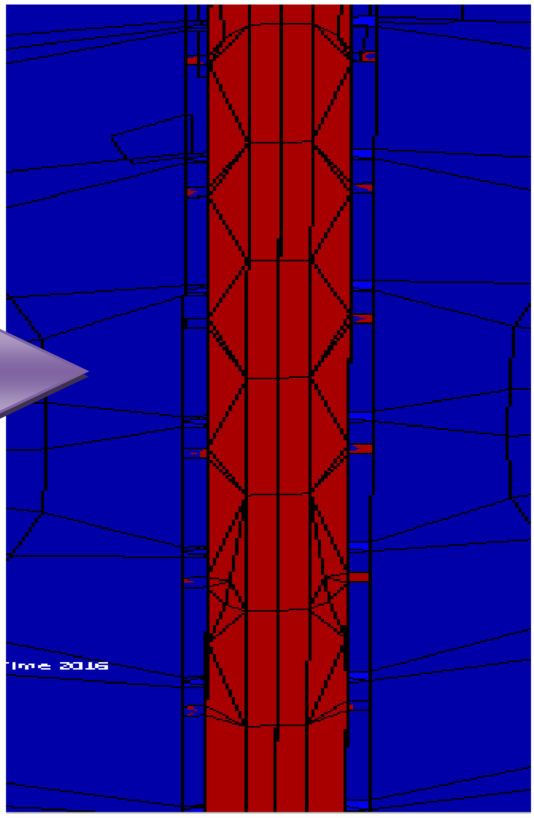

**Figure 24 Strain contours for corrugation Thickness =0.01m**

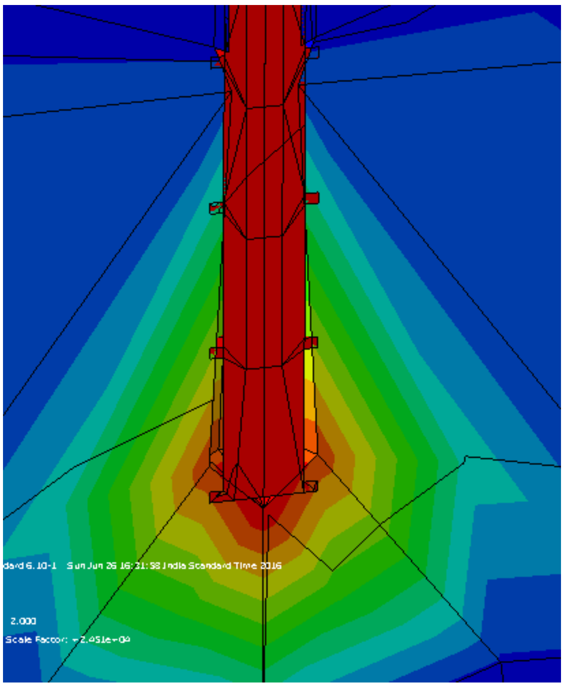

**Figure 25 Strain Contours for corrugation Thickness =0.01m**

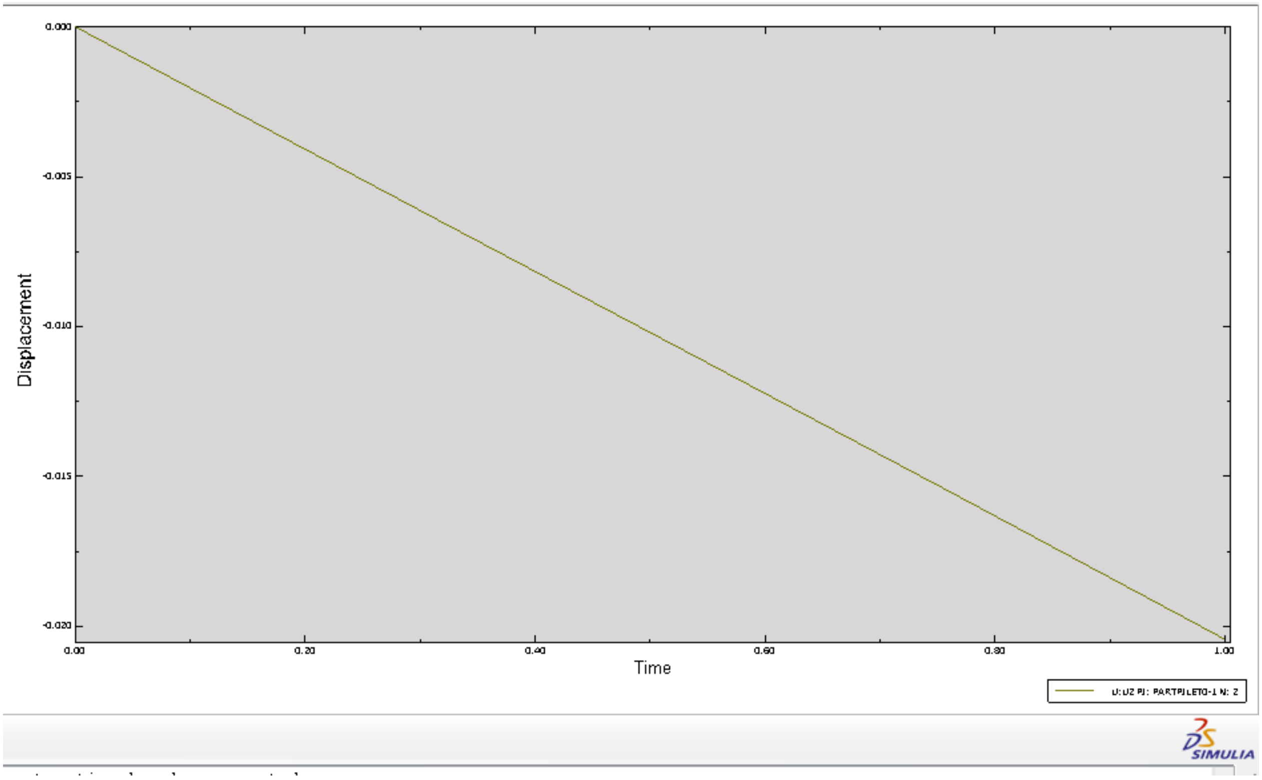


**Figure 26: Displacement plot (at pile head) for Pile 2(corrugation thickness =0.01m)**

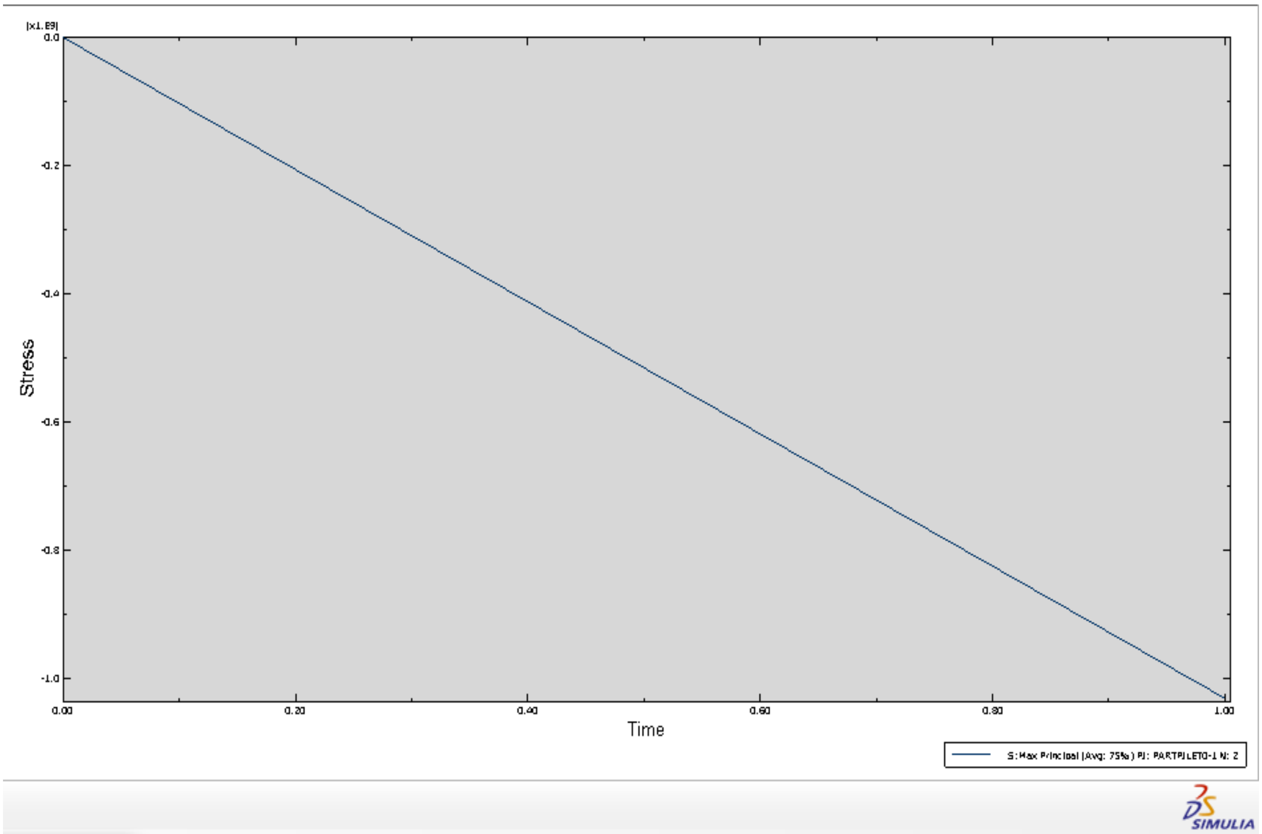


**Figure 27: Stress plot (at pile head) for Pile 2(corrugation thickness =0.01m)**

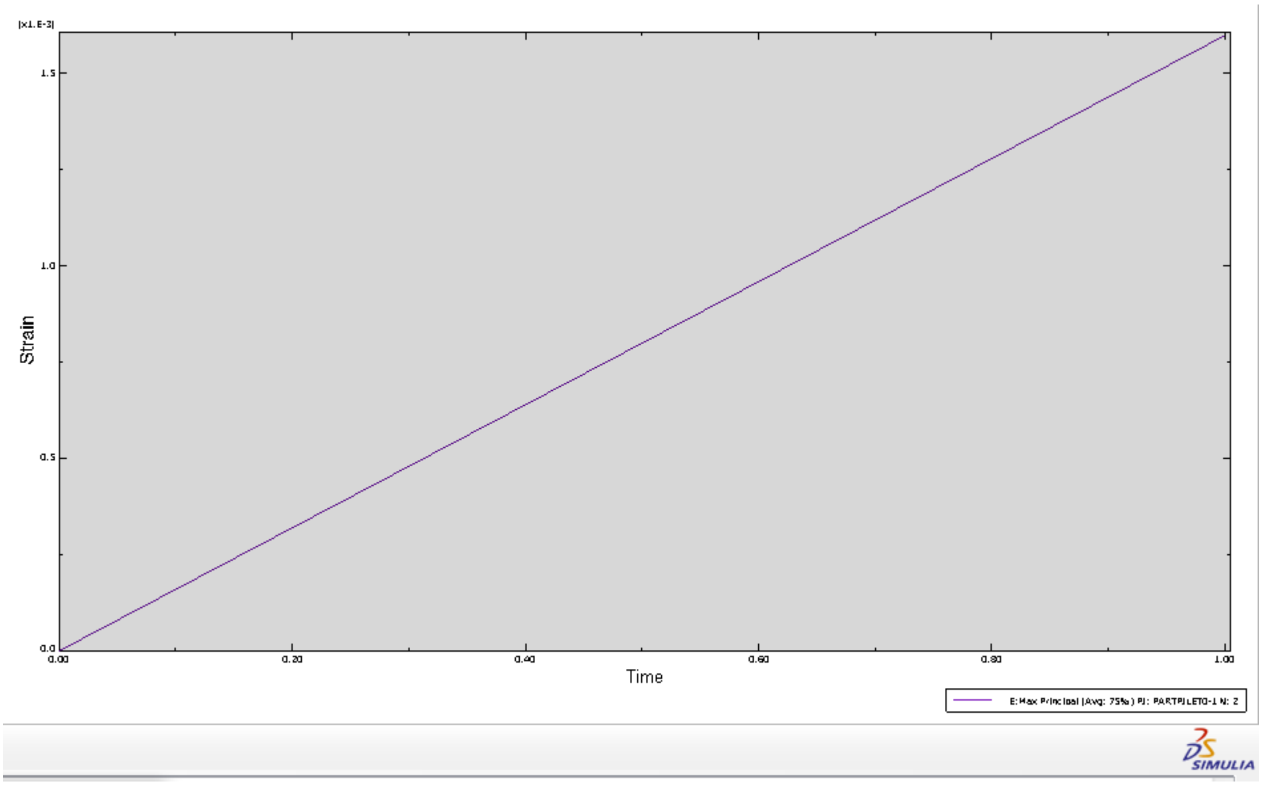


**Figure 28: Strain plot (at pile head) for Pile 2(corrugation thickness =0.01m)**

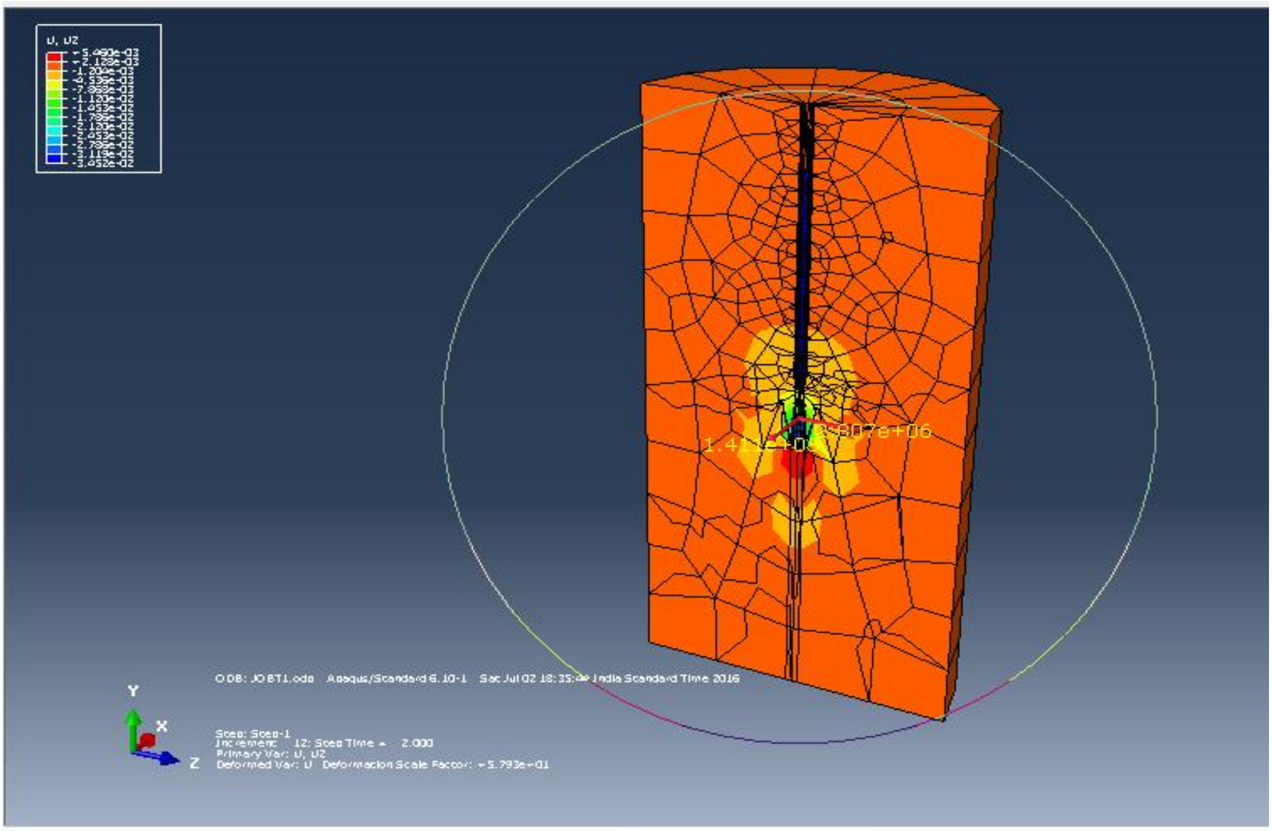


**Figure 29: Displacement Contours for Pile 3(corrugation thickness =0.02m)**

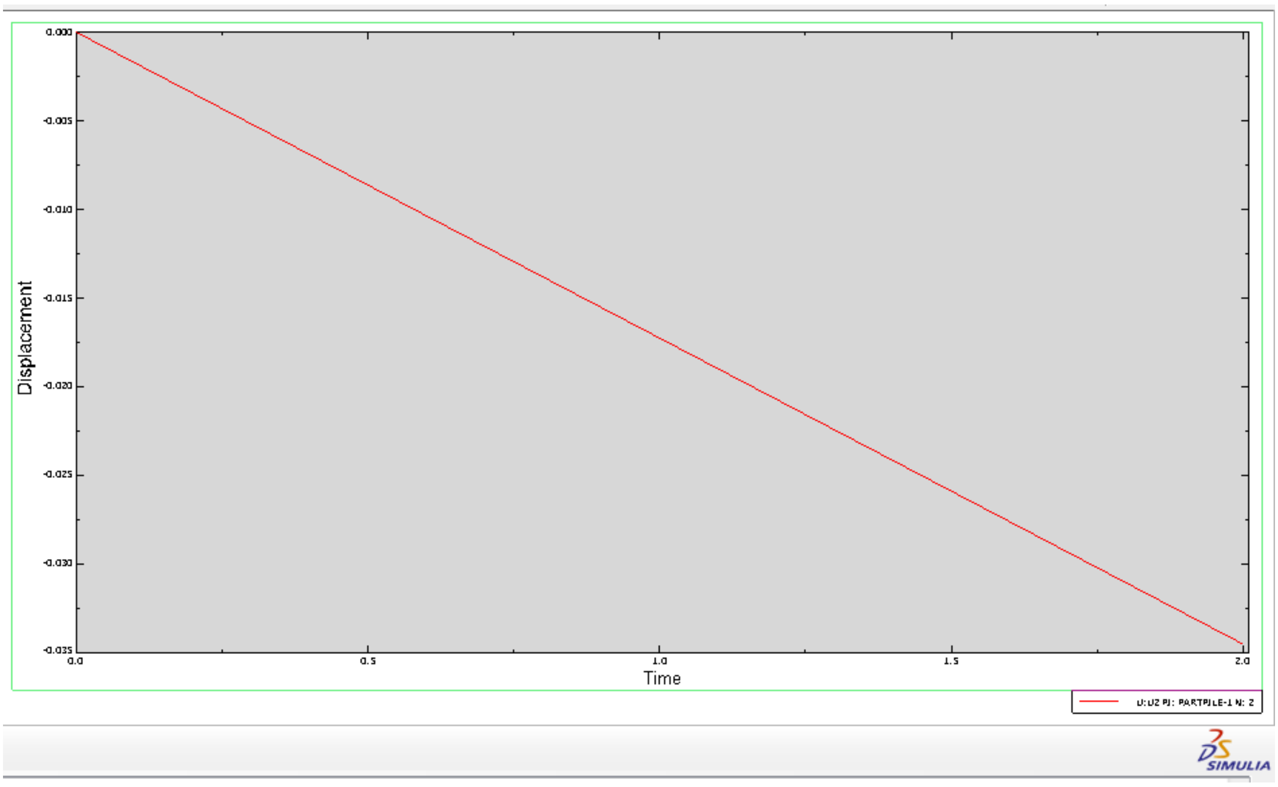


**Figure 30: Displacement plot (at pile head) for Pile 3(corrugation thickness =0.02m)**

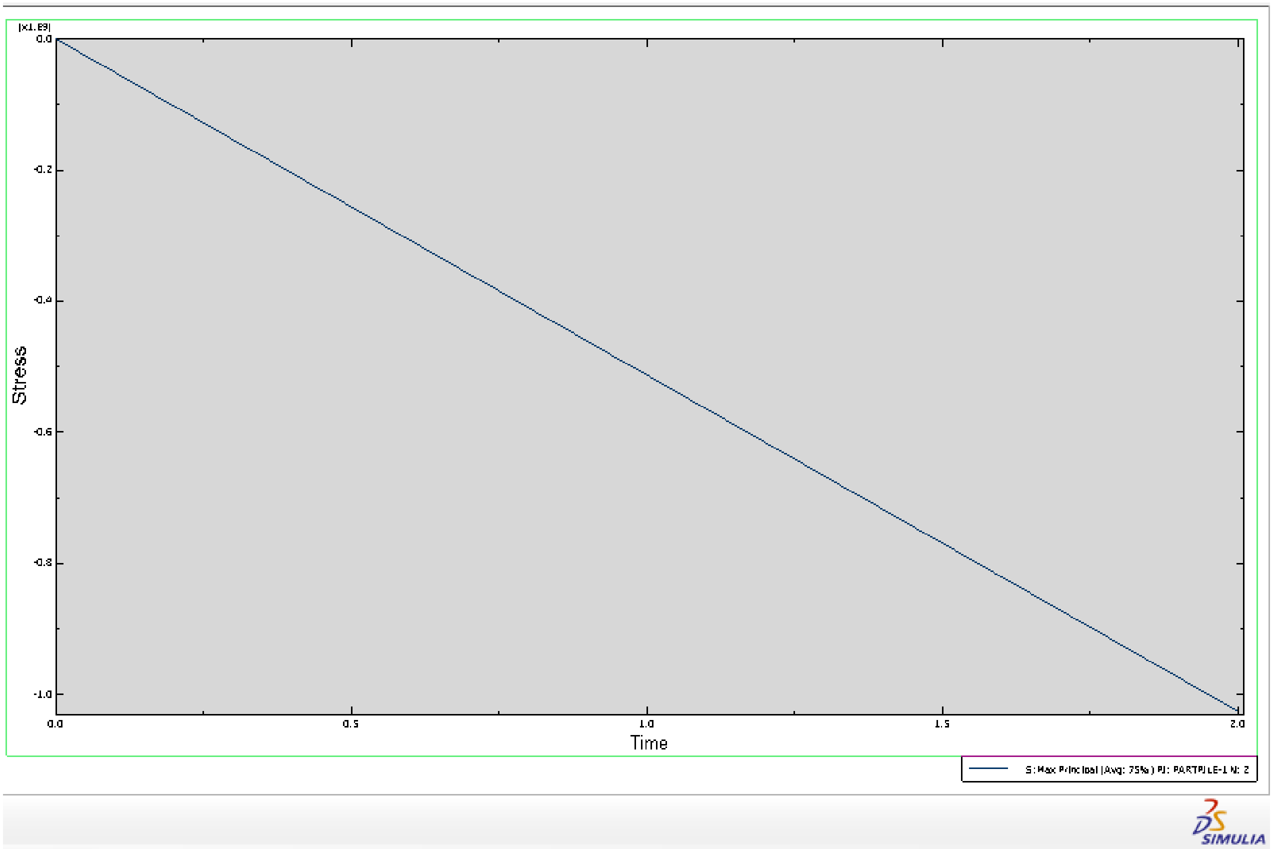


**Figure 31: Stress plot (at pile head) for Pile 3(corrugation thickness =0.02m)**

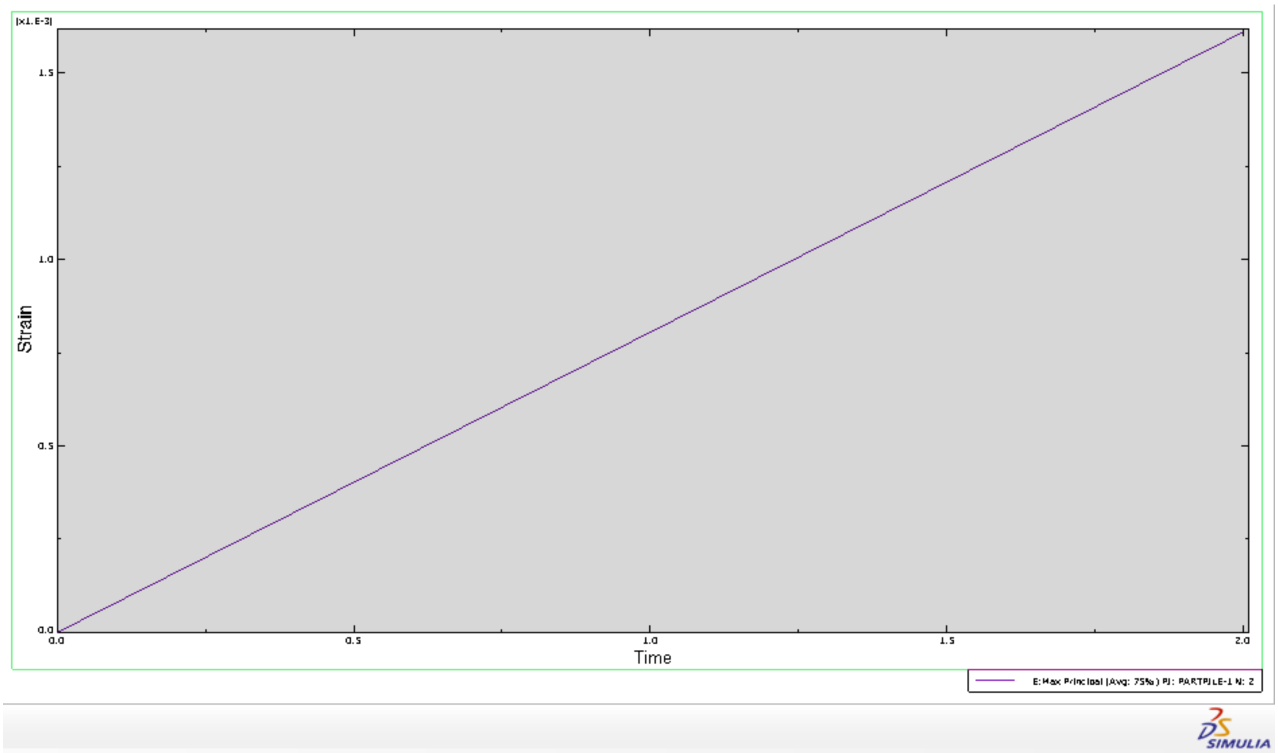


**Figure 32: Strain plot (at pile head) for Pile 3(corrugation thickness =0.02m)**

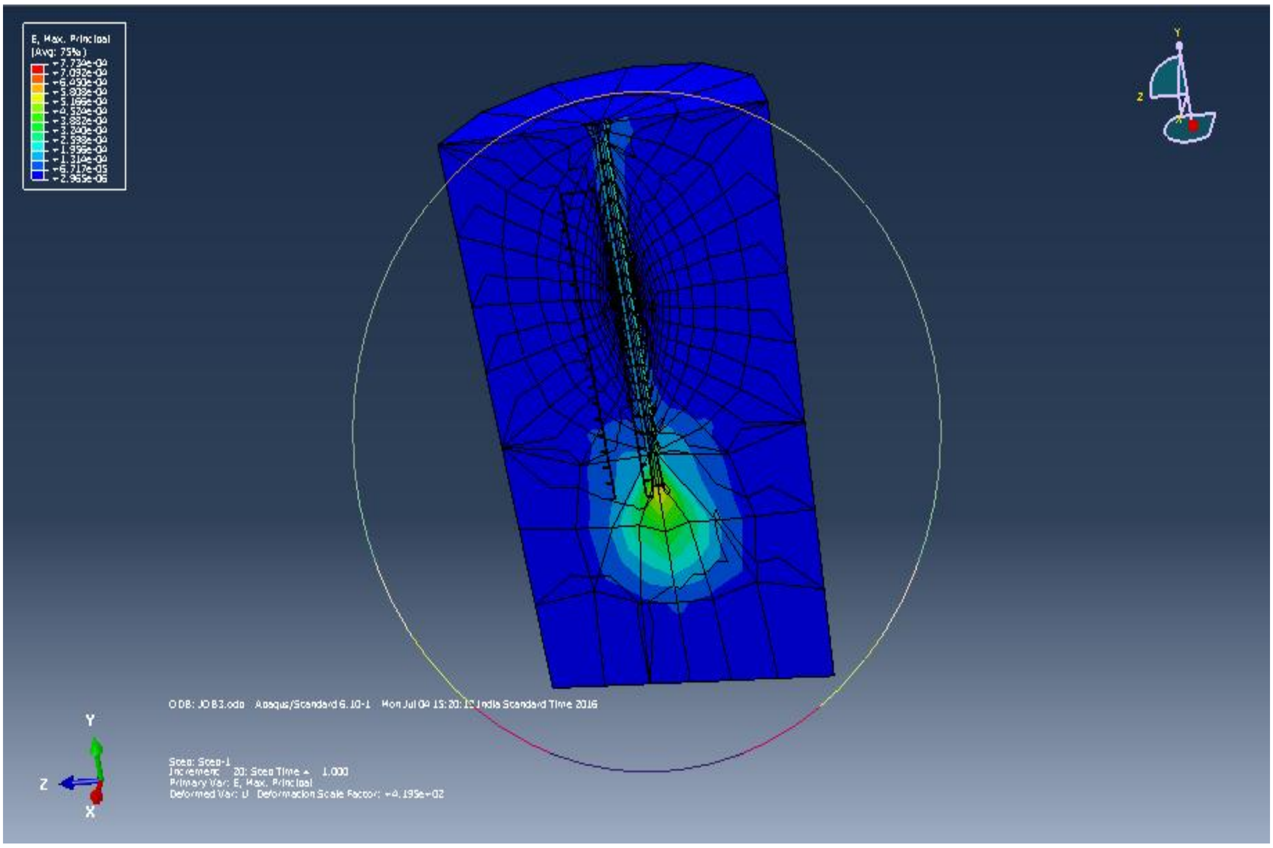


**Figure 33: Strain Energy Contours for Pile 4(corrugation thickness =0.03m)**

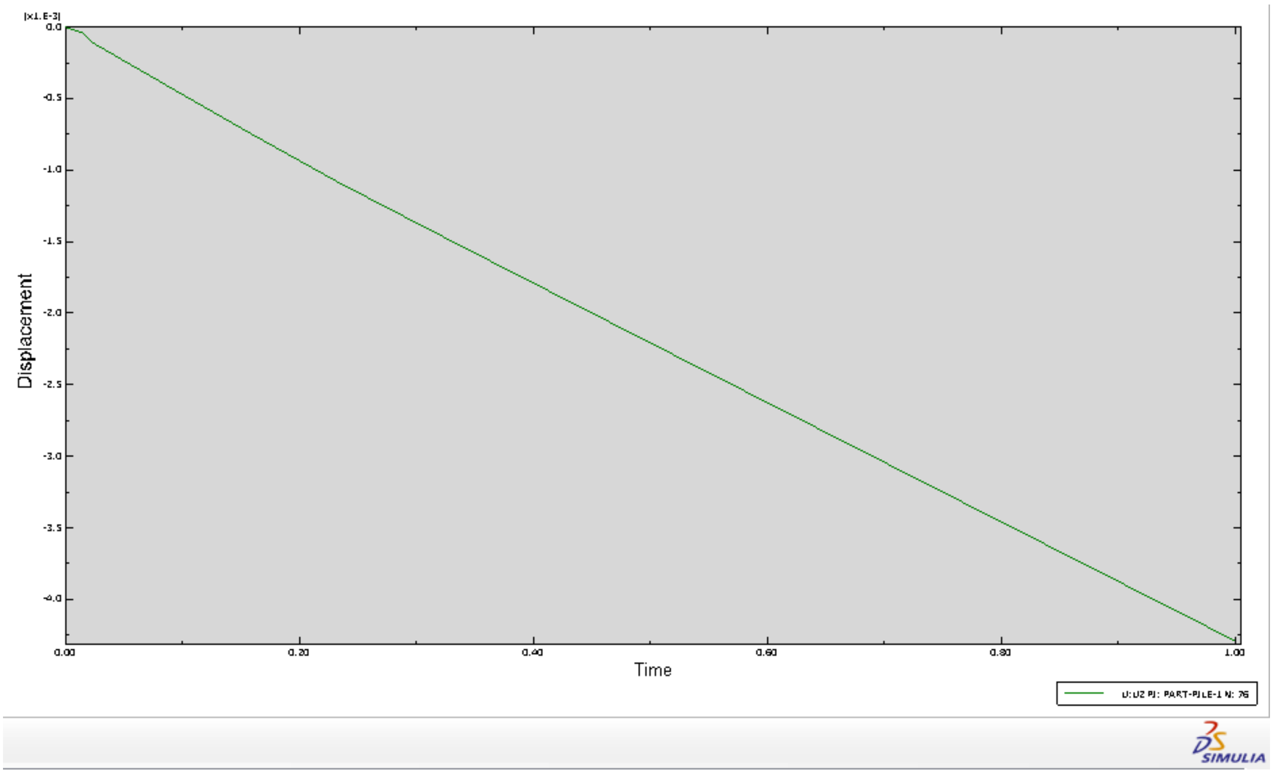


**Figure 34: Displacement plot (at pile head) for Pile 4(corrugation thickness =0.03m)**

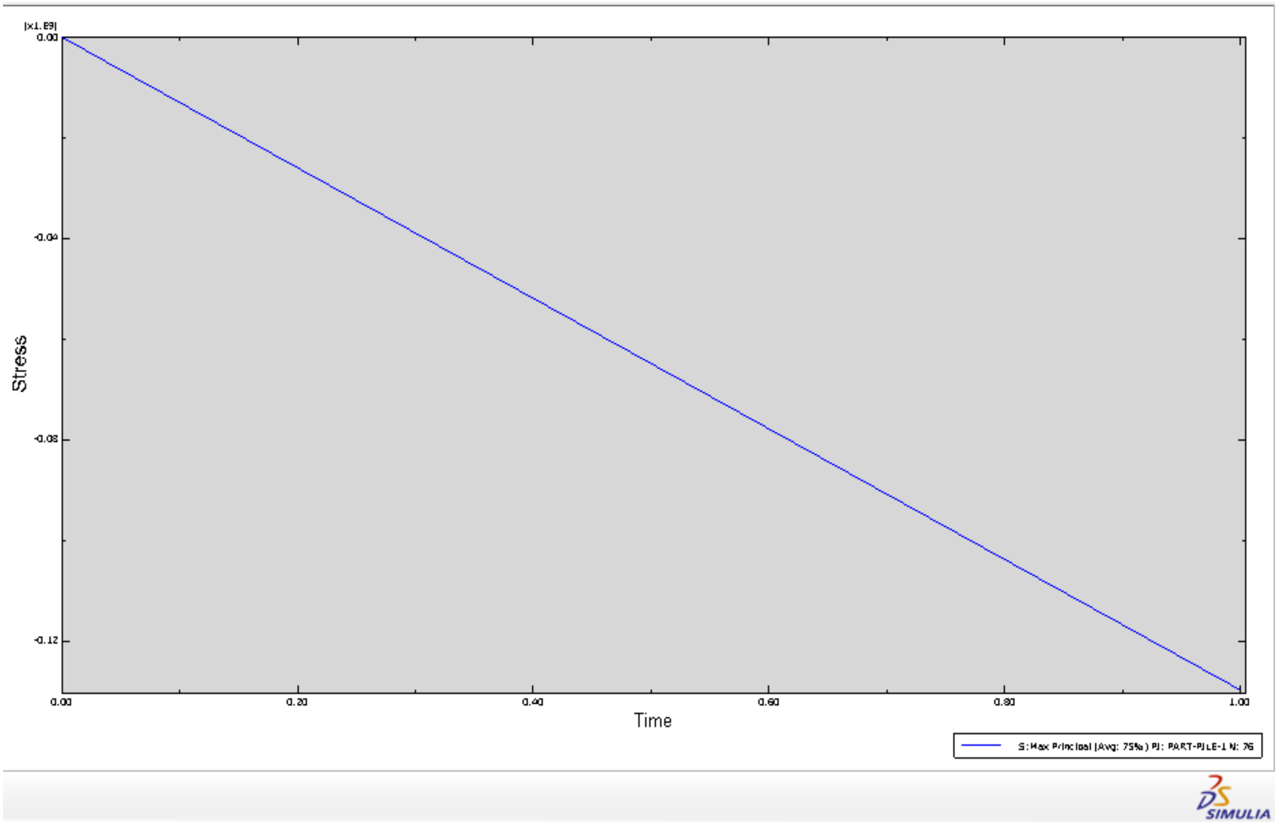


**Figure 35: Stress plot (at pile head) for Pile 4(corrugation thickness =0.03m)**

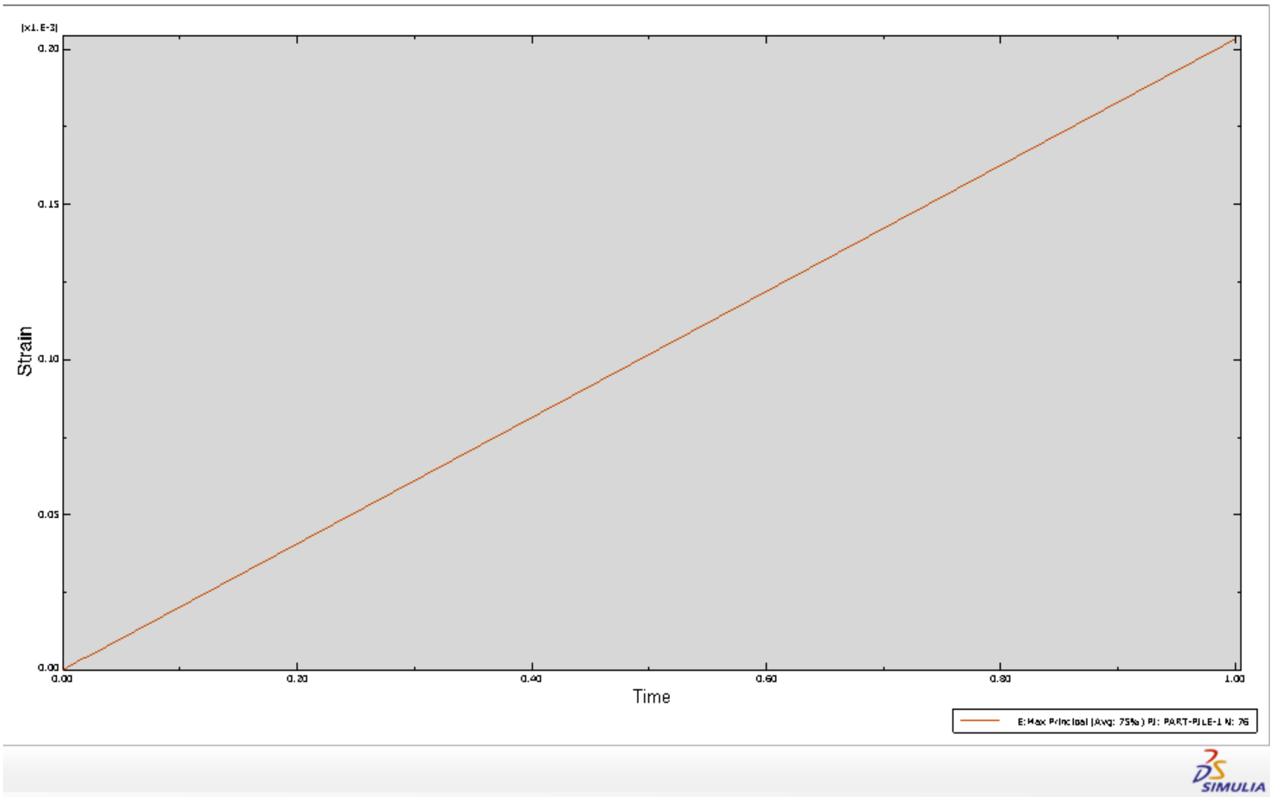


**Figure 36: Strain plot (at pile head) for Pile 4(corrugation thickness =0.03m)**

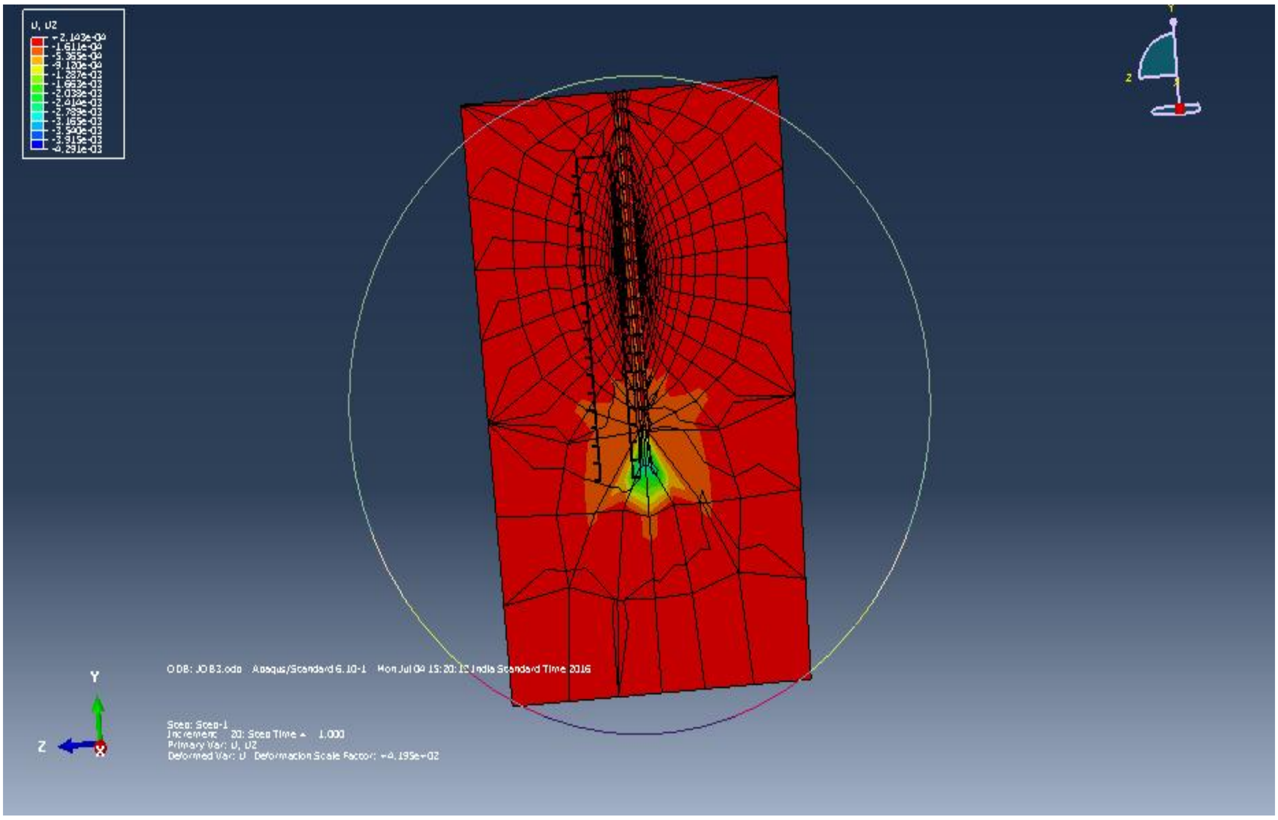


**Figure 37: Displacement Contours for Pile 5(corrugation thickness =0.04m)**

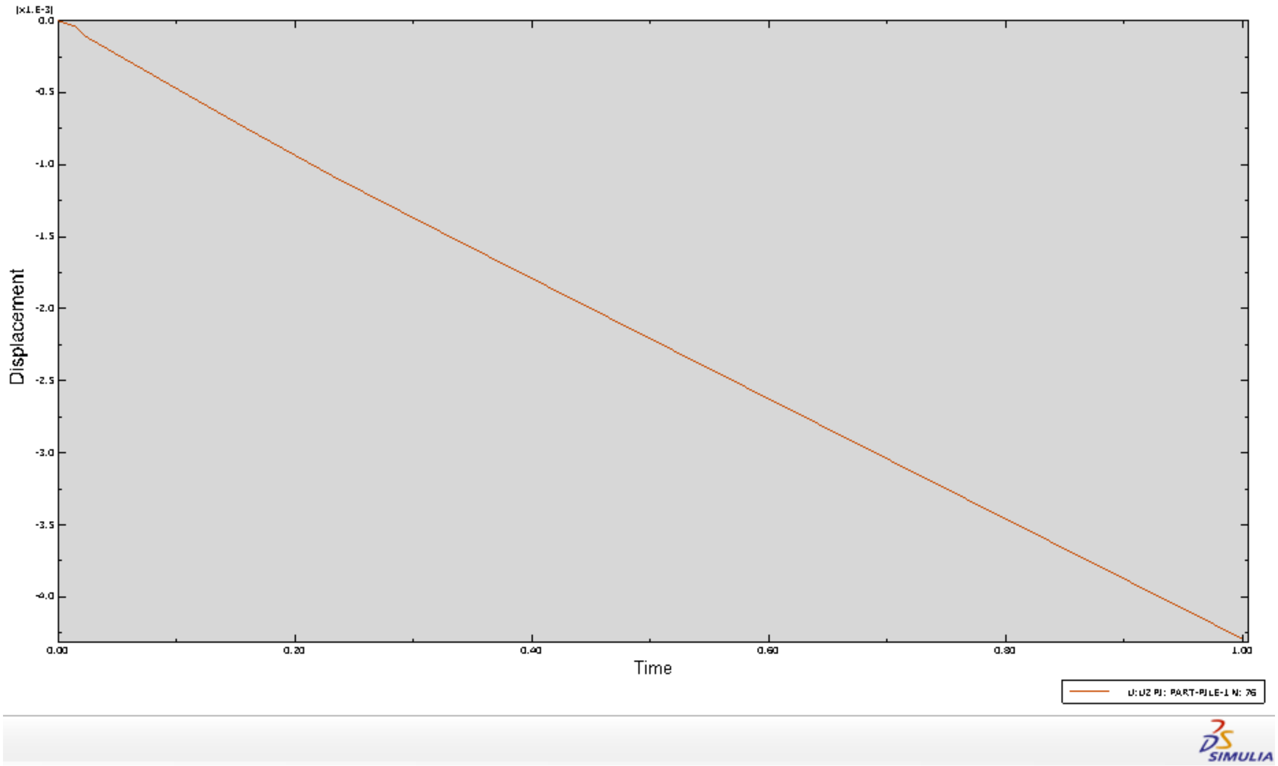


**Figure 38: Displacement plot (at pile head) for Pile 5(corrugation thickness =0.04m)**

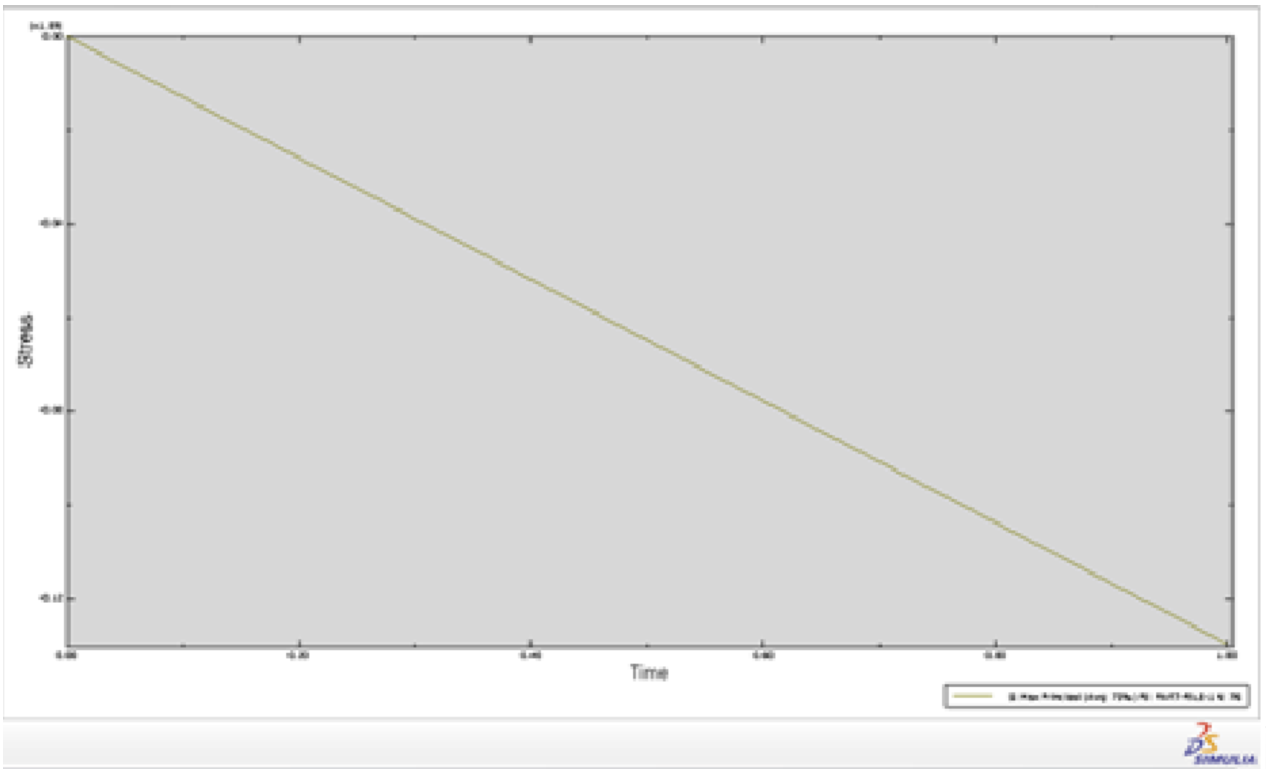


**Figure 39: Stress plot (at pile head) for Pile 5(corrugation thickness =0.04m)**

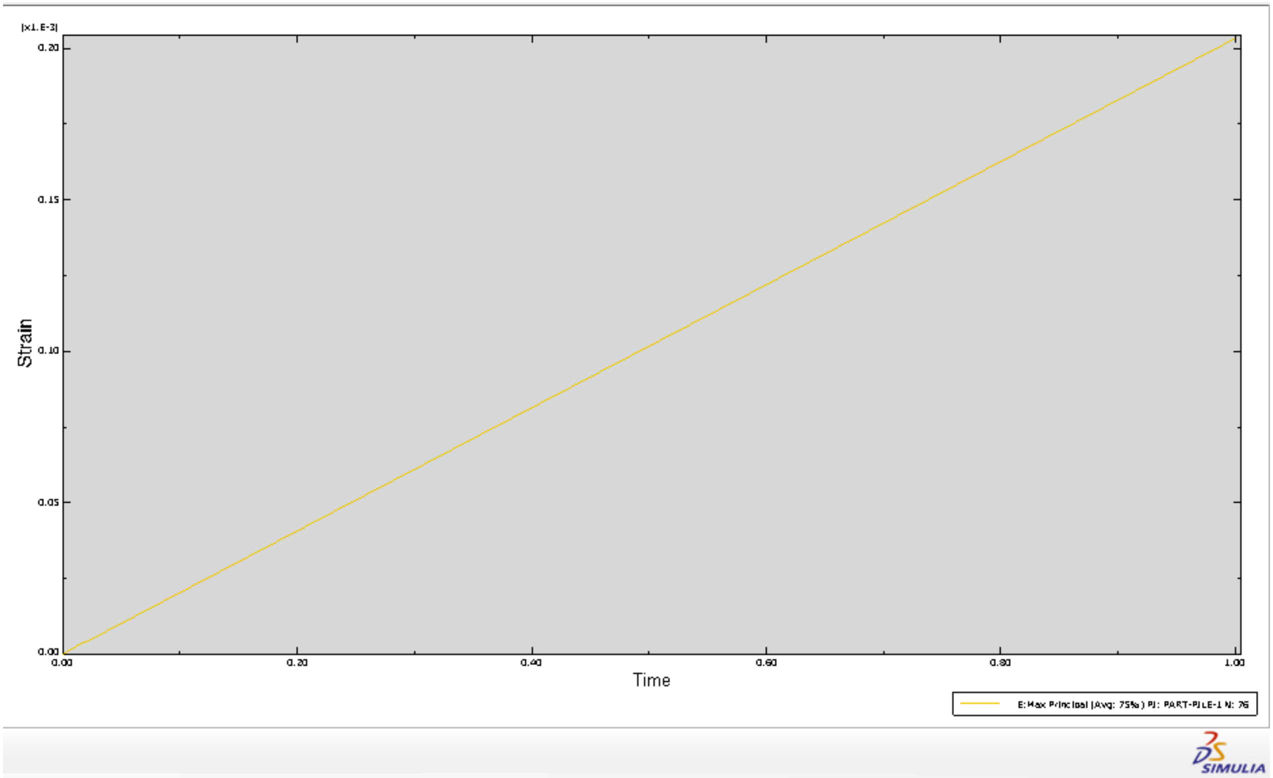


**Figure 40: Strain plot (at pile head) for Pile 5(corrugation thickness =0.04m)**

# CHAPTER-4 RESULTS AND CONCLUSIONS

**The load v/s displacement results for simple pile and corrugated piles are as follows:**

| S.NO. | LOAD(kN) | PILE HEAD DISPLACEMENT(mm) |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 100 | 17.4 |
| 3. | 200 | 30.2 |
| 4. | 300 | 52 |
| 5. | 400 | 73.1 |
| 6. | 500 | 96 |
| 7. | 600 | 125 |
| 8. | 700 | 173 |
| 9. | 800 | 220 |

Table 3: Load v/s Pile Head Displacement for Pile1( no corrugation)

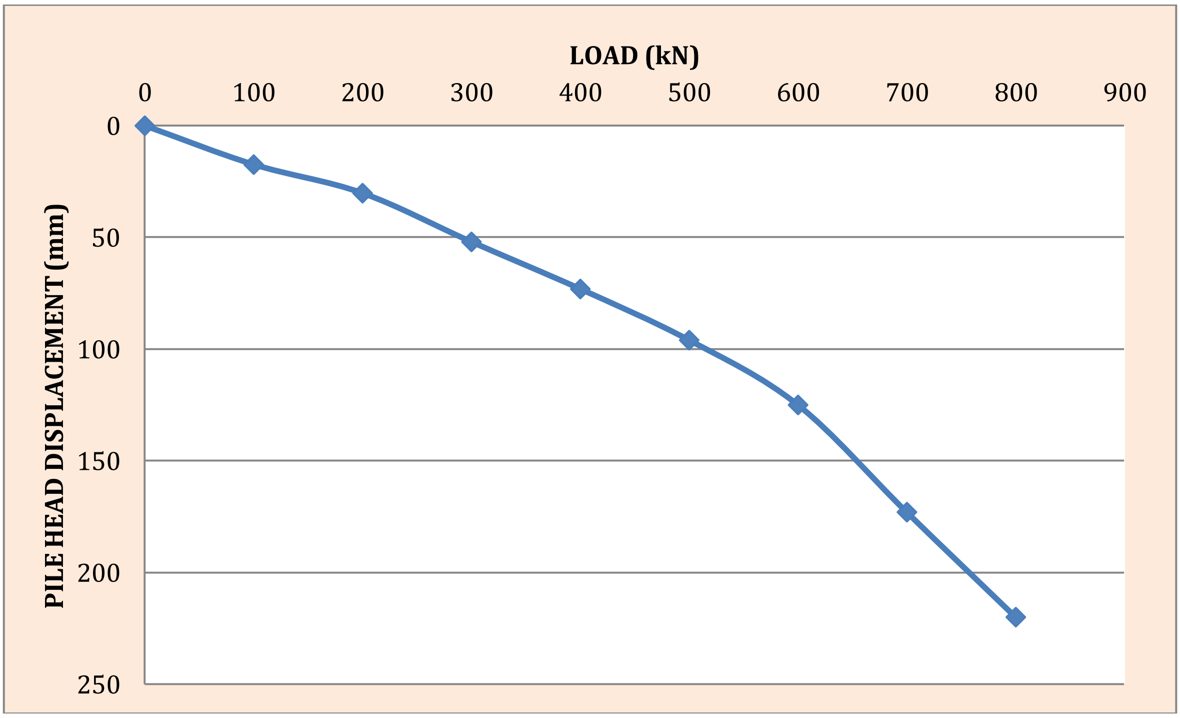


Figure 41: Load v/s displacement for Pile 1( no corrugation)

| S.NO. | LOAD(kN) | PILE HEAD DISPLACEMENT(mm) |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 100 | 2.5 |
| 3. | 200 | 5.1 |
| 4. | 300 | 7.6 |
| 5. | 400 | 10.19 |
| 6. | 500 | 12.7 |
| 7. | 600 | 15.29 |
| 8. | 700 | 17.85 |
| 9. | 800 | 20.4 |

Table 4: Load v/s Pile Head Displacement for Pile 2(corrugation thickness =0.01m)

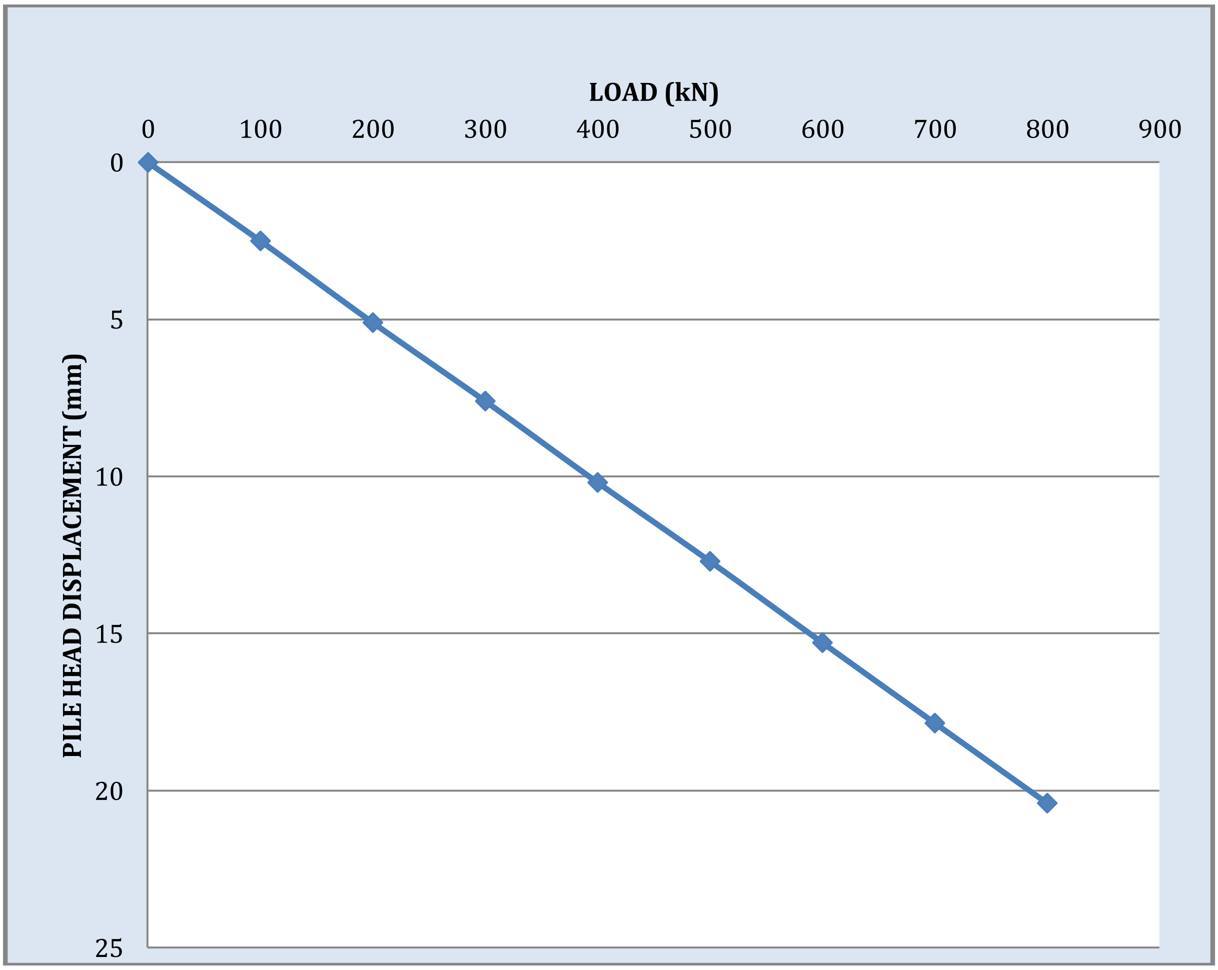


Figure 42 : Load v/s displacement for Pile 2 (corrugation thickness =0.01m)

| S.NO. | LOAD(kN) | PILE HEAD DISPLACEMENT(mm) |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 100 | 4.3 |
| 3. | 200 | 8.6 |
| 4. | 300 | 12.94 |
| 5. | 400 | 17.25 |
| 6. | 500 | 21.57 |
| 7. | 600 | 25.89 |
| 8. | 700 | 30.2 |
| 9. | 800 | 34.52 |

Table 5: Load v/s Pile Head Displacement for Pile 3(corrugation thickness =0.02m)

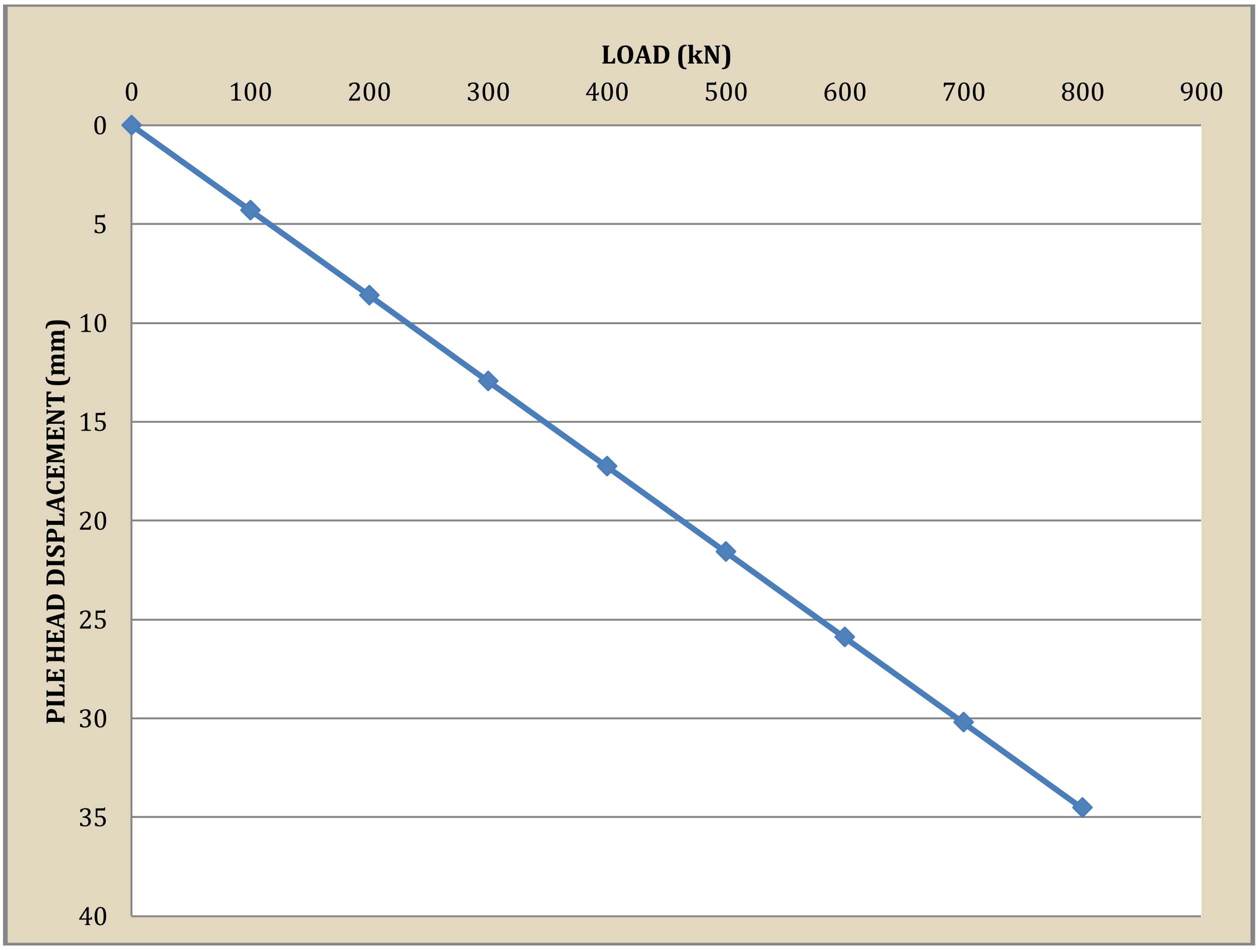


Figure 43: Load v/s displacement for Pile 3 (corrugation thickness =0.02m)

| S.NO. | LOAD(kN) | PILE HEAD DISPLACEMENT(mm) |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 100 | 6.8 |
| 3. | 200 | 13.58 |
| 4. | 300 | 20.33 |
| 5. | 400 | 27.06 |
| 6. | 500 | 33.76 |
| 7. | 600 | 40 |
| 8. | 700 | 46.3 |
| 9. | 800 | 52.5 |

Table 6 : Load v/s Pile Head Displacement for Pile 4( corrugation thickness =0.03m)


Figure 44: Load v/s displacement for Pile 4( corrugation thickness =0.03m)

| S.NO. | LOAD(kN) | PILE HEAD DISPLACEMENT(mm) |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 100 | 8.2 |
| 3. | 200 | 18 |
| 4. | 300 | 28.2 |
| 5. | 400 | 36 |
| 6. | 500 | 45.56 |
| 7. | 600 | 56.7 |
| 8. | 700 | 62 |
| 9. | 800 | 78 |

Table 7: Load v/s Pile Head Displacement for Pile 5(with corrugation thickness =0.04m)

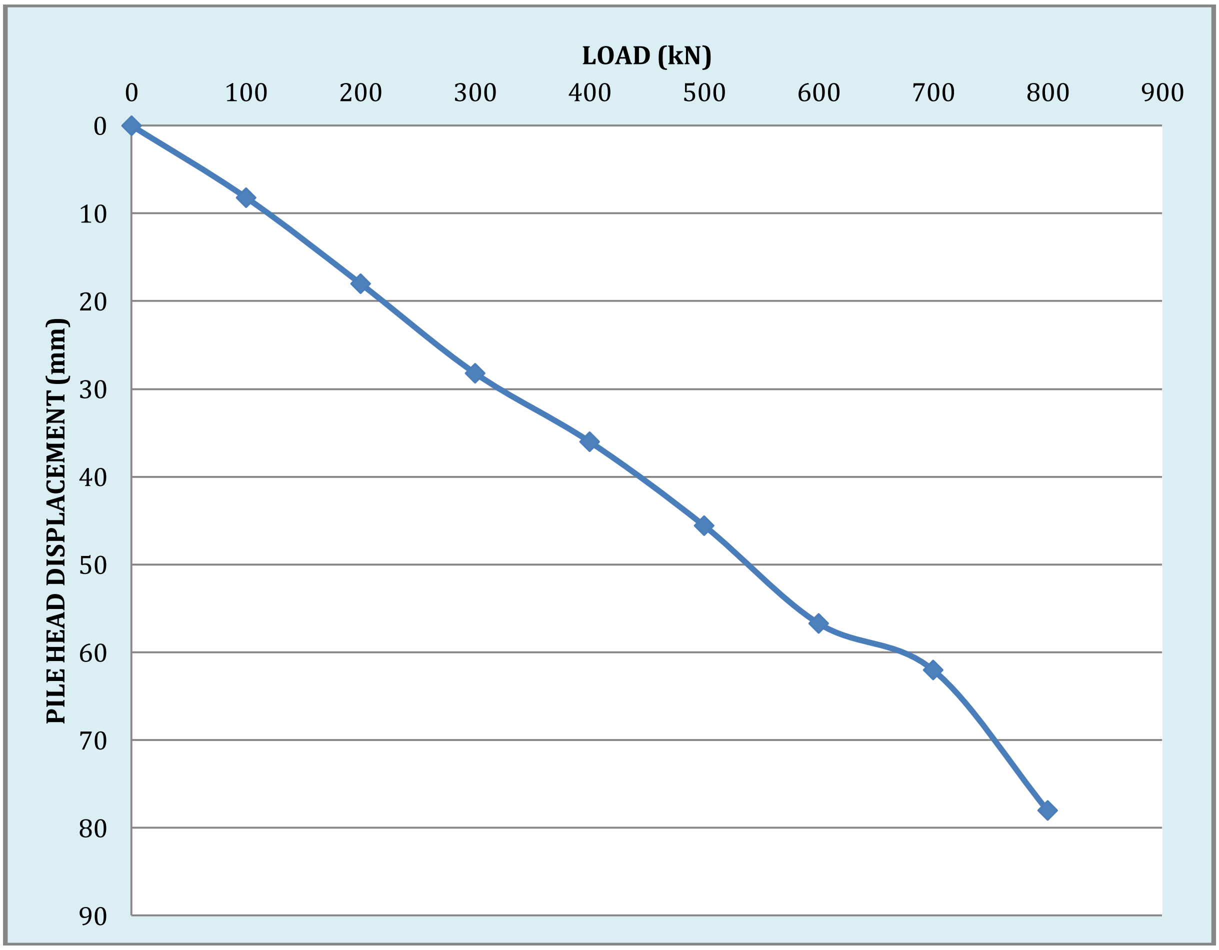


Figure 45: Load v/s displacement for Pile 5(with corrugation thickness =0.04m)

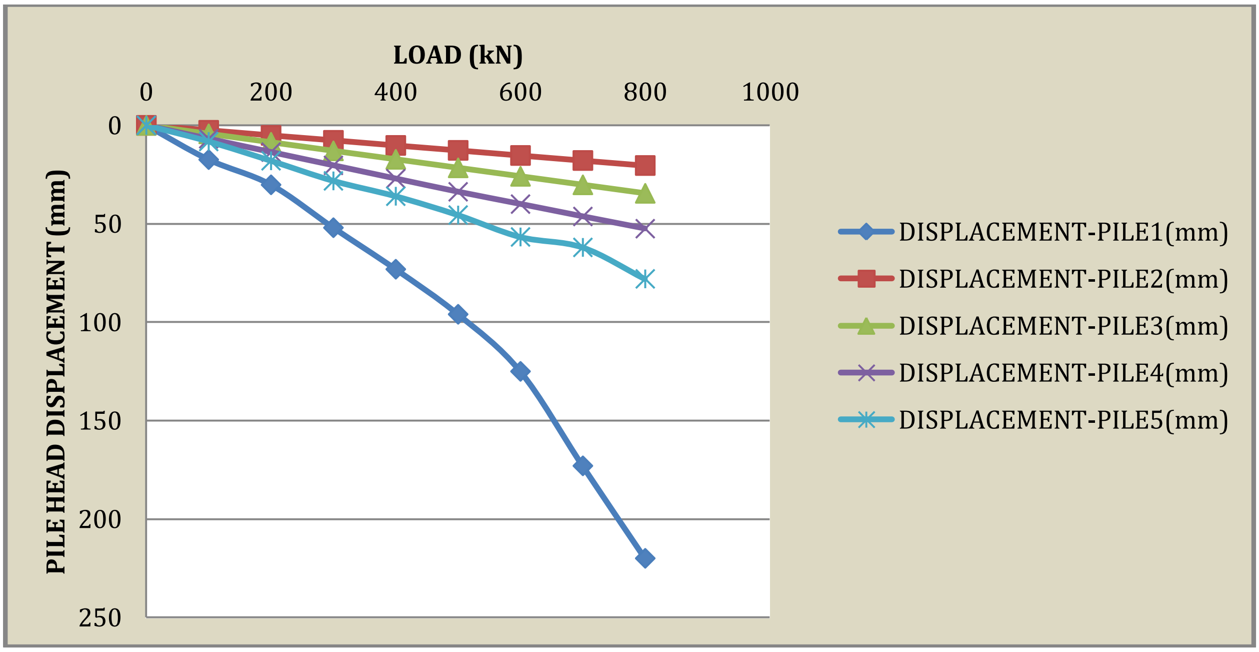


Figure 46: Load v/s displacement for all piles

The above graphs and tables depict the linear deformation response of corrugated piles in elastic soil media. On increasing the axial compressive loading from 100kN to 800kN, a linear curve of load-displacement is obtained. This trend is observed for all piles.

Further, on introduction of corrugation on piles, settlement values have found to be decreased as is evident from the graph.

On increasing the thickness of corrugation on piles, it was observed that slight increase in the settlement of piles takes place.

# CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The Load-deformation behaviour of single corrugated piles with variation in thickness is studied and maintained here by careful and deliberate effort. The numerical pile model development was decorously done in software package ABAQUS in keeping with the propriety of the conventionally accepted standards. The soil media as well as the pile material were assumed as elastic materials. Hence, for load-displacement a linear elastic curve is observed which is also simultaneously contemplated. Further, analysis was performed for corrugated piles with variation in corrugation thickness. The changes in load-deformation behaviour and settlements are starkly juxtaposed.

All the results have been compiled in the chapter-4 and an input file is attached with the report for verification.

ABAQUS is vigorous, high-powered, cogent and sophisticated software that provides a Finite Element analysis approach and computer-aided engineering for Engineers, students and others.

It has element library, material models for analysis of labyrinth networks and complex engineering problems.

In this project, static analysis of pile-soil system is enterprised using elastic models for pile and soil.

Future recommendations put forward are as follows:

- Elasto-plastic models Mohr-Coulomb and Drucker-Prager can also be explored for plastic analysis.
- For Elasto-plastic models, geostatic analysis needs to be conducted.
- Further, this analysis was for length of pile/diameter of pile = 30.For various other disparate and divergent ratios also this analysis can be performed.
- With plastic analysis, pile load capacity can also be resolved.
- Additionally, the analysis can also be carried out for pile-group.

Wrapping the ribbon round the edge of this project, I would like to convey that I have made sincere efforts of mentioning various aspects and divergent dimensions of my experience with this software. I hope this thesis may act as crucial help for others who would further join this ABAQUS chain.

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