PILE GROUP SUBJECTED TO COMBINED AXIAL AND LATERAL LOAD

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Submitted by

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CANDIDATES'S DECLARATION

I, **FAIZA MUSHTAQ**, M. Tech Geotechnical Engineering, Roll No. 2K20/GTE/08, hereby declare that the Dissertation titled "**Pile Group Subjected to Combined Axial and Lateral Loads**" that I submitted to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of Master of Technology is original and has not been copied from any source. In the past, this work has never been used to confer a degree, diploma associateship, fellowship or any other equivalent title or honour.

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CERTIFICATE

I hereby certify that the project Dissertation titled "**Pile Group Subjected to Combined Axial and Lateral Loads**" submitted by Faiza Mushtaq, roll no. 2K20/GTE/08 (Civil Engineering), Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of Master of Technology degree, is a record of the project work completed by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or in full for any degree or diploma at this University or elsewhere.

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Date: **SUPERVISOR**

Abstract

Pile groups have been used as a foundation for bridges, transmission towers, offshore structures, and other complex structures. These foundations experience extensive axial and lateral loading, and as a result, they undergo vertical and lateral displacements. Moreover, in the current practice, pile groups have been independently analyzed first for the vertical load to determine their loading capacity and settlement while the lateral load capacity has been normally associated with flexural behavior. The behavior of pile groups subjected to combined loading has been more complex, and its solutions have been largely elusive. Therefore, a novel numerical scheme has been presented to capture the nonlinear pile−soil interaction for (2, 2) pile groups under the application of combined axial and lateral loads. Based upon the numerical scheme, the three-dimensional finite element analysis has been performed on a (2, 2) pile group subjected to combined axial and lateral loads in a soil medium using a computational program. The load-displacement relationship of the (2, 2) pile group has been compared with the numerical results reported in the literature which in turn depend upon the dilation angle and plastic strain of the soil medium.

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Table of Contents

List of Tables

List of Figures

Abbreviations

The following symbols have been used in the thesis:

A/A_{max} = normalized axial load, the ratio of instantaneous axial load, A to the maximum axial load considered, Amax = 600kN

H/H_{max} = = normalized lateral load, the ratio of instantaneous lateral load, H to the maximum axial load considered, H_{max} = 300kN

D_p = diameter of pile (m)

(E_p) = Young's modulus of pile (MPa)

(E_s) = Modulus of elasticity of dense sand (MPa)

(μ_p) = poisson's ratio of pile

(μ_s) = poisson's ratio of soil

$Ø_d$ = dilation angle of soil (degrees)

$Ø_s$ = friction angle of the soil (degrees)

(γ_s) = unit weight of soil (kN/m^3)

(γ_p) = unit weight of pile (kN/m^3)

δ/δ_{max} = normalized pile head displacement, ratio of the instantaneous resultant displacement, δ to the maximum resultant displacement obtained δ_{max} = 68mm

y = deflection of the pile along depth (mm)

S/S_{max} = normalized vertical settlement, ratio of the instantaneous settlement, S to the maximum settlement obtained S_{max} = 31mm

Chapter 1 Introduction

1.1 General Introduction

Pile foundation is a part of substructure which transmits the load of a superstructure to a deep layer of strong bearing strata in the soil. Pile group consists of a series of piles, held by a pile cap at the top which behaves as a single unit contributing to its additional strength as compared to an individual pile. Pile groups might experience excessive settlements when used as a foundation for complex structures on unstable soils with a shallow base. Pile foundation on the whole can carry vertical or lateral loads and sometimes exposed to a combination of vertical and lateral loads. Vertical piles withstand vertical compression loads imposed by massive constructions like high-rise skyscrapers but in case of bridges, off shore structures and other type of complex structures piles are often subjected to lateral loads due to a variety of phenomena such as earthquakes, wind, and waves. Numerous studies on pile foundations bearing vertical or lateral loads solely have been done due to the intricacy of the loads imparted to piles separately or in combination, but solutions for pile groups subjected to combined axial and lateral stresses remain elusive.

(IS 2911-Part I/sec 1 to 4 2010) has given the methods to solve the pile foundation carrying vertical loads and lateral loads individually. The load bearing capability of piles is generally determined by the soil properties in which they are laid. Axial loading on the pile is typically transmitted to the soil through skin friction along the length of the shaft and an end bearing at the tip, whereas horizontal loading on the vertical pile is primarily transferred to the subsoil through horizontal subgrade reaction in the upper part of the pile shaft. As the piles are subjected to horizontal stresses, the soil mass next to the pile contributes to the pile's lateral support.

But this method remains valid presuming that the magnitude of lateral load is only up to 5% of the vertical load. The soil–pile interaction effect owing to combined vertical (axial) and lateral load can become crucial in case the magnitude of lateral load increases beyond the specified limit. In a broader sense we can say that there is no rational method available which can compute the lateral pile response under combined axial and lateral loads.

1.2 Vertical Load Capacity of Pile:

According to (IS 2911-Part I/sec 1 to 4 2010) ultimate load bearing capacity of a pile depends upon the properties of the soil surrounding the pile. Axial loads from the superstructure are transported to the soil with help of skin friction along the length of the shaft and end bearing resistance at the tip of the pile. While the horizontal load coming on a vertical pile is usually conveyed by the horizontal subgrade reaction on the top of the shaft. The load carrying capability of a pile is determined by using static analysis. The accuracy of the static analysis depend upon the soil properties. The ultimate load bearing capacity (Qs) of piles in kN in sandy soils is given by the following formula:

$$Q_u = Q_p + Q_s$$

$Q_u =$ Ultimate load at failure

Q_p = Point resistance of the pile at the end

Q_s = Shaft resistance of the pile along the length

$$Q_p = q_p \times A_p$$

And $Q_s = q_f \times A_s$

Where,

$$q_f = \sum_{i=1}^{n} ki\ P_{Di} \tan \delta_i$$

$$q_p = A_p\,(0.5\ \gamma D\gamma\ N\gamma + P_D\ N_q)$$

Therefore:

$$Q_u = A_p\,(0.5\ \gamma D\gamma\ N\gamma + P_D\ N_q) + \sum_{i=1}^{n} ki\ P_{Di} \tan \delta_i\ A_s$$

A_p = Cross sectional area of the pile tip (m^2)

D = Diameter of pile shaft in m

γ = Effective unit weight of the soil at pile tip in kN/m^2

$N\gamma$ and N_q = Depending on the internal friction angle Ø at the pile tip, bearing capacity factors are calculated.

P_D = Effective overburden pressure at the pile tip in kN/m^2

$\sum_{i=1}^{n}$ = Summation for pile-installed in layers 1–n that contribute to positive skin friction.

K_i = Coefficient of earth pressure applicable for ith layer

P_{Di} = Effective overburden pressure in kN/m2 for the ith layer

δ_i = Angle of wall friction between pile and soil for the ith layer

A_{si} = Surface area of pile shaft in the ith layer in m^2.

The piles which derive their load capacity primarily from friction must be spaced sufficiently apart so that the area of soils from which the piles derive their support do not overlap to the point where the overall bearing capacity is harmed and the piles' strength is reduced. Generally the spacing in case of friction piles shall not be less than 3 times the diameter of the pile shaft. However, in the case of piles built on hard stratum and whose capacity is mostly derived from end-bearing, the minimum spacing must be 2.5 times the diameter of the shaft's cross section. The pile’s group capacity may be equal to or less than the load-carrying capacity of an individual pile multiplied by the number of piles in the group. The former applies for both friction and end-bearing piles, whether cast or driven.

1.3 Lateral Load Capacity of Pile:

Wind, water currents, ground pressure, the action of moving cars or ships, earthquakes, and other factors can all create lateral force on a pile. The lateral load bearing capability of a single pile is often determined by the horizontal subgrade modulus of the surrounding soil. The load carrying capacity of a pile in lateral direction also depends on the structural strength of the pile shaft against bending. During the lateral analysis of a pile, effect of vertical load is also taken into consideration in order to determine the structural capacity of the pile shaft. But the knowledge of soil subgrade is very limited so it requires a much analytical approach. The lateral piles have two kinds of head condition;

1. Fixed head condition
2. Free head condition

A group of three or more piles having a rigid pile cap is generally kept fixed. Single piles are mostly free headed piles. According to IS 2911 (Part 1/Sec 4): 2010, for granular soils and normally consolidated clays, the ultimate lateral resistance which have varying soil modulus is given by:

$$\frac{p}{y} = \eta_h z$$

Where:

p = Soil lateral response per unit length at a depth z below ground level

y = Lateral deflection of the pile

η_h = Horizontal subgrade modulus reaction in MN/m^3

As the load rises up to its final value, the load bearing capability of a vertical pile subjected to lateral load produces deflection of the pile. This is a complicated phenomenon because it includes a semi-rigid structural element interacting with soil that partially deforms elastically and plastically. The failure of the piles depend upon the length and also on the head condition of the pile. The failure mechanism of infinitely long and short rigid pile is different and this depends on the stiffness factor.

Stiffness factor T in m = $\sqrt[5]{\frac{EI}{\eta_h}}$

Where:

E = Young's modulus of pile material, in MN/m^2

I = Moment of inertia of the pile cross-section in m^4

η_h = Horizontal subgrade modulus reaction in MN/m^3

For long (elastic) piles L $\geq$ 4T

For short (rigid) piles L $\leq$ 2T

The deflection of the pile head, y shall be computed using the following equations:

Deflection for free headed pile:

$$\mathrm{y} = \frac{H(e+\mathrm{zf})^3}{3EI} \times 10^3$$

Deflection for fixed headed pile:

$$\mathrm{y} = \frac{H(e+\mathrm{zf})^3}{12EI} \times 10^3$$

Where:

H = Lateral load, in kN

y = Pile head deflection, in mm

E = Modulus of elasticity of pile material, in kN/m^2

I = Moment of inertia of the pile cross-section, in m^4

z_f = Depth to point of fixity, in m and

e = cantilever length above ground/bed to the point of load application, in m.

1.4 Dilatancy of the Soil

Dilatancy is the characteristic of the soil which is defined as the change in volume of the soil due to shear deformation. Dense soils tend to dilate when exposed to loading in which the particles tend to move apart from each other for effective shear deformation which results to the change in volume of the soil. Dilation angle is the ratio of change in volumetric strain to the change in shear strain. The shearing behavior of the soil depends on its density. In case of dense soils, the particles are packed closely together. When pressure is applied to this soil the particles move apart from each other in order to shear effectively which cause the change in volume and in case of dense soil volume increases and this increase in volume in soil mechanics is called dilation. While the soil which is initially loose will not require much energy for shearing to take place. Instead of moving apart the particles will come closer to each other causing the volume to decrease and this phenomenon is called compression. Fig 1.shows the shear stress vs shear strain and Fig 2.shows volumetric strain and shear strain for dense and loose soils.

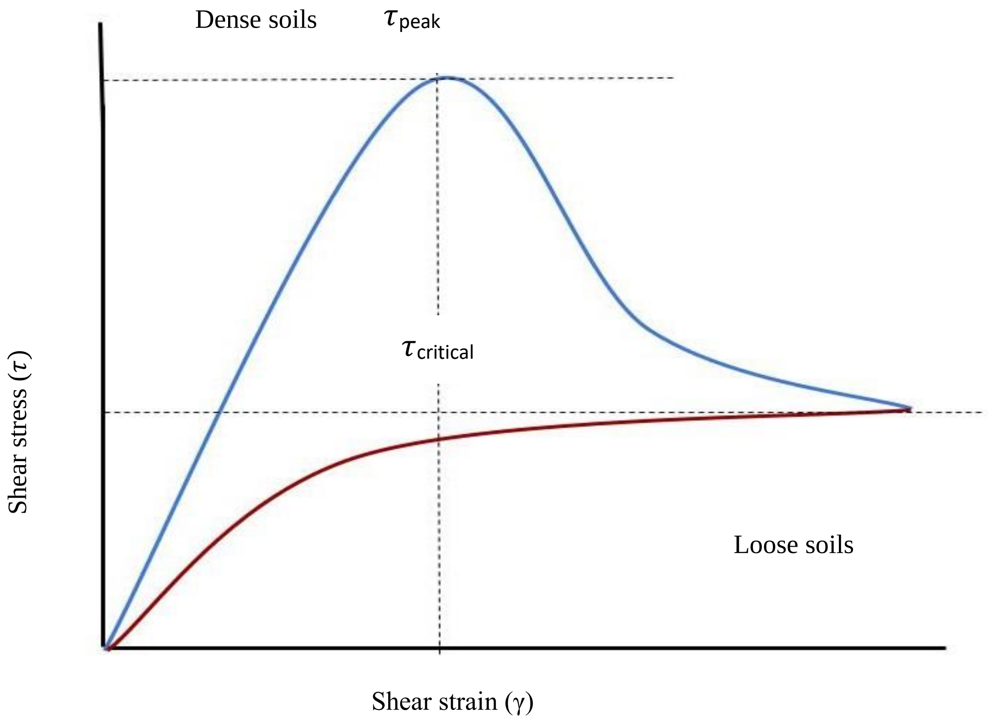


Figure 1. Shear stress vs shear strain for dense and loose soils

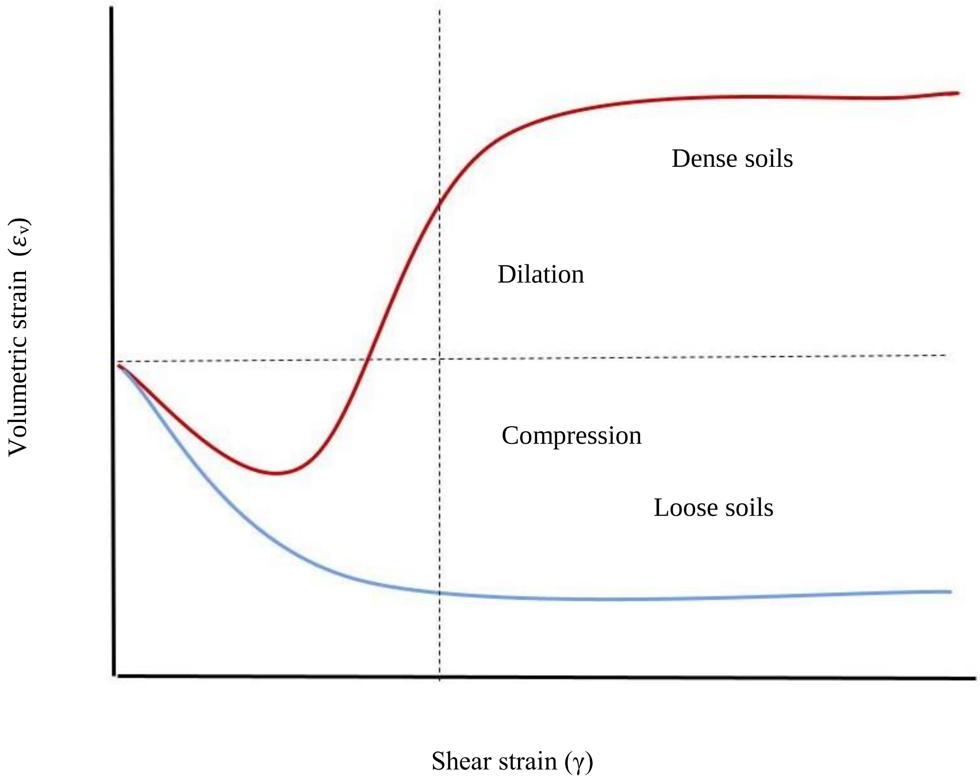


Figure 2. Shear strain vs volumetric strain for loose and dense soils.

When we plot the volumetric strain vs shear strain graph for dense sands, the slope of the graph gives the dilation angle. The peak strength for the dense soil in the upper plot corresponds to the point at which the rate of dilation is at its maximum in the lower plot. With further strain in the soil the dilation effect will reduce and the soil reaches to its critical shear strength. Loose soils do not have peak strengths, they reach the same point of critical shear strengths. Once the critical shear strength is achieved there is no further volume change. In Fig. 3 volumetric strain vs shear strain is plotted for dense soils. The slope of the graph gives the dilation angle. It can be seen in the graph that in the initial stage of deformation, the volumetric strain has decreased with the increase in shear strain. But as the stress reaches its maximum value the volumetric stress starts to increase which implies that after some shear the soil has an increased volume until it reaches to its critical point. The maximum value of slope of the volumetric strain vs shear strain corresponds to the maximum dilation angle after which there is no change in volume.

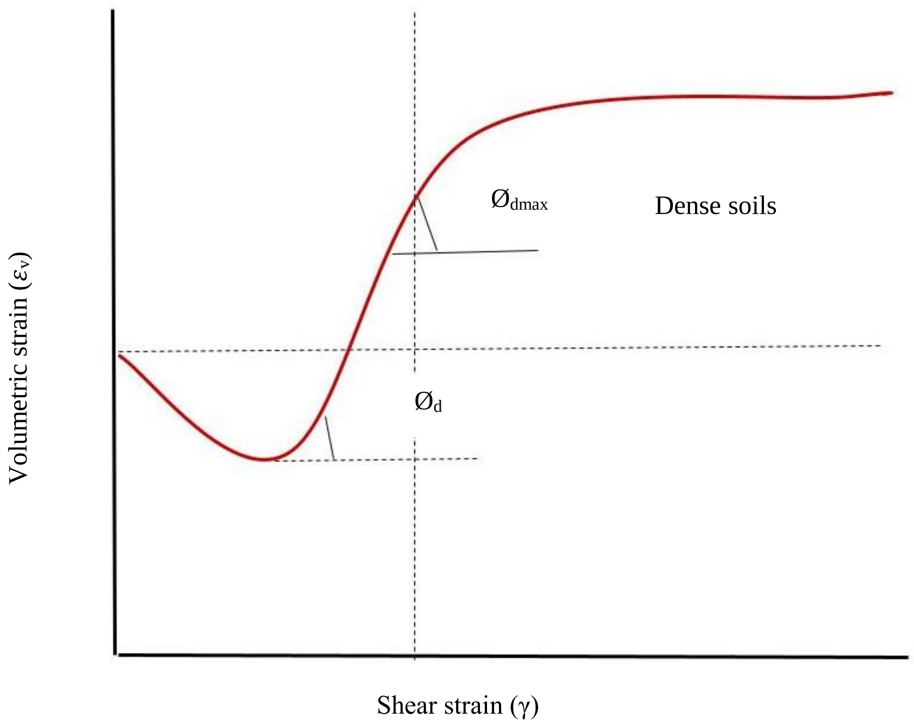


Figure 3. Shear strain vs volumetric strain for dense soil showing dilation angle

1.5 Objectives of the Study

i. The main objective of the study is to present a novel numerical scheme to capture the nonlinear pile−soil interaction for (2 × 2) pile groups under the application of combined axial and lateral loads by using computational program.

ii. The load-displacement relationship of the (2 × 2) pile group has been computed which depends upon the dilation angle.

iii. The load-displacement relationship of the (2 × 2) pile group has been computed which depend on the modulus of elasticity of soil continuum.

iv. The load-displacement relationship of the (2 × 2) pile group has been compared with the numerical results which in turn depend upon the dilation angle and plastic strain of the soil medium.

v. The deflection of the pile along the depth is determined for both front and back piles and also for lateral load increments.

1.6 Organisation of the Chapters

Chapter 1 consists for the introduction about the pile groups.

Chapter 2 consists of the literature review of the present work and how it evolved.

Chapter 3 discusses the material and methods which involves type of material used, properties of materials, method to conduct the numerical analysis, procedure to follow to do the numerical modelling.

Chapter 4 consists of results and discussions. It discusses all the results obtained and the graphs plotted according to the results.

Chapter 5 consists of the necessary conclusions and recommendations for future scope.

Chapter 2 Literature Review

2.1 Introduction

Several researchers Anagnostopoulus and Georgiadis (1993), Holloway et al., (1983), Chow (1987) etc., have analysed the piles of different materials in different soils experimentally and numerically. Most of the studies were restricted to the idea of analysing the pile groups independently for the vertical load at first to determine their loading capacity and settlement while the lateral load capacity has been normally associated with flexural behaviour. The study on piles exposed to combined vertical and lateral loads simultaneously is very limited.

2.2 Review of Literature

A detailed review of literature is as follows;

- Karthigeyan et al., (2007) has determined the influence of vertical loads on the lateral response of piles under the combined action of vertical and lateral loads. Numerical investigation has been performed by using 3D finite element program, GEOFEM3D. The analysis has been carried out for both sandy and clayey soil. It was observed that the presence of vertical loads significantly improved the load carrying capacity of the pile in sand while in case of clay the vertical loads tend to decrease the lateral capacity of the piles. Bending moment increases by 30-35% in sandy soils and 15% in case of clayey soil. It was observed that the piles lateral response under combined loading is much more dependent on the L/B ratio of the piles. With the increase in L/B ratio the influence of vertical loads on the lateral capacity decreases.

- Mehra and Trivedi (2021) investigated pile groups subjected to combined axial and torsional loads in flow controlled geo-materials using Abaqus program. A comparison of load displacement relationships was drawn between the large diameter pile and pile groups (1, 2 and 2, 2) with the experimental pile load test and it was observed that displacement increases with the torsional loads and the twist also increases with increase in axial loads. They suggested that while designing a pile group subjected to combined axial and torsional loads, the ultimate load carrying capacity of the pile is not the only criterion but displacement and twist parameters should also be considered. The plastic strain and dilation angles of the geo-material were used to analyse the displacement and twist parameters.

- Chow (1987) presented axial and lateral response analysis of pile groups based on elastic theory taking into consideration the effect of non-homogeneity of the soil and the non-linearity of the soil. The analysis has been carried out in two sections, the first one dealing with pile group subjected to external applied loads and the pile soil interaction forces while in the second part a layered soil medium is considered in which the interaction forces between pile and soil are studied at imaginary positions located on the piles. The load deformation relationship is obtained by considering the equilibrium of pile soil interaction forces and the compatibility of pile soil displacements. The solution obtained are compared with results obtained from the field tests and they show a good agreement except in case of closely spaced laterally loaded pile group.

- Leung and chow (1987) compared the pile groups subjected to lateral loads on the basis of linear and non-linear load deformation behaviour. In the study the response of individual piles was obtained by using p-y curves but on the other hand the response of pile group interaction was obtained by using Mindlin's solution. The author has tried to predict an approach for the lateral load- deflection behaviour of pile groups. A comparison has been made between method used with the commonly used interaction factor approach for the pile groups in a homogeneous, isotropic elastic half space and the results were showing a good agreement. The results obtained were also compared with the field test results obtained from the field test of laterally loaded piles. Bending moment was also obtained along the depth of the pile. They found out that the shear, moment, deflection of the pile head can be easily obtained accurately but in case of closely spaced 10 pile group this method tends to over predict the pile head shear at high loads.

- Georgiadis (1987) in his paper interaction between torsional and axial pile responses determined the torsional pile response by the effect of axial load and the axial pile response by the effect of torque. The analysis was performed in a computer based program which works on the principle of transfer matrix method. The analysis was conducted on steel pipe pile embedded in clay with a diameter of 1.5m and a thickness of 37mm. The combined loading was applied on the pile and it was found out that both the ultimate pile capacity and the pile rotation and axial displacement were greatly affected. When the torque is applied on the pile head, the axial displacement is increased which eventually decreases the ultimate load carrying capacity of the pile. The results demonstrate that piles loaded simultaneously with torque and axial force show lesser values of torsional and axial load capacities and on the other hand they show very high rotations and axial displacements when compared to the piles subjected to individual loads.

- Anagnostopoulus and Georgiadis (1993) conducted experimental investigation to determine any possible effects of lateral loading on the axial pile displacement and the influence of axial load on lateral pile response. Six model tests were conducted on an Aluminium closed end piles and the displacement of the pile head (horizontal, vertical and rotation) was obtained by three displacement transducers. Strain gauges were added along the length of the pile so that bending moment and axial forces can be determined. It was found out that axial pile displacement increased significantly with the addition of lateral loading while we can also see that the lateral loads have negligible effect on the axial pile displacement at lower level and low values of vertical loading. The axial pile stresses were reduced at the ground surface due to the application of lateral loads.

- Holloway et al., (1983) conducted an experimental investigation on an eight-pile group embedded in sand and was laterally loaded up to failure point under constant axial loads. Axial thrust, moment, shear distribution along the length of the pile was measured by strain gauge. Slope of moment distribution curves along the length was obtained and it was observed that at failure load a significant major portion of the shear load is transferred to the front piles. The results depicted that failure mechanism involved continuous punching of front piles into the soil adjacent to the pile under the action of constant loading but the piles showed a negligible structural distress.

- Chick et al., (2009) conducted a research on a single pile under pure lateral loading and combined loading (lateral and vertical) in cohesion less soil having water table at different elevations. Finite element analysis was performed by using PLAXIS 3D FOUNDATION version 1.1. The pile material is based on linear elastic model and the surrounding soil is stimulated using Mohr- Coulomb model. Lateral soil pressure is obtained along the depth and width of the pile. When only pure lateral load was applied a small amount of lateral pressure response along the width of pile was obtained at different water levels. It was fund out the water table elevation influenced the lateral pile response by significantly increasing the load carrying capacity of the pile in dry soil while decreasing the capacity of the soil when it is fully saturated. Initially the lateral displacement was small but when the vertical load increment reached 12 and 16 the lateral displacement was quite large which signifies that lateral response is sensitive under large vertical loading.

- Mohti and Khodiar (2013) presented a numerical study of piles embedded in sand subjected to combined axial and lateral loads in order to determine the pile soil interaction. A comparison has been drawn between the results obtained from three different software namely L-Pile, Abaqus/Cae, Sap 2000. L-Pile is a 2D finite difference software while the Abaqus/ Cae and Sap 2000 works on finite element method. In the analysis the soil used is soft, medium and dense sand. Bending moment and displacement is obtained by the software and the results obtained from all three software are compared and the results were found to be in good agreement. The finite element analysis was used to determine pile soil interaction. A parametric study was conducted for modulus of elasticity and the number of soil springs on the bending moment and lateral displacement due to the application of combined axial and lateral loading.

- Stalin et al., (2021) investigated the behaviour of piles subjected to lateral and vertical loads for the varying layers of soil. Experimental setup consisting of a model tank of size 500 x 500mm and height 700mm which is filled with sand, clay and clay-sand medium to conduct pile load test in order to determine the behaviour of single and group pile under vertical and lateral loads. Two dial gauges were used to determine lateral deflection and vertical measurements having a least count of 0.002mm. The load settlement curve was obtained by the application of load on the single pile and pile group and the load was applied up to the failure point. It was observed that the vertical load capacity of pile increase with increase in number of piles and L/D ratio particularly for sands rather than clayey soil while it was observed that lateral load capacity of soil increased with L/D ratio but irrespective of the type of soil for a known deflection. Also lateral capacity was decreased with increase in number of piles.

- Zadeh and Kalentari (2011) conducted two case studies , the first case comprised of a single pile subjected to pure lateral loads embedded in sand, clay, and a layered soil system and the results obtained were pressure- displacement (p-y) curves, shear force, bending moment, lateral pressure and the displacement of pile head along the depth of pile. The second case comprised of a single pile subjected to combined effect of vertical and lateral loads in order to compare the p-y curves and pile deflection. In the analysis the effect of slenderness ratio (L/B) on the lateral load capacity was also taken into account. It was found out that the application of combined loading on the lateral response significantly increased the lateral capacity in sand but in case of clay it decreased marginally. The maximum design bending moment of the single pile under combined loading was seen rising with increase in vertical loads for both soils.

- Satyam and Kumar (2010) presented a study on the lateral load resistance of pile foundations. Analysis was carried out on a single pile and a group of piles subjected to lateral loading using nonlinear finite element method of analysis and the load carrying capacity and load deformation characteristics of the pies were obtained. Mohr Coulomb model was used to determine the bearing capacity and failure loads. It was found out that the lateral loading capacity along the depth of pile is affected with the increase in lateral loading. Also the water table can considerably affect the pile response such that in case of dry soil the pile was showing high lateral resistance compared to fully saturated soil where the lateral resistance of the pile was found to be low.

- Kahribt and Abbas (2018) conducted a series of investigation of the combined axial and lateral cycling loading on dense sandy soil to determine the lateral response of a single pile. The two way lateral cyclic loading was applied to the model piles with the help of mechanical loading system in addition to the vertical loads. The slenderness ratio has also been considered in the study of L/D = 25 and 40. Here the number of cycles foe each test was taken to be 100 so that it could represent the actual environment as seen in offshore structures. It was discovered that lateral pile head displacement reduced as vertical loading increased under the effect of combined vertical and cyclic lateral loads. In addition, as the cyclic load and number of cycles grew, so did the bending moment.

- Karthigeyan and Rajgopal (2009) conducted numerical investigation to determine the lateral capacity of a 2x2 pile group in sand under the action of combined axial and lateral loads. The pile was considered to be a linear elastic material. The analysis was done by using a three dimensional finite element program GEOFEM 3D. The main focus was put on the method of loading and centre to centre spacing of piles so that its effects could be determined. It was found out that lateral capacity of pile group has increased by the influence of combined loading and it greatly depends on sequence of loading and the c/c spacing of piles. As the c/c increases the lateral capacity decreases. Efficiency of the pile group also increased with combined loading.

- Rahman and Achmus (2006) presented a numerical modelling of vertical steel pipe piles in sand subjected to combined axial and lateral loads. The three dimensional numerical model was developed by using a finite element program Abaqus. Piles used were steel pipe pile with a length of 20m and a wall thickness of 2cm. Two different sections were taken with varying outer diameters of 2m and other of 3m. Results obtained were used to plat graph between vertical load and settlement, horizontal load ad horizontal displacement, vertical load and heave. It was found out that the horizontal pile stiffness remains unaffected by vertical compression loads but vertical pile stiffness and capacity is increased due to the application of horizontal loads. It was summarised that horizontal and vertical loads should only be employed to determine axial displacements.

- Rajagopal and Karthigeyan (2008) presented a finite element based numerical analysis showing the influence of combined loading on the lateral response of the pile. The analysis was carried out for two different soils – homogeneous clay and homogeneous sand. The analysis was conducted in a three dimensional finite element program GEOFEM3D. During the analysis the lateral load was kept constant and vertical load was increased (0.2-1) and it was observed that the lateral capacity of the pile increased significantly with increase in vertical loads particularly in case of sandy soils where the lateral capacity increased marginally to about 40% while in case of clayey soil it was restricted to 20%. It also states that lateral response depends on L/B ratio of the pile. With increase in L/B ratio lateral capacity of the piles subjected to combined loading reduced but it remained constant for L/B ratio of 25 in case of sands and 16 for clays.

- Patra and Pise (2001) investigated model pile groups of configuration 1 × 1, 2 × 1, 3 × 1, 2 × 2, and 3 × 2 experimentally for an embedded length to diameter ratio L/d = 12 and 38 with a varying spacing of 3 to 6 times diameter of pile and friction angle of 20° and 31° on dry Ennore sand of Chennai. The pile groups were exposed to lateral loads and the load-displacement response, ultimate resistance, and the group efficiency was recorded taking into consideration the variables such as shape, size, spacing between piles and friction angle. It was observed that the load carrying capacity of the pile group depends on length to diameter ratio, friction angle, geometry of the pile group, spacing between the piles and the density of the soil. Group efficiency of the pile increases with the pile spacing. Load-displacement curves are non-linear. Load carrying capacity increases with the pile spacing.

- Basack (2009) analysed the response of vertical pile group subjected to horizontal cyclic load in soft clayey soil. Laboratory model tests were carried out on a 2 × 2 pile group having a pile of hollow circular stainless steel bar of 20mm diameter and 600mm length. As there is no standard equipment for lateral cyclic loads therefore a loading device was designed and fabricated which consists of two devices, one for imparting static load and other for imparting cyclic lateral loads which were connected with a motor and gear system. The load deflection curve for the pile group in sands was observed to be hyperbolic in nature. It was observed that pile capacity deteriorated when subjected to lateral cyclic loading.

- Trivedi (2010) conducted a study on jointed rocks having granular fill. The experimental investigation of the prepared cylindrical cores of kota sand stone having diameter 38mm was conducted with varying gouge thickness. It was observed that increase in thickness results in considerable reduction of the strength of the jointed rock. The material characteristics and mean confining pressure was related to dilatancy in order to study the strength of the jointed rock. It was observed that dilatancy characteristic is involved in progressive failure of the rock.

2.3 Research Gaps

As per the literature review, it is clear that piles have been studied for bending moment, deflection, c/c spacing, soil pressure. But the characteristic property of the soil i.e dilatancy and modulus of elasticity has not gained much importance therefore, an attempt has been made to study the variation of displacement of pile group when subjected to different dilation angles and modulus of elasticity under the action of combined axial and lateral loads.

Chapter 3 Material and Methods

3.1 Material Properties

The soil used in the analysis is dense sand. The soil is assumed to be homogeneous, isotropic and elastic. Mohr-Coulomb criteria is used to model the soil. In the elastic analysis, it is assumed that the soil around the pile adheres to it. But the soil has a restricted capability to take tension and a notable deformation is likely to occur near the top of pile. This deformation and local yield of the soil is the main reason behind the non-linear behavior of the soil even when subjected to lower load levels. Each pile node has been assumed to be morphed and placed around the lumped mass of soil, which may change its position in space when combined loads are applied. The pile group along with pile cap is made of steel. All the piles of pile group are assumed as an elastic beam and the pile material is considered to be linear, homogeneous and isotropic. The piles are considered to be friction piles having the coefficient of friction = 0.3.

According to (IS 2911-Part I/sec 1 to 4 2010)

The spacing between the friction piles is 3d (3 × 0.4 = 1.2m) where d is the diameter of the pile.

The size of the piles cap according to (IS 2911-Part I/sec 1 to 4 2010):

Length = $(\propto\ +1)\ \emptyset + 0.3$

Where $\propto$ is the spacing factor of piles and here for friction piles according to IS CODE = 3

Therefore, length of the pile cap = (3+1) 0.4 + 0.3 = 1.9m

Therefore size of pile cap = 1.9 × 1.9 × 0.9m

The pile group is connected to the rigid pile cap to have a fixed head connection. A 200mm length is inserted in the pile cap and 11.5m is embedded in the soil.

The dimensions and properties of the materials used in analysis are specified in the following tables.

Table 1. Input parameters for the numerical analysis of dense sandy soil

S. No.	Soil Parameter	Dimensions	Units
1.	Length	20	m
2.	Width	20	m
3.	Depth	30	m
4.	Unit weight of soil (γ_s)	20	(kN/m^3)
5.	Modulus of elasticity (E_s)	50-80	(MPa)
6.	Poisson's ratio (μ_s)	0.3	-
7.	Dilation angle ($\text{Ø}_{d)}$	6-14°	-
8.	Angle of internal friction (Ø_s)	36°	-

Table 2. Input parameters for the numerical analysis of steel pile

S. No.	Pile Parameters	Dimensions	Units
1.	Diameter (D_p)	0.4	m
2.	Length	12	m
3.	Unit weight of steel (γ_p)	78	(kN/m^3)
4.	Modulus of elasticity (E_p)	210000	(MPa)
5.	Poisson's ratio (μ_p)	0.3	-

Table 3. Input Parameters for the numerical analysis of pile cap

S. No.	Pile Cap Parameters	Dimensions	Units
1.	Length	1.9	m
2.	Width	1.9	m
3.	Depth	0.9	m
4.	Spacing between pile	1.2	m
5.	Unit weight of steel (γ_p)	78	(kN/m^3)
6.	Modulus of elasticity (E_p)	210000	(MPa)
7.	Poisson's ratio (μ_p)	0.3	-

3.2 Numerical Model

3.2.1 Finite Element Analysis

Finite element method is an efficient numerical technique that uses computational program to provide approximate solution for complex engineering problems. It is utilized extensively in all major engineering sectors. Finite element analysis software may be used to solve a variety of solid mechanics issues including static, dynamic analysis. Finite element analysis is a computational technique used to determine approximate solutions for the boundary value problems. The process involves the representation of a physical domain with finite elements and this can be achieved by meshing and the resulting set is called finite element mesh. Finite element analysis consists of two processes:

1. Pre processing
2. Post processing

Pre-processing step involves creation of the model and input of data in the model such as geometric and material properties, loading etc. while the post processing step involves the analysis and evaluation of the model created in the former step so as to develop the required results in order to determine the stability and performance of the model. It helps in the generation of graphs, plot the deformed structural shape etc.

3.2.2 Methodology

The three dimensional numerical modelling has been carried out using Abaqus software. This software works on the principle of finite element analysis. It is used for both modelling and analysis of the elements and assemblies and then visualization of the result by the use of finite element method. It is widely known to provide linear and non-linear behavior of the models. A continuum is divided into a number of component sections using the finite element method. Each component consists of a number of nodes. All the nodes bears a certain degree of freedom that corresponds to a discrete values of unknowns in the problem that the program must solve. Finite element mesh is a composite made up of finite elements. In this study, an 8-noded brick element is employed to discretize the pile group and soil continuum. The analysis was carried out in the following steps:

1. Create the model: The model consists of three parts (a) soil continuum, (b) piles cap and

(c) piles shown in the Fig. 1, 2, and 3. The dimensions of the parts are kept as specified in material section. The soil model is created and the pile length 11.5m is extruded in it for a (2 × 2) pile group. Similarly in case of pile cap 0.2m is extruded so that the piles are fixed in the pile cap. All the three parts are kept as deformable sections. Further the offsets are created in all the three parts as required so that assembly and meshing can be carried out easily.

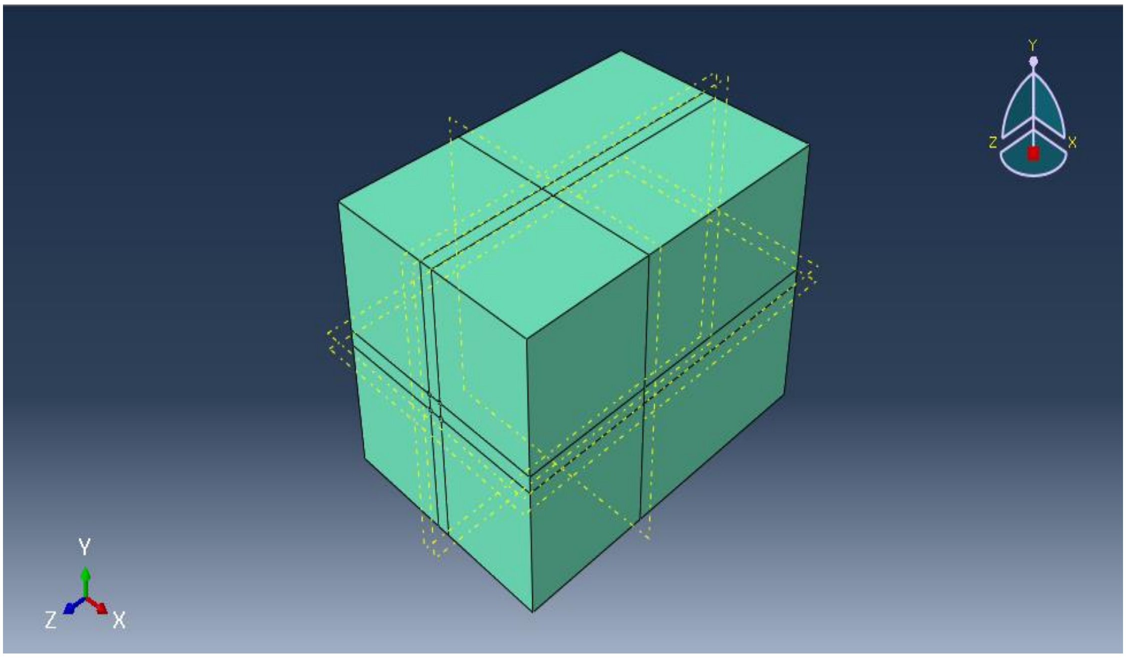


Figure 4. Model represents the soil continuum having dimensions 20 × 20 × 30m and offsets for pile extrusions at 11.5m

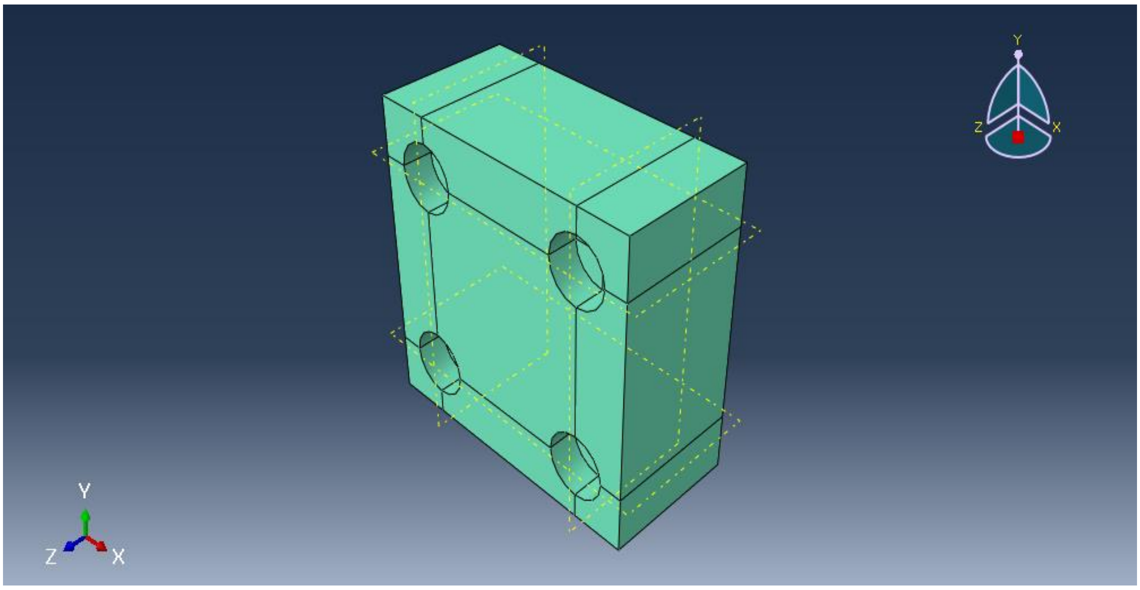


Figure 5. Model represents the pile cap having dimensions 1.9 × 1.9 × 0.9m

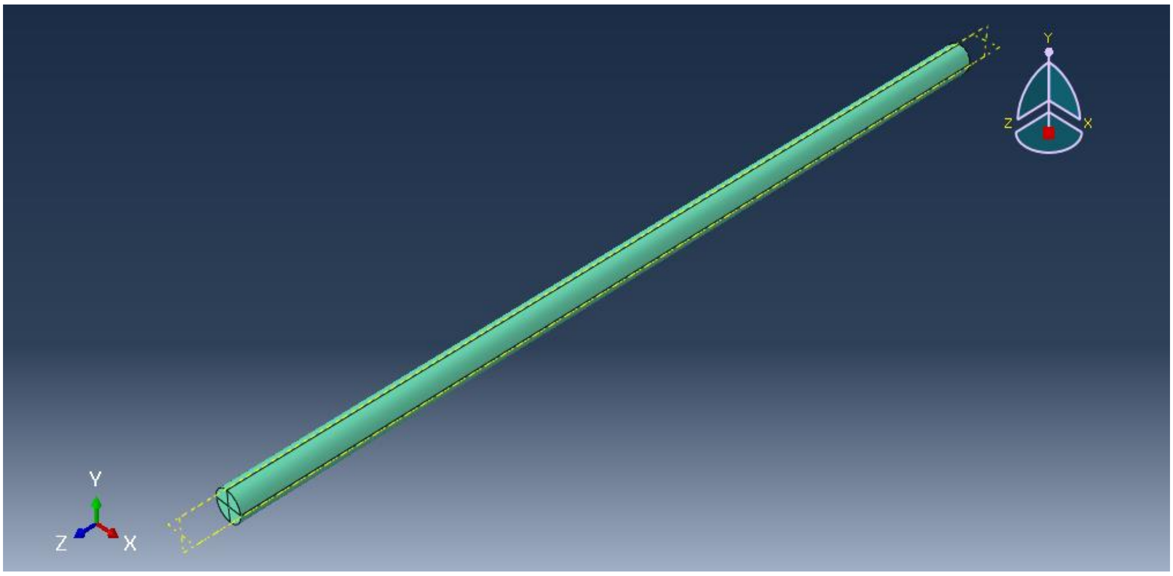


Figure 6. Model represents the pile having diameter 0.4m and length 12m

2. Assign the material properties to each part as specified in the material section. The soil is elastic and Mohr Coulomb criteria is followed.
3. Assemble the three parts into one model. Fig. 4 shows how to put the three sections together to make a model.

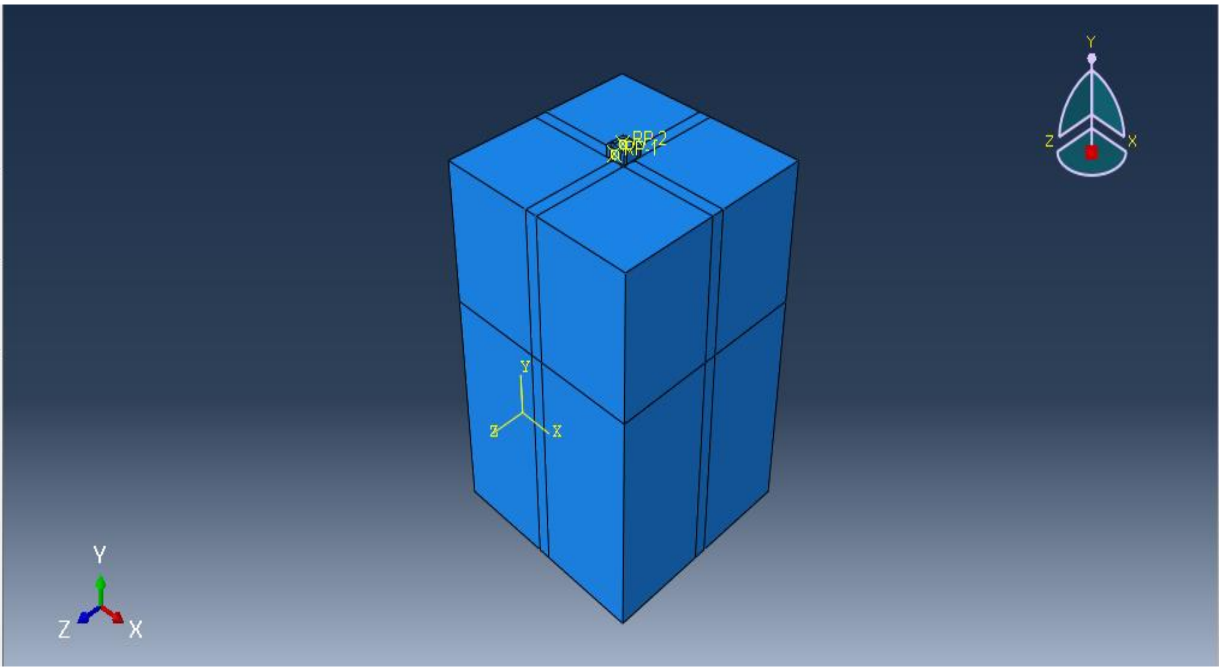


Figure 7. Model assembly consisting of soil, (2 × 2) pile group and a pile cap

4. Define the interaction properties, assign the reference points of loads one on the top of

the pile cap Rp1 and other Rp2 on the lateral side and tie the piles with the pile cap with the help of interaction property. Also provide the coefficient of friction = 0.3.

5. Define the step. Here one step loading is done simultaneously for two load combinations vertical and lateral load. In the step analysis define the time increment as well.
6. In the load module, define the load combinations. The loading is carried out in single step with two different loads simultaneously. Assign the load quantity and the amplitude of loading. Vertical loading was applied as pressure force while the lateral load was applied as concentrated force. Define the boundary conditions for the soil continuum in the load module. Here the base of the model is encastered in each direction and rotation. The x and z planes are restrained from moving in their respective directions.

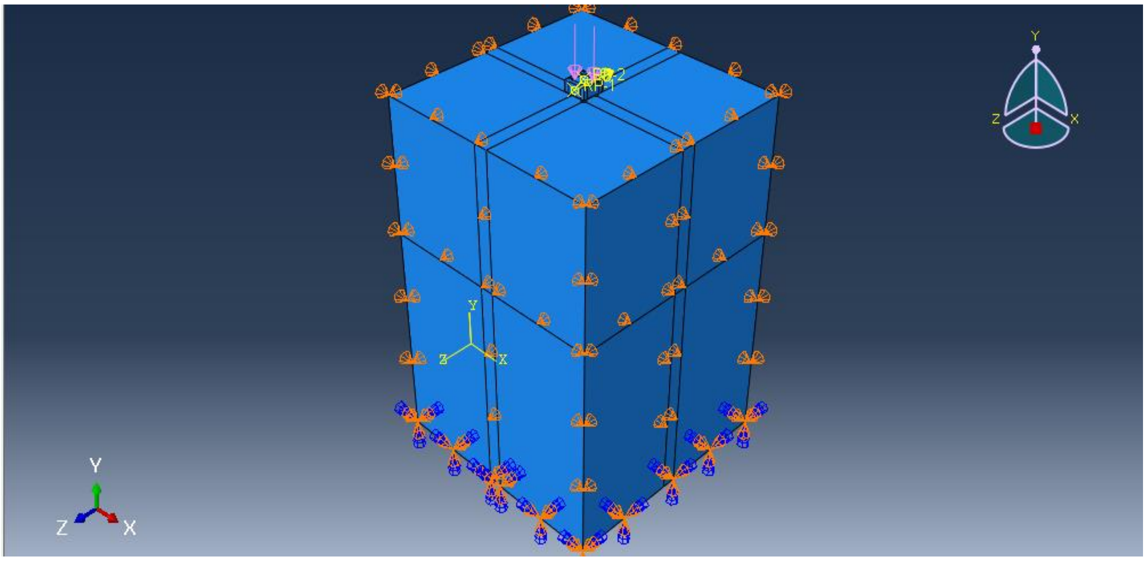


Figure 8. Model assembly with loads and boundary conditions

7. Assign the local and global meshing. Meshing is carried out to discretize a large mass into small parts. Coarse meshing gives inaccurate results while finer meshing takes a longer time to analyze the model but the results are reliable. 8-noded brick element is used in the analysis to discretize the soil continuum. Both local and global seeding is done to soil continuum and pile group in order to achieve the most accurate and fine mesh so that results are well founded.

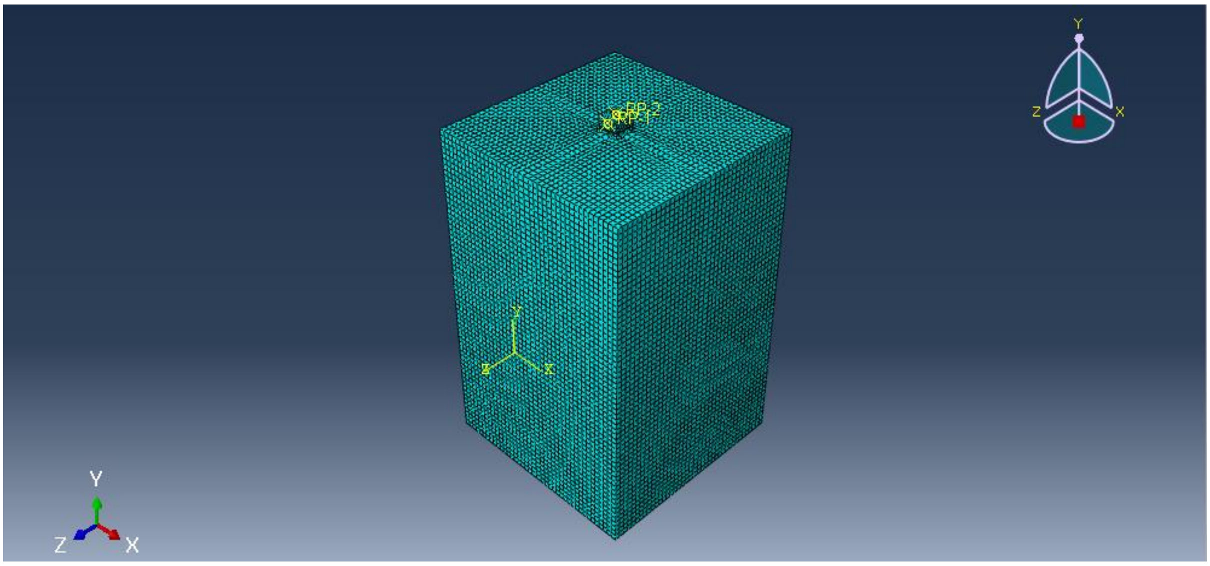


Figure 9. Model assembly representing the finite element mesh

8. Create a job. Check the data and let the analysis run.
9. Once the job is completed. Check the results and visualization.

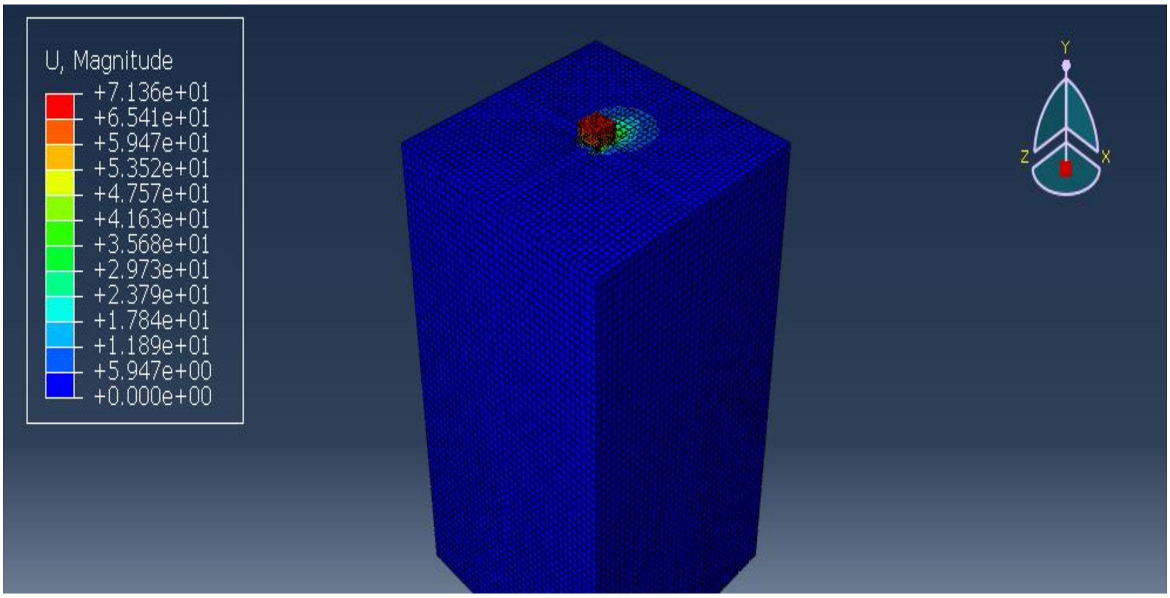


Figure 10. Visualization of the model results showing displacement

10. Plot the load vs settlement, load vs deflection, load vs displacement graphs, and plastic strain with the variation of dilation angle and modulus of elasticity. Derive the necessary conclusions.

3.3 Finite Element Analysis of a Laboratory Tested Model

In order to validate the results, a case study has been carried out. Anagnostopoulos and Georgiadis in 1993 conducted laboratory model tests on aluminium closed-ended piles of 19 mm outside diameter and 1.5 mm wall thickness, embedded 500 mm into a prepared soft clay bed of length 1000mm, width 700mm and depth 800mm with w_l = 42%, w_p = 24% and cu = 28kN/m^2. The loading pattern has been followed as per the model test data. Load has been applied in two stages. The stage one consists of application of pure vertical load and in the second stage a combined load has been applied. Vertical load of 350N and a lateral load of 130N. Both the loads were applied at ground level individually in the laboratory model. The modulus of elasticity of the soil was taken as 7.5MPa using the relation Es = 250 to 400 cu (Poulos and Davis 1980) and poisson's ratio of the clayey soil was taken as 0.4. The modulus of elasticity of the pile is 70000 MPa and poisson's ratio is 0.31. In the present analysis a free standing pile was modelled having length of 550mm (500mm in the soil and 50mm above the ground level). Mohr Coulomb criteria is used to model the soil. Fig. 12 and Fig. 13 demonstrate the comparison of test data and anticipated results for piles under pure vertical and combined vertical and lateral loads. From the figures it can be visualized that the comparison is effective both at lower and greater load levels. For both the vertical and lateral response of the piles, the percentage difference is 16.67 percent for vertical load only and 13.74 percent for combined axial and lateral loading at all load levels. The finite-element prediction in both the cases matched reasonably well with the test data. As a result, it is possible to infer that the numerical approach used in this study is capable of modelling the pile-soil interaction under pure vertical, lateral, and combined vertical and lateral loads.

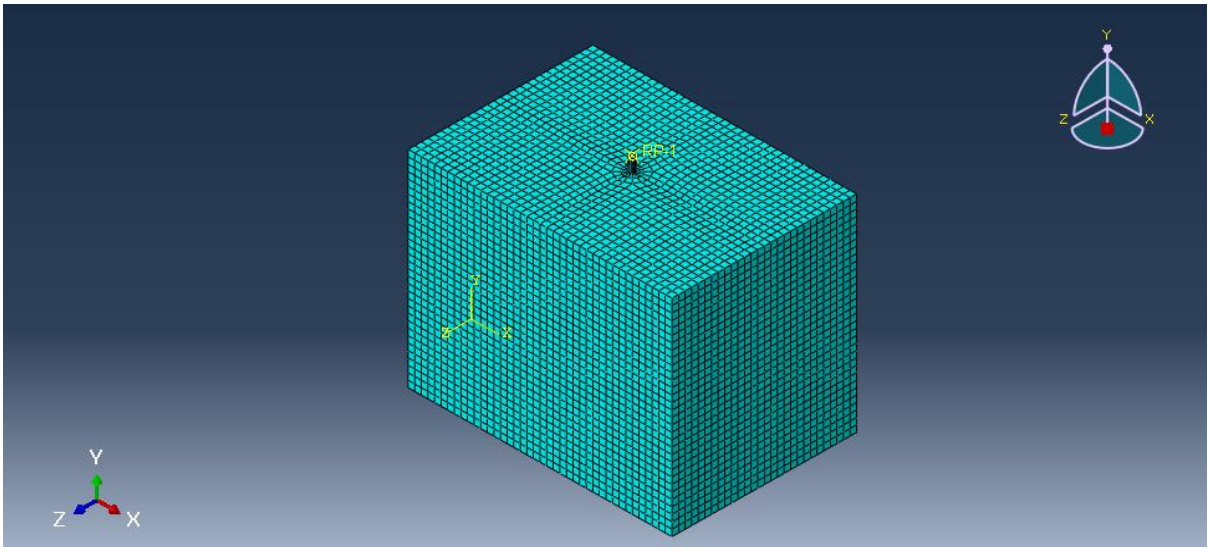


Figure 11. Isometric view of soil-pile model representing finite element mesh.

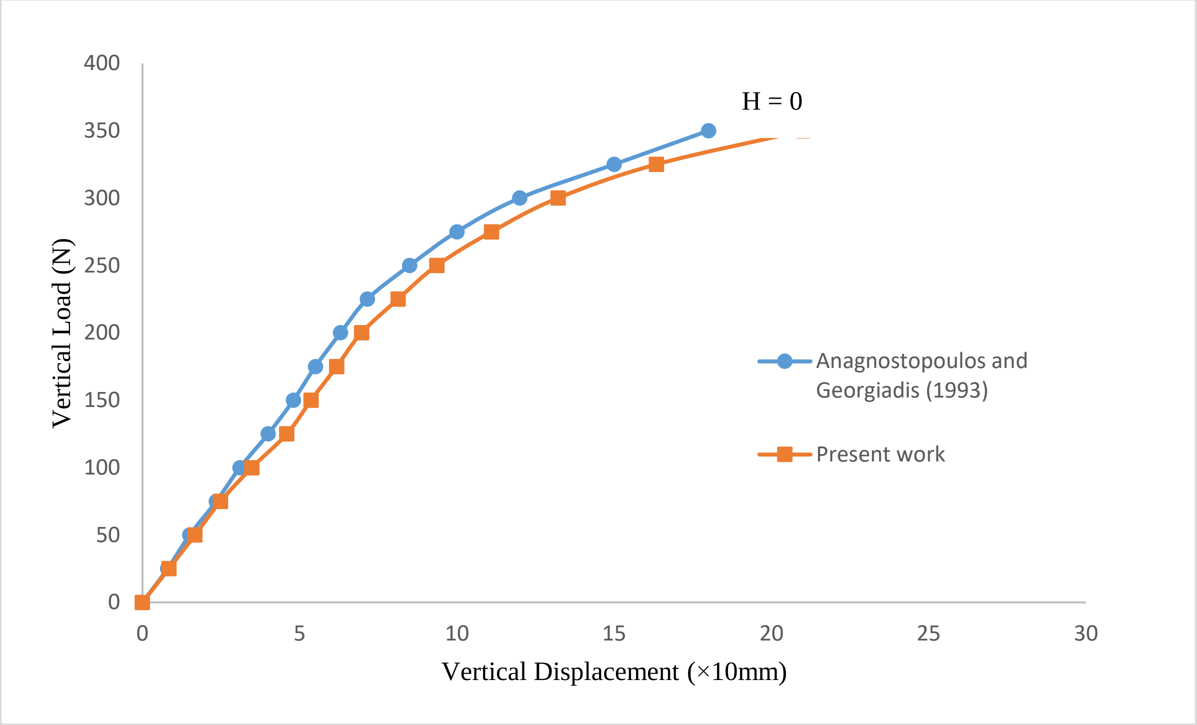


Figure 12. Comparison of vertical response of present work on pile with the experimental data of Anagnostopoulos and Georgiadis (1993)

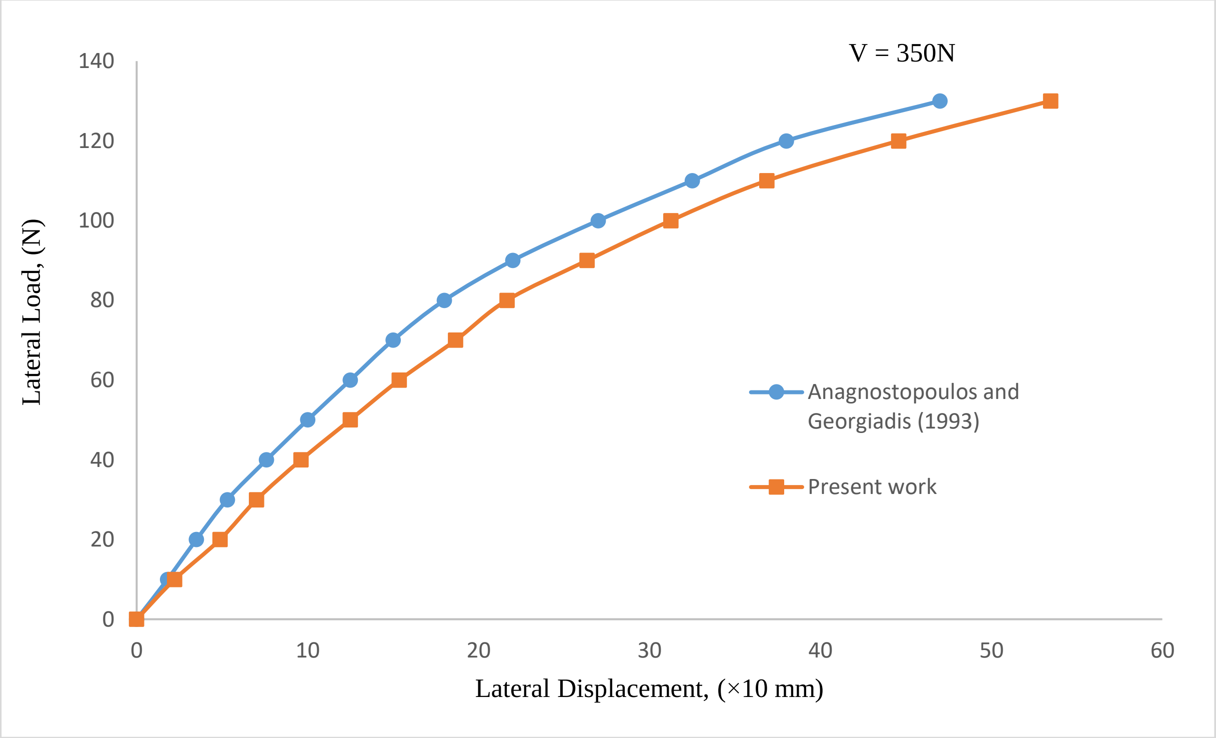


Figure 13. Comparison of lateral response of present work on pile with the experimental data of Anagnostopoulos and Georgiadis (1993)

Chapter 4 Results and Discussions

4.1 Results

A 2 × 2 pile group was analyzed in Abaqus software using three dimensional finite element analysis. A number of constitutive simulations were carried out to model the soil-pile interaction for three different combination of loading.

4.2 Load – Displacement for Dilation Angle:

In the first case the soil- pile model was only subjected to vertical load and the variation of settlement of pile with the maximum axial load was recorded with respect to range of dilation angle as displayed in Fig. 14. In the second case the soil- pile model was only subjected to lateral load and the change of lateral deflection of the pile with the maximum axial load was recorded with regard to the range of dilation angle as displayed in Fig. 15.

In the third case the pile group (2 × 2) was subjected to combined effect of lateral and vertical loads and the variation of pile head displacement was obtained by keeping the vertical load constant and applying the lateral load in increments of 0.2, 0.4, 0.6, 0.8, and 1 of the maximum lateral load as shown in Fig. 16. It was observed that the lateral pile head displacement increased with increase in lateral loads but when the results were obtained for vertical pile settlement, it showed a considerable decrease in the vertical settlement with increase in lateral loads as displayed in Fig.17.

A/A_{max} is the normalized axial load and the maximum vertical load applied is 600kN. H/H_{max} is the normalized lateral load and the maximum lateral load applied is 300kN. The maximum pile head displacement observed in case of combined axial and lateral loads is 68mm. The maximum pile head displacement observed in vertical load only is 31mm and in case of lateral load only is 26mm. In each case the variation of pile head displacement with combined loading (vertical and lateral) with respect to dilation angle in the range of 6 to 14° is observed. The results corresponding to these variations are shown in the Fig. 18 to 22. All these results are then compiled in Fig. 23 showing the comparison of pile head displacement at A/A_{max} =1, H/H_{max} = (0.2 to 1) and dilation angle $Ø_d$ = (6 -14°). It was observed that with increase in lateral loading the pile displacement increases but with increase in dilation angle pile displacement decreases due to the confinement of the soil surrounding the soil.

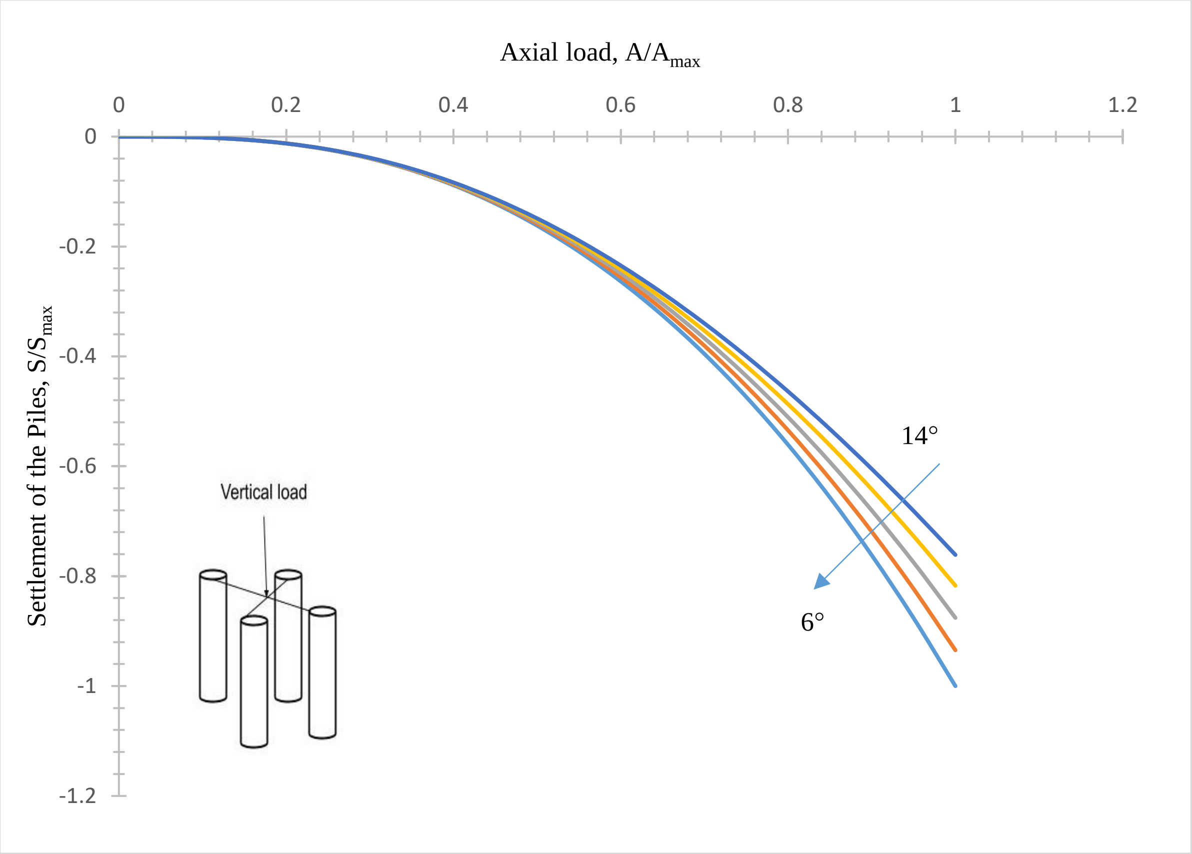


Figure 14. Variation settlement of pile with axial load captured for $Ø_d$ = (6-14°)

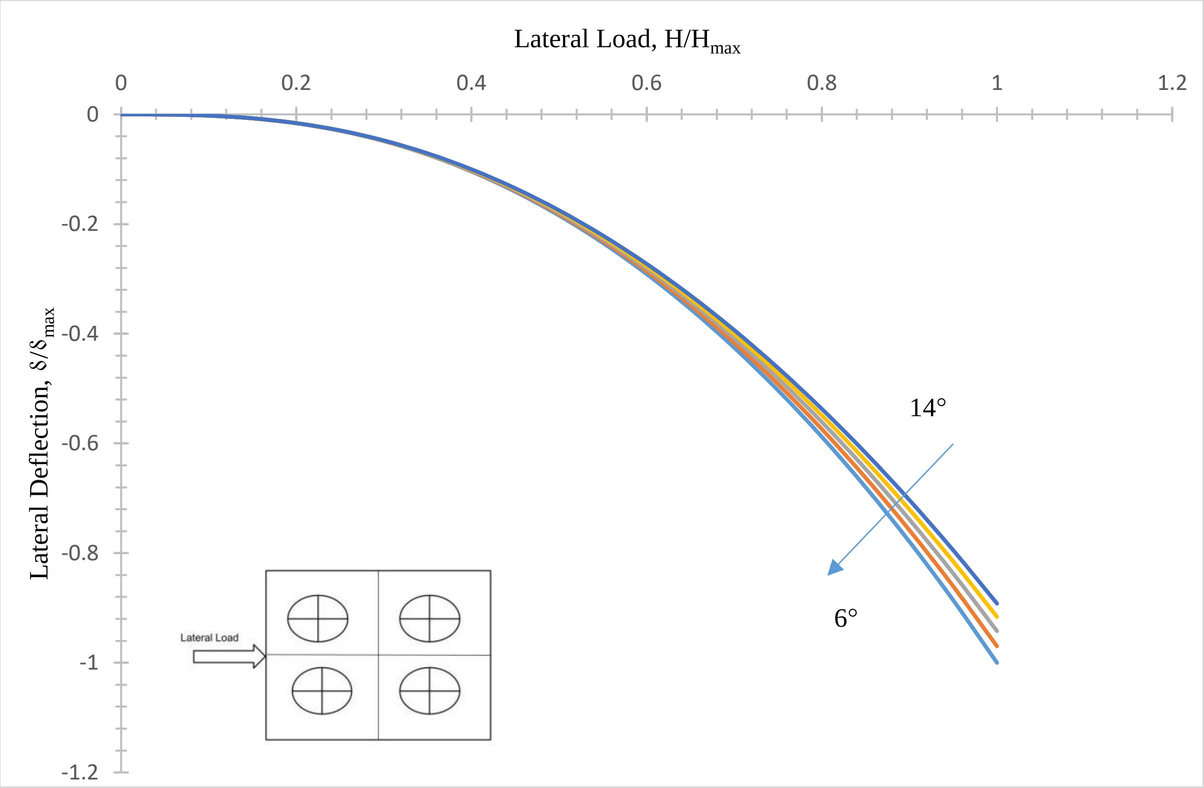


Figure 15. Variation of lateral deflection of pile with lateral load captured for $Ø_d$ = (6-14°)

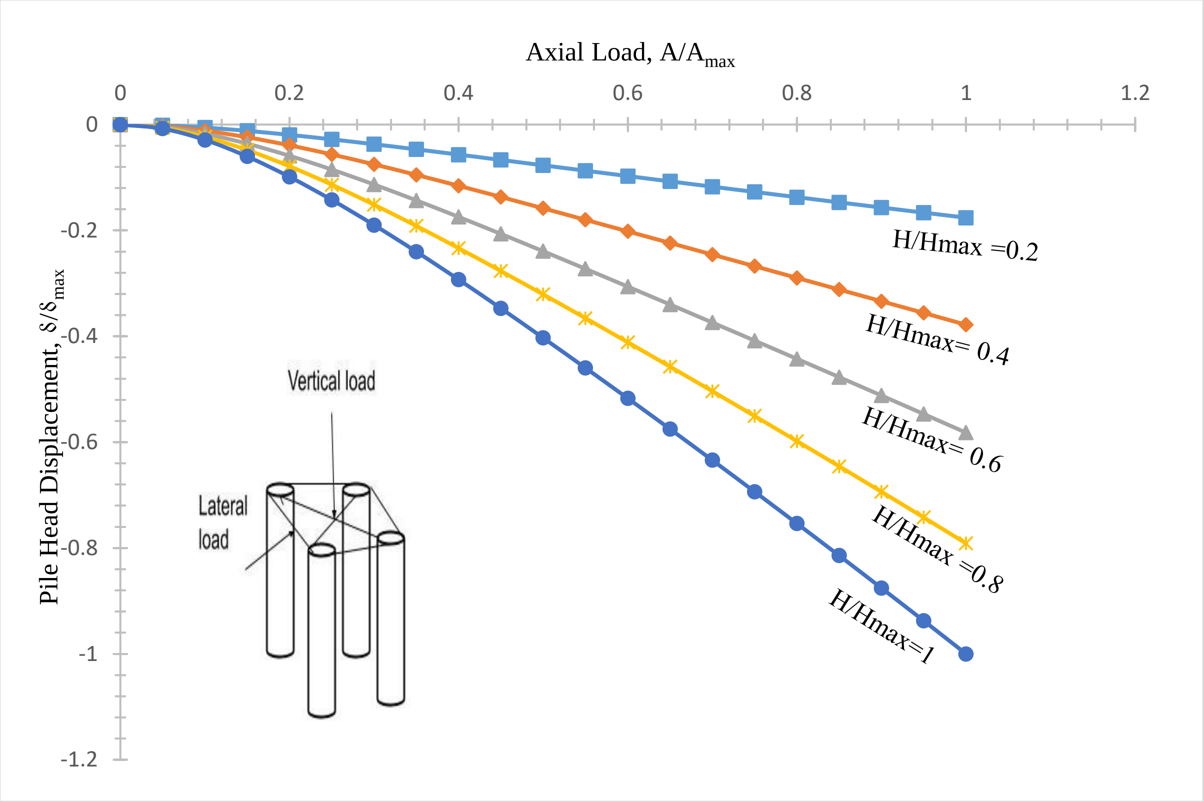


Figure 16. Variation of pile head displacement and axial load with lateral load increments (0.2 to 1)

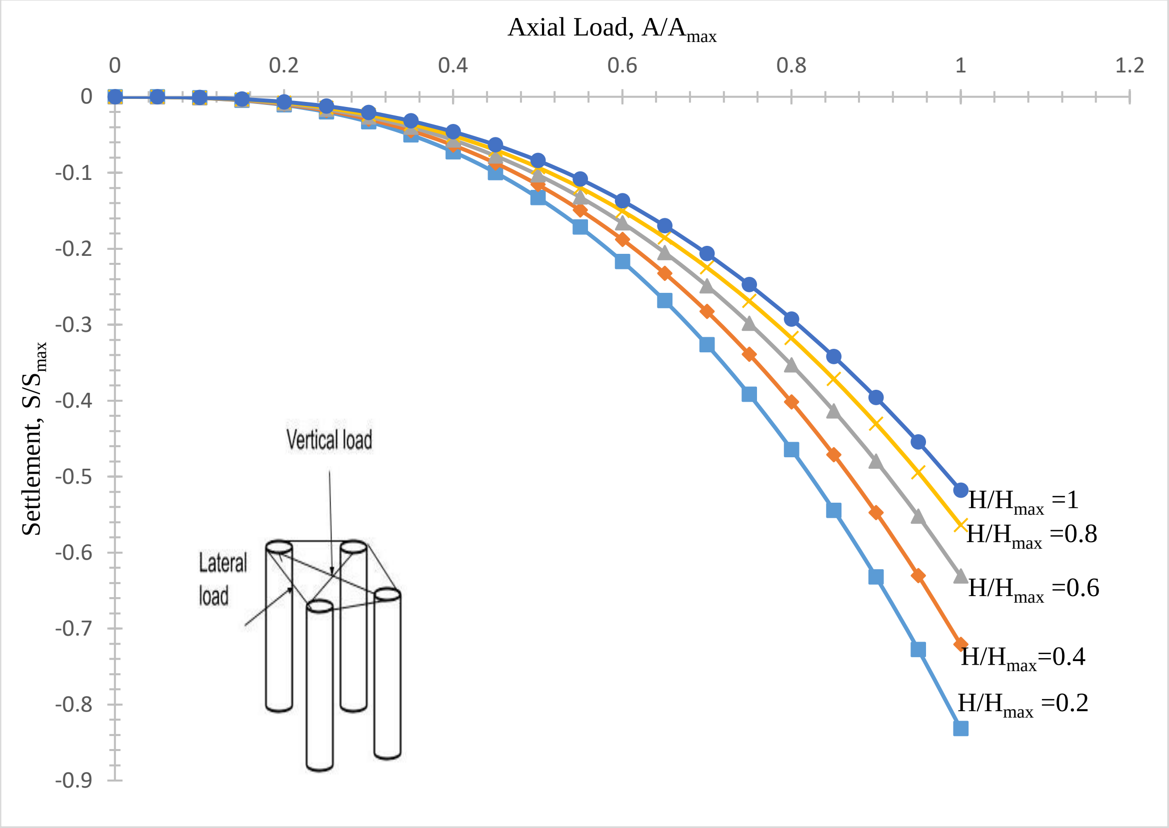


Figure 17. Variation of vertical settlement of the soil with axial load and lateral load increments (0.2 to 1)

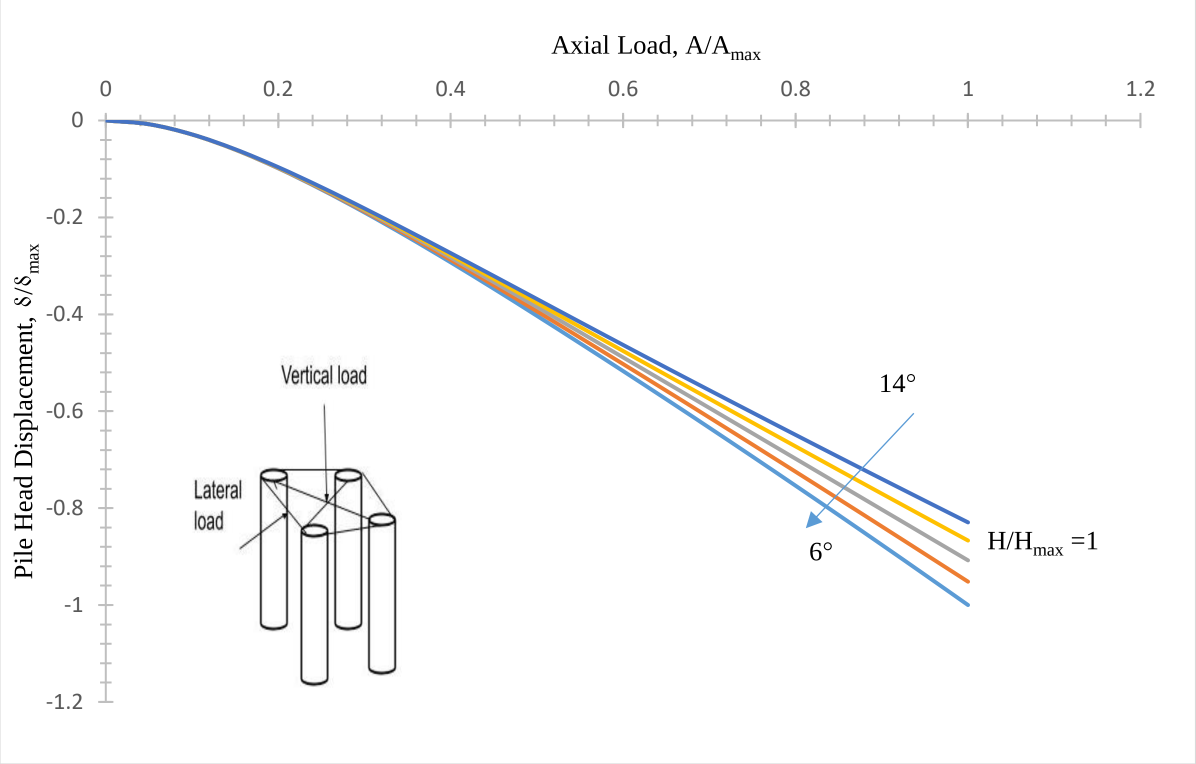


Figure 18. Variation of pile head displacement and axial load with lateral load increments $H/H_{max} = 1$ and variation of dilation angle $Ø_d$ = (6-14°)

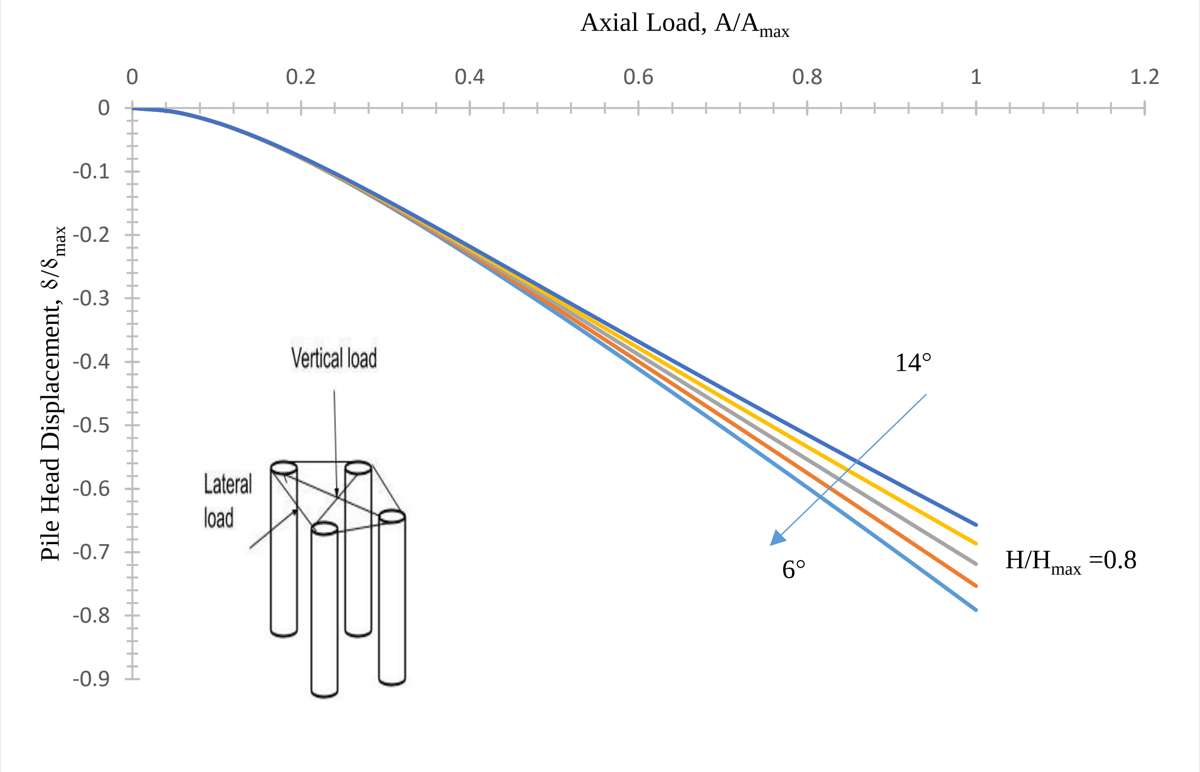


Figure 19. Variation of pile head displacement and axial load with lateral load increments $H/H_{max} = 0.8$ and variation of dilation angle $Ø_d$ = (6-14°)

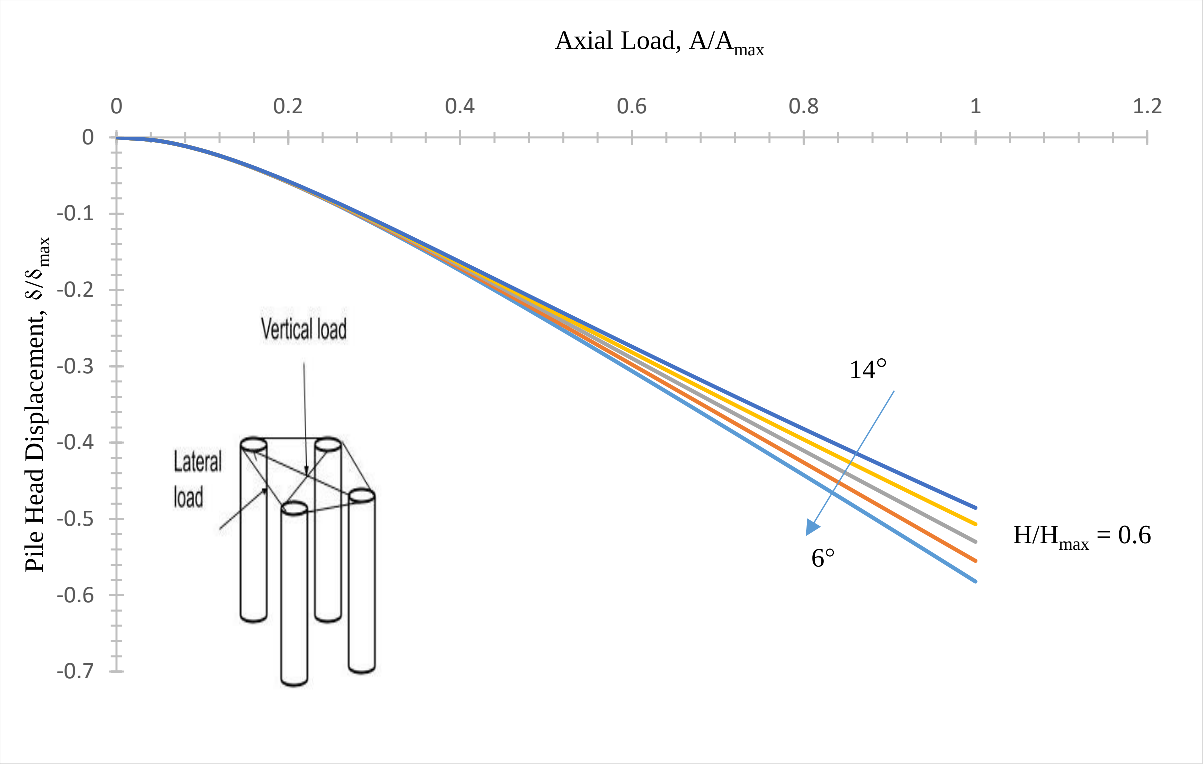


Figure 20. Variation of pile head displacement and axial load with lateral load increments H/H_{max} = 0.6 and variation of dilation angle $Ø_d$ = (6 -14°)

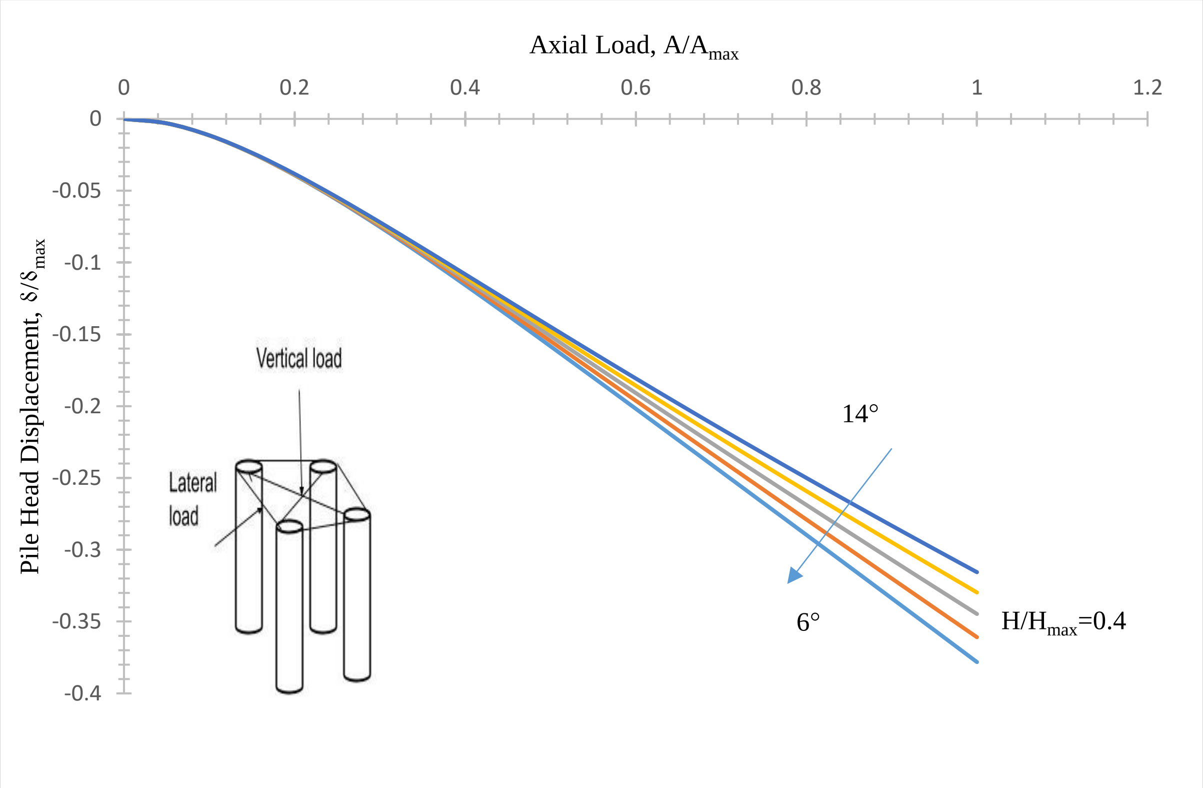


Figure 21. Variation of pile head displacement and axial load with lateral load increments H/H_{max} = 0.4 and variation of dilation angle $Ø_d$ = (6-14°)

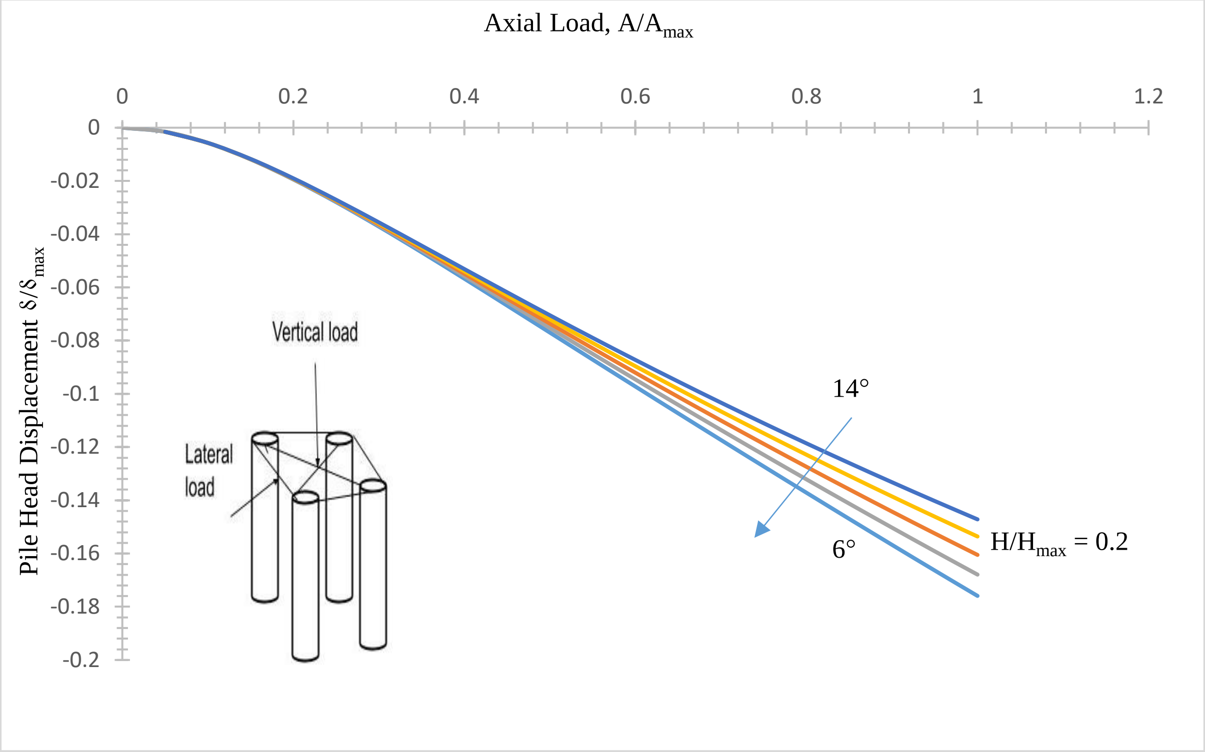


Figure 22. Variation of pile head displacement and axial load with lateral load increments H/H_{max} = 0.2 and variation of dilation angle $Ø_d$ = (6-14°)

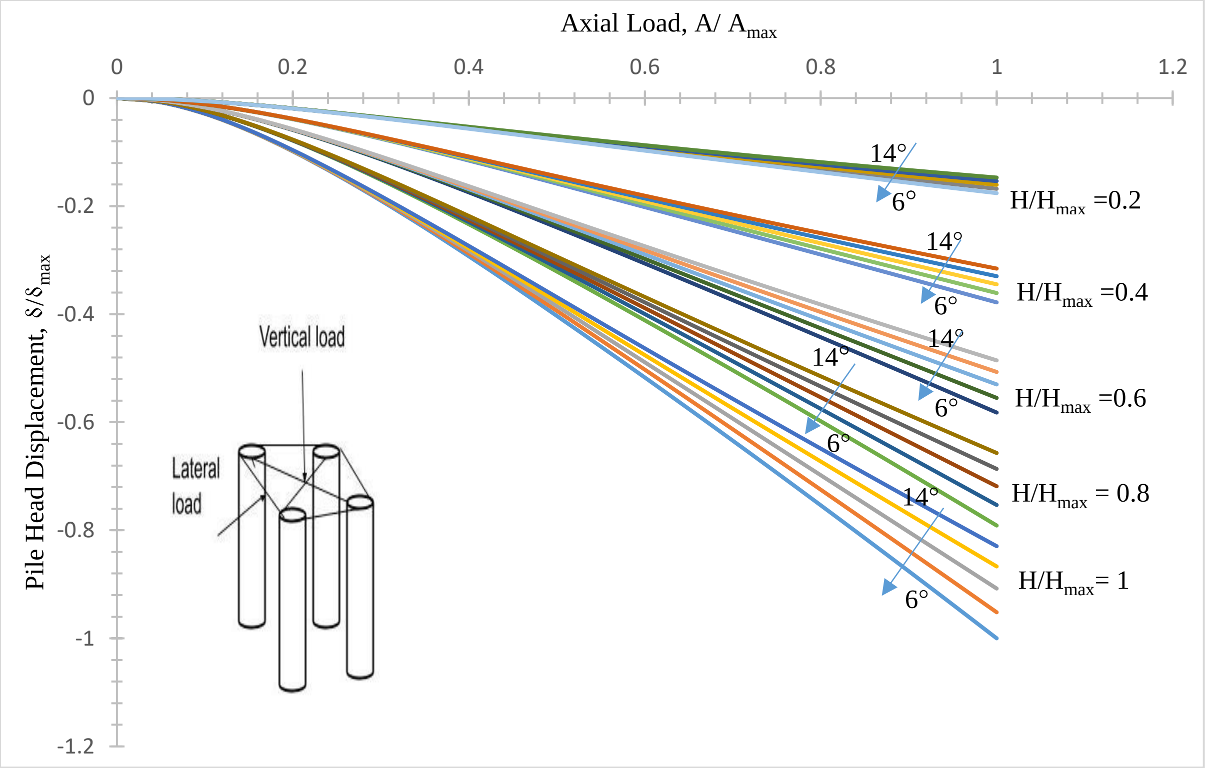


Figure 23: Variation of pile head displacement with axial load A/A_{max} and H/H_{max} captured for dilation angle (6-14◦)

4.3 Load- Displacement for Modulus of Elasticity

Variation of pile head displacement with A/A_{max} (ratio of normalized axial load) = 1 and H/H_{max} (ratio of normalized lateral load) = (0.2 to 1) with respect to modulus of elasticity in the range of 50 to 80 MPa with an increment of 5 MPa at each simulations is recorded. It was observed that with increase in lateral load pile head displacement increases and with increase in modulus of elasticity the pile head displacement decreases because of the increases in stiffness of the soil. As the modulus of elasticity increases the soil surrounding the pile gets packed making it more stiff and dense and allowing lesser displacement of the pile. Fig. 24 to 28 shows the variation of pile head displacement with the modulus of elasticity of the soil. Also Fig. 29 shows a comparison of the results obtained in all five cases.

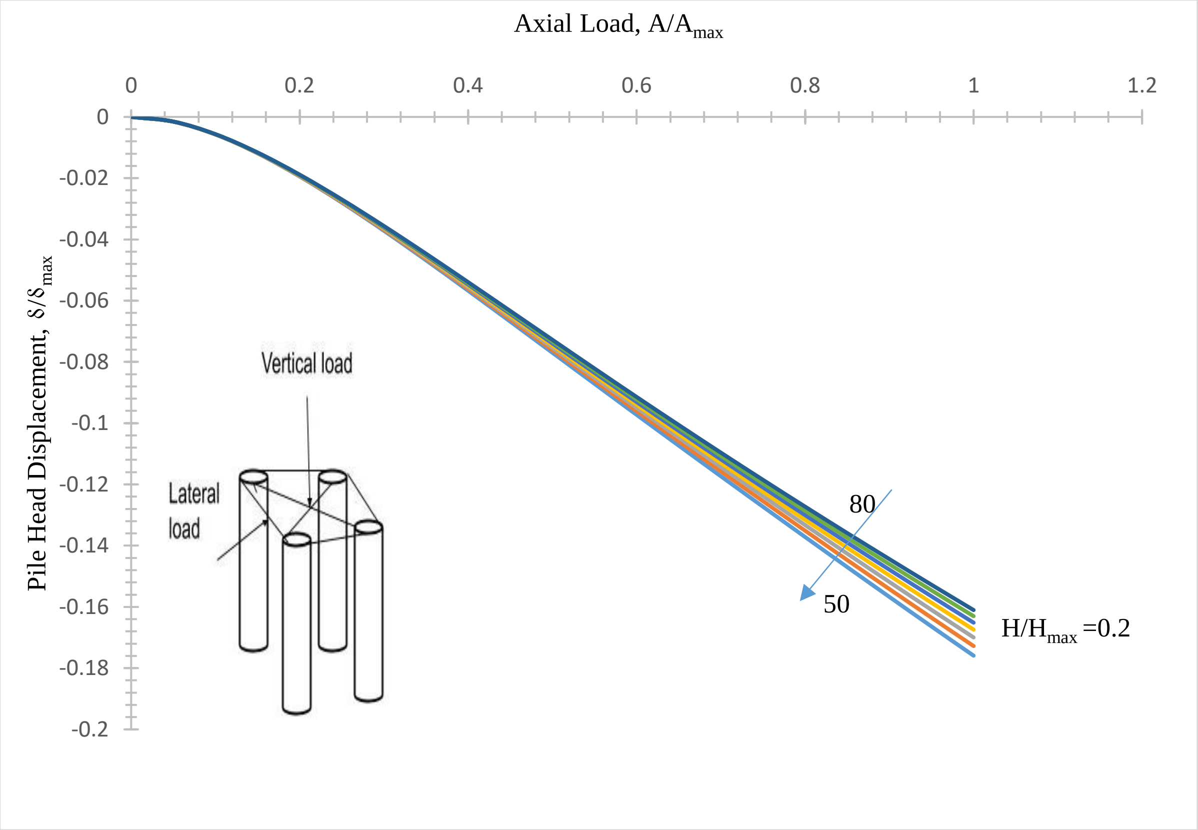


Figure 24. Variation of pile head displacement and axial load with lateral load increments H/H_{max} = 0.2 and variation of modulus of elasticity (50 to 80 MPa)

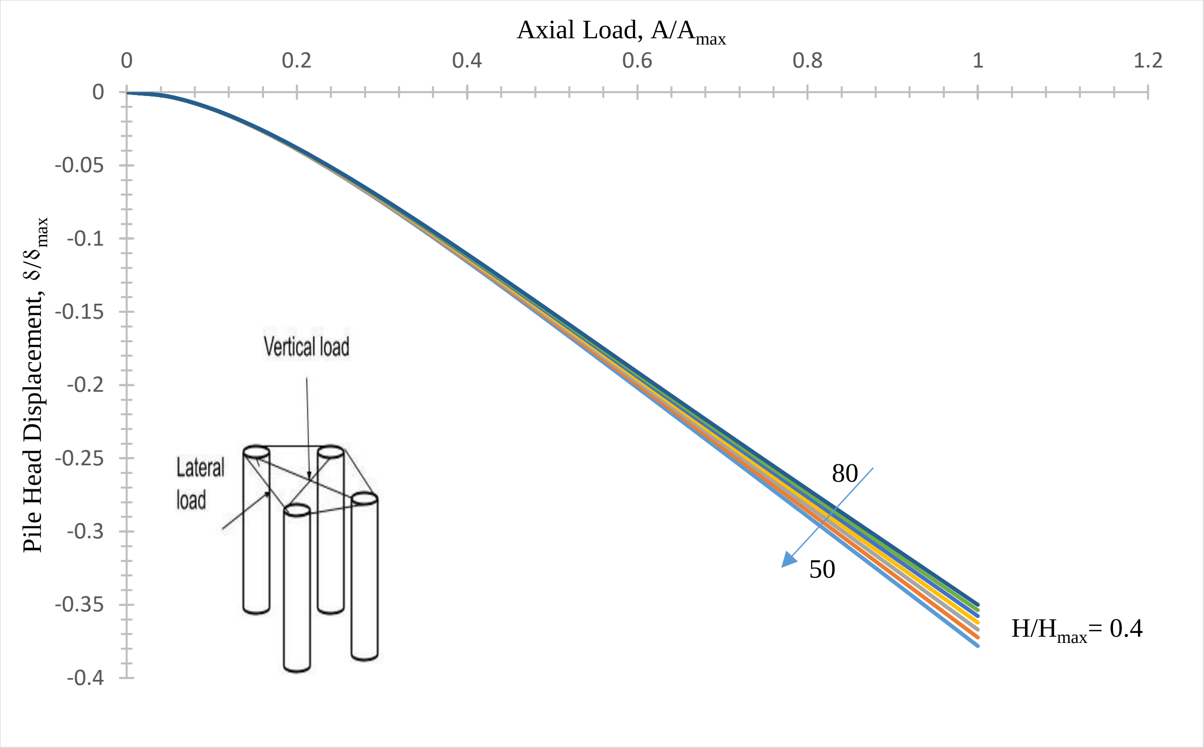


Figure 25. Variation of pile head displacement and axial load with lateral load increments H/H_{max} = 0.4 with the variation of modulus of elasticity (50 to 80 MPa).

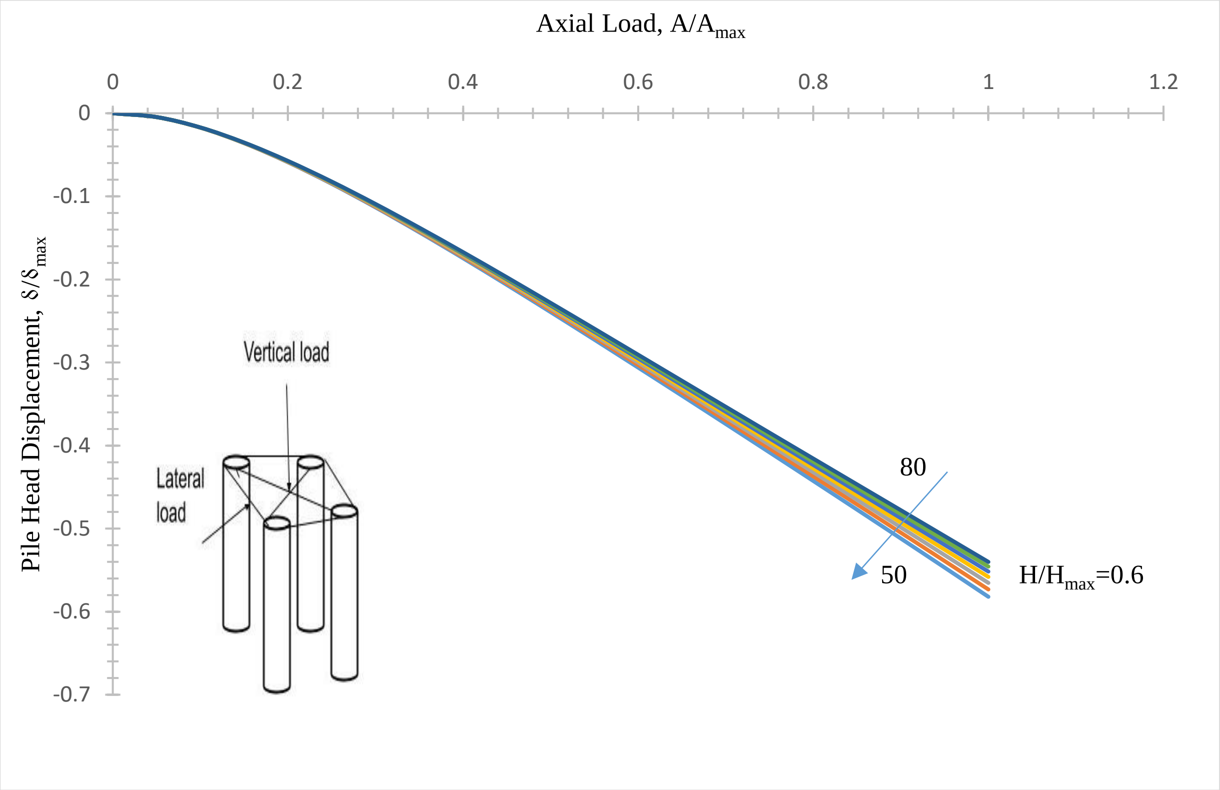


Figure 26. Variation of pile head displacement and axial load with lateral load increments H/H_{max} = 0.6 with the variation of modulus of elasticity (50 to 80 MPa)

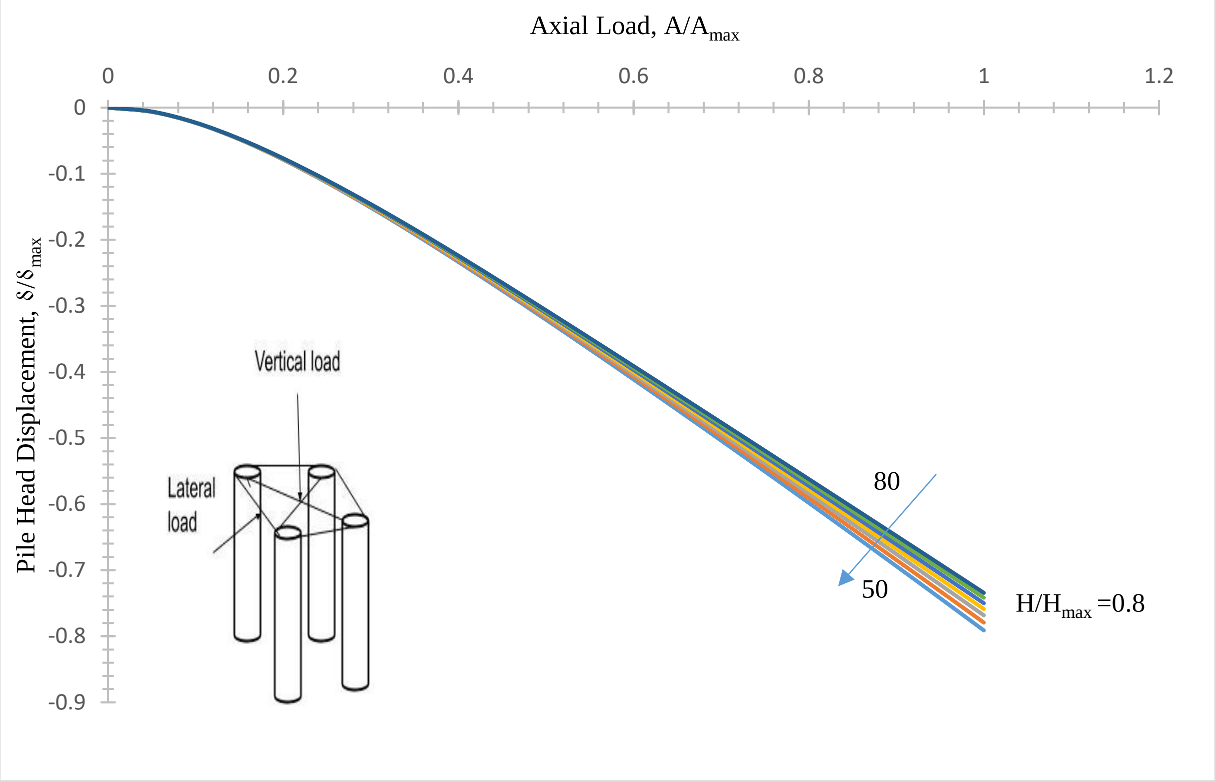


Figure 27. Variation of pile head displacement and axial load with lateral load increments $H/H_{max} = 0.8$ with the variation of modulus of elasticity (50 to 80 MPa)

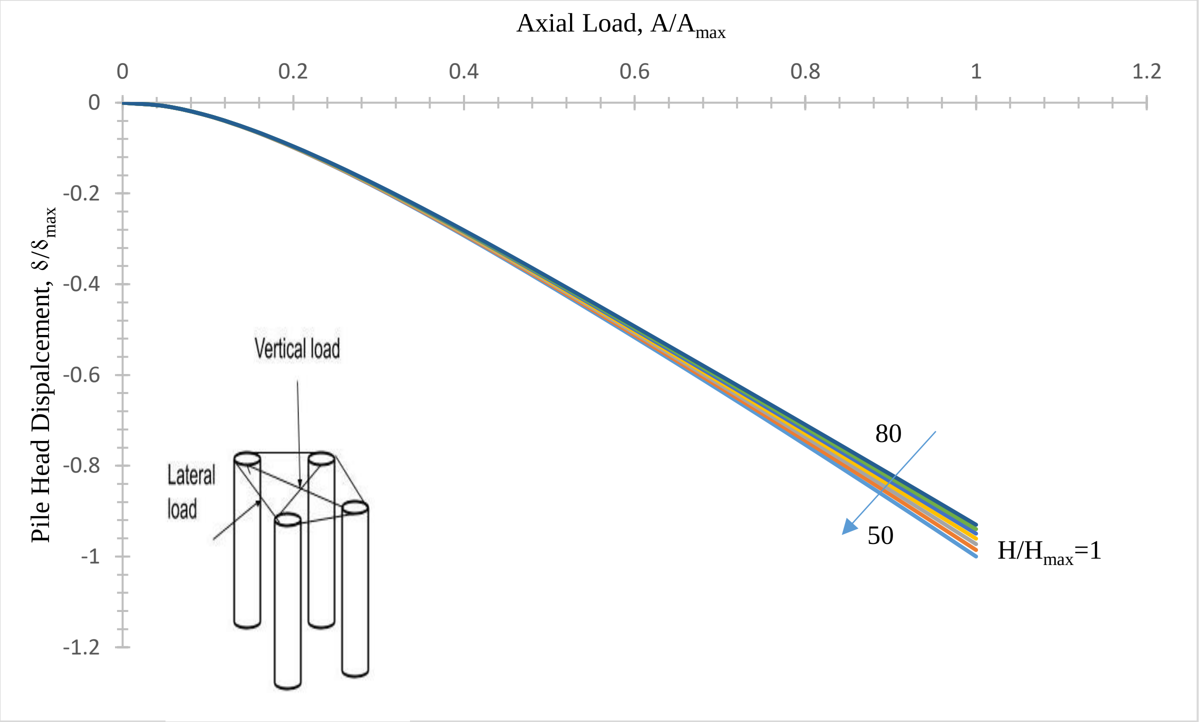


Figure 28. Variation of pile head displacement and axial load with lateral load increments $H/H_{max} = 1$ with the variation of modulus of elasticity (50 to 80 MPa)

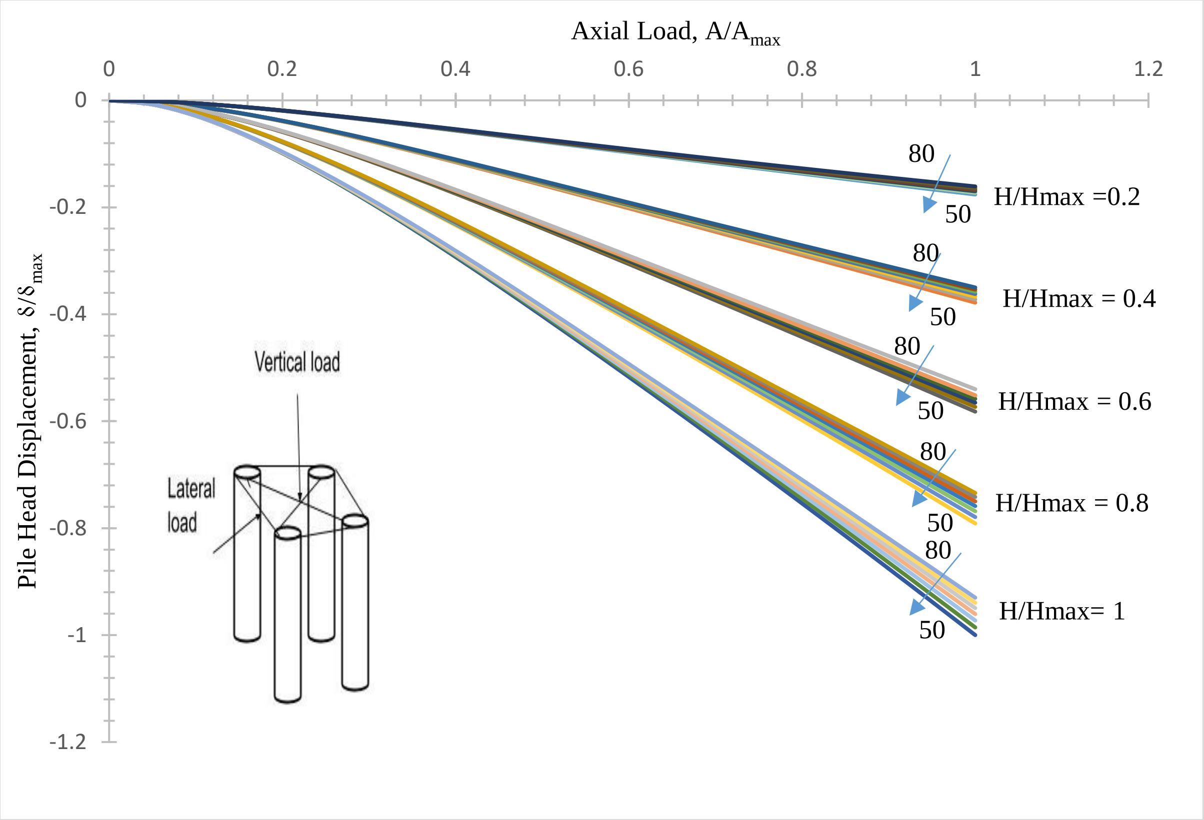


Figure 29. Comparison of pile head displacement with axial load A/Amax and H/H_{max} captured for modulus of elasticity (50-80 MPa)

4.4 Plastic Strain – Dilation Angle

Plastic strain is the deformation of the element due to application of loads. It is irreversible and stays even after the removal of load. Plastic strain of simulations where the axial load A/A_{max} = 1 was constant and lateral load H/H_{max} increases from 0.2 to 1 with a range of dilation angle 6 to 14° was observed. At first it was observed that with increase in lateral load displacement increases and plastic strain also increases. Then it was observed that for the same loading conditions if we increase the dilation angle plastic strain decreases. Fig. 30 shows the variation of Plastic strain with dilation angle for axial load A/A_{max} = 1 and lateral load H/H_{max} = (0.2 to 1)

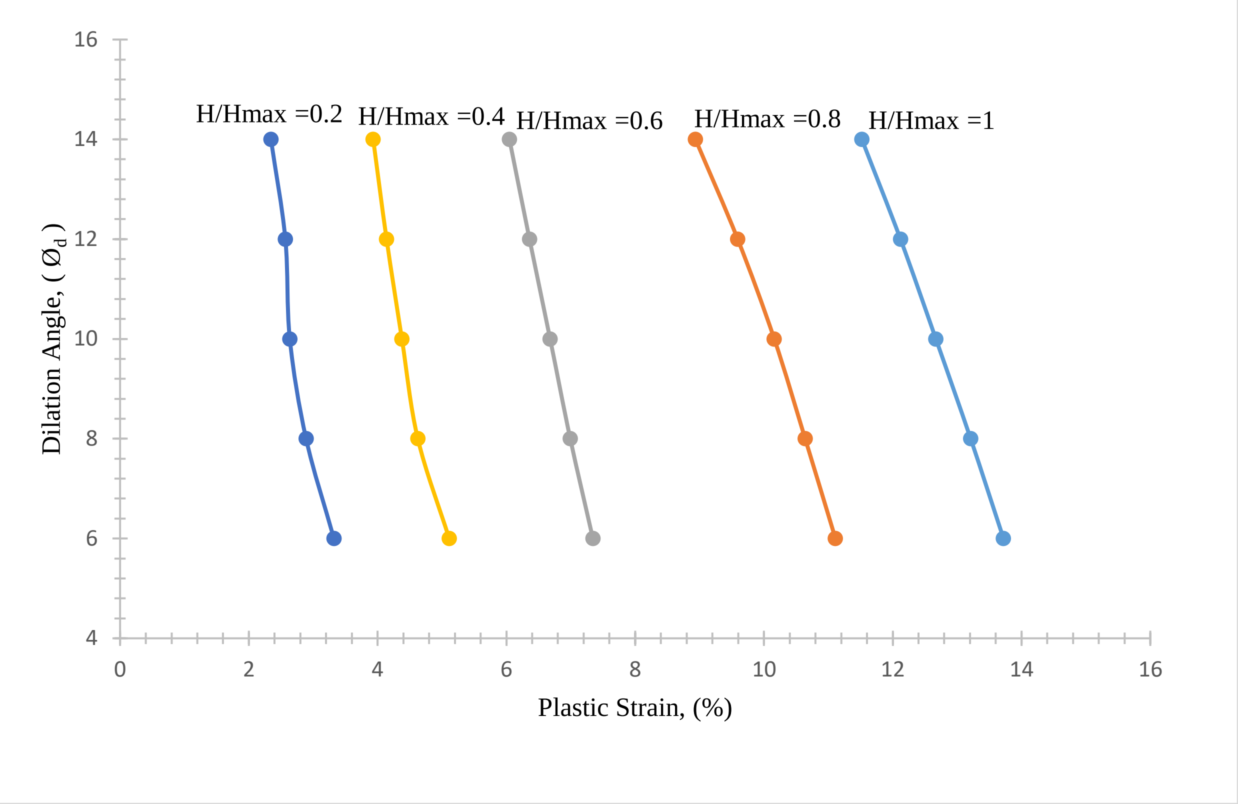


Figure 30. Variation of plastic strain with dilation angle for axial load A/A$_{max}$ = 1 and lateral load H/H$_{max}$ (0.2 to 1)

4.5 Deflection of Pile along the Depth

Linear Elastic model is used to model the pile structural material. The upper part of a pile in case of lateral loads is supposed to be most critical as it is subjected to more deflection and has higher load carrying capacity in comparison to the lower part of the pile. Fig. 31 shows the failure modes of vertical piles under lateral loads. The lateral resistance of the soil distributes uniformly between the two sides of piles. In case of short piles it is assumed that rotation occurs near the base of pile which corresponds to the failure of the pile without any fracture while long piles do not have point of rotation, they have a point of fracture just below the soil [15].

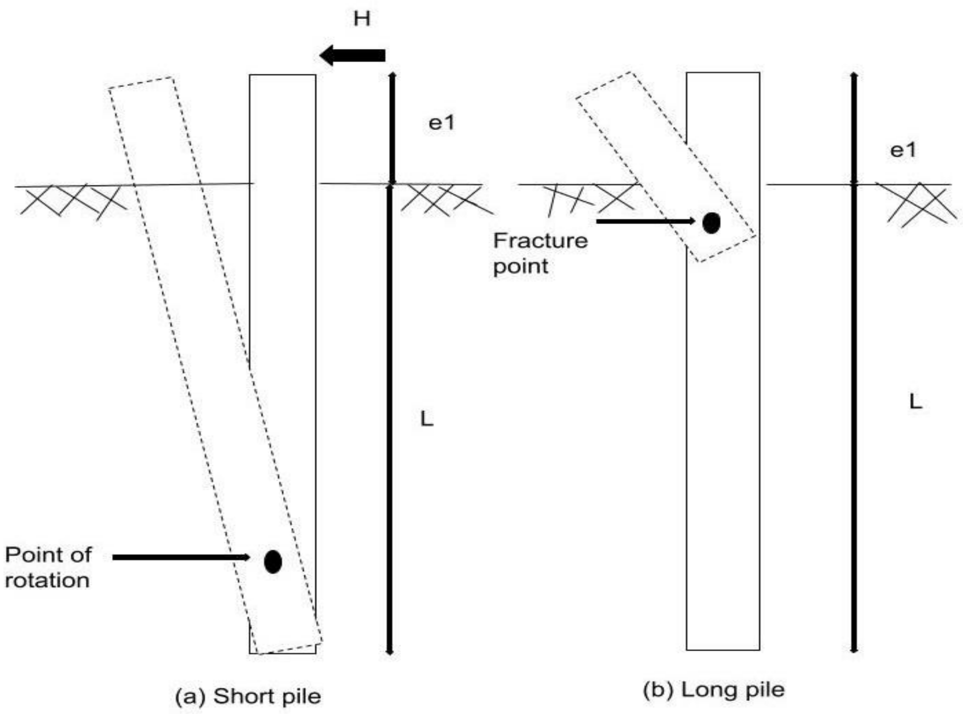


Figure 31. Failure modes of vertical piles under lateral loads (Poulos & Davis, 1980)

The deflection of the pile along the depth was measured at every 0.5m up to 12m. The failure mechanism involved continuous punching of the front piles in the surrounding soil under the influence of lateral load increments which in turn causes the back piles to displace more. It was observed that with increase in depth deflection decreased. Fig. 32 demonstrates the mechanism of deflection of piles along the depth for a 12m pile. In this the point of rotation is just near the base which is validating the theory for short piles given by (Poulos & Davis, 1980). The piles at the back had more displacement than the piles at the front. Fig. 33 shows the deflection of pile along the depth for front and back piles. The deflection along the depth was observed for combined loading where in the vertical load was kept constant $A/A_{max} = 1$ and the lateral load was applied in increment of 0.2, 0.4, 0.6, 0.8 and1. The results indicated that with increase in lateral load the deflection increased but only for the upper part of the shaft which is more critical to lateral loads. The lower parts had less deflection for higher load values as displayed in Fig. 34.

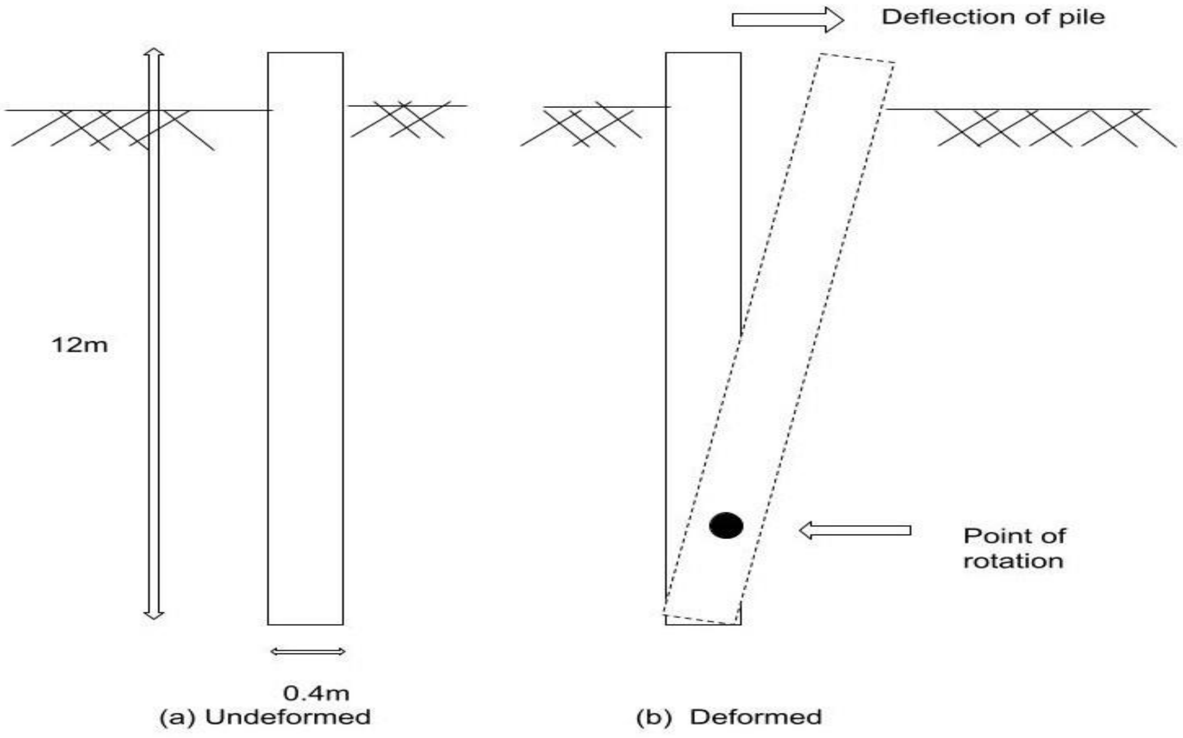


Figure 32. Deflection of the pile along the depth of the pile (a) undeformed, (b) deformed

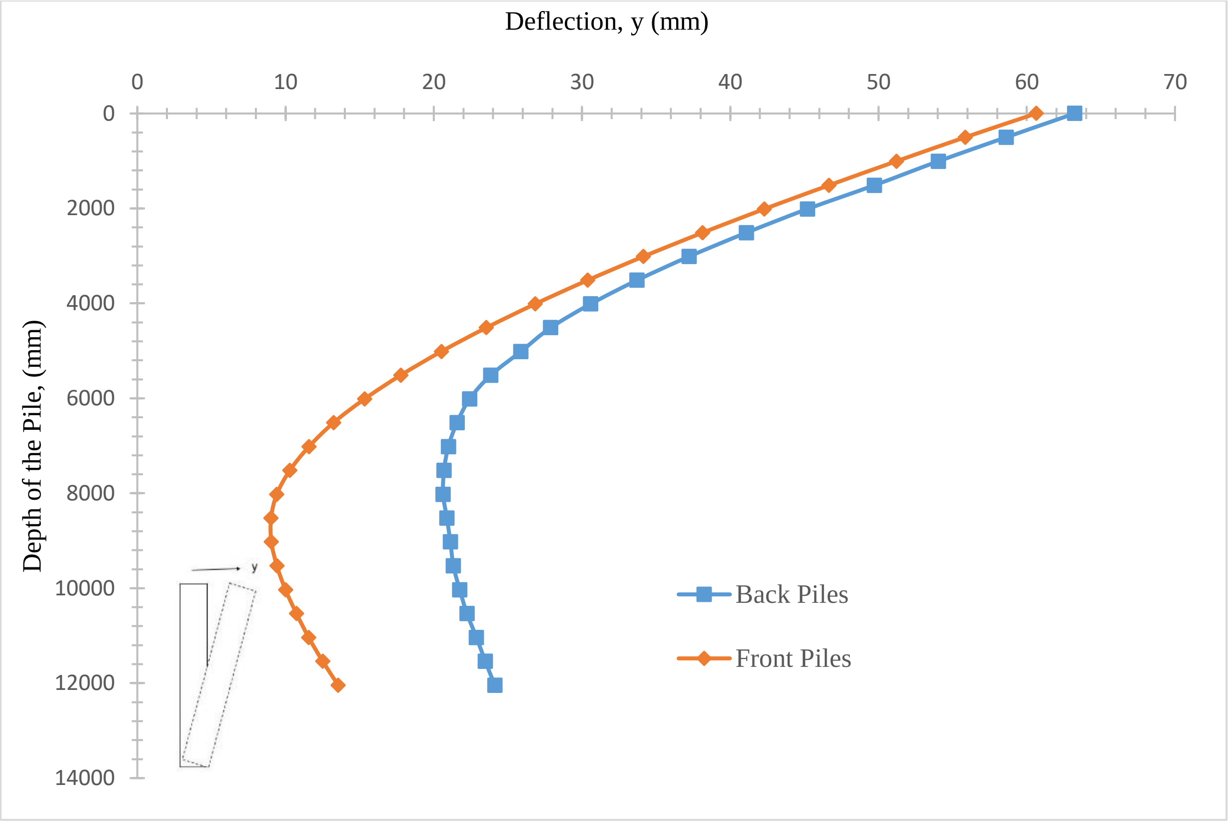


Figure 33.Variation of deflection of pile along the depth of piles

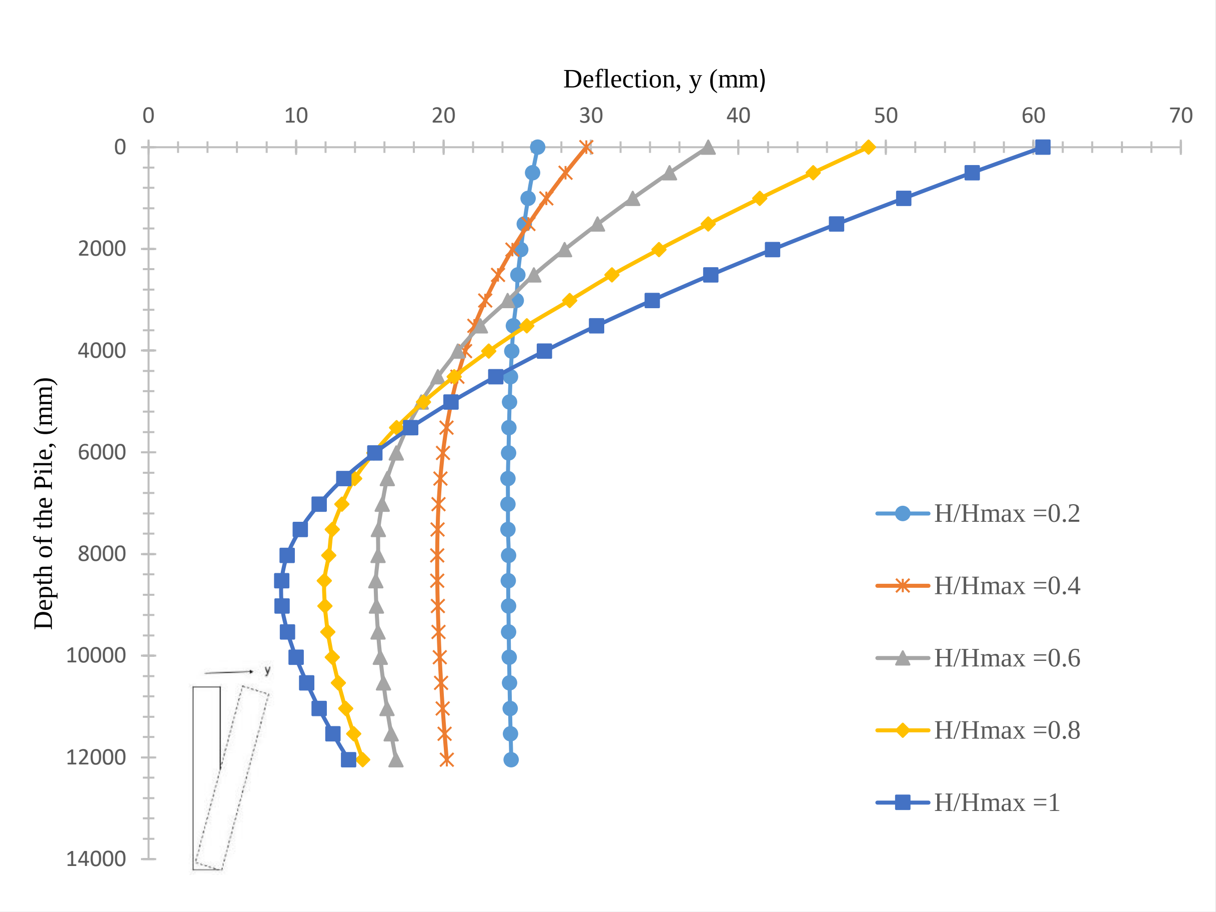


Figure 34. Deflection of the pile along the depth with $A/A_{max} = 1$ and $H/H_{max} = (0.2 \text{ to } 1)$

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

The following conclusions may be formed based on the findings:

i. In comparison to the traditional subgrade reaction technique of pile analysis, a three-dimensional finite element analysis can be used to investigate the combined influence of axial load and lateral loads on the lateral response of the pile and vice versa.

ii. Pile head displacement was obtained under the influence of combined axial and lateral loads. Lateral pile head displacement increased with increase in lateral loading but the vertical settlement of the pile reduced.

iii. At dilation angles ranging from 6 to 14°, the pile head displacement was obtained under the influence of combined axial and lateral loads. The lateral pile head displacement reduces as the dilation angle rises. The reduction in pile head displacement is due to the confining of the soil.

iv. The resultant pile head displacement increases upon the application of combined loads. The resultant displacement increases in the range of 83 to 125%, 50 to 79%, and 10 to 28% for $H/H_{max} =$ 1, 0.8, and 0.6 respectively while in case of lower values of H/H_{max} =0.2 and 0.4 pile head displacement decreases showing a resistance to settlement and increase in the lateral capacity of the pile group.

v. The variation of axial load with pile head displacement was recorded at a range of modulus of elasticity of 50 - 80 MPa. It was observed that with increase in modulus of elasticity the pile head displacement decreases. Such a decrease in pile head displacement is caused due to the denseness of the soil.

vi. Plastic strain increases with increase in lateral load but decreases with increase in dilation angle. It should be considered in design of piles.

vii. Deflection increased with increase in lateral load increments but with increase in depth of the pile, deflection decreases. The two piles at the back deflect more compared to the two piles at the front.

viii. Lateral deflection along the length of the pile was obtained. It was found that deflection increased with increase in lateral loading while keeping the vertical loading constant but only for the upper part of the soil which is more critical. For the lower part of the soil deflection decreased with increase in lateral load.

5.2 Recommendations

The results presented are for 2 × 2 pile group with circular piles. This needs to be further verified with different shapes and pile configuration for broader spectrum of results.

References

[1] Mehra, S., and Trivedi, A. 2021. “Pile groups subjected to axial and torsional loads in flow-controlled geomaterial*.” International Journal of Geomechanics*. 21(3): 1-15.

[2] Karthigeyan, S., Ramakrishna, VVGST., and Rajgopal, K. 2007. “Numerical investigation of the effect of vertical load on lateral response of piles”. *Journal of Geotechnical and Geoenvironmental Engineering.* 133 (5): 542-549.

[3] Georgiadis, M. 1986. “Interaction between torsional and axial pile responses.” *International Journal for Numerical and Analytical Methods of Geomechanics.* 11(6): 645-650

[4] IS: 2911 Part I: sec 1-4 2010. *Code of Practice for Design of Piles*. Bureau of Indian Standards.

[5] Chow, Y.K. 1987. “Axial and lateral response of pile groups embedded in non-homogeneous soils.” *International Journal for Numerical and Analytical Methods of Geomechanics.* 11(6): 621-628

[6] Hutton, V.D. 2004. *Fundamentals of Finite element analysis*. New York: McGraw-Hill.

[7] Karthigeyan, S., and Rajgopal, K. 2009. “Lateral Response of 2x2 pile group under combined axial and lateral loading*.” Indian Geotechnical Society, Guntur India*. 665-668.

[8] Leung, C.F., and Chow, Y.K. 1987. “Response of pile groups subjected to lateral loads.” *International Journal for Numerical and Analytical Methods of Geomechanics.* 11(3): 307-314.

[9] Anagnostopoulos, C., and Georgiadis, M. 1993. “Interaction of axial and lateral pile responses.” *Journal of Geotechnical Engineering*. 119(4): 793-798

[10] Holloway, D.M., Moriwaki, Y., Stevens, J.B., and Perez, J.Y. 1981. “Response of pile group to combined axial and lateral load.” *International Conference on Soil Mechanics and Foundation Engineering, Stockholm.* 20(6): 731-734.

[11] Chick, Z.H., Abbas, J.M., and Taha, M.R. 2004. “Lateral behaviour of single pile in cohesionless soil subjected to both vertical and horizontal loads.” *European Journal of Scientific Research.* 29(2): 194-205.

[12] Mohti, A.A., and Khodair, Y. 2014. “Analytical investigation of pile–soil interaction in sand under axial and lateral loads.” *International Journal of Advanced Structural Engineering.* 6(1) DOI 10.1007/s40091-014-0054-5

[13] Stalin, V.K., Priyadharshini, A., Deepan, P., and Abudaheer, A. 2021. “Study on piles subjected to axial and lateral loading.” *In Proc., Indian Geotechnical conference,* 527-541.

[14] Zadeh, N.G., and Kalantari, B. 2011. “Performance of Single Pile under Vertical and Lateral Load in Sand, Clay and Layered Soil.” *European Journal of Government and Economics.* 16: 1131-1146.

[15] Poulos, H.G., and Davis, E.H. 1980. *Pile Foundation Analysis and Design.* New York: Wiley

[16] Satyam, N., and Ramancharla P. 2010. “Numerical analysis of a pile subjected to lateral loads.” *7th European Conference on Numerical Methods in Geotechnical Engineering,* Trondheim.

[17] Rajapakse, R., 2016. *Pile Design and Construction Rules of Thumb*. Oxford, UK: Butterworth- Heinemann.

[18] Basack, S. 2010. “Response of vertical pile group subjected to horizontal cyclic load in soft clay.” *Latin American Journal of Solids and Structures.* 7 (2): 91-103.

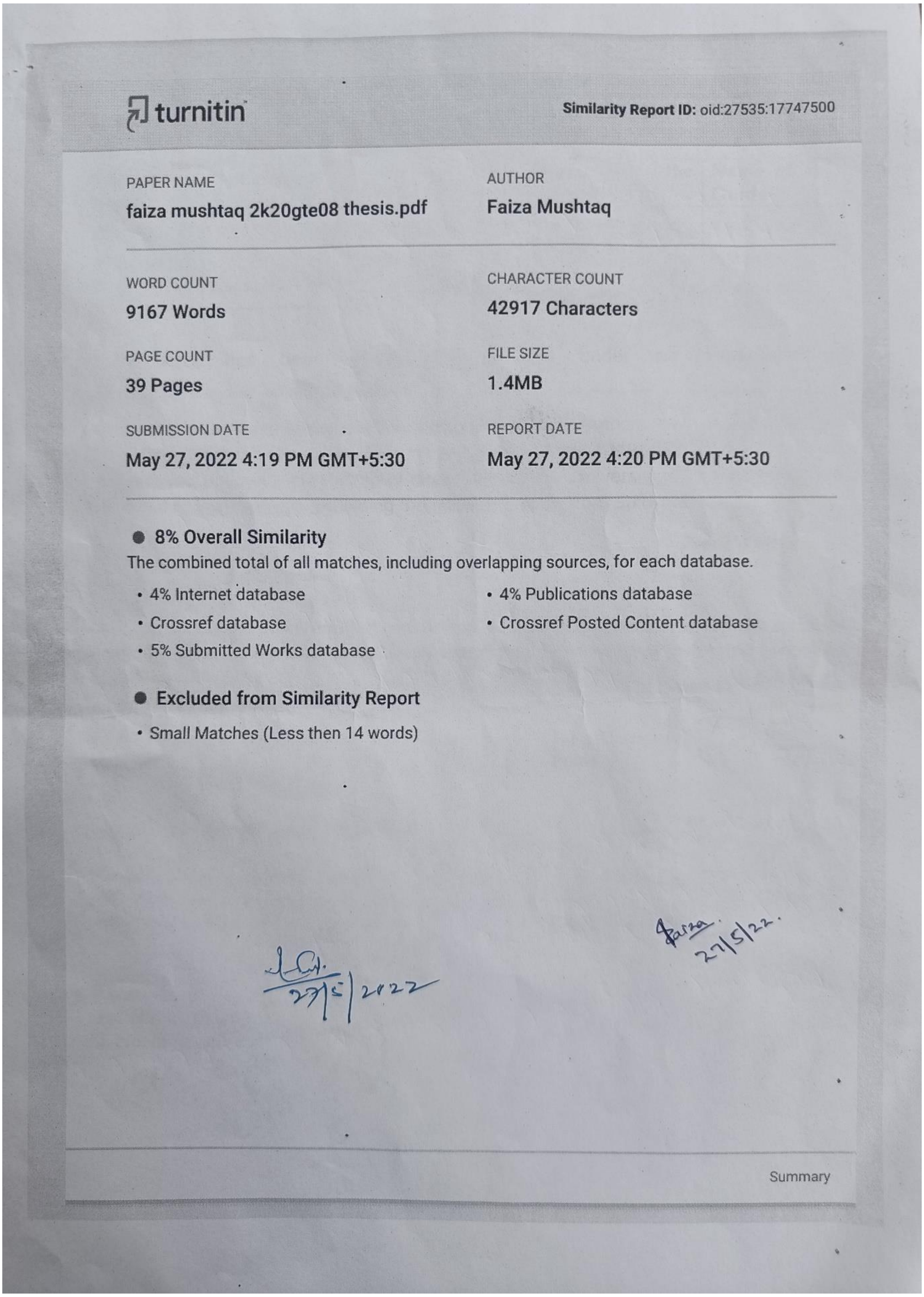
[19] Rajagopal, K., and Karthigeyan, S. 2008. “Influence of combined vertical and lateral loading on lateral response of piles.” *International Association for Computer Methods and Advances in Geomechanics.* 3272-3282.

[20] Patra, N.R., and Pise, P.J. 2001. “Ultimate lateral resistance of pile groups in sand.” *Journal of Geotechnical and Geo-environmental Engineering, Proc. ASCE,* 6: 481-487.

[21]. Rahman, K.A., and Achmus, M. 2006. “Numerical modelling of the combined axial and lateral loading of vertical piles.” *Numerical Methods in Geotechnical Engineering.* 575-581.

[22] Kahribt, M.A., and Abbas, J.M. 2018. “Lateral response of a single pile under combined axial and lateral cyclic loading in sandy soil.” *Civil Engineering Journal.* 4(9): 1996-2010.

[23] Trivedi A. 2010. “Strength and dilatancy of jointed rocks with granular fill” *Acta Geotechnica Journal.* 5(1): 15-31.



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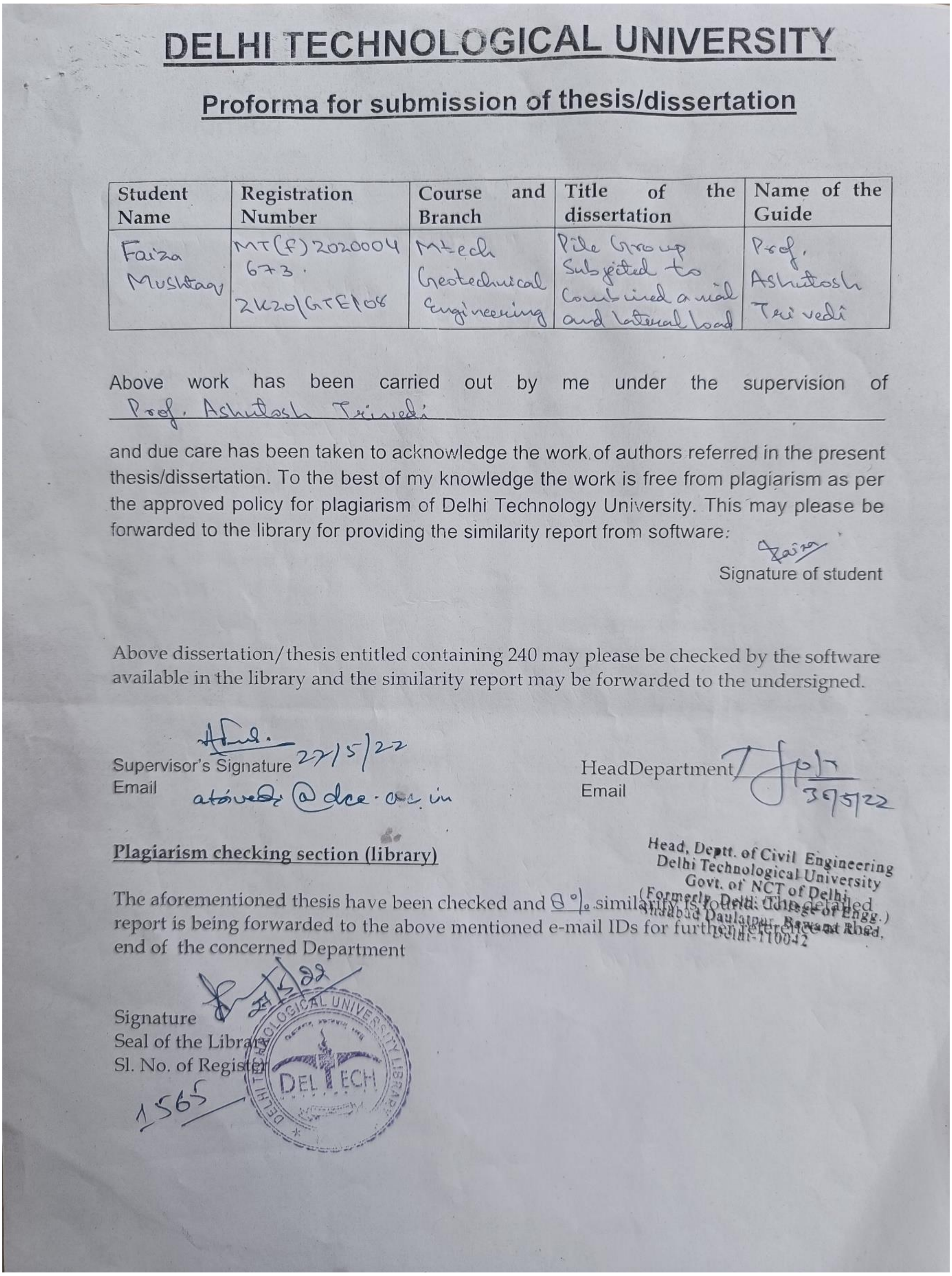

DELHI TECHNOLOGICAL UNIVERSITY

Proforma for submission of thesis/dissertation

Student Name	Registration Number	Course and Branch	Title of the dissertation	Name of the Guide
Faiza Mushtaq	MT(F)2020004673. 2K20/GTE/08	M.tech Geotechnical Engineering	Pile Group Subjected to Combined axial and lateral load	Prof. Ashutosh Trivedi

Above work has been carried out by me under the supervision of Prof. Ashutosh Trivedi and due care has been taken to acknowledge the work of authors referred in the present thesis/dissertation. To the best of my knowledge the work is free from plagiarism as per the approved policy for plagiarism of Delhi Technology University. This may please be forwarded to the library for providing the similarity report from software.

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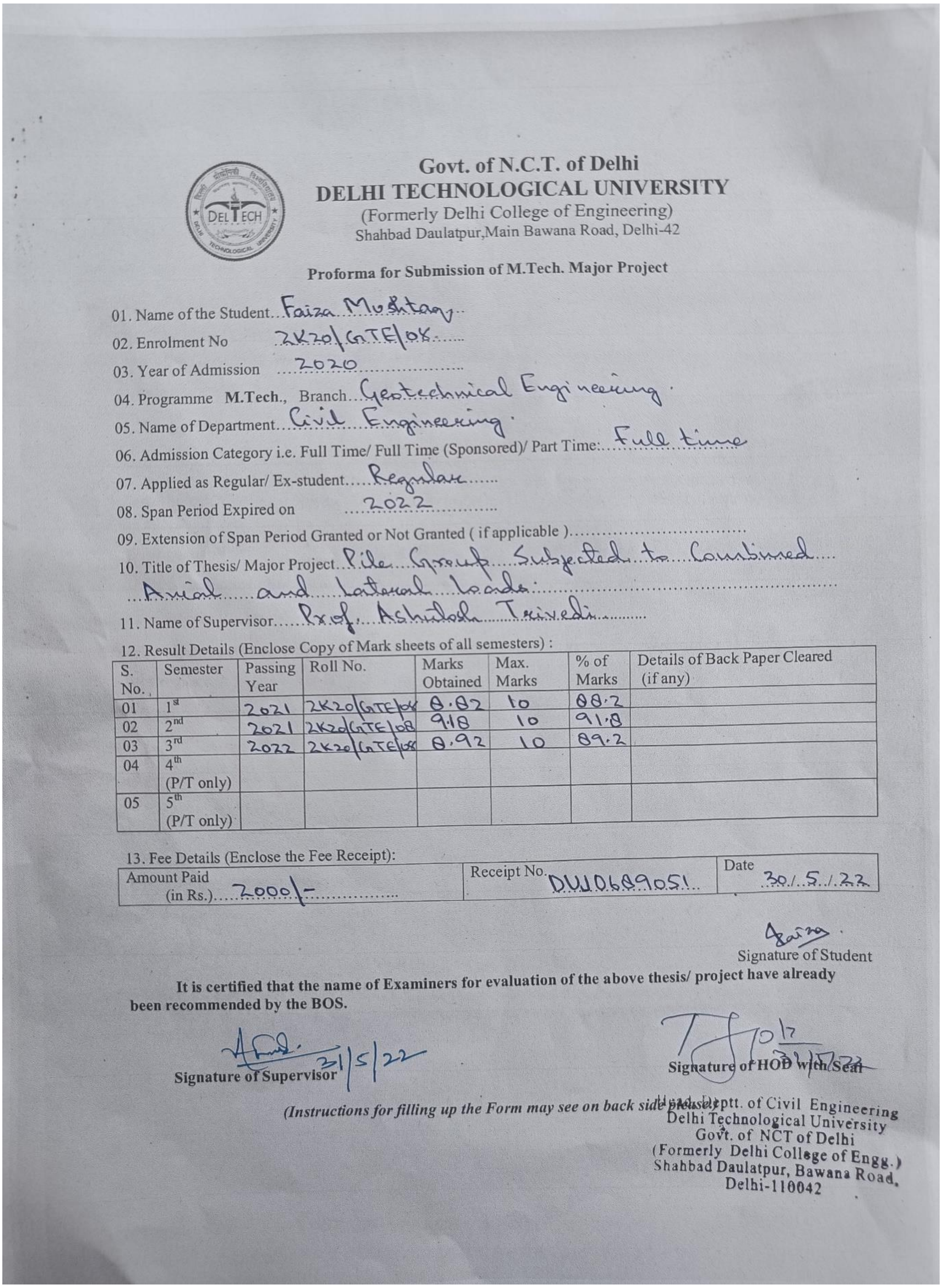

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DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur,Main Bawana Road, Delhi-42

Proforma for Submission of M.Tech. Major Project

01. Name of the Student Faiza Mushtaq
02. Enrolment No 2K20/GTE/08
03. Year of Admission 2020
04. Programme **M.Tech.**, Branch Geotechnical Engineering.
05. Name of Department Civil Engineering.
06. Admission Category i.e. Full Time/ Full Time (Sponsored)/ Part Time: Full time
07. Applied as Regular/ Ex-student Regular
08. Span Period Expired on 2022
09. Extension of Span Period Granted or Not Granted (if applicable)
10. Title of Thesis/ Major Project Pile Group Subjected to Combined Axial and Lateral loads.
11. Name of Supervisor Prof. Ashutosh Trivedi

12. Result Details (Enclose Copy of Mark sheets of all semesters) :

S. No.	Semester	Passing Year	Roll No.	Marks Obtained	Max. Marks	% of Marks	Details of Back Paper Cleared (if any)
01	1st	2021	2K20/GTE/08	8.82	10	88.2	
02	2nd	2021	2K20/GTE/08	9.18	10	91.8	
03	3rd	2022	2K20/GTE/08	8.92	10	89.2	
04	4th (P/T only)						
05	5th (P/T only)						

13. Fee Details (Enclose the Fee Receipt):

Amount Paid (in Rs.) 2000/-	Receipt No. DUJ0689051	Date 30/5/22

Faiza
Signature of Student

It is certified that the name of Examiners for evaluation of the above thesis/ project have already been recommended by the BOS.

31/5/22
Signature of Supervisor

Signature of HOD with Seal

(Instructions for filling up the Form may see on back side please)

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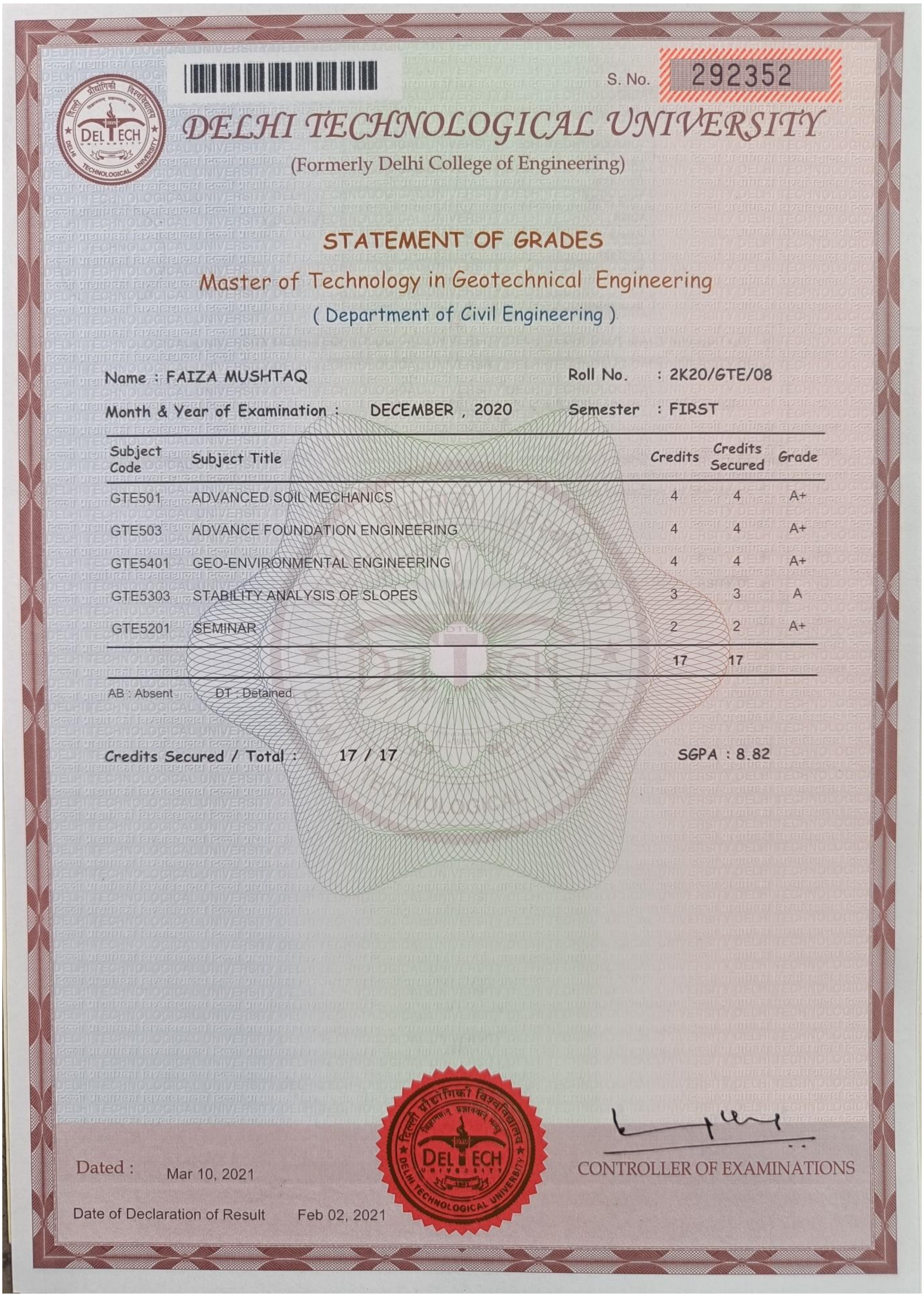

S. No. 292352

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

STATEMENT OF GRADES

Master of Technology in Geotechnical Engineering

(Department of Civil Engineering)

Name : FAIZA MUSHTAQ
Roll No. : 2K20/GTE/08

Month & Year of Examination : DECEMBER , 2020
Semester : FIRST

Subject Code	Subject Title	Credits	Credits Secured	Grade
GTE501	ADVANCED SOIL MECHANICS	4	4	A+
GTE503	ADVANCE FOUNDATION ENGINEERING	4	4	A+
GTE5401	GEO-ENVIRONMENTAL ENGINEERING	4	4	A+
GTE5303	STABILITY ANALYSIS OF SLOPES	3	3	A
GTE5201	SEMINAR	2	2	A+
		17	17	

AB : Absent DT : Detained

Credits Secured / Total : 17 / 17
SGPA : 8.82

Dated : Mar 10, 2021

Date of Declaration of Result Feb 02, 2021

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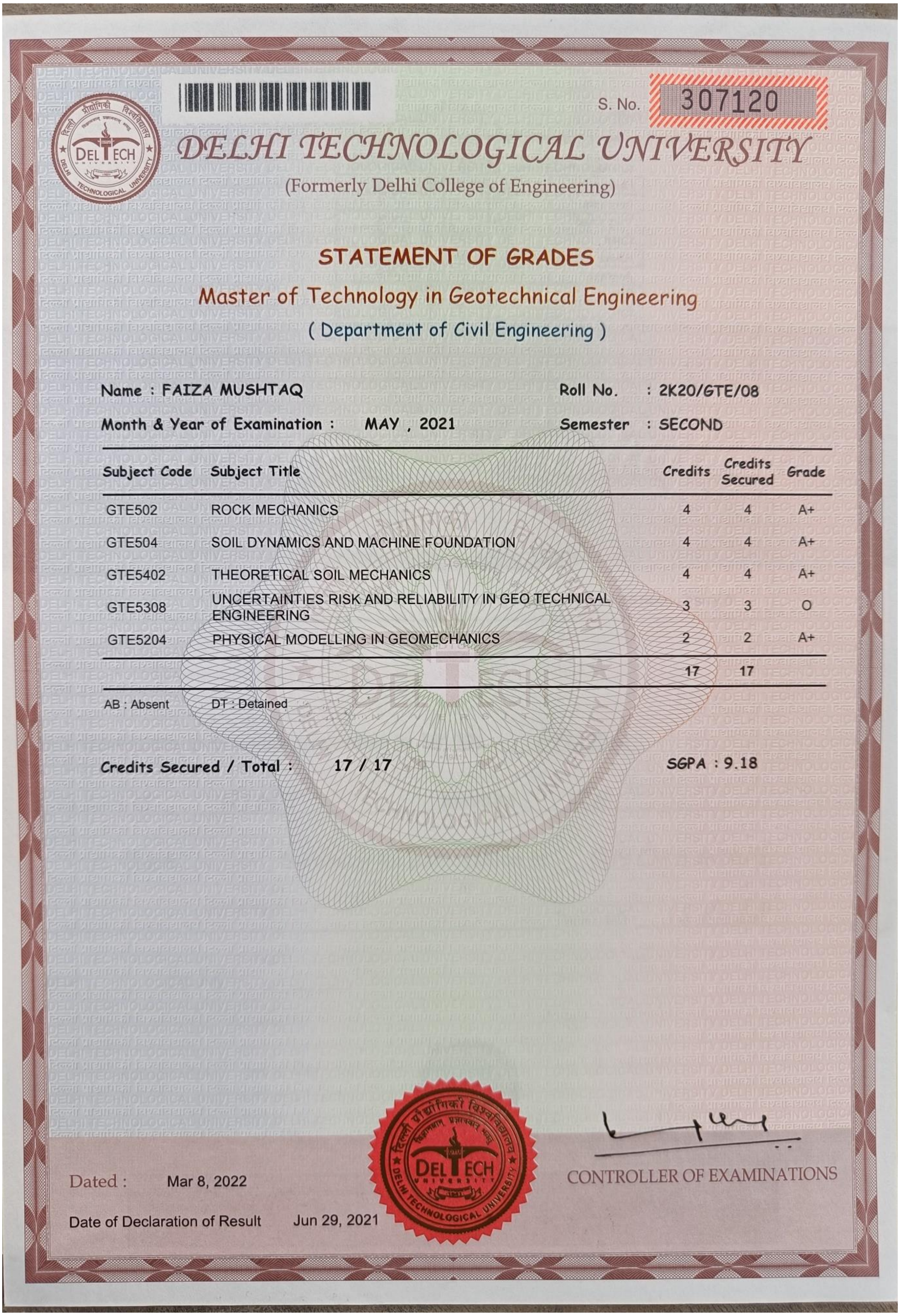

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DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

STATEMENT OF GRADES

Master of Technology in Geotechnical Engineering

(Department of Civil Engineering)

Name : FAIZA MUSHTAQ **Roll No. : 2K20/GTE/08**

Month & Year of Examination : MAY , 2021 **Semester : SECOND**

Subject Code	Subject Title	Credits	Credits Secured	Grade
GTE502	ROCK MECHANICS	4	4	A+
GTE504	SOIL DYNAMICS AND MACHINE FOUNDATION	4	4	A+
GTE5402	THEORETICAL SOIL MECHANICS	4	4	A+
GTE5308	UNCERTAINTIES RISK AND RELIABILITY IN GEO TECHNICAL ENGINEERING	3	3	O
GTE5204	PHYSICAL MODELLING IN GEOMECHANICS	2	2	A+
		17	17	

AB : Absent DT : Detained

Credits Secured / Total : 17 / 17 **SGPA : 9.18**

Dated : Mar 8, 2022

Date of Declaration of Result Jun 29, 2021

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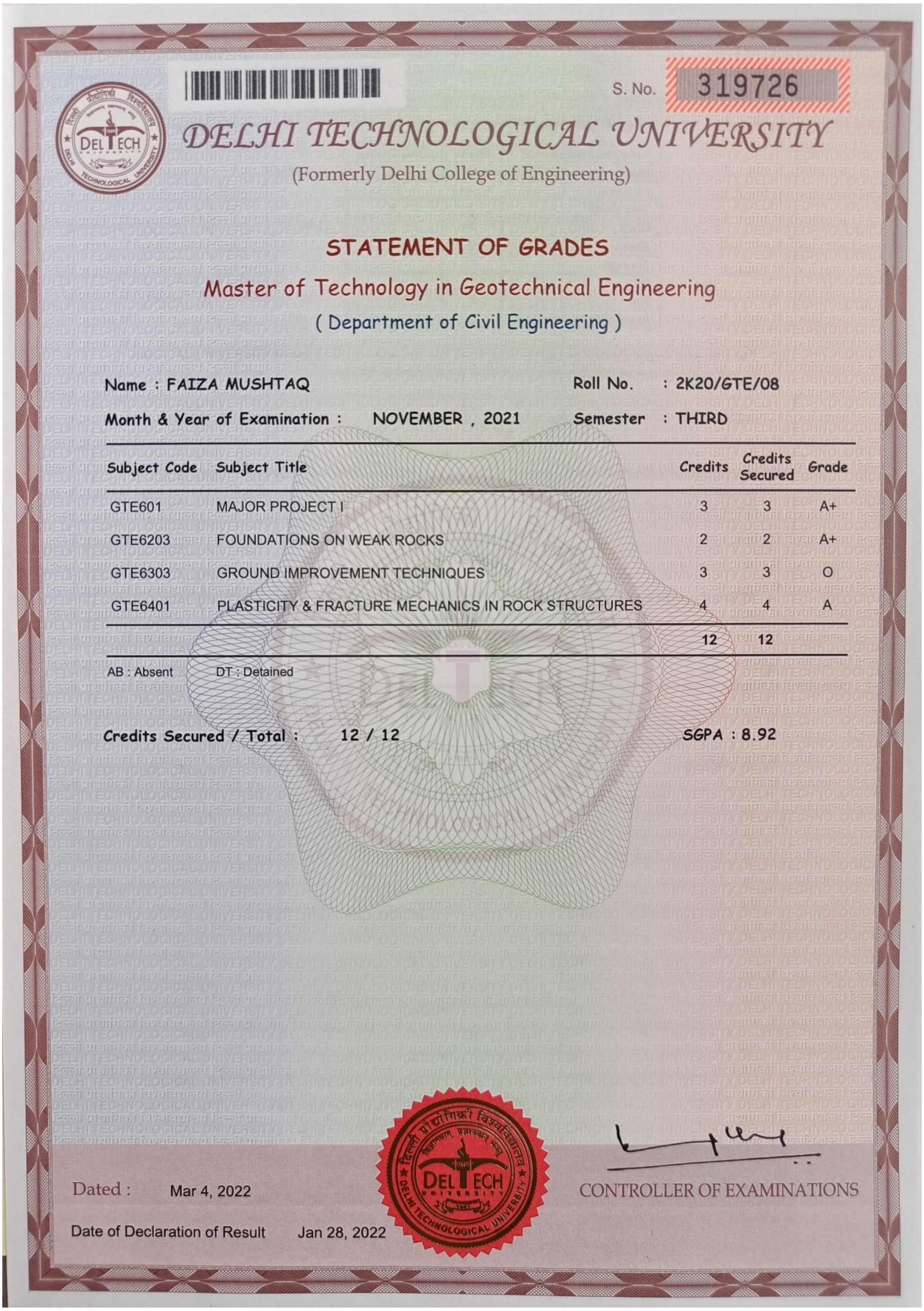

S. No. 319726

DELHI TECHNOLOGICAL UNIVERSITY

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STATEMENT OF GRADES

Master of Technology in Geotechnical Engineering

(Department of Civil Engineering)

Name : FAIZA MUSHTAQ **Roll No.** : 2K20/GTE/08

Month & Year of Examination : NOVEMBER , 2021 **Semester** : THIRD

Subject Code	Subject Title	Credits	Credits Secured	Grade
GTE601	MAJOR PROJECT I	3	3	A+
GTE6203	FOUNDATIONS ON WEAK ROCKS	2	2	A+
GTE6303	GROUND IMPROVEMENT TECHNIQUES	3	3	O
GTE6401	PLASTICITY & FRACTURE MECHANICS IN ROCK STRUCTURES	4	4	A
		12	12	

AB : Absent DT : Detained

Credits Secured / Total : 12 / 12 **SGPA :** 8.92

Dated : Mar 4, 2022

Date of Declaration of Result Jan 28, 2022

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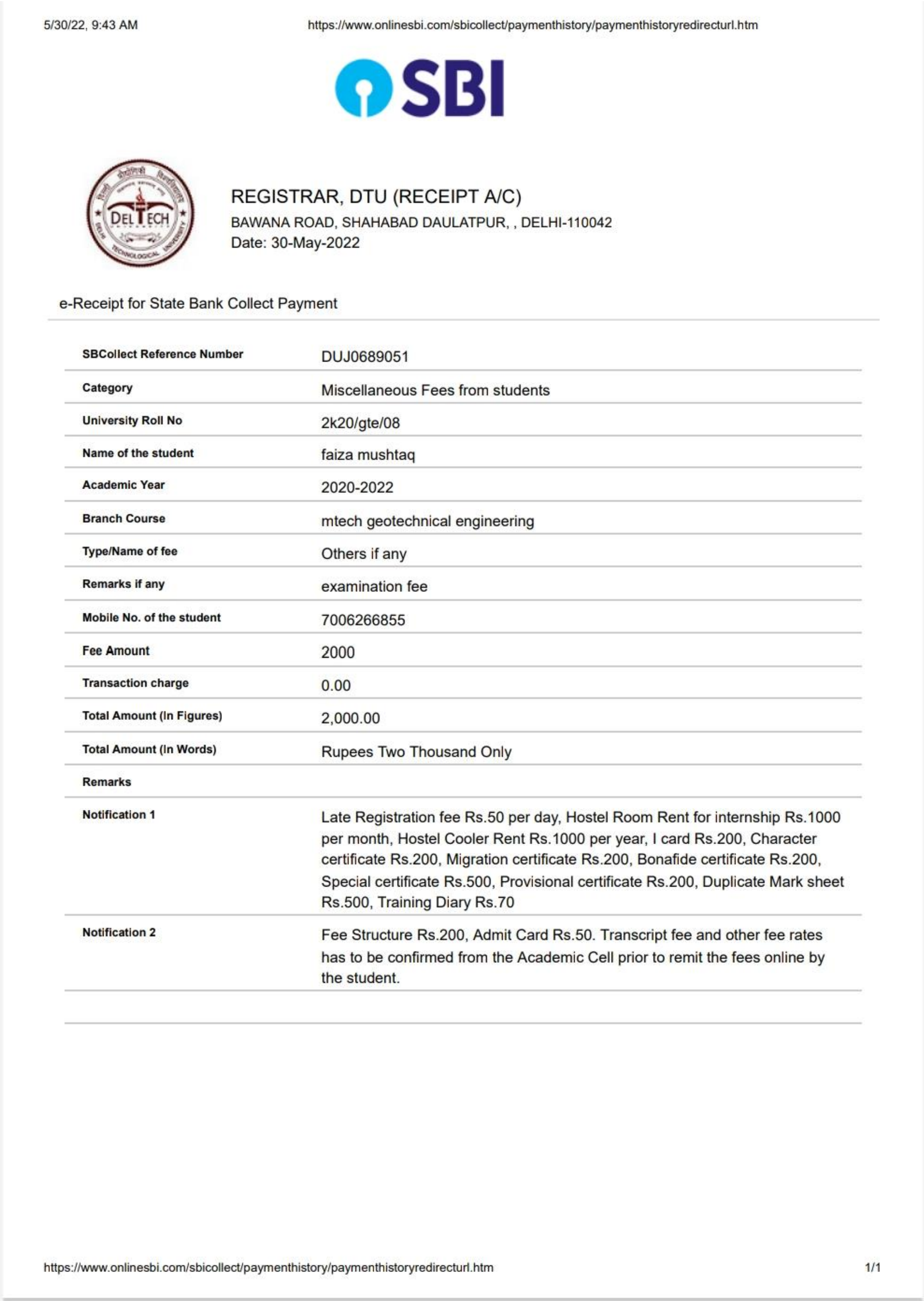

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University Roll No	2k20/gte/08
Name of the student	faiza mushtaq
Academic Year	2020-2022
Branch Course	mtech geotechnical engineering
Type/Name of fee	Others if any
Remarks if any	examination fee
Mobile No. of the student	7006266855
Fee Amount	2000
Transaction charge	0.00
Total Amount (In Figures)	2,000.00
Total Amount (In Words)	Rupees Two Thousand Only
Remarks	
Notification 1	Late Registration fee Rs.50 per day, Hostel Room Rent for internship Rs.1000 per month, Hostel Cooler Rent Rs.1000 per year, I card Rs.200, Character certificate Rs.200, Migration certificate Rs.200, Bonafide certificate Rs.200, Special certificate Rs.500, Provisional certificate Rs.200, Duplicate Mark sheet Rs.500, Training Diary Rs.70
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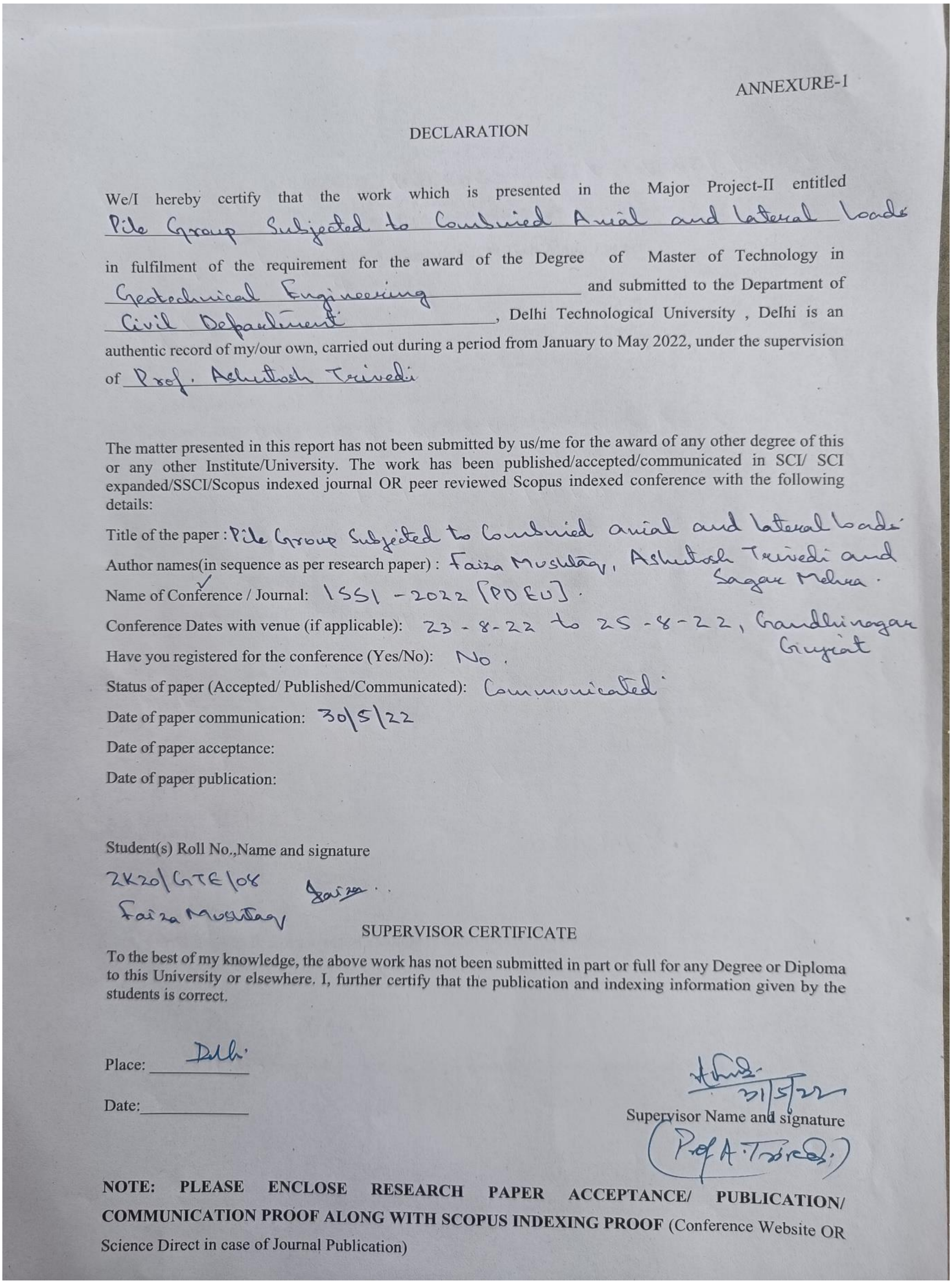

ANNEXURE-I

DECLARATION

We/I hereby certify that the work which is presented in the Major Project-II entitled Pile Group Subjected to Combined Axial and lateral loads in fulfilment of the requirement for the award of the Degree of Master of Technology in Geotechnical Engineering and submitted to the Department of Civil Department, Delhi Technological University, Delhi is an authentic record of my/our own, carried out during a period from January to May 2022, under the supervision of Prof. Ashutosh Trivedi

The matter presented in this report has not been submitted by us/me for the award of any other degree of this or any other Institute/University. The work has been published/accepted/communicated in SCI/ SCI expanded/SSCI/Scopus indexed journal OR peer reviewed Scopus indexed conference with the following details:

Title of the paper : Pile Group Subjected to Combined axial and lateral loads.

Author names(in sequence as per research paper) : Faiza Mushtaq, Ashutosh Trivedi and Sagar Mehra.

Name of Conference ✓ / Journal: ISSI - 2022 [PDEU].

Conference Dates with venue (if applicable): 23-8-22 to 25-8-22, Gandhinagar Gujrat

Have you registered for the conference (Yes/No): No.

Status of paper (Accepted/ Published/Communicated): Communicated.

Date of paper communication: 30/5/22

Date of paper acceptance:

Date of paper publication:

Student(s) Roll No.,Name and signature

2K20/GTE/08

Faiza Mushtaq

Faiza

SUPERVISOR CERTIFICATE

To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I, further certify that the publication and indexing information given by the students is correct.

Place: Delhi

Date:

31/5/22

Supervisor Name and signature

(Prof A. Trivedi)

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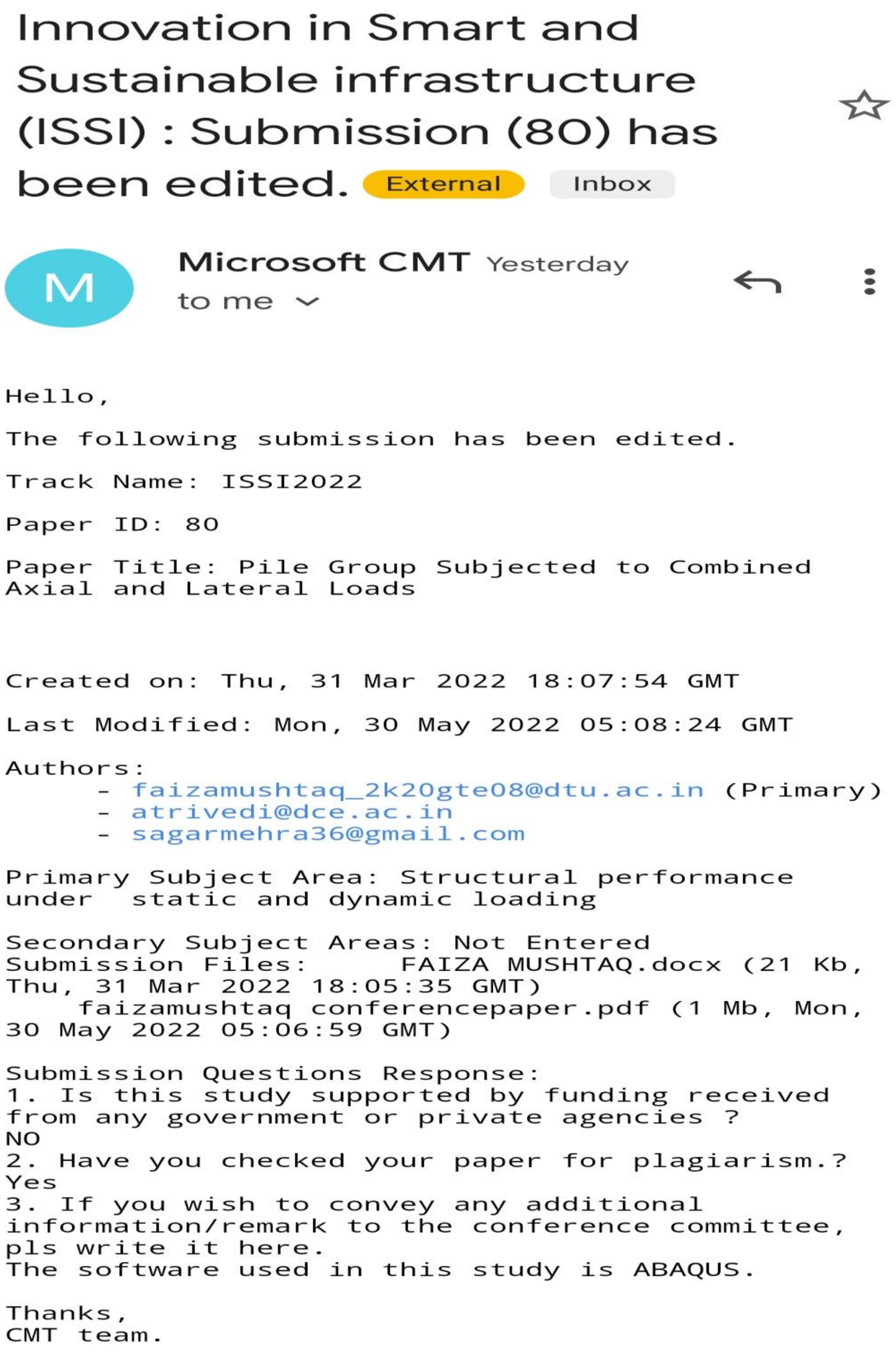

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Track Name: ISSI2022

Paper ID: 80

Paper Title: Pile Group Subjected to Combined Axial and Lateral Loads

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Last Modified: Mon, 30 May 2022 05:08:24 GMT

Authors:
- faizamushtaq_2k20gte08@dtu.ac.in (Primary)
- atrivedi@dce.ac.in
- sagarmehra36@gmail.com

Primary Subject Area: Structural performance under static and dynamic loading

Secondary Subject Areas: Not Entered
Submission Files: FAIZA MUSHTAQ.docx (21 Kb, Thu, 31 Mar 2022 18:05:35 GMT)
faizamushtaq conferencepaper.pdf (1 Mb, Mon, 30 May 2022 05:06:59 GMT)

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1. Is this study supported by funding received from any government or private agencies ?
NO
2. Have you checked your paper for plagiarism.?
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3. If you wish to convey any additional information/remark to the conference committee, pls write it here.
The software used in this study is ABAQUS.

Thanks,
CMT team.