Stability Enhancement of Existing Cantilever Retaining Wall

By

Saria Khan

(Registration No: 326937)

Department of Geotechnical Engineering

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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By

Saria Khan

(Registration No: NUST-2020-MS GEOTECH-0000326937)

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Thesis Supervisor: Dr. Abbas Haider

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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Signature (HOD): ____________

HoD Geotechnical Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Date: 8/7/2024

Signature (Associate Dean): ____________

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

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Principal & Dean
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1. Name: Dr. Badee Alshameri Signature: ____________

2. Name: Dr. Zain Maqsood Signature: ____________

Supervisor's name: Dr. Abbas Haider Signature: ____________

Head of Department

HoD [illegible] Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

(Associate Dean)

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

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Student Name: **Saria Khan** Signature:____________

Examination Committee:

a) **Dr. Badee Alshameri** Signature:____________
HOD Geotechnical Engineering
(SCEE, NUST)

b) **Dr. Zain Maqsood** Signature:____________
(Assistant Professor, SCEE, NUST)

Dr. Abbas Haider Signature:____________
(Supervisor)

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ivil & Environmental Engineering
al University of Sciences and Technology

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Associate Dean: Dr. Syed Muhammad Jamil Signature:____________

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

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ABSTRACT

Start typing the abstract here. The increased surcharge on existing retaining walls, resulting from new infrastructure or pavement construction, heightens lateral pressure and may destabilize the retaining wall. Researchers explored various techniques like relief shelves, EPS geofoam, and soil reinforcement to address high lateral earth pressure, but found them impractical for existing retaining walls. This study aims to evaluate the feasibility and effectiveness of vertical plate anchors for stabilizing existing cantilever retaining walls. In this study, Redistribution of lateral earth pressure of existing cantilever retaining wall with and without vertical plate anchors has been evaluated using FEM on Plaxis 2D. In the parametric analysis, different models were examined to explore the impact of geometrical and soil strength parameters on the Factor of Safety (FOS) of the cantilever retaining wall. Based on the findings of this study, the use of a vertical plate anchor can significantly enhance the stability of the wall. The FEM model's validation involves comparing lateral earth pressure values obtained from PLAXIS program with the analytical equations. Non-linear regression analysis using a polynomial regression model was performed to predict the Factor of Safety (FOS). The predicted FOS values showed a high level of accuracy when compared to those determined by Plaxis 2D.

Key words: Finite element method, parametric analysis, Retaining wall, Surcharge load · Vertical plate anchor, Non-linear regression analysis.

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LIST OF SYMBOLS & ABBREVIATION

Pa	Active earth pressure
P	Total lateral thrust
$\emptyset$	Angle of internal friction
c	Cohesion
FOS	Factor of safety
γ	Unit weight
ψ	Angle of dilatancy
E	Young’s modulus
K0	Coefficient of earth pressure at rest
Ka	Coefficient of active earth pressure
v	Poisson’s ratio
θ	Angle of failure plane with horizontal
T	Thickness of base slab of retaining wall
H	Height of retaining wall
EA	Axial stiffness
EI	Bending stiffness
FEM	Finite Element Method
d	Thickness of plate element in Plaxis
ML	Machine Learning
SVM	Support Vector Machine

CHAPTER: 1 INTRODUCTION

1.1 General

Cantilever retaining walls have played a pivotal role in civil engineering, providing essential lateral support for excavations, slopes, and embankments. Historically, their development has evolved from basic gravity walls to more sophisticated designs capable of withstanding significant earth pressures. The primary design principles of cantilever retaining walls involve leveraging the weight of the wall itself, combined with the properties of the retained soil, to resist lateral forces. Common materials used in their construction include reinforced concrete, which offers both strength and durability. Basic cross-section of cantilever retaining wall is shown in the Figure 1.1. Despite their widespread application, these structures are not without challenges. Typical failure mechanisms include overturning, sliding, and structural failure due to excessive lateral earth pressure.

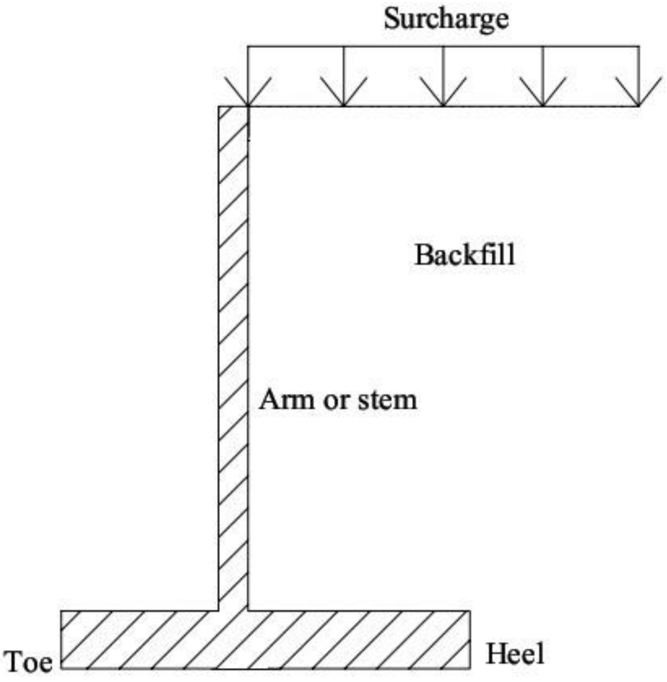


Figure 1.1 General Cross section of Cantilever retaining wall

Additionally, stability issues often arise from inadequate design, construction errors, or changes in the surrounding environment, such as increased surcharge loads from new infrastructure developments. Understanding these aspects is crucial for developing effective stabilization strategies, particularly for existing retaining walls subjected to increased lateral earth pressures.

1.2 Stability issues of Retaining walls

Stabilizing existing cantilever retaining walls poses significant challenges in modern civil engineering practice, exacerbated by escalating lateral earth pressures induced by new constructions and urban developments. These pressures often exceed the design capacities of traditional stabilization methods, necessitating innovative approaches to ensure long-term structural integrity.

Traditional methods, such as relief shelves and soil reinforcement with geogrids or soil nails, have inherent limitations that hinder their effectiveness in retrofitting existing walls. Relief shelves, for instance, redistribute lateral earth pressures but are constrained by their application feasibility and cost-effectiveness, especially in densely populated urban environments.

The introduction of new infrastructures and facilities adjacent to existing retaining walls amplifies these challenges, increasing the risk of instability and structural failure. This scenario demands adaptive solutions capable of accommodating varying soil conditions, site constraints, and project timelines without compromising safety or operational continuity.

Moreover, the spatial constraints inherent in urban settings often restrict the implementation of conventional stabilization techniques. The need to minimize disruption to existing infrastructure and surrounding environments further complicates the retrofitting process, necessitating solutions that are both efficient and minimally invasive.

Addressing these challenges requires a paradigm shift towards more robust and versatile stabilization methods, such as vertical plate anchors. These anchors offer a promising alternative by effectively transferring lateral pressures deeper into stable soil layers, thereby enhancing the overall stability and load-bearing capacity of existing retaining walls.

Recognizing the existing research gap in the application of embedded plate anchors to enhance stability in earth retention systems, this study employs numerical simulation using the adaptive finite element method to investigate optimal parameters for vertical plate anchors embedded behind cantilever retaining walls. The primary objective is to evaluate the feasibility of reinforcing a cantilever retaining wall using vertical plate anchors. The study aims to determine the optimal position and length of tie rods for the plate anchor. Additionally, it proposes the use of machine learning methods to predict the factor of safety with and without vertical plate anchor, and to assess how effectively the wall can withstand surcharges across different parameter variations. This research seeks to advance understanding and provide practical insights into optimizing plate anchor systems for improving the stability and load-bearing capacity of retaining walls under surcharge conditions.

1.3 Vertical plate anchors

Vertical plate anchors have emerged as a promising innovation in the field of civil engineering, offering a robust solution for stabilizing retaining walls amidst increasing urbanization and infrastructure development. Originating from maritime and foundation engineering practices, these anchors have transitioned into land-based applications, demonstrating versatility and effectiveness in diverse structural contexts.

Historically, vertical plate anchors were initially employed to secure marine structures and foundations against lateral forces. Their adaptation for use in land-based structures has proven transformative, particularly in stabilizing basement walls and other critical infrastructure susceptible to lateral earth pressures.

Recent applications of vertical plate anchors showcase their efficacy in enhancing the stability of retaining walls compared to traditional methods. Unlike relief shelves, which redistribute lateral pressures superficially, and soil reinforcement techniques like geogrids or soil nails, which require extensive excavation and backfilling, vertical plate anchors penetrate deep into stable soil layers. This method effectively transfers loads away from the wall face, thereby reducing the risk of structural failure and improving long-term performance.

The advantages of vertical plate anchors lie in their ability to provide robust reinforcement without significantly altering existing wall configurations or adjacent environments. This minimally invasive approach is particularly advantageous in urban settings where space constraints and operational continuity are critical considerations.

By leveraging vertical plate anchors, engineers can optimize structural stability while reducing construction costs and environmental impact. Their adoption signifies a shift towards sustainable engineering practices that prioritize efficiency, durability, and adaptability in retaining wall design and retrofitting projects.

Through an exploration of their historical evolution, contemporary applications, and comparative advantages over conventional methods, this study aims to evaluate the feasibility and effectiveness of vertical plate anchors in enhancing the resilience of existing cantilever retaining walls. By doing so, it seeks to contribute to the advancement of engineering solutions that address modern challenges in urban infrastructure development.

1.4 Problem statement

Existing cantilever retaining walls often face increased lateral earth pressure due to new infrastructure developments, leading to potential stability issues. Traditional methods like relief shelves, EPS geofoam, and soil reinforcement are impractical for retrofitting these walls due to high costs and construction complexities. Additionally, these methods often require significant space and can disrupt existing facilities, making them unsuitable for many urban and confined settings. The need for an effective, practical solution to enhance the stability of existing cantilever retaining walls is critical. Plate anchors have emerged as a potential solution to address these limitations and ability to stabilize existing retaining walls. However, the feasibility and effectiveness of these anchors for stabilizing existing cantilever retaining walls have not been thoroughly investigated. There is a lack of comprehensive guidelines on the optimal design and placement of vertical plate anchors for this purpose. This study aims to fill this gap by evaluating the potential of vertical plate anchors to improve the stability of existing cantilever retaining walls using Finite Element Method (FEM) analysis and developing practical design recommendations.

1.5 Aims and Objectives

- To analyze the redistribution of lateral earth pressure for existing cantilever retaining wall with and without vertical plate anchors.
- To perform a parametric analysis using PLAXIS to investigate the effects of geometrical & soil strength parameters on the FOS of the cantilever retaining wall.
- To develop an Artificial Neural Network (ANN) model for the FOS prediction using python.

CHAPTER: 2 LITERATURE REVIEW

2.1 General

The significance of cantilever retaining walls lies in their ability to resist the lateral pressure exerted by soil and retained materials. By distributing forces effectively through their structure, these walls mitigate risks of collapse and ensure the integrity of adjacent structures and environments. This role is particularly critical in urban settings here space constraints and soil conditions present constant challenges to infrastructure development.

In addressing these challenges, engineers have continuously refined the design and construction of cantilever walls, integrating advanced materials such as reinforced concrete and steel. These improvements enhance durability and structural integrity while accommodating diverse environmental conditions and project requirements. As such, understanding the historical evolution and contemporary applications of these walls provides a foundation for exploring innovative methods, such as vertical plate anchors, to further enhance their performance and sustainability in modern civil engineering practice.

The construction of new infrastructure, pavements, or similar facilities adjacent to preexisting retaining walls increases the surcharge on the backfill surface, resulting in increased lateral thrust on the wall. In these scenarios, the existing cross-section of the wall stem may be inadequate to withstand the internal stresses generated by the additional lateral earth pressure induced by the surcharge. To address this issue, one conventional solution is to revise the cross-section of the existing wall or to provide a buttress wall. However, these measures significantly increase overall costs and can disrupt existing traffic on the non-backfill side during construction or maintenance, if such traffic exists. Additionally, space constraints on the non-backfill side often preclude these methods. An alternative approach is to stabilize the wall stem using soil nailing, which can mitigate deformation(Srinivasa Murthy et al., 2002). Nonetheless, the effectiveness of soil nailing as a retrofitting technique is contingent on the availability of suitable backfill material(Jaiswal et al., 2022), thereby limiting the feasibility of this method in certain situations.

To mitigate the lateral thrust on retaining walls, researchers have proposed the use of relief shelves(Chauhan, 2021; Chauhan & Dasaka, 2018, 2022) or the insertion of expanded polystyrene geofoam between the wall and backfill (Dasaka et al., 2014). However, these approaches often face practical challenges and high costs. To overcome these limitations, plate anchors have been identified as a viable solution for stabilizing existing walls(Hua et al., 1987a; Moghadam et al., 2019; Trandafir et al., 2009). By embedding single or multiple plate anchors, lateral thrust can be transferred to stabilized soil, enhancing wall stability. The cost-effectiveness of plate anchors is influenced by factors such as the length of the tie rod and the depth of the plate anchor from the backfill ground level. These parameters dictate the internal resistance (shear force and bending moment) generated within the embedded plate anchor system and the potential failure plane of the retained backfill behind the wall. While several studies have examined the behavior of plate anchors in retaining walls (Hua et al., 1987b; Moghadam et al., 2019), they do not sufficiently address the optimal specifications for tie rod length or plate anchor depth from the backfill ground level to maximize the effectiveness of an earth retention system under surcharge loading.

2.2 Methods to stabilize Retaining Walls

Stabilizing existing cantilever retaining walls presents unique challenges, especially in urban settings where increased lateral earth pressure due to new constructions can increase stability issues. Traditional stabilization methods, such as relief shelves, EPS geofoam, and soil reinforcement, often prove impractical for retrofitting existing walls due to their high costs, construction complexities, and space constraints. Moreover, implementing these methods can cause significant disruption to existing facilities and traffic on the non-backfill side of the wall. These limitations underscore the need for innovative, cost-effective solutions that can be applied without extensive reconstruction or disturbance. The emergence of vertical plate anchors as a potential stabilization method offers a promising alternative, necessitating thorough investigation into their effectiveness and practical application.

Several existing techniques have been explored to stabilize retaining walls, each with its own set of advantages and limitations. Relief shelves, for instance, are designed to reduce lateral earth pressure by altering the load distribution on the wall; however, their effectiveness is often limited by construction challenges and high implementation costs. EPS geofoam, known for its lightweight and compressible properties, provides another option by decreasing the overall pressure on the wall, though its application is hindered by cost and long-term durability concerns. Soil reinforcement methods, including geogrids and soil nails, enhance the shear strength of the retained soil but require extensive installation efforts and may not be suitable for all soil types. Buttress walls offer additional support by increasing the cross-sectional area of the wall, yet they demand substantial space and can significantly disrupt existing infrastructures during construction.

2.3 Failure plane of the active wedge

The failure plane of the active wedge in the context of a retaining wall is a critical concept in geotechnical engineering. When a retaining wall is subjected to lateral earth pressures, the soil behind the wall can potentially fail along a specific plane known as the failure plane. Here's an overview of the key concepts:

2.3.1 Active Earth Pressure

When the retaining wall moves away from the backfill soil (typically rotating about its base), it relieves pressure, causing the soil to exert less force on the wall. This condition is known as the active state, and the corresponding lateral earth pressure is called active earth pressure.

2.3.2 Failure Plane

The failure plane, also known as the slip plane or rupture surface, is the surface along which the soil mass fails and slides. For the active wedge, this plane typically forms at an angle where the soil shear strength is mobilized to resist the movement.

2.3.3 Angle of Failure Plane

In classical soil mechanics, the angle of the failure plane can be approximated using Rankine's theory. According to this theory, the failure plane for the active wedge in cohesionless soil forms an angle with the horizontal given by:

$$\theta = 45° + \frac{\emptyset}{2} \tag{2.1}$$

2.4 Understanding the Geometry of the Failure Wedge

2.4.1 Active Wedge Shape

The active wedge is typically triangular, with the retaining wall forming one boundary, the ground surface forming another, and the failure plane forming the hypotenuse as shown in Figure 2.1.

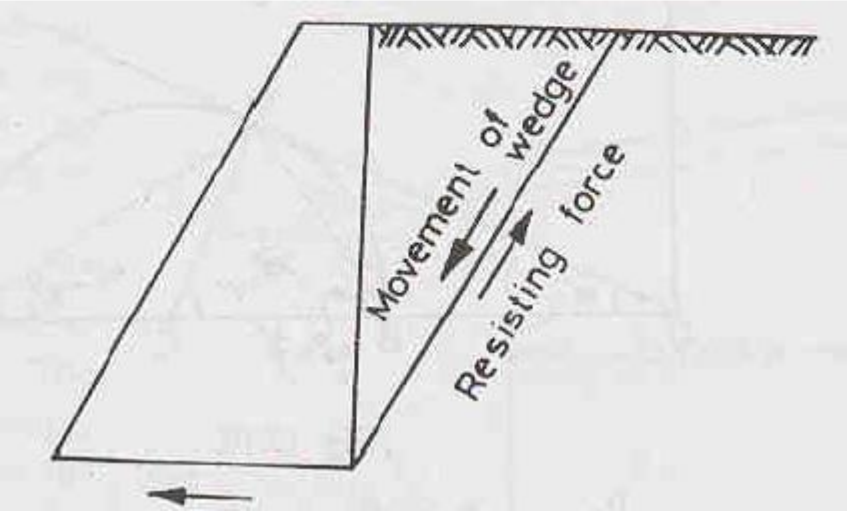


Figure 2.1 Triangular soil wedge in Rankine active state

(Soil Mechanics and Foundation Engineering By Dr K.R. Arora - Civilenggforall, N.D.)

2.4.2 Stress Distribution

The lateral earth pressure varies along the height of the retaining wall, with the maximum pressure at the base. The distribution of this pressure is typically triangular for the active state.

2.5 Factors Influencing the Failure Plane

2.5.1 Soil Properties

The internal friction angle (ϕ\phiϕ) and cohesion of the soil are primary factors. Cohesive soils will have different failure plane characteristics compared to cohesionless soils.

2.5.2 Wall Movement

The magnitude and direction of wall movement influence whether the soil reaches an active state. Sufficient wall movement is necessary to mobilize the active earth pressure conditions.

2.5.3 Backfill Geometry

The slope and type of the backfill can affect the orientation and length of the failure plane.

2.6 Rankine's Theory for Cohesionless Soil and Level Backfill

2.6.1 Assumptions

- The soil is cohesionless, meaning the cohesion (ccc) is zero.
- The backfill surface is level (horizontal).
- The wall is smooth and vertical.
- The soil is homogeneous and isotropic.
- The failure plane develops at an angle determined by the soil's internal friction angle (ϕ\phiϕ).

For a cohesionless soil, the angle of the failure plane with respect to the horizontal can be determined using Rankine’s theory:

$$\theta = 45° + \frac{\emptyset}{2} \qquad 2.2$$

2.7 Use of vertical plate anchors

Vertical plate anchors represent a modern approach to stabilizing retaining walls, leveraging historical principles adapted for contemporary engineering challenges. Originally developed to secure marine structures and foundations, vertical plate anchors have transitioned to land-based applications, particularly in stabilizing basement walls and other structures susceptible to lateral earth pressure. Their versatility and effectiveness stem from their ability to transfer loads deeper into stable soil layers, reducing the reliance on surface-level reinforcements.

Recent applications of vertical plate anchors highlight their success in enhancing the stability of retaining structures while minimizing the disruptive impact on surrounding environments. This method has been particularly effective in urban settings where space constraints and existing infrastructure limit the feasibility of traditional stabilization techniques. By distributing forces more efficiently and reducing overall structural loads, vertical plate anchors offer significant advantages over relief shelves, EPS geofoam, and other conventional methods.

The mechanism of action behind vertical plate anchors involves embedding steel plates vertically into the soil behind the retaining wall. These plates are connected to tie rods that extend into the wall, creating a secure anchor point. When lateral earth pressure applies force to the wall, the anchors resist these forces by transferring them through the plates and tie rods into the deeper, more stable soil layers. This load transfer principle enhances the wall's overall stability and reduces the risk of failure under surcharge loads, making vertical plate anchors a reliable choice for retrofitting existing retaining walls.

2.8 Installation of vertical plate anchors

Generally, the following steps are needed to install vertical plate anchors.

2.8.1 Step 1

The sod is carefully removed, and a hole is excavated to install the vertical plate anchor as shown in Figure 2.2

Figure 2.2 Drilling hole in soil for vertical plate anchor installation

(Helical Piles and Anchors Hydraulically Driven Push Piers Polyurethane Injection Supplemental Support Systems, n.d.)

2.8.2 Step 2

A small hole is drilled through the retaining wall, and the anchor rod is driven through it to reach the augured hole as shown in Figure 2.3

Figure 2.3 Drilling hole inside wall for tie rod installation

(Helical Piles and Anchors Hydraulically Driven Push Piers Polyurethane Injection Supplemental Support Systems, n.d.)

2.8.3 Step 3

Exterior wall plate is placed in the hole and attached to the tie rod as shown in Figure 2.4

Figure 2.4 Placing exterior wall plate

(Helical Piles and Anchors Hydraulically Driven Push Piers Polyurethane Injection Supplemental Support Systems, n.d.)

2.8.4 Step 4

The interior wall plate is placed over the tie rod and tightened it up to specified limit as shown in Figure 2.5

Figure 2.5 Tightening interior wall plate

(Helical Piles and Anchors Hydraulically Driven Push Piers Polyurethane Injection Supplemental Support Systems, n.d.)

2.8.5 Step 5

Outside hole is then backfilled and cover it with sod as shown in Figure 2.6

Figure 2.6 covering hole after anchor installation

(Helical Piles and Anchors Hydraulically Driven Push Piers Polyurethane Injection Supplemental Support Systems, n.d.)

2.9 Use of Finite Element Method (FEM)

The Finite Element Method (FEM) is widely utilized in geotechnical engineering for analyzing soil-structure interaction, providing a powerful tool to simulate complex behaviors of retaining walls under various loading conditions. FEM divides the structure and soil into smaller, manageable elements to model their interactions and responses accurately.

In geotechnical research, FEM has been extensively applied to analyze retaining walls, offering insights into stress distributions, deformations, and stability conditions. Previous studies have demonstrated FEM's capability to predict the behavior of retaining walls under different loading scenarios, providing valuable data for design and optimization.

Validation of FEM models is crucial to ensure their accuracy and reliability. Researchers validate these models by comparing FEM results with analytical solutions based on classical theories like Rankine and Coulomb, as well as experimental data from field tests and laboratory experiments. This validation process confirms the applicability of FEM in simulating real-world scenarios and enhances confidence in its predictive capabilities for geotechnical applications.

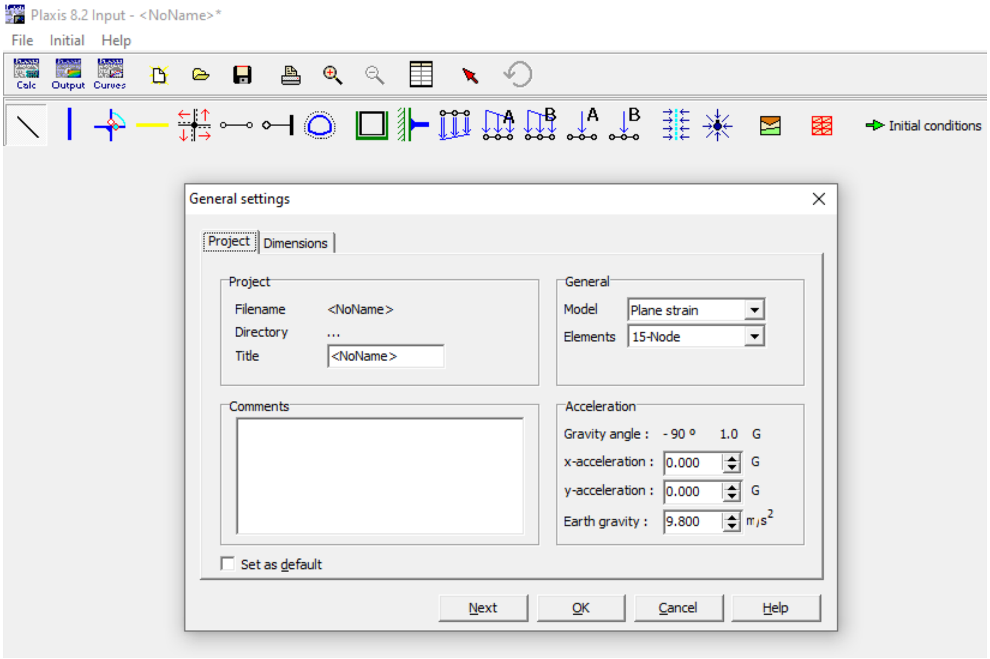
2.10 General steps to use Plaxis 2d

Finite Element Method (FEM) analysis using Plaxis 2D for checking the Factor of Safety (FOS) of a retaining wall involves several steps. Here’s a structured guide to follow:

2.10.1 Setup and Initial Steps

- Open Plaxis 2D: Start the Plaxis 2D software on your computer.
- Create a New Project: Go to File > New Project. Enter the project details such as name, location, and description as shown in Figure 2.7.

- Set Units and Model Dimensions: Define the units (e.g., meters, kN) and the model dimensions (e.g., 2D plane strain).



Project
Filename <NoName>
Directory ...
Title <NoName>

General
Model Plane strain
Elements 15-Node

Comments

Acceleration
Gravity angle : - 90 ° 1.0 G
x-acceleration : 0.000 G
y-acceleration : 0.000 G
Earth gravity : 9.800 m/s^2

☐ Set as default

Figure 2.7 Creating new project in plaxis 2d

2.10.2 Geometry Definition

- Draw the Retaining Wall and Soil Layers.
- Use geometry tools to draw the retaining wall as shown in Figure 2.8.
- Define the soil layers beneath and behind the wall.
- Specify dimensions, thicknesses, and any slopes or other relevant features.

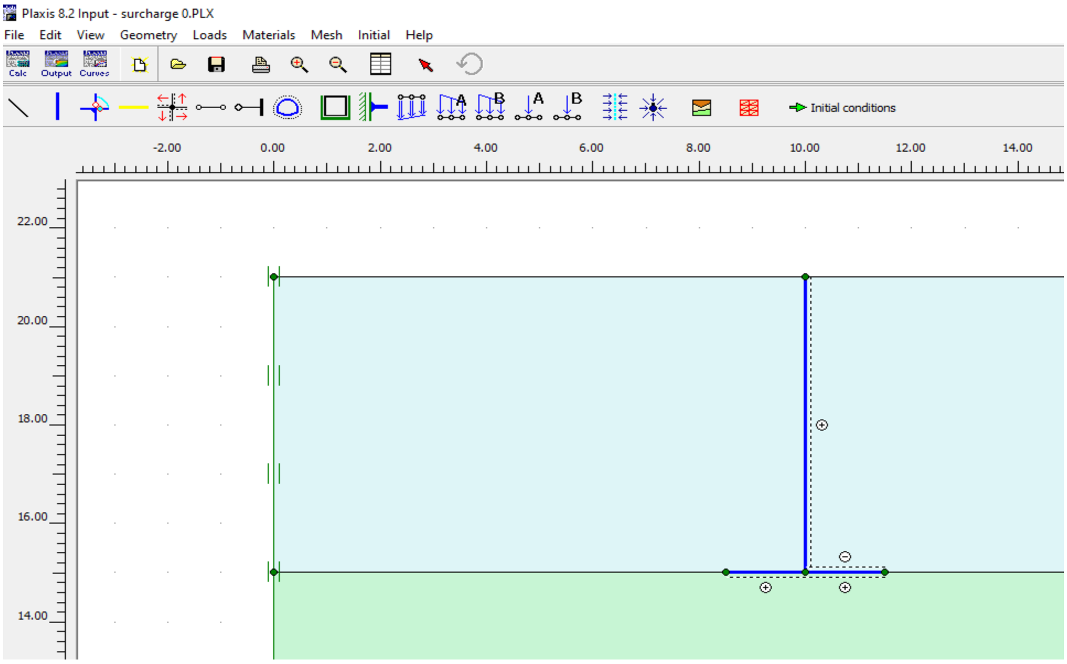
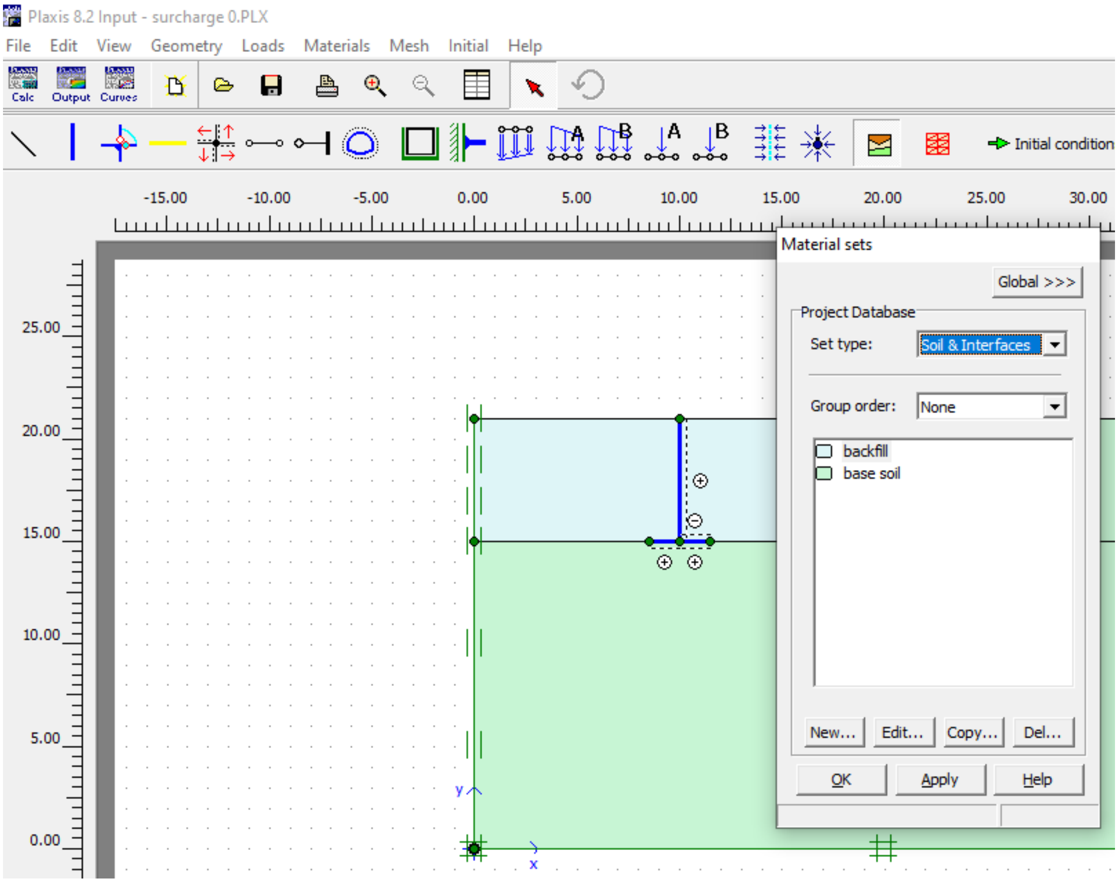


Figure 2.8 Defining wall geometry

2.10.3 Material Properties

- Assign Material Properties:
- Go to the Materials tab.

Define the material properties for the soil and retaining wall. This includes parameters such as Young’s modulus, Poisson’s ratio, cohesion, friction angle, and unit weight. Assign these materials to the corresponding geometry parts as shown in Figure 2.9.



Set type: Soil & Interfaces

Group order: None

☐ backfill
☐ base soil

Figure 2.9 Assigning material properties

2.10.4 Boundary Conditions and Mesh Generation

- Set Boundary Conditions:

Apply boundary conditions to the model. Typically, the bottom boundary is fixed, while the sides are restrained horizontally.

Ensure that the boundary conditions realistically represent the physical problem.

- Generate the Mesh:

Create a finite element mesh for the model by selecting Mesh > Generate Mesh as shown in Figure 2.10.

Choose an appropriate mesh density. A finer mesh provides more accuracy but requires more computational power.

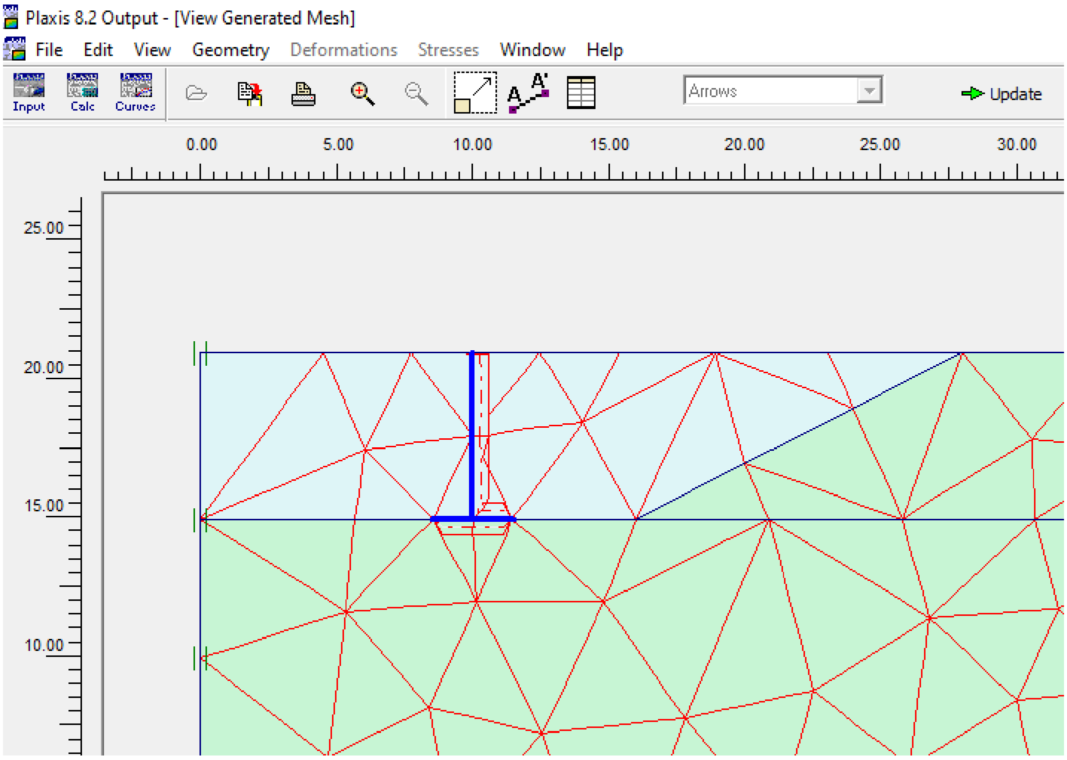


Figure 2.10 Mesh generation in Plaxis 2D

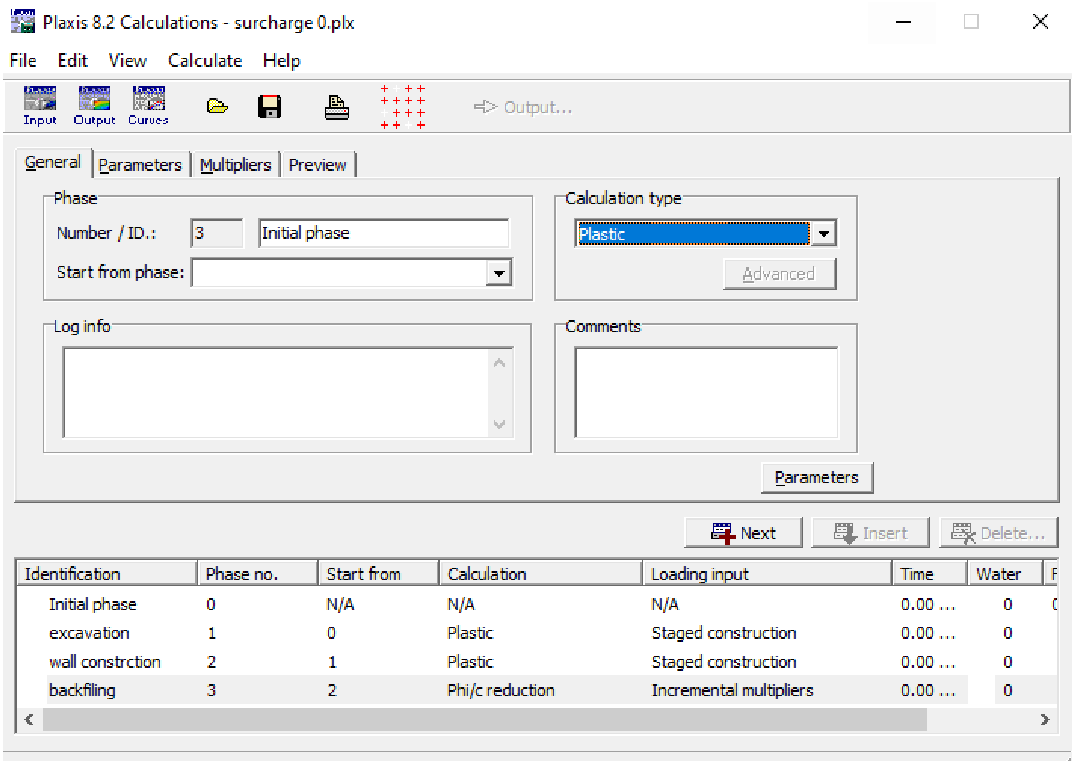
2.10.5 Construction Stages

- Define Construction Stages:

- Go to the Phases tab.

Define different construction stages including excavation, wall construction, backfilling as shown in Figure 2.11.

Each stage should reflect the actual sequence of construction events.



Phase
Number / ID.: 3 Initial phase
Start from phase:

Calculation type: Plastic

Identification	Phase no.	Start from	Calculation	Loading input	Time	Water
Initial phase	0	N/A	N/A	N/A	0.00 ...	0
excavation	1	0	Plastic	Staged construction	0.00 ...	0
wall constrction	2	1	Plastic	Staged construction	0.00 ...	0
backfiling	3	2	Phi/c reduction	Incremental multipliers	0.00 ...	0

Figure 2.11 Define phases and Calculation

2.10.6 Load Application

- Apply Loads:

Apply loads on the retaining wall and the surrounding soil.

Define any additional loads such as surcharge loads, water pressure, or live loads.

2.10.7 Calculation Phases

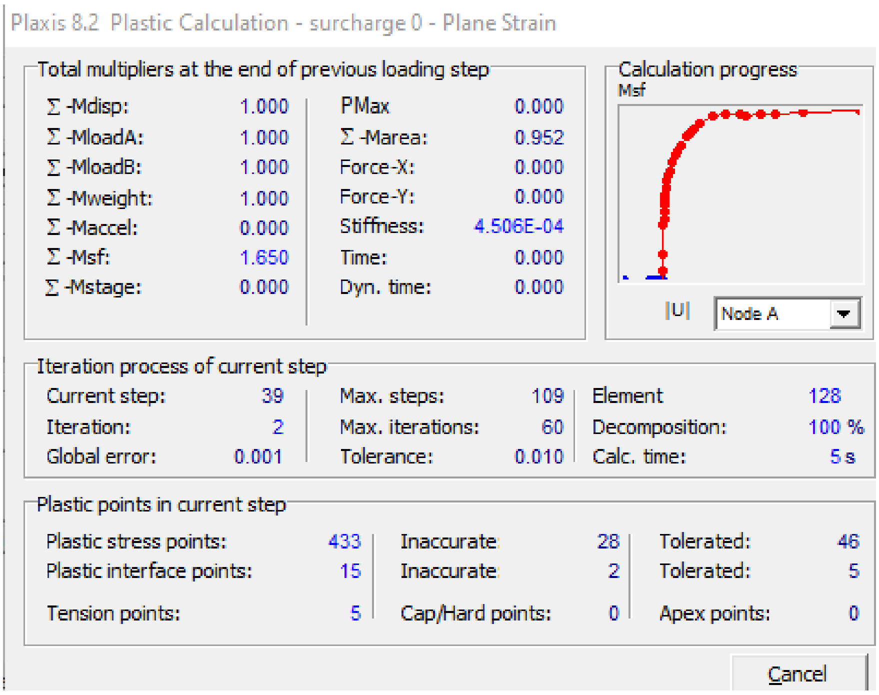
- Define Calculation Settings:
- Specify the calculation type for each phase.

For FOS analysis, select the appropriate safety analysis method (e.g., Phi-c reduction).

2.10.8 Run the Analysis

- Perform the Calculations:
- Run the analysis for each construction stage as shown in Figure 2.12.

Monitor the convergence and ensure that the solution is stable.


Plaxis 8.2 Plastic Calculation - surcharge 0 - Plane Strain

Total multipliers at the end of previous loading step

Σ -Mdisp: 1.000
Σ -MloadA: 1.000
Σ -MloadB: 1.000
Σ -Mweight: 1.000
Σ -Maccel: 0.000
Σ -Msf: 1.650
Σ -Mstage: 0.000
PMax 0.000
Σ -Marea: 0.952
Force-X: 0.000
Force-Y: 0.000
Stiffness: 4.506E-04
Time: 0.000
Dyn. time: 0.000

Calculation progress

Iteration process of current step

Current step: 39
Iteration: 2
Global error: 0.001
Max. steps: 109
Max. iterations: 60
Tolerance: 0.010
Element 128
Decomposition: 100 %
Calc. time: 5 s

Plastic points in current step

Plastic stress points: 433
Plastic interface points: 15
Tension points: 5
Inaccurate 28
Inaccurate 2
Cap/Hard points: 0
Tolerated: 46
Tolerated: 5
Apex points: 0

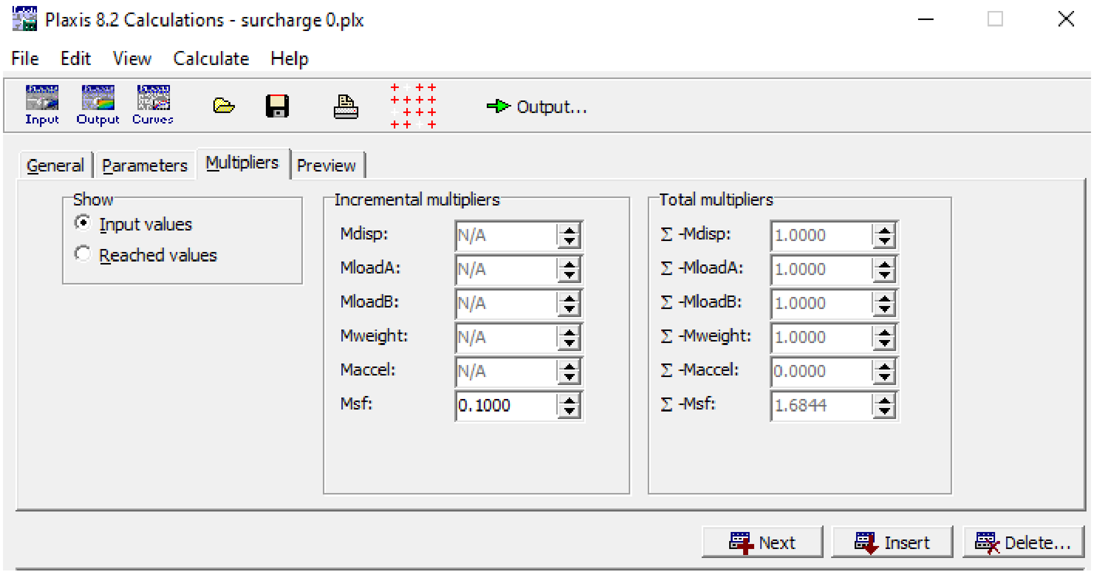
Figure 2.12 Analysis of different phases

2.10.9 Results Interpretation

- View Results:

After the analysis is complete, view the results. Check deformations, stress distributions, and other relevant parameters as shown in Figure 2.13.

- For FOS, look at the safety analysis results to determine the factor of safety.
- Go to the Results tab and select the Safety plot to visualize the FOS.


Plaxis 8.2 Calculations - surcharge 0.plx

Show
● Input values
○ Reached values

Incremental multipliers

Mdisp: N/A
MloadA: N/A
MloadB: N/A
Mweight: N/A
Maccel: N/A
Msf: 0.1000

Total multipliers

Σ -Mdisp: 1.0000
Σ -MloadA: 1.0000
Σ -MloadB: 1.0000
Σ -Mweight: 1.0000
Σ -Maccel: 0.0000
Σ -Msf: 1.6844

Figure 2.13 Result Interpretation in Plaxis

2.10.10 Report Generation

- Generate and Export Reports:
- Create a detailed report of the analysis.
- Include all relevant plots, graphs, and interpretations.
- Export the report in a suitable format (e.g., PDF).

2.11 Parametric Analysis in Retaining Wall Design

Parametric analysis plays a crucial role in advancing the understanding of retaining wall behavior by systematically varying key design parameters and evaluating their impact on stability and performance. These studies provide valuable insights into how variations in soil properties, such as cohesion and internal friction angle, and wall geometry, including height influence the structural response under different loading conditions.

Key parameters influencing retaining wall stability encompass a range of factors. Soil properties, such as strength characteristics and permeability, dictate the wall's ability to withstand lateral pressures and maintain stability over time. Wall geometry, including backfill slope angle and base width, also significantly impacts load distribution and internal forces within the structure.

Previous research on parametric analysis has investigated various stabilization methods for retaining walls, including traditional techniques like soil reinforcement with geogrids or soil nails, as well as innovative approaches such as vertical plate anchors. These studies have explored how different methods interact with soil and structural configurations, providing comparative evaluations of their effectiveness in enhancing stability and mitigating failure mechanisms.

By systematically varying these parameters through computational simulations and experimental studies, researchers can optimize retaining wall designs to achieve desired safety factors and performance levels. This knowledge informs practical applications and contributes to the development of design guidelines that account for site-specific conditions and project requirements.

2.12 Machine Learning and Predictive Modelling

Machine learning applications have increasingly influenced civil engineering, offering advanced tools to analyze complex data and predict outcomes in geotechnical engineering. Machine learning techniques such as neural networks and decision trees have been applied to model soil behavior, predict settlement patterns, and optimize construction processes.

Polynomial regression is commonly employed in geotechnical engineering to predict stability factors of retaining walls and other structures. This statistical method fits a polynomial function to data points, providing a simplified yet effective means to estimate factors of safety and deformation characteristics under varying conditions.

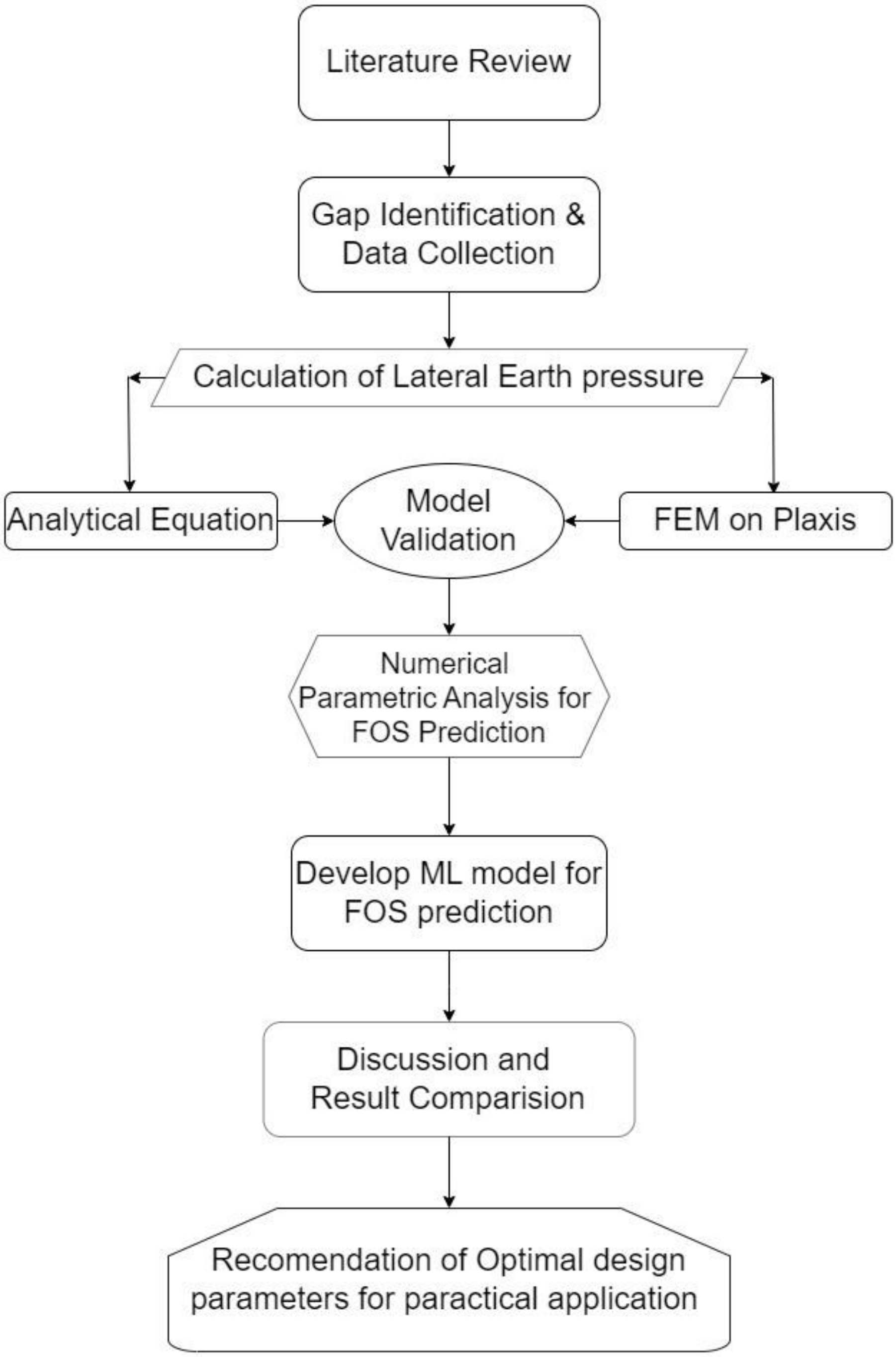
Integrating machine learning with Finite Element Method (FEM) analysis presents both benefits and challenges in geotechnical engineering. Benefits include enhanced predictive accuracy by capturing nonlinear relationships and complex interactions between parameters. Machine learning models can handle large datasets and non-standard inputs, providing robust predictions for geotechnical applications.

Challenges arise in data quality and model interpretability, as machine learning models require significant amounts of high-quality data for training and validation. Moreover, integrating machine learning with FEM analysis requires expertise in both fields, ensuring proper model calibration and validation against experimental or field data.

By leveraging machine learning techniques alongside established engineering methodologies like FEM, researchers can enhance the accuracy of predictions and optimize designs for retaining walls and other geotechnical structures. Future research may explore hybrid approaches that combine the strengths of machine learning with traditional engineering principles to address complex geotechnical challenges effectively.

CHAPTER: 3 METHODOLOGY

This chapter reports the specification of cantilever retaining wall under consideration and procedure used for the numerical simulations in Plaxis 2d program. This chapter reports the methodology used for achieving all the objectives of this study.



3.1 Numerical Analysis on Plaxis 2D

A two-dimensional finite element model was developed using material properties adapted from (Shehata, 2016) shown in the

Table 1. The analysis was performed using the commercial software PLAXIS 2015. The retaining wall and the backfill material were modeled using 15-node triangular elements. The backfill and foundation soil were both modeled as Hardening soil elastoplastic materials, whereas concrete and plate anchor was modeled as linear elastic material. The retaining wall and plate anchor were modeled as plate elements. Vertical plate anchor and wall parameters are given in the Table 2.

A general cross section of cantilever retaining wall of height, H, with an embedded vertical plate anchor positioned at a depth, z, from the horizontal ground level shown in the Figure 3.1. And properties of plate element used in FEM are given in Table 3.

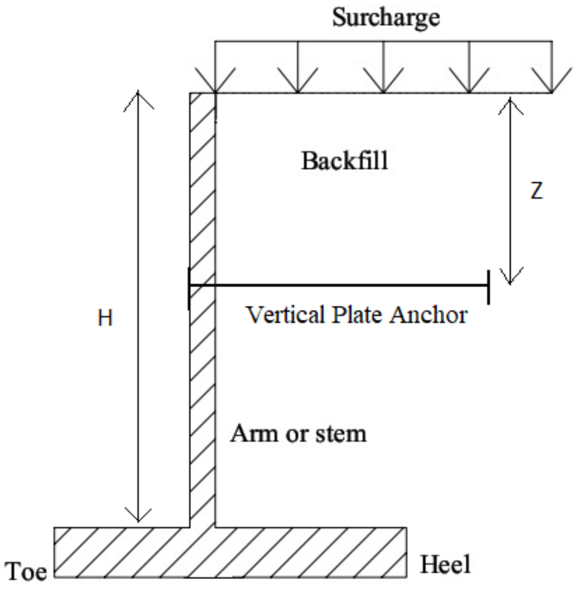


Figure 3.1 Cross section of cantilever retaining wall used in FEM

Table 1: Material Properties used FEM

Property	**Backfill soil**	**Foundation soil**	**Retaining wall**	**Plate anchor**
Material Model	Hardening soil	Hardening soil	Linear elastic	Linear elastic
Unit weight(KN/m^3)	17	18	24	78.5
Internal friction angle (ø)	32	38	-	-
Dilatency angle ψ	2	8	-	-
E_{50}	10000	40000	-	-
E_{ur}	30000	120000	-	-
Young Modulus,E(KN/m^2)	-	-	21x10^6	200x10^6
Power factor (m)	0.5	0.5	-	-

The steps taken in modeling can be summarized as follows: (1) the foundation bed is first generated, (2) the wall and the base are activated, (3) backfill material is added, (4) vertical plate anchor activated.

Table 2: General dimensions of Retaining wall used in FEM

Wall height	10 m
Footing width	5 m
Wall stem thickness	0.5 m
Footing thickness	0.8 m
Wall Toe	2m
Wall heel	3m
Tie-rod length	4-10 m
Tie-rod thickness (diameter)	0.0254 m= 1inch
Anchor plate length	0.5 m = 20 inch

Anchor plate width	0.5 m = 20 inch
Anchor plate thickness	0.0254 m= 1inch

3.2 Analytical Equations used for Model Validation

In the current research, analytical equations based on Jacky's and Rankine's theories are utilized to validate the Finite Element Method (FEM) models. These theories provide the necessary mathematical frameworks to assess lateral earth pressure and ensure the accuracy of the FEM simulations as shown in the Figure 3.2.

$$\text{Lateral Earth Pressure: } P = \frac{1}{2}(K.\gamma.h^2) \qquad 3.1$$

At rest earth pressure coefficient (K_o) for the cohesionless soil calculated by

$$\text{Jacky equation (1944): } Ko = 1 - \sin(\varphi) \qquad 3.2$$

Active earth pressure coefficient for the cohesionless soil of a horizontal backfill surface can be calculated by Rankine theory (1857):

$$Ka = \frac{1 - \sin(\varphi)}{1 + \sin(\varphi)} \qquad 3.3$$

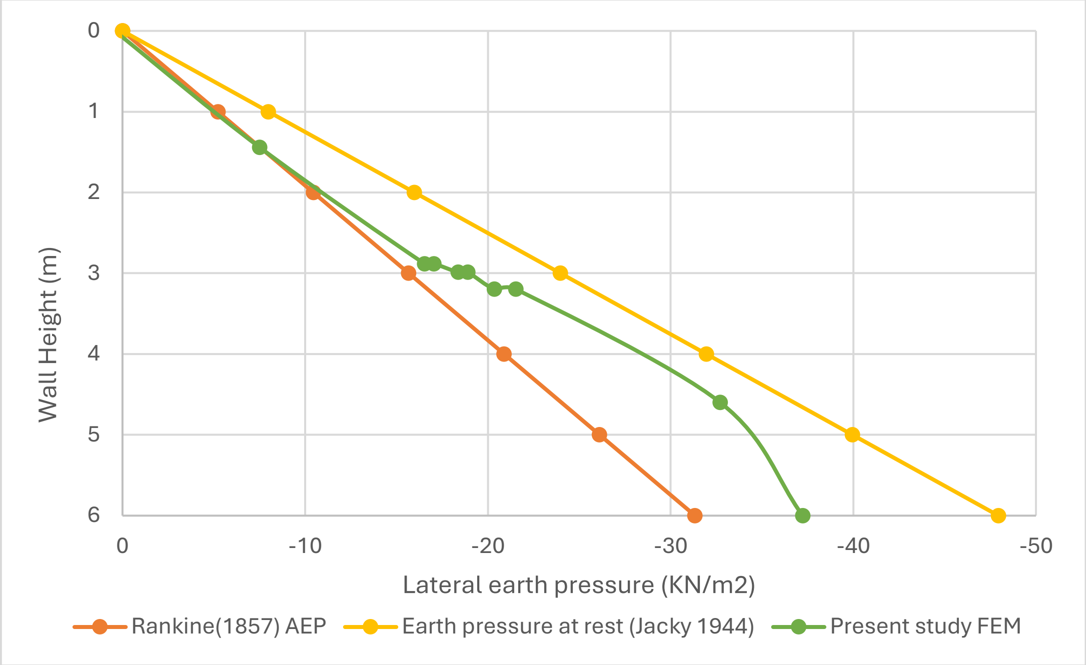


Figure 3.2 Lateral earth pressure comparison for model validation

Table 3: Properties of plate elements used in FEM

Property	Wall stem	Wall base	Anchor plate	Anchor rod
Normal stiffness, EA (Kn/m)	10500000	16800000	2540000	101290.12
Flexural Rigidity, EI (Kn m2/m)	218750	896000	136.5588667	4.084270864
weight, w (Kn/m/m)	12.5	20	1.9939	0.05064506
Poisson’s Ratio	0.15	0.15	0.15	0.15

3.3 Parametric Analysis

A comprehensive parametric analysis was performed, where 162 models were examined to explore the impact of various geometrical and soil strength parameters on the Factor of Safety (FOS) of the cantilever retaining wall as shown in Figure 3.3. This extensive analysis helps in identifying the critical factors that influence the stability and safety of the retaining wall under different conditions.

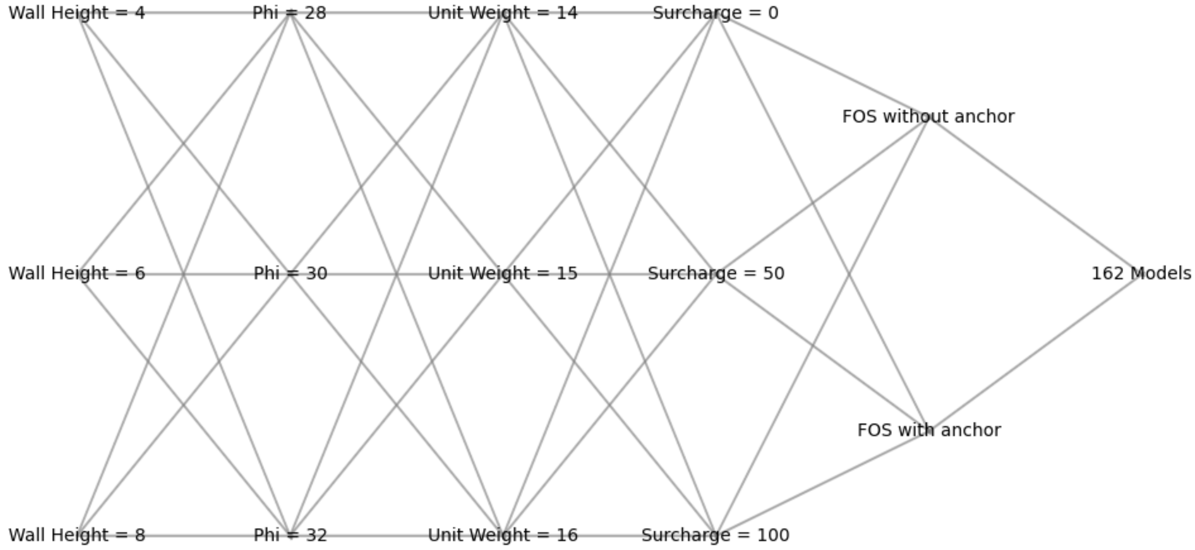


Figure 3.3 Different model combinations for parametric analysis

3.4 Machine learning model for FOS prediction

Non-linear regression analysis using a polynomial regression model was performed to predict the Factor of Safety (FOS). The scikit-learn library in Python was used to implement the polynomial regression model.

First, the data was split into independent and dependent variables. The independent variables (X) included 'Wall Height', 'Backfill Friction Angle', 'Anchor Length', 'Surcharge', and 'Unit Weight', while the dependent variable (y) was the 'FOS'.

Next, the Polynomial Features class from sklearn preprocessing was used to create polynomial features.

The polynomial regression model was fit on the training data (X_train and y_train). Predictions were made on the training, testing, validation, and overall datasets using the fitted model.

The coefficient of determination (R-squared) was calculated for each set to evaluate the model's performance. The R-squared values were calculated using the r2_score function from sklearn metrics.

Finally, the actual vs. predicted values were plotted for each dataset, along with the corresponding R-squared values. The plots were created using Matplotlib.

This polynomial regression approach allowed for modeling the non-linear relationship between the predictor variables and the FOS. The resulting model can be used to predict the FOS for new data points.

3.4.1 Model Architecture

- Polynomial Regression
- Number of Input Features: 5
- Number of Neurons in Output Layer: 1
- Training Dataset Size: 70% of the total dataset
- Testing Dataset Size: 15% of the total dataset
- Validation Dataset Size: 15% of the total dataset

The polynomial regression model includes a transformation of the original features into a higher-dimensional polynomial feature space, specifically of degree 2, to capture non-linear relationships. The model is trained using a linear regression approach applied to these polynomial features.

CHAPTER: 4 RESULT AND DISCUSSION

4.1 Retaining wall FOS with and without vertical Plate anchor

Factor of Safety (FOS) of a cantilever retaining wall as a function of the backfill friction angle, comparing scenarios with and without anchors as shown in Figure 4.1.

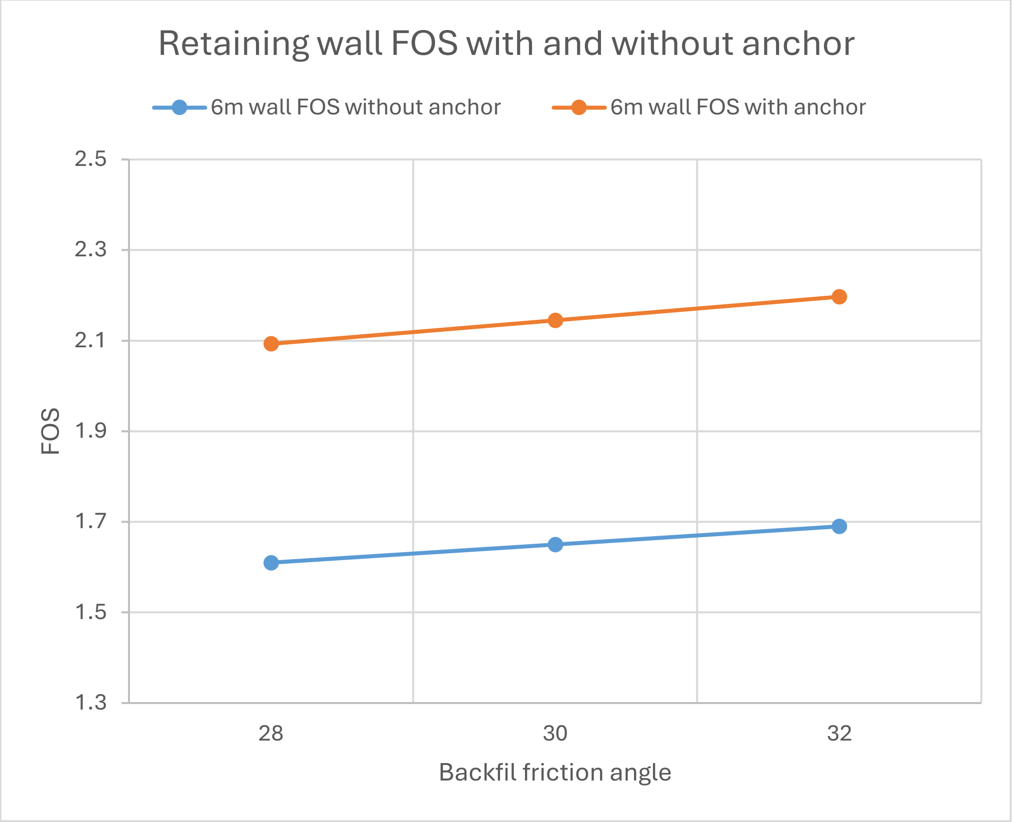


Figure 4.1 FOS of retaining wall with and without anchor

- The x-axis represents the backfill friction angle in degrees, with data points at 28°, 30°, and 32°.
- The y-axis represents the FOS.
- FOS without anchor: This line shows the FOS values (1.61, 1.65, and 1.69) for the wall without using any anchors, indicating how the stability of the wall changes with increasing backfill friction angle.
- FOS with anchor: This line shows the FOS values (2.09, 2.15, and 2.20) for the

wall with anchors, demonstrating the increased stability provided by the anchors as the backfill friction angle increases.

The plot reveals that the FOS is consistently higher when anchors are used, indicating improved stability of the retaining wall. The increase in FOS with higher backfill friction angles is also evident in both scenarios, though the anchored scenario shows a more significant improvement.

4.2 Effect of Surcharge on FOS of retaining wall

Factor of Safety (FOS) of a cantilever retaining wall as a function of surcharge, comparing scenarios with and without anchors as shown in Figure 4.2.

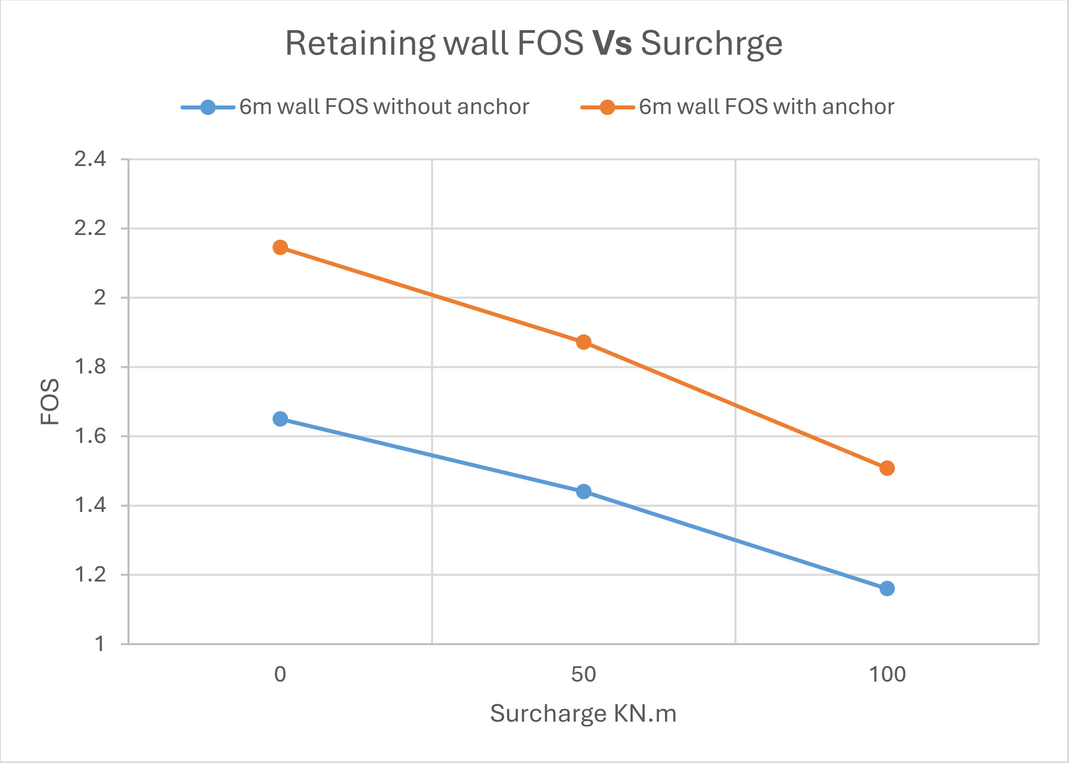


Figure 4.2 Effect of surcharge on FOS of wall

- The x-axis represents the surcharge in kilonewton-meters (KN.m), with data points at 0, 50, and 100 KN.m.
- The y-axis represents the FOS.

- FOS without anchor: This line shows the FOS values (1.65, 1.44, and 1.16) for the wall without using any anchors. As the surcharge increases, the FOS decreases, indicating reduced stability of the wall.
- FOS with anchor: This line shows the FOS values (2.15, 1.87, and 1.51) for the wall with anchors. Similar to the previous case, the FOS decreases with increasing surcharge, but the values are consistently higher than those without anchors, demonstrating improved stability due to the anchors.

The plot reveals that the FOS is consistently higher when anchors are used, indicating better stability of the retaining wall under increasing surcharge. The decrease in FOS with higher surcharge is evident in both scenarios, though the anchored scenario shows less reduction, highlighting the effectiveness of anchors in maintaining wall stability under load.

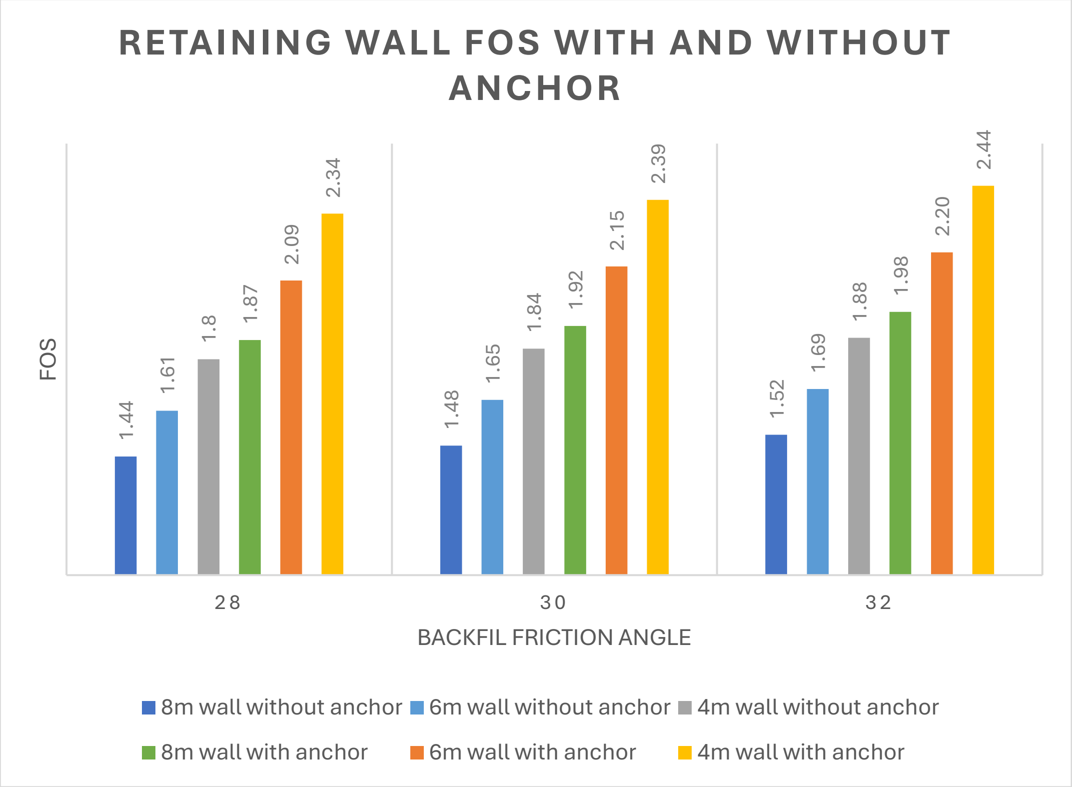


Figure 4.3 FOS of different wall heights with and without anchors

The bar chart provides a comparison of the Factor of Safety (FOS) for retaining walls of different heights, both with and without anchors, at various backfill friction angles (28°, 30°, and 32°) as shown in Figure 4.3.

- The x-axis represents the backfill friction angle.
- The y-axis represents the FOS.
- The data is grouped into six categories:
- 8m wall without anchor: FOS values (1.44, 1.48, 1.52).
- 6m wall without anchor: FOS values (1.61, 1.65, 1.69).
- 4m wall without anchor: FOS values (1.80, 1.84, 1.88).
- 8m wall with anchor: FOS values (1.87, 1.92, 1.98).
- 6m wall with anchor: FOS values (2.09, 2.15, 2.20).
- 4m wall with anchor: FOS values (2.34, 2.39, 2.44).

4.2.1 Key observations

- The FOS increases with the backfill friction angle for all scenarios.
- Walls with anchors consistently show higher FOS compared to walls without anchors.
- Shorter walls generally have higher FOS values.
- The highest FOS is observed for the 4m wall with anchors at a backfill friction angle of 32°.
- The chart provides a visual representation of how both the presence of anchors and the height of the wall influence the stability of the retaining wall.

4.3 Polynomial regression model

Retaining wall FOS observed in plaxis 2d (actual FOS) is compared with the predicted FOS by polynomial regression model as shown in Figure 4.5.

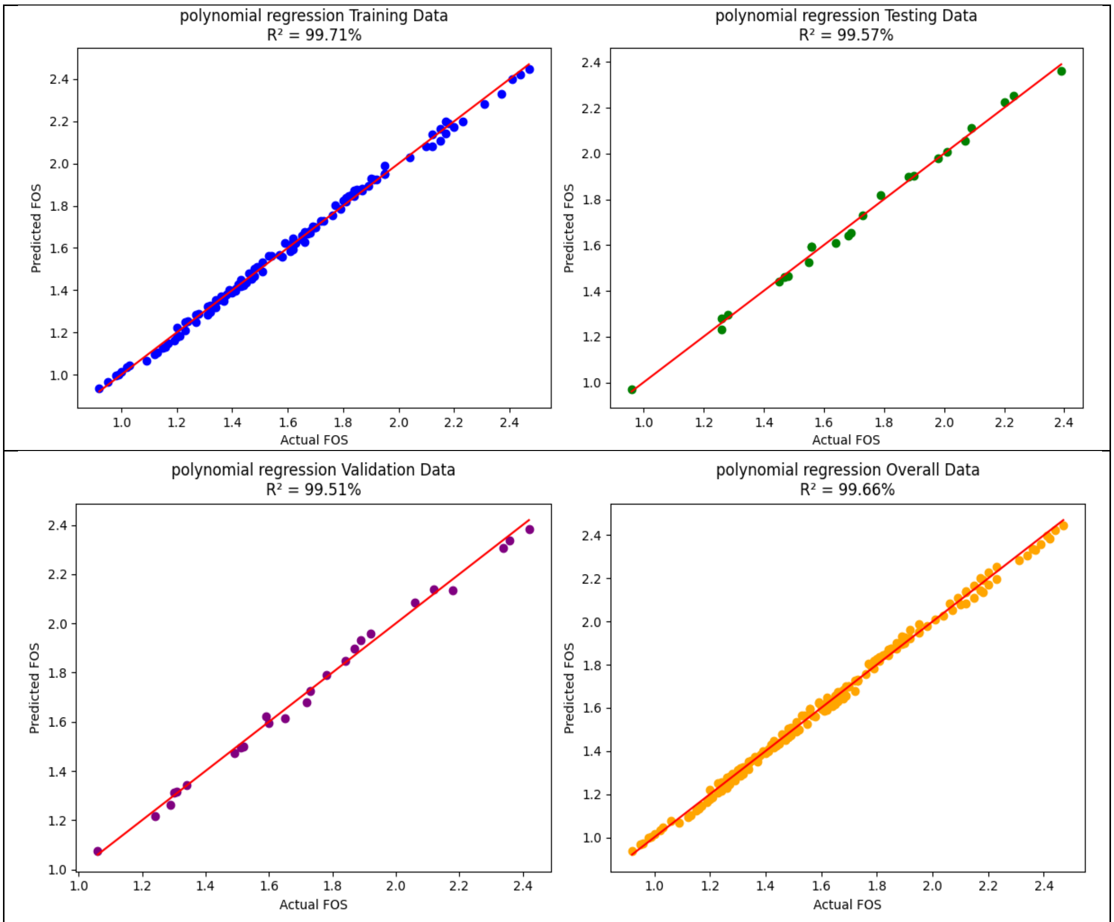


Figure 4.4 Comparison of observed and predicted value of FOS

The given four plots provide a comprehensive visualization of the polynomial regression model's performance in predicting the Factor of Safety (FOS) across training, testing, validation, and overall datasets. Each plot displays actual FOS values against predicted FOS values, with an R-squared value indicating model accuracy. The training plot (R^2: 99.71%) shows how well the model learned from the data, while the testing plot (R^2: 99.57%) evaluates its performance on unseen data, highlighting its generalization capability. The validation plot (R^2: 99.51%) helps in fine-tuning the model to prevent overfitting. The overall plot (R^2: 99.66%) provides a holistic view of model accuracy across all data points. These plots, with scatter points close to the ideal prediction line, indicate strong predictive performance and reliability of the polynomial regression model in estimating FOS.

4.4 Comparison of different Machine Learning models

Comparison of three regression models—Linear Regression, Polynomial Regression and Support Vector Machine (SVM) in predicting the Factor of Safety (FOS), using R-squared (R^2) values are shown in Figure 4.5.

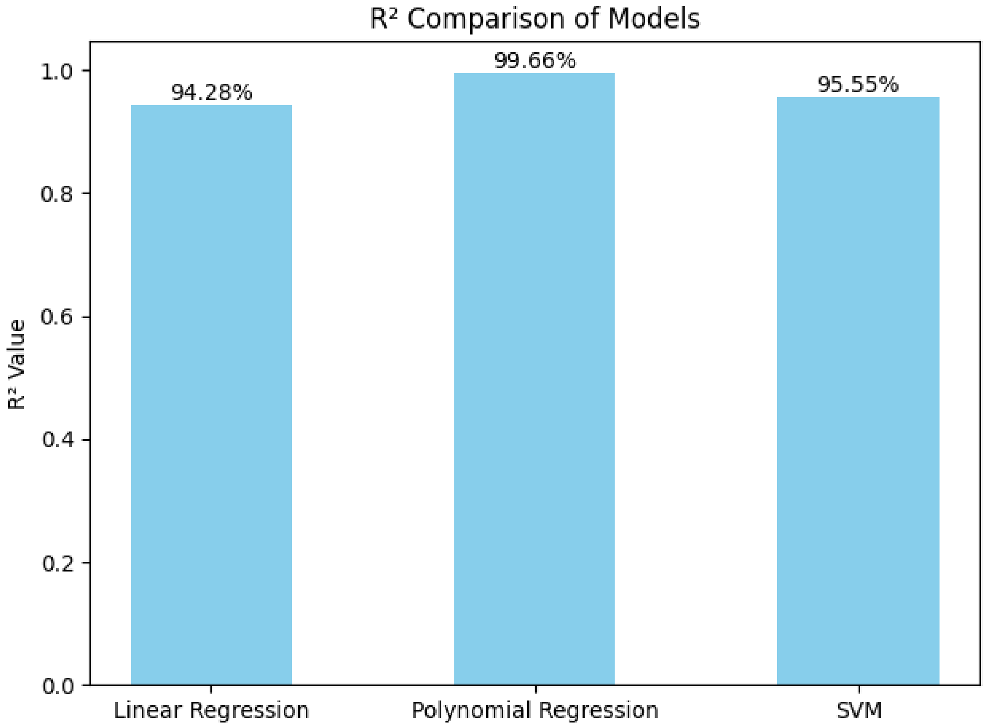


Figure 4.5 Performance comparison of three different regression models

Polynomial Regression achieved the highest R^2 value of approximately 99.66%, indicating the best fit, followed by the Linear Regression at 94.28% and SVM at 95.55%.

4.5 Relative Importance parameters effecting FOS

The relative importance index (RI) is used to evaluate how much each input variable affects the output variable, in this case, the factor of safety (FOS) of a retaining wall as shown in Figure 4.6.

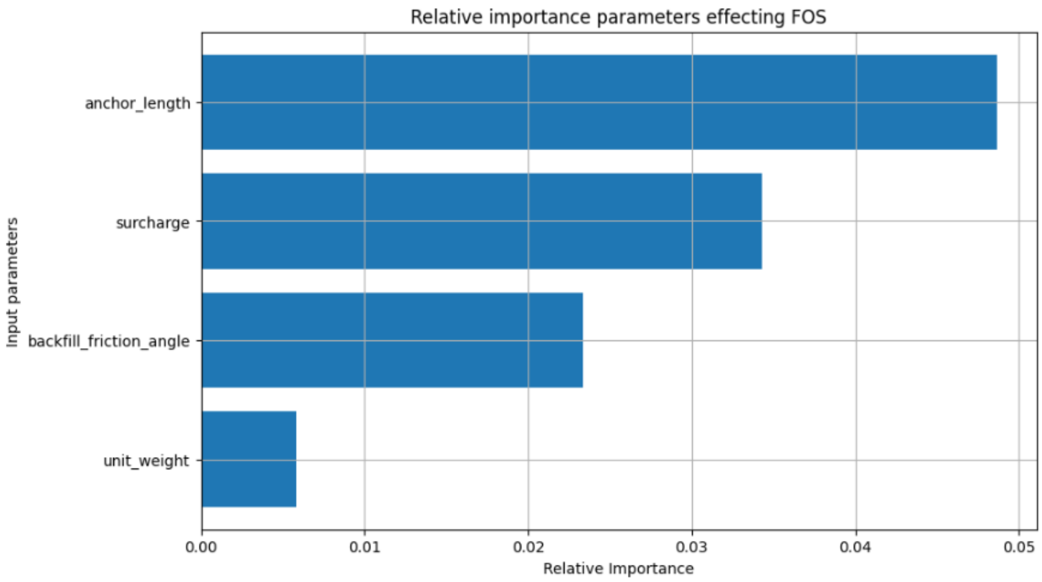


Figure 4.6 Parameters effecting FOS of retaining wall

In the plot presented, it illustrates that among the four input variables analysed by keeping wall height constant, the vertical plate anchor has the most significant impact on the FOS, contributing 48%. This suggests that changes in the presence or absence of vertical plate anchors can substantially influence the stability and safety margin of the retaining wall. Surcharge and the friction angle of the backfill material also play significant roles, contributing 33% and 22% respectively to the FOS variations observed. While unit weight of backfill has the least impact, with only a 5% relative importance. This implies that while variations in material density do affect FOS, their influence is comparatively minor compared to other factors like structural design features (such as vertical plate anchors) and external loads (surcharge).

Overall, the RI analysis helps prioritize which factors should be carefully considered and potentially modified to optimize the stability and safety of retaining walls in engineering and construction practices.

CHAPTER: 5 CONCLUSION

This research employs a finite element method (FEM) analysis to assess the feasibility of using vertical plate anchors in retaining walls to enhance stability and increase the surcharge carrying capacity applied to the backfill surface. The study conducts a quantitative evaluation of the factor of safety (FOS) and surcharge carrying capacity of the wall both before and after the installation of vertical plate anchors. The findings indicate significant improvements in wall stability due to the application of plate anchors, demonstrating their potential for retrofitting existing walls under proposed surcharge loads.

A key advantage of this technique is its compatibility with existing walls, facilitating additional construction in surrounding areas without disruption to facilities on the non-backfill side. The study employed polynomial regression to predict the FOS of retaining walls with vertical plate anchors. The model demonstrated high predictive accuracy, with a coefficient of determination (R^2) of 0.95, making it a valuable tool for practical applications.

The outcomes of this investigation are instrumental in establishing appropriate design criteria and promoting the widespread adoption of vertical plate anchors in practical applications. Future research directions could explore three-dimensional analyses to deepen understanding of material conservation and failure mechanisms in retaining walls employing this technique. Additionally, further studies could investigate the performance of different backfill materials, particularly cohesive and cohesive-frictional soils, when used in conjunction with plate anchors.

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