NUMERICAL ANALYSIS
OF
SOIL NAILED WALL

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
GEOTECHNICAL ENGINEERING

Submitted by

HUNNY BHADANA(2K20/GTE/10)

Under the supervision of

PROF. A.K SAHU

DEPARTMENT OF CIVIL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

DEPARTMENT OF CIVIL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

CANDIDATE'S DECLARATION

I, HUNNY BHADANA (Roll No.– 2K20/GTE/10) student of M.Tech (Geotechnical Engineering), hereby declare that the project Dissertation entitled "Numerical Analysis of soil nailed wall " which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

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(Hunny Bhadana)

Date: May 2022

DEPARTMENT OF CIVIL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

CERTIFICATE

I hereby certify that the Project Dissertation entitled "Numerical Analysis of soil nailed wall" which is submitted by Hunny Bhadana (Roll No. –2K20/GTE/10) Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

(A.K. SAHU)

Date: May 2022

PROFESSOR & SUPERVISOR

DEPARTMENT OF CIVIL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

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Place: Delhi

(Hunny Bhadana)

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Abstract

Soil nailing is the technique that is used in the stabilization of existing ground by increasing the normal loads on potential sliding surfaces through the nails. This project discusses the guidance presented in the FHWA (2013) and how it can be used to design soil nail walls along with temporary facing and various checks for safety are also mentioned and studied in this work. This study provides an insight into the behavior of soil-nailed structures. The slope stabilization was investigated with three methods, the conventional method of FHWA (2013), the finite element method (PLAXIS), and Bishop's method. This study also provides an insight into the use of two types of soil nail structure namely a plate element and a geogrid element.

The study shows that to simulate soil nail wall, a plate element should be adopted for accurate results as the plate element in nail accounts for bending and shear stresses which are ignored when a geogrid element is used.

Chapter 1: Introduction

1.1 Background of the study

Soil nailing is considered earth retention and slope stabilization technique that has been used in different construction works, namely tunnel portals construction, railways and highways construction, slope stabilization, earth-retention structures (both temporary and permanent), and steep cuts for construction, basements, and much more. The guidelines on standard designs are in accordance with the scale models and theories on classical earth pressure. Therefore, the FHWA - Federal Highway Administration maintains the guide or manuals on construction and design details that include resisting and load mechanisms and restrict certain states such as global safety, limit-state strength, and limit-state service to be included for soil nail walls designs.

Various methods of existing systems developed for soil nail walls depend on the stability analysis based on the LEM - limit equilibrium method because of the simplicity and the minimized used parameters. While using the LEM design, it is significant to satisfy the major requirements such as facing stability (punching shear and flexure), internal stability (pullout and tensile strength of soil nail), and external stability (includes sliding and global).

Moreover, soil nail walls distort vertically and horizontally after and while processing the construction. Normally, the maximum displacements on vertical and horizontal may appear on the top of the wall or the magnitude order. Therefore, it is vital to estimate the soil nail wall's maximum displacements, and it should be considered a part of the design. However, displacement is considered the main concern in construction. Further, soil nail walls are also known as passive reinforcement methods, and deformation is required to gather the resisting forces in the soil nails.

1.2 Motivation of the research

The soil nailing design has been considered by analyzing the two states utilized in developing the service and strength limit states. Normally, the strength limit identifies the failure mechanism that occurred, and the service limit defines the service function loss that results from excessive deformation of the wall. The initial design state examination consists of wall layout with length and height, nail pattern, horizontal and vertical spacing, nail length, material, nail inclination, and ground properties. The final designs will be considered with the proper testing on internal and external failure modes, aesthetic qualities, and seismic considerations. Finally, it is necessary to give frost penetration, drainage, and external loads, including hydrostatic and wind forces, in order to examine the design. Moreover, soil nailing has been used in various applications such as Excavation shoring, bridge abutments, roadway, highway, tunnel, ground slope stabilization, and retaining walls. Eventually, the design of soil nails on verification of different factors with the appropriate elements helps in checking various failures facing in the construction field in the current scenario, whether it is temporary or permanent.

1.3 Significance of the study

Soil nailing is considered a ground stabilization method utilized to strengthen and reinforce the existing ground. Therefore, these can be utilized on either excavated or natural slopes. The main significance of the current research on soil nailing is that it is adapted for confined spaces with limited access with minimized environmental effects. Certainly, it is simple and quick to install and utilizes lesser shoring and materials. Moreover, it can be utilized on temporary structures, remodeling processes, and new constructions by using the soil nailing, the process developed with fewer traffic obstructions and noise. These can be utilized to strengthen either cut slopes by artificial or natural slopes with reduced backfilling and excavation. In this research, temporary facing has been examined and adopted in every construction stage. Further, the main benefits of utilizing the FEM - Finite Element Method is not pre-defined in the failure, and it can use used to analyze the wall in the construction stage. Plaxis - Computer Software allows construction in stages and is able to assess the global safety factor after every construction stage.

1.4 Various components in soil nailing

The soil nailing has various components associated with it and the overall stability of the soil nail wall depends upon the mutual interaction of these components. The primary component is a soil nail, a steel bar that can be driven into the slope to increase the normal force on the potential failure plane and thus allowing the slope to withstand more load. The nails are grouted and then the facing element is constructed. The facing element can be temporary or permanent depending upon the purpose the wall was intended to design. Fig 1.1 shows the various components of soil nail wall.

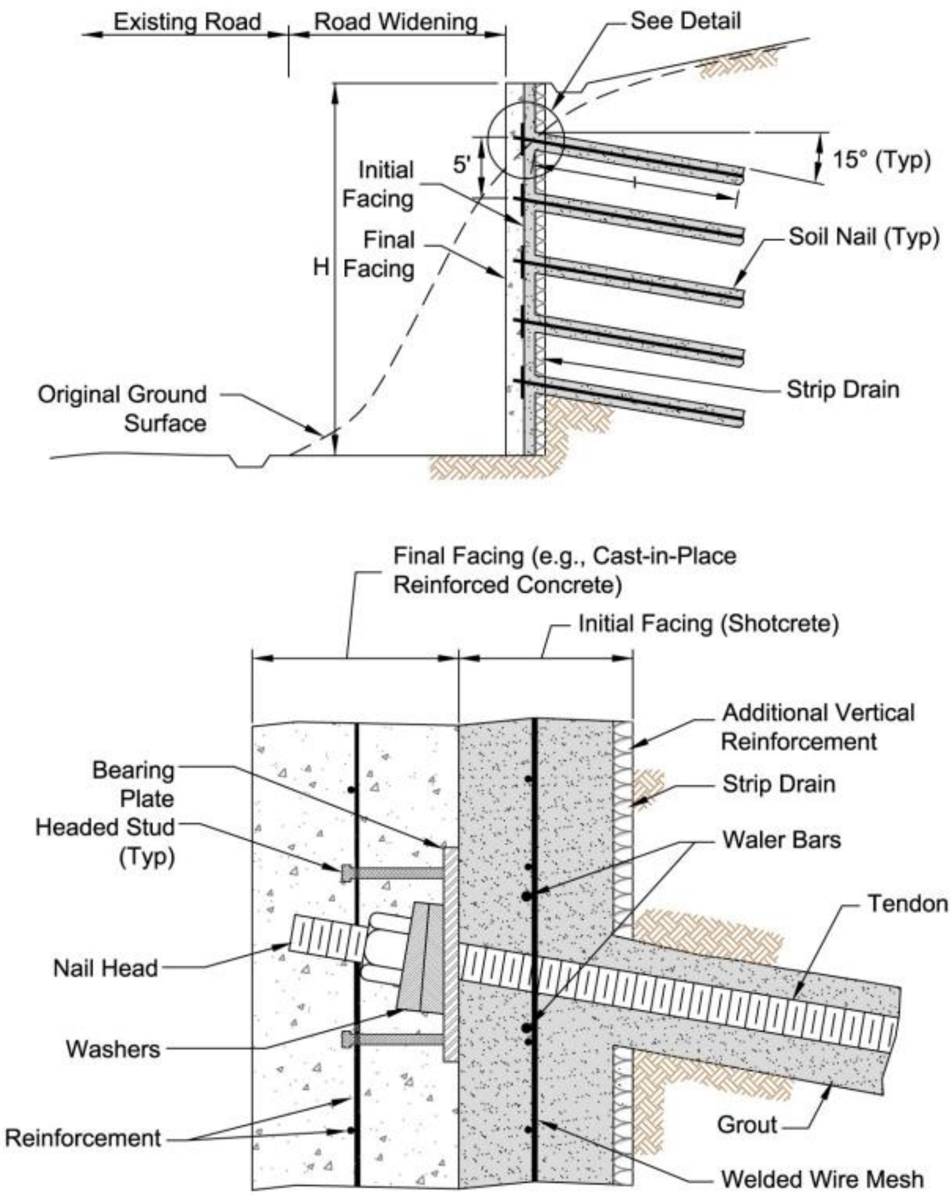

Fig 1.1 Typical sectional view of soil nail FHWA(2003)

1.5 Various failure modes in soil nailing

The soil nailed wall can have mainly three types of failure. They can be an external failure, internal failure, and facing failure. The external failure occurs because of soil mass bypassing the soil nails, or due to sliding of soil mass.

The internal failure is associated with the failure of the nail bar. This can occur due to pullout failure and tension failure of the nail bar itself. And the final type of failure is facing failure, which is caused due to bending of the facing plate. Fig 1.2 shows the various failure modes associated with soil nailing.

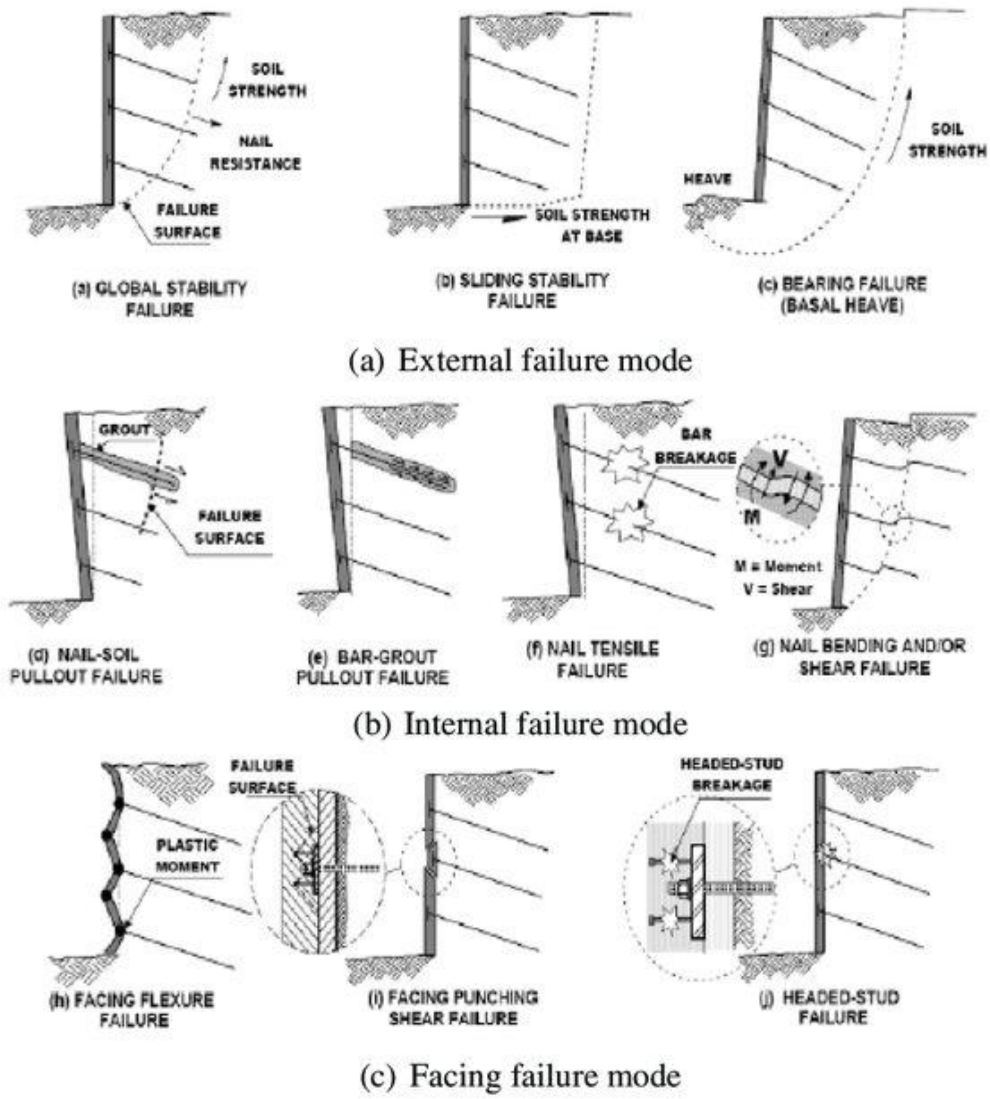

Fig 1.2 Various Failure Modes associated with soil nailing

1.6 Objectives of the Project

On the basis of literature review the following objectives were framed:

To design soil nail wall of height 8m and 12m using FHWA(Federal Highway Administration) manual.

To evaluate external stability, internal stability of the soil nail wall and to design the temporary facing of the wall and check for various facing failures.

The finite element model to be performed using Plaxis to simulate the soil nails and various parameters to be estimated. The stability at various construction stages of the wall to be evaluated.

The simulation of soil nails to be performed using geogrid structure element and plate structure element.

The stability to be assesed by Bishop's method and the comparison of factor of safety to be deduced from the conventional method, finite element method, and Bishop's method.

Chapter 2: Literature Review

Yuan, J et. al. (2019) carried out Statistical evaluation and calibration of two methods for predicting nail loads of soil nail walls in China, the soil nail walls designed in China were enforced by 2-technical specifications such as Protecting and Retaining of building's excavation by CABR - China Academy of Building Research and Soil Nailing specifications in excavation by CECS - China Association for Engineering Construction Standardization. Therefore, every specification develops a computation approach of increased nail loads; however, the accuracy during prediction was not assessed entirely. Hence, these issues are solved by developing 2-methods utilizing 144 nail loads gathered from nail walls. Eventually, the measured CECS and CABR approaches were experimented with to be unbiased on average, and identification dispersion was minimized to 50%

Zevgolis et. al. (2018) carried out System reliability assessment of soil nail walls, an analytical method determining the failure probability of soil nail walls referring to internal and external stability has been developed. Therefore, the bond strength, shear strength, and unit weight with the soil-nail interface are developed as reliable computations, and random variables are evaluated utilizing Monte-Carlo simulations. These techniques are demonstrated via a case example to determine the dependency and failure modes.

Razavi, et. al. (2017) studied soil nailed walls under service loading conditions, a 3-D finite-difference technique has been used for verification and wall deformation prediction, and the results are compared with the numerical analysis and experimental wall. Further, the numerical method has been utilized to examine the behavior of soil-nailed walls under certain service load terms based on surface settlement, soil strain, and nail forces. Therefore, these behaviors are considered to study the effect of nail length distribution, soil strength, vertical nail spacing, and nail elasticity modulus, and eventually, these results are utilized for soil nail design structures.

Khodaverdian et. al. (2021) performed three-dimensional Numerical Study of the Effect of Convex Corners on the Displacements Induced by Excavation for Soil-Nailed Walls, numerical modeling methods are utilized to examine the convex corners geometry effects effect on the deformation of the soil-nailed walls. Therefore, the FLAC3D software has been used for the simulation process with certain parameters known as PSR - Plane Strain Ratio that defines the 3D settlement ratio to 2D. The main contribution of the research is to identify the affected zone length generally depends on the type of soil that enhances the soil strength.

Han, W. et. al. (2020) carried out numerical investigation of a foundation pit supported by a composite soil nailing structure, the FLAC3D - numerical modeling has been utilized in order to examine the deformation and sensitivity features of a symmetrical-foundation pit that was endorsed by composite soil nailing applied in soft muddy soil. Hence, the affected factors on stability have been identified by the silt-soil foundation pit and experimented with the orthogonal tests with the main design with certain factors, levels, indicators, and other factors in order to examine multi-influence optimization. However, it is significant to support certain parameters that restrict the composite soil-nailing effects in order to meet the security requirements and economically.

Alexander Y. (2015) carried out study on effect of axial stiffnss on soil nail forces.Currently used soil nails normally ignore axial stiffness of nails and assumes the rigid connection between soil-nails. Using fiber-reinforced polymers provide advantages in construction due to their light weight, and high durability.

The paper discussed that the soil nails of lower axial stiffness can also be used and this can be overcome in design.

Felipe A. (2018) carried out parametric study of the seismic design of soil nailed walls. Various values of soil and nail have been varied to assess their effect on factor of safety. The pseudo-static force analysis was performed with horizontal seismic coefficient of 0.15. It was found that factor of safety increases with increase in soil strength parameters and with nail length, inclination and diameter. However, nail inclination beyond 15^0 can become detrimental.

Bayat et. al. (2021) conducted Probabilistic Seismic Demand Analysis of Soil Nail Wall Structures Using Bayesian Linear Regression Approach exhibits the seismic analytic fragility curve of soil nail wall structures, and the numerical modeling has been utilized elaborately. Further, the nonlinear elements are utilized to deliver precise finite-element modeling, and the various modeling techniques' effects are studied properly. The detailed methods utilized to generate soil modeling include the HSS - Hardening Soil model along with stiffness impact from small strains, HS - Hardening Soil, and MC - Mohr-Coulomb has been studied. Moreover, the various performance levels were determined to formulate analytical fragility curves for various damage levels.

Baoan Liu et. al. (2021) carried out numerical simulation research on the influence of the soil nail wall on the adjacent cable tunnel. The study shows that the horizontal displacement is the dominant deformation on the slope stability of soil nailed walls. With the increase of the excavation pit depth, the factor of safety was reduced while with an increase in spacing between the tunnel and the wall, the safety increased nonlinearly.

Fadila B. (2021) carried out the study of parametric optimization in soil nailing by taking nail configuration into account. The study demonstrated that the impact of nail length is significant on the stability and on the cost as well followed by the vertical spacing and inclination.

Puja Rajhans et. al. (2022) carried out stability analysis of mine dump on soil nailed wall. The stability analysis found that the dump is in a critical state with a factor of safety value of 0.92 with a circular failure surface. The reinforcement of the dump using soil nails has effectively improved the dump stability. The factor of safety was increased by 11% using soil nails. However, the effect of nail orientation on dump stability was less significant.

Hua-Fu pei (2013) performed slope stability analysis based on measured strains along soil nails using sensing technology. Based on the strain measured, the axial force distribution in the nails can be calculated. Though there was not any developed relationship between the measured strain value and the factor of safety of the slope.

Chapter 3: Methodology

In order to fulfill the objectives of the project following methodology is adopted.

The design of soil nail walls of heights 8m and 12m is carried out using the conventional method. The conventional method is developed by FHWA (Federal Highway Administration) reference manual. The main objective of this manual is to provide simple methods and guidelines that will allow the user to analyze, design, and inspect soil nail structures. The design of soil nailed wall using these guidelines takes into account the factor of safety used in the ASD (Allowable Stress Design) method while integrating LRFD (Load and Resistance factor Design) principles.

The numerical simulation using Plaxis is also carried out for comparative study. The plane strain analysis was performed using 15 node elements. The mesh model of medium mesh density was selected. The construction of the wall was achieved through various construction stages to simulate the field conditions. The phi/c reduction technique is used to calculate the global factor of safety. This technique allows a gradual reduction of soil strength until the failure stage is achieved.

The slope is also assessed using Bishop's Method. This method uses the method of slices to divide the soil mass and determine the FS(factor of safety). In the ordinary method of slices, the effect of horizontal and shearing forces acting on the slice is neglected. This method eliminates these errors and provides more accurate results. The analysis is based on an effective stress approach.

Chapter 4: Numerical Analysis

Firstly, the wall of heights 8m and 12m are designed conventionally as per FHWA0-IF-03-017(Lazarte et al. 2003).

In this approach, two wall heights of 8m and 12m are designed and checked for various failure modes that can occur in the wall. The walls have also been designed conventionally with temporary facing and checked for facing failure modes also. The results of the two wall heights obtained are compared and discussed.

The conventional method pre-defined the failure surface as wedge failure and the computation of safety factors are based on this assumption. Table 4.1 summarizes the properties adopted for the study.

4.1 Design of soil nail wall using Conventional Method (FHWA).

Table 4.1 Input Parameters adopted for conventional method

Height of wall	8m
Backslope angle; β degrees	0
Face batter;α degrees	0
Nailing type	Driven Nails
Soil Nailing spacing $s_h = s_v$	1.0m
Soil Nail inclination i, degrees	15
Soil Nail Material	Fe 415
Soil properties	
Soil type	Dense sand
Cohesion c, kPa	5
Friction angle ϕ, degrees	35
Unit Weight γ,kN/m^3	18.9
Ultimate bond strength q_u, kPa	100
Surcharge q_s, kPa	0.0

Source: G.L Sivakumar Babu and Vikas Pratap Singh, (2009) First, the preliminary design has to be done. The following procedure is to be followed for the conventional design.

4.1.1 Determination of maximum axial Force "T_{max}"

Using equation 4.1 and equation 4.2 the maximum axial force can be calculated.

$$T_{max} = K_a(q_s + \gamma H)S_h S_v \quad (4.1)$$

$$K_a = \frac{1-\sin\phi}{1+\sin\phi} \quad (4.2)$$

Where, K_a is earth pressure coefficient; S_h and S_v are horizontal and vertical spacing; q_s is the surcharge load.

T_{max}=0.27(0+18.9x8)1x1 kN

$T_{max} = 40.82$ kN

4.1.2 Determination of minimum nail diameter “d”

Minimum Factor of Safety against tensile failure = 1.8

$FS_T = 1.8$

$$A_t(mm^2) = \frac{T_{max}.FS_T}{f_y} \quad (4.3)$$

$A_t(mm^2)$ =177

Select bar of diameter d =20mm

$A_t(mm^2)$=314

4.1.3 Determination of minimum nail length “L”

For soil nail walls, the minimum nail length should be at least 0.6H.

L=0.6 x H (4.4)

L=4.8m

Adopt a nail length of 4.8m and a diameter of 20mm.

We should check the wall for various failure modes for the above-opted results. To determine the check, various other parameters need to be calculated first.

4.1.4 Determination of equivalent nail force "T_{eq}"

The equivalent nail force is the sum of allowable axial forces developed in the nails per unit spacing. The allowable axial force developed in the nail is the minimum of nail pullout capacity R_P and nail tensile capacity R_T.

The nail pullout capacity can be determined using equation 4.5 and the nail tensile capacity using equation 4.7. The pullout length can be derived from equation 4.6.

Table 4.2 summarizes the calculation for allowable axial force.

$$R_P(kN) = \pi d L_P q_u = \pi x 0.02 x L_P x 100 = 6.28\ L_P \quad (4.5)$$

$$L_P(m) = L - \left(\frac{(H-Z)\cos\psi}{\sin(\psi+i)}\right) \quad (4.6)$$

$$R_T(kN) = \frac{\pi d^2 x\ f_y}{4\ x\ 1000} \quad (4.7)$$

Table 4.2 Calculation of allowable axial force T_{all}

Nail No.	Depth of wall (z) m	Pullout Length L_P	Nail Pullout Capacity R_P	Nail Tensile Capacity R_T	Allowable Axial Force (Min. of R_T and R_P)
1	1m	1.48	9.29	130.37	9.29
2	2m	1.96	12.30	130.37	12.30
3	3m	2.43	15.26	130.37	15.26
4	4m	2.90	18.21	130.37	18.21
5	5m	3.38	21.22	130.37	21.22
6	6m	3.85	24.17	130.37	24.17
7	7m	4.32	27.12	130.37	27.12
8	8m	4.8	30.14	130.37	30.14

For Spacing of 1m , equivalent nail force T_{eq} can be determined as

$$T_{eq} = \frac{1}{S_h}\sum_{j=1}^{n}(T_{all}) \quad (4.8)$$

T_{eq}= 157.51 kN

4.1.5 Determination of weight of failure wedge "W"

weight of failure wedge can be determined as

$$W(kN\text{-}m)=0.5\gamma H^2 cot\psi \quad (4.9)$$

W=0.5 x 18.9 x8^2x cot 62.5

W=302.4 kn-m

To check for external stability of the wall, the global factor of safety and sliding factor of safety is to be evaluated.

4.1.6 Global factor of safety "FS_G" under static conditions

The global safety factor under static conditions is calculated using equation 4.10. The various parameters of the equation are calculated using equations 4.8 and 4.9.

$$FS_G = \frac{T_{eq}\cos(\psi-i)+[(w+Q_T)\cos\psi+T_{eq}\operatorname{Sin}(\psi-i)]\operatorname{Tan}\phi}{[(w+Q_T)\sin\psi]} \qquad (4.10)$$

FS_G=1.36

4.1.7 Sliding factor of safety "FS_{SL}" under static condition

The sliding safety factor under static conditions is calculated using

equation 4.11.

$$FS_{SL} = \frac{C_b B_l+(w+Q_T+P_A\sin\beta)\tan\phi_b}{P_A\cos\beta} \qquad (4.11)$$

Where; Q_T=surcharge load x nail Length=0x4.8

For static case;

$P_A=0.5K_a\gamma H^2$

FS_{SL}=3.26

This concludes the external safety factor determination. Now Internal safety factors are to be evaluated.

4.1.8 Internal stability of soil nail wall

The internal stability of soil nail walls is governed by soil nail pullout capacity and soil nail tensile capacity. In this section both the capacities for the nails are calculated using equation 4.12 and equation 4.13.

$$(FS_P)_Z = \left(\frac{R_P}{T}\right)_Z \qquad (4.12)$$

$$(FS_T)_Z = \left(\frac{R_T}{T}\right)_Z \qquad (4.13)$$

The internal stability should be checked for all nails at subsequent depths. The result obtained after evaluating with above equations 4.12 and 4.13 and the values of R_P and R_T were obtained from Table4.2. The Soil nail pullout failure and soil nail tensile failure is shown in Table 4.3.

Table 4.3 Internal Stability failure safety values

SOIL NAIL NO.	**DEPTH (Z)**	FS_P	FS_T
1	1m	1.82	25.54
2	2m	1.21	12.77
3	3m	1.00	8.51
4	4m	0.91	6.38
5	5m	Low	5.11
6	6m	Low	4.25
7	7m	Low	3.65
8	8m	Low	3.19

This concludes the internal stability check for our soil nail wall. The temporary facing is also designed and checked for various failure modes.

To design the facing, the nail head tensile force at the face should be calculated first and accordingly, the facing parameters are to be considered.

4.1.9 Calculation of design nailhead force at face "T_o"

For T_{max}=40.82kN and S_{max}=1.0m, the nail head force at the face can be calculated by equation 4.14

$$T_o = T_{max}[0.6+0.2(S_{max}-1)] \quad (4.14)$$

T_o=24.49kN

Now we can adopt various parameters for the facing. The parameters adopted in this study are :

4.1.10 Adopted properties of facing element

Temporary facing thickness; h=150mm

Steel reinforcement: Fe415

Shotcrete: M20 with characteristic strength of 20 MPa

Welded wire mesh(temporary facing): WMM102x102-MW19xMW19

Horizontal and vertical waler bars= 2x10mm dia(f_y=415MPa)

Bearing Plate: Grade250(f_y=250MPa)

Shape: Square

Length:$L_{BP} = 225$mm

Thickness: $t_p = 25$mm

4.1.11 Facing flexure resistance "R_{ff}"

This can be determined from equation 3.15.

$$R_{ff}=\frac{C_f}{265}(a_{vn} + a_{vm})\left[\frac{S_H h}{S_v}\right]f_y \quad (4.15)$$

Where C_f is a correction factor that takes account of non-uniform soil pressure. A_v represents vertical cross-sectional area per unit width and m and n represent mid-span and nail head.

The correction factor depends upon the types of structure and facing thickness. For the temporary structure of facing thickness, this value is considered 1.5.

This will lead to an R_{ff} of 166.415 kN.

4.1.12 Safety factor against facing flexure "FS_{ff}"

This can be calculated by equation 3.16.

$$FS_{FF} = \frac{R_{ff}}{T_o} \tag{4.16}$$

The R_{ff} is obtained from equation 4.15 and T_o from equation 4.14. Computing these results in the above equation provides a safety factor against facing flexure of 6.79.

4.1.13 Facing Punching resistance " R_{fp}"

This is determined from equation 4.17

$$R_{fp}=330\sqrt{f_{ck}}\Pi D_c h_c \tag{4.17}$$

Here: f_{ck}=20Mpa;

H_c=h=.150m

$D_c=L_{BP}$+h=225+150=375mm=.375m

R_{fp}= 260.78

4.1.14 Safety factor against punching resistance " FS_{fp}"

This can be calculated by equation 3.18.

$$FS_{FP}= \frac{R_{fp}}{T_o} \tag{4.18}$$

The safety factor against punching failure comes out to be 10.64

This concludes the facing design and various failure checks associated with it.

The wall height of 12 m was also designed similarly and the summary of the results obtained from both the walls is listed in table 4.4

Table 4.4 Summary of Results from the Conventional Method

PARAMETERS	Values (H=8m)	Values(H=12m)
Maximum axial force; T_{max}	40.82 kN	61.23 kN
Nail bar diameter; d	20mm	20mm
Nail bar length; L	4.8 m	7.2m
Global safety factor; FS_G	1.36	1.02
Sliding Safety factor; FS_{SL}	3.26	2.33
Safety factor against tension; FS_T	3.19	2.55
Safety factors against pullout; FS_P	1.82	0.77
Nail tensile force at face; T_0	24.49 kN	36.74 kN
Adopted temporary facing thickness; h	150mm	150mm
Safety factor against facing flexure; FS_{FF}	6.79	4.34
Safety factor against punching failure; FS_{FP}	10.64	7.22

4.2 Numerical Simulation Using Plaxis

Plaxis is a geotechnical engineering simulation software used for the analysis of soils and rocks. Plaxis allows the user to simulate the site conditions and loading and analyze the stability of the structure without predefining the failure surface. The software allows the development of failure surfaces to occur and also allows for staged construction to achieve accurate simulation of site problems. In this study, the plane strain model analysis of 15 node elements was considered. The 15 nodes triangular element is considered to provide accurate stress results.

The soil nail wall requires the simulation of three structural elements. Soil, nail, and facing element. Soil can be simulated as per various soil models available in the software. While to simulate the facing, the plate element is considered. And to simulate the nails, a plate element or geogrid element can be considered.

The software allows for various soil models like the Modified cam-clay model, Hardening soil model, Mohr-Coulomb Model (MC) , and HS small model. But other than Mohr-Coulomb Model, other models require various parameters that are generally not available hence MC model is widely used and considered for the analysis.

The input parameters adopted in this study for simulation of soil nail walls are provided in Table 4.5

Table 4.5 Input Parameters for Numerical Simulation

Vertical Height of the Wall (m)	**8**	**12**
Face Batter, α, degrees	0.0	0.0
Soil Type	Dense Sand	Dense Sand
The slope of the Backfill, β degrees	0.0	0.0
Cohesion, c, kPa	5.0	5.0
Friction angle φ degrees	35	35
Unit weightγ, kN/m^3	18.9	18.9
Modulus of elasticity of Soil E_s MPa	20.0	20.0
Poisson's ratio v	0.3	0.3
Grade of steel	Fe-415	Fe-415
Modulus of Elasticity of nail E_n GPa	200.0	200.0
Nail Spacing $S_V \times S_H$, m × m	1.0 x 1.0	1.0 x 1.0
Nail inclination (wrt horizontal), i, degrees	15	15
Drill hole diameter, D_{DH}, mm	100	100
Compressive strength of grout E_g	20	20
Ultimate Bond strength q_u kPa	100.0	100.0
Modulus of elasticity of grout E_g GPa	22.0	22.0

To account for grouted nailing in Plaxis, the equivalent modulus of elasticity E_{eq} shall be calculated to include the contribution of stiffness from both nails and the grout. This can be determined using equation 4.19

$$E_{eq} = E_n\left(\frac{A_n}{A}\right) + E_g\left(\frac{A_g}{A}\right) \qquad (4.19)$$

Where, E_n is the elastic modulus of nails and E_g is the elastic modulus of grout and A_n and A_g represent the cross-sectional area of nail and grout respectively. The A_g is calculated after subtracting the nail area from grouted nail area which is calculated using the drill hole diameter D_{DH}.

Using E_{eq} from equation 4.19 , the axial stiffness EA and bending stiffness EI can be determined using equations 4.20 and 4.21 respectively.

$$\text{Axial Stiffness EA [kN/m]} = \frac{E_{eq}}{S_h}\left(\frac{\pi\, {D_{DH}}^2}{4}\right) \qquad (4.20)$$

$$\text{Bending Stiffness EI [kNm}^2\text{/m]} = \frac{E_{eq}}{S_h}\left(\frac{\pi\, {D_{DH}}^4}{64}\right) \qquad (4.21)$$

In plane strain analysis, the element is considered to be continuous in the out-plane direction, therefore to reduce the soil nail inertia the above values are to be determined by dividing the horizontal spacing between nails.

The numerical analysis was performed for two nail models. Nails are simulated using plate element and then they were simulated using geogrid element. Values of axial stiffness and bending stiffness used for simulating the facing plate are as follows

$EA=4.5x10^6 kN/m$ and $EI=1.22x10^4 kNm^2/m$

4.2.1 Finite Element Mesh

Figure 4.1 shows the mesh diagram generated for 8m wall height with plate face element and plate nail element. The medium-coarse mesh was generated because it provides accurate results along with quick calculation time as one of the advantages.

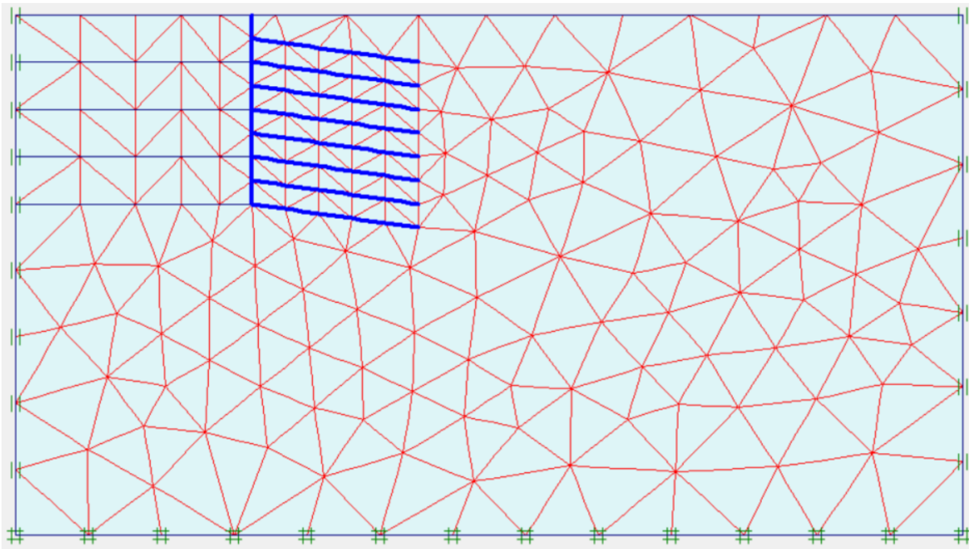

Fig 4.1 Mesh Model used for Analysis

Plaxis allows for various types of calculation like plastic analysis, consolidation analysis, and phi/c reduction analysis. Depending upon the calculation type the plaxis generates an output.

4.2.2 Analysis at various Construction Stages in Wall Construction

The Plaxis allows for staged construction of the problem which provides insight into the mechanical behavior of the wall after every construction phase.

Fig 4.2 presents the various construction stages and the sequence followed for thr numerical analysis.

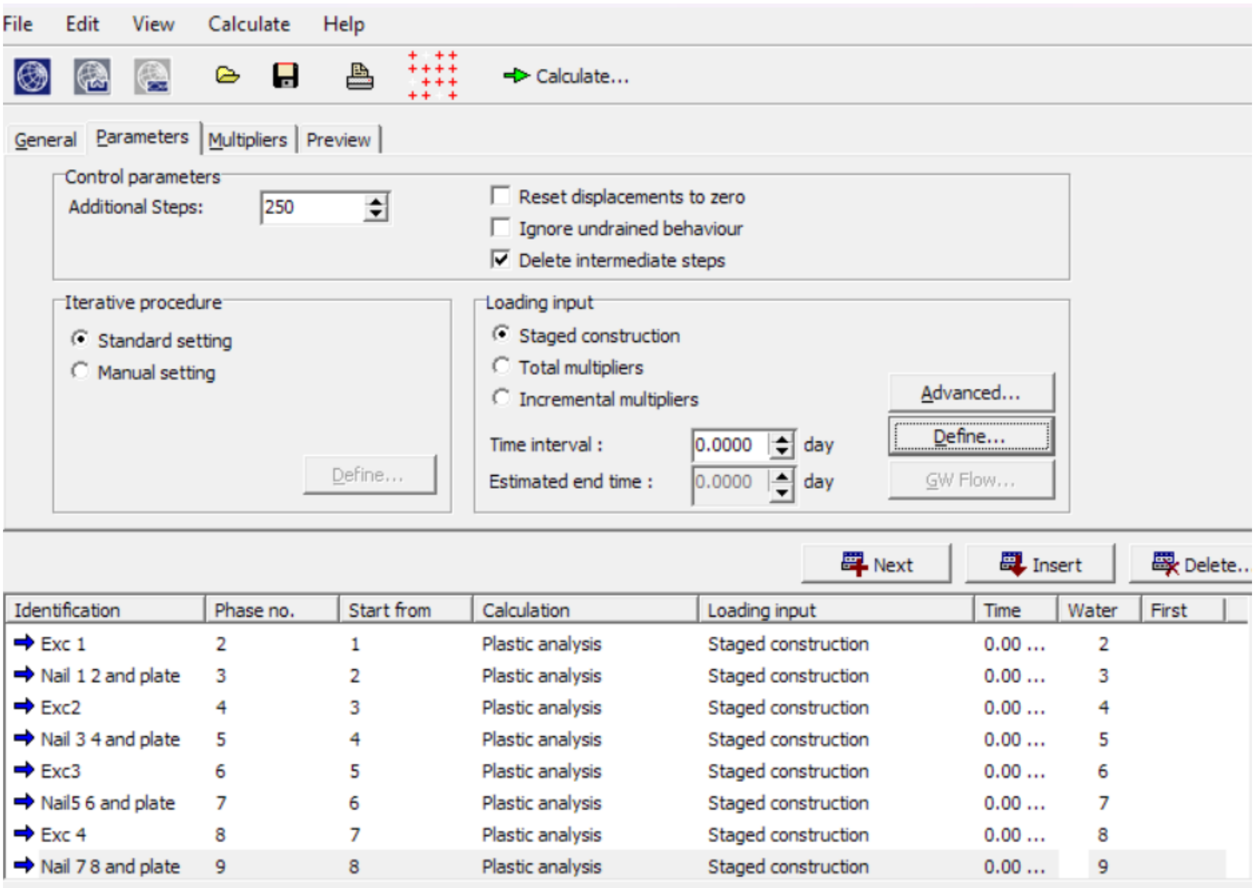

Fig 4.2 Construction stages of the soil nail wall

Fig 4.3 shows the Finite element Model depicting the various construction stages analyzed for 8m wall height with plate element facing and nail.

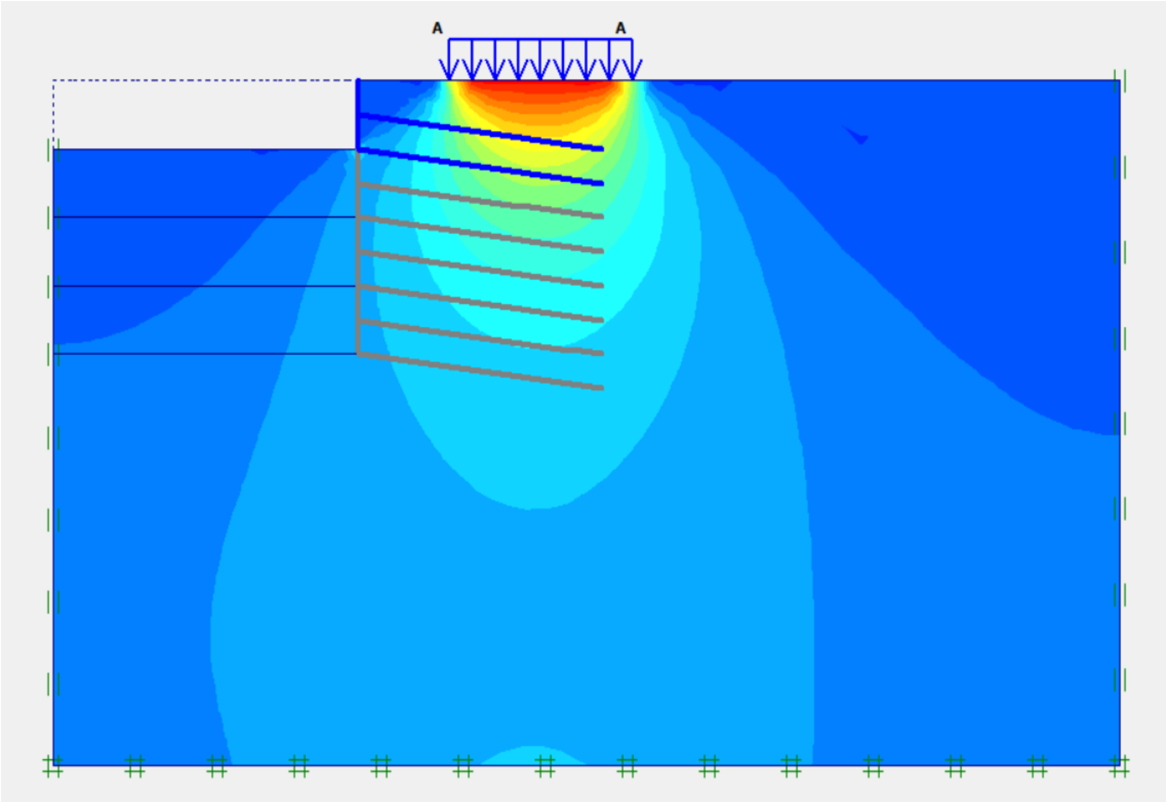

Fig 4.3(a) Construction stage 1

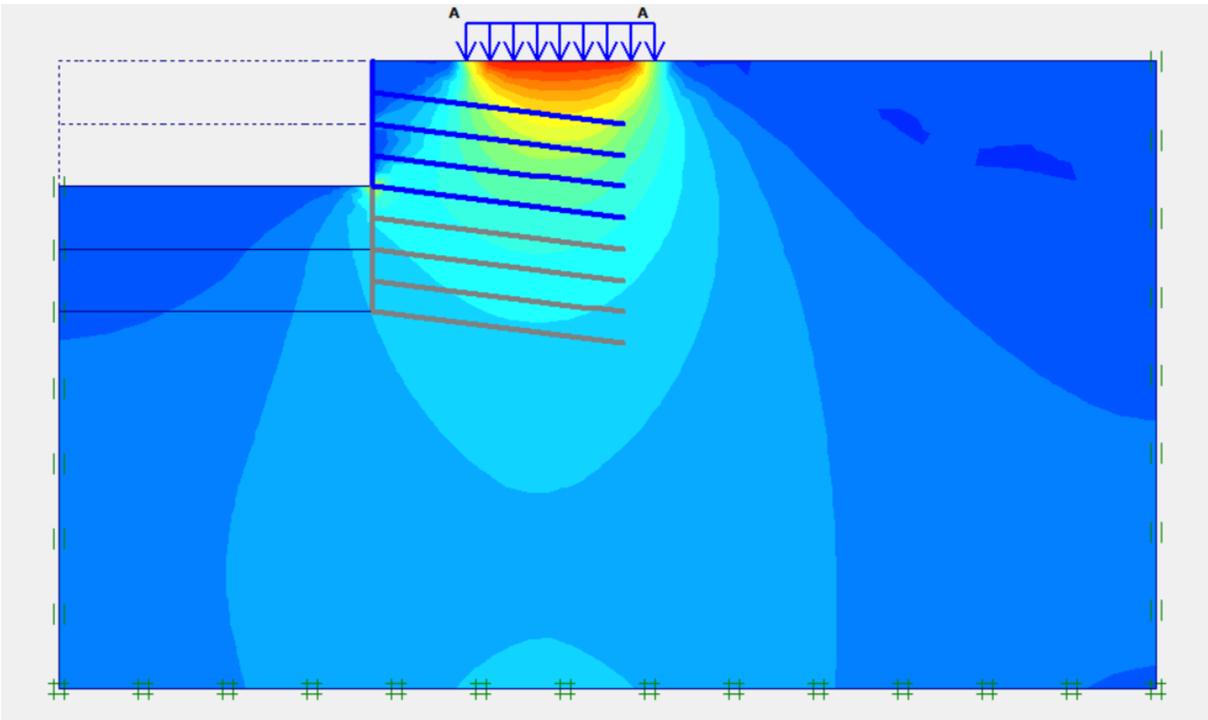

Fig 4.3(b) Construction stage 2

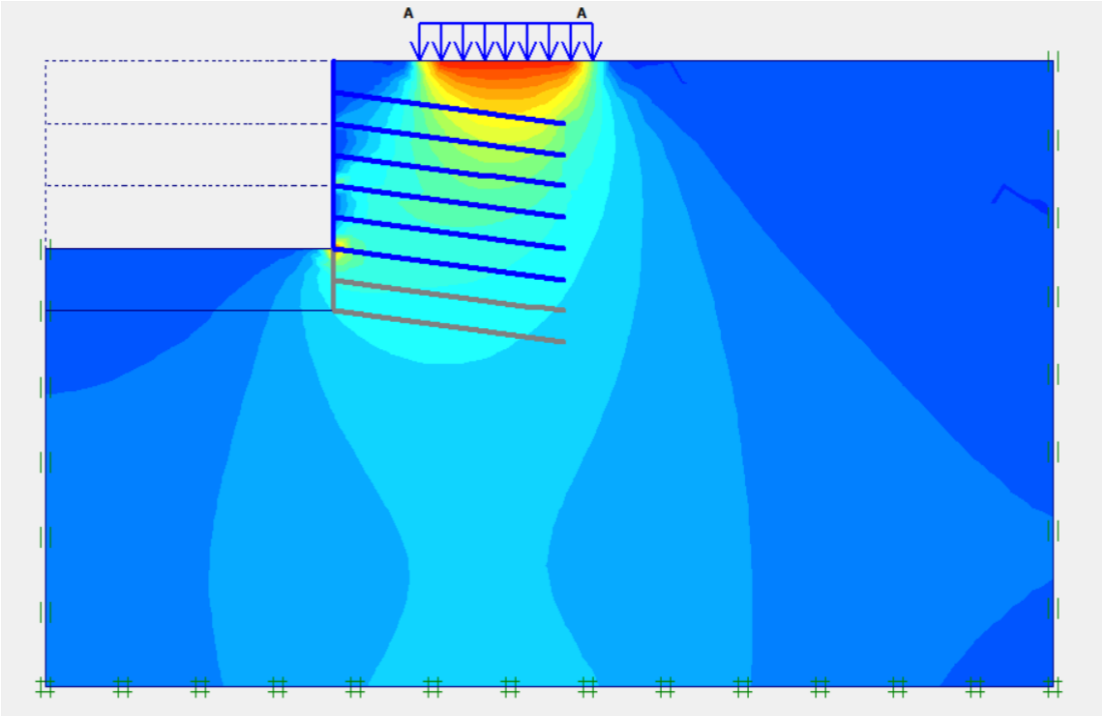

Fig 4.3 (c) Construction Stage 3

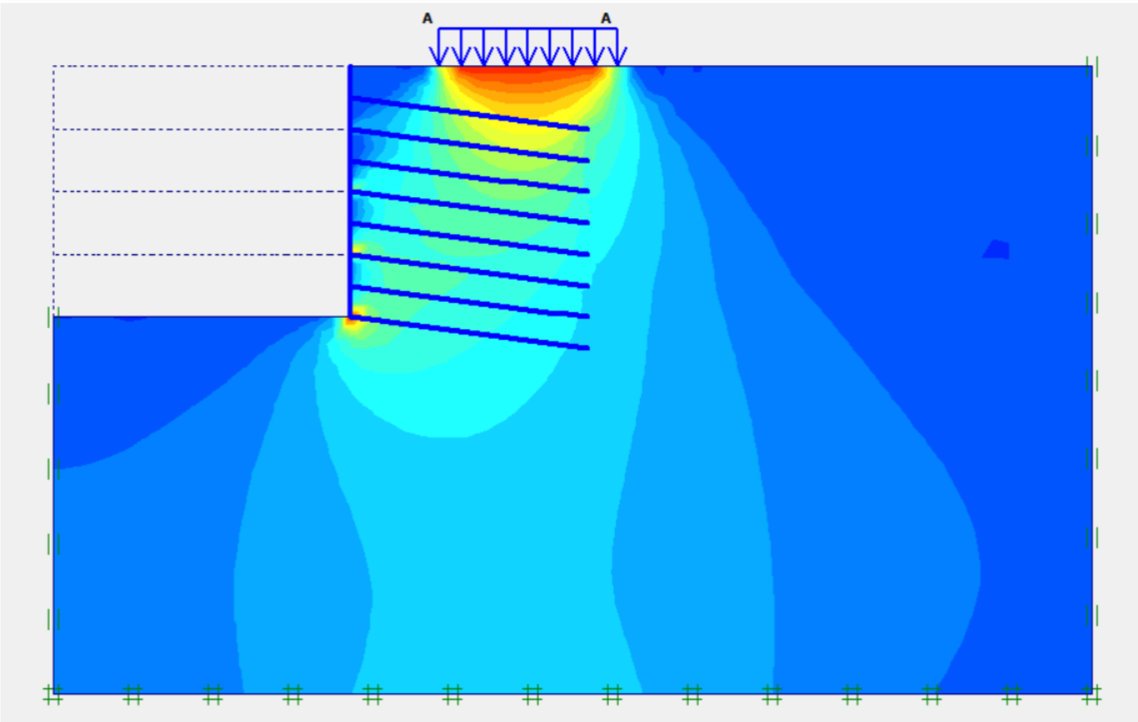

Fig 4.3 (d) construction stage 4

To determine the global factor of safety, phi/c reduction analysis was done. This method allows gradual reduction of soil's phi and c value until the soil loses its strength and fails. The factor of safety and horizontal displacement of the wall was recorded after every construction stage.

The values obtained for displacement and global safety factor after every construction phase is provided in Table 4.6

Table 4.6 values of FS_G and y_{max} with construction stage

Construction stage	Global safety factor FS_G	Maximum displacement y_{max} (mm)
25%	11.21	1.26
50%	9.64	1.88
75%	7.38	3.56
100%	3.96	7.67

4.2.3 Effect of using Geogrid structural element as soil nail

The study was also carried out on the use of simulating soil nail walls with the geogrid element. The geogrid element is simulated as a tension element only. This model requires axial rigidity as the main input for simulating the nail.

The mesh diagram of geogrid element nail for 8m wall height is provided in Fig 4.4

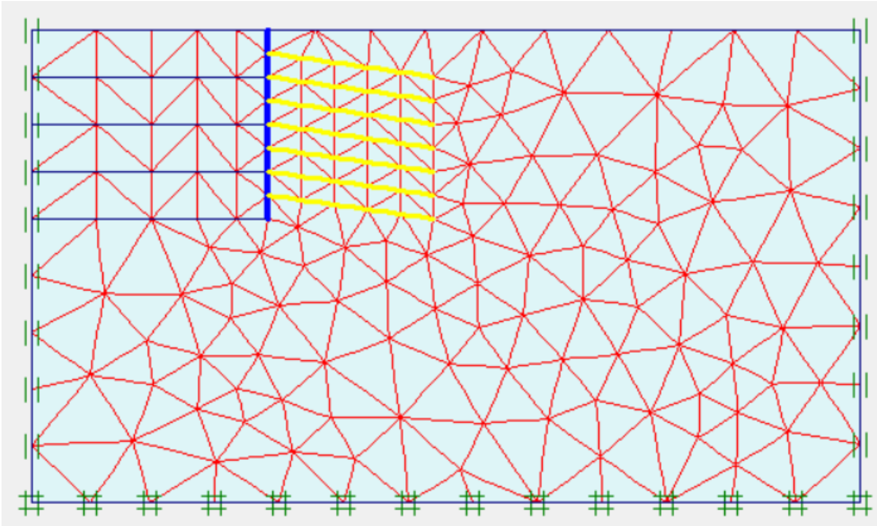

Fig 4.4 Mesh Model of geogrid nails

Table 4.7 provides the value of the global safety factor after every construction stage for plate element and geogrid element nails.

Table 4.7 Global factor of safety FS_G of geogrid nail element and plate nail

Construction stage	**Global safety factor FS_G(Geogrid)**	**Global safety factor FS_G(Plate)**
25%	6.15	11.21
50%	5.83	9.64
75%	5.23	7.38
100%	2.47	3.96

As walls of two heights 8m and 12m respectively were designed through the conventional method. The numerical simulation of the walls was conducted in Plaxis to assess the stability of the soil nail wall. Table 4.8 provides a summary of various parameters obtained from numerical simulations and then they are compared with the results obtained from the conventional method. The internal and facing stability was analyzed by getting values of T_{max} and T_0. And then using these values in equations 4.12, 4.13, 4.16, and 4.18.

Table 4.8 Summary of results from numerical simulations

Analysis parameter	**H=8m**	**H=12m**
Soil nail wall		
FS_G	3.96	3.28
Maximum Horizontal displacement, %	0.86	1.31
Nail		
Maximum axial force, T_{max-s}, kN	16.33	40.26
Axial force at the head, T_0,kN	12.57	36.65
Maximum bending moment, M_N,kNm	1.37	2.37
Maximum shear force V_N,kN	6.71	12.56
FS against pullout FS_P	3.11	1.89
FS against tensile strength FS_T	8.61	5.76
Facing		
Maximum axial force, T_F,kN	40.05	127.31
Maximum shear force, V_F,kN	35.46	69.53
Maximum bending Moment, M_F,knm	14.24	16.11
FS against facing flexure FS_{FF}	3.23	3.22
FS against punching shear failure FS_{FP}	2.61	1.97

4.3 Slope Stability Analysis Using Bishop's Method

After analysis from the conventional method and Numerical simulation from the Plaxis method. The application "simple Slope" developed by Geomecanica was used for Bishop's method calculation. The application allows users to define Soil material, slope Geometry, Surface loading, Water table, and Reinforcement as well. To simulate the soil nail wall, input parameters of reinforcement were taken as that of soil nails and the faceplate was activated to simulate the temporary facing of the wall.

The properties of material and geometry were kept constant as that with previous methods and then the analysis was performed. Figure 4.5 shows the slip circle and factor of safety associated with it for 8m wall height.

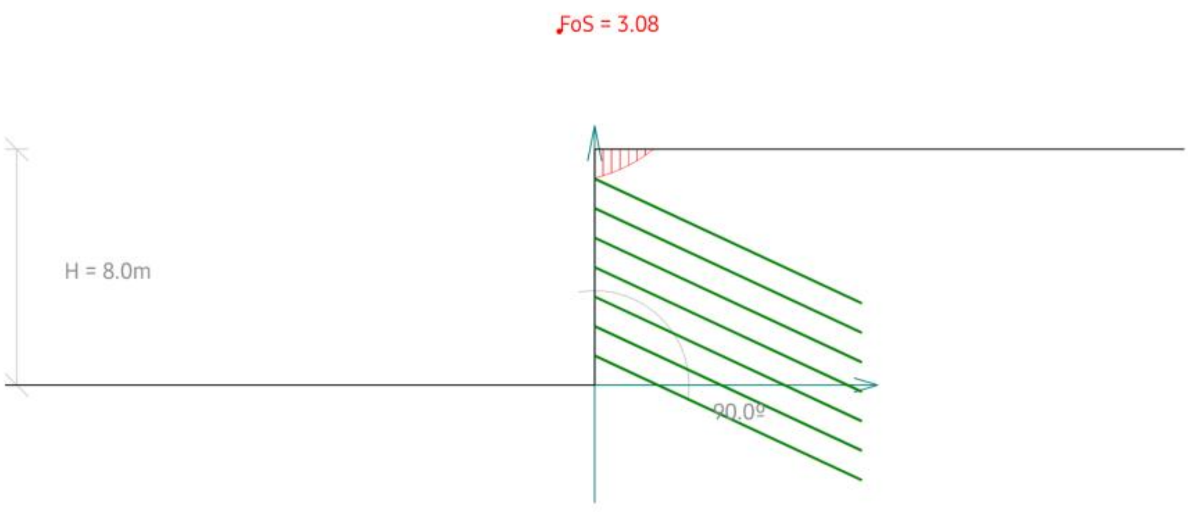

Fig 4.5 slip circle for slope (H=8m)

The calculation from the Bishop's method for a wall height of 8m is provided in Table 4.9

Slice	Area (m^2)	Weight (kN)	Base Inclination (^{0})	Driving Force (kN)	Resisting Force (kN)
1	0.0	0.0	0.0	0.0	0.0
2	0.2676	5.058	15.21	1.327	4.848
3	0.243	4.592	18.55	1.46	4.548
4	0.2129	4.024	21.95	1.504	4.191
5	0.1772	3.349	25.44	1.439	3.768
6	0.1353	2.558	29.03	1.241	3.267
7	0.0866	1.637	32.75	0.886	2.668
8	0.0302	0.571	36.64	0.341	1.946
Sum		21.789		8.198	25.236

Table 4.9 Bishop's calculation Table (H=8m)

$$FOS=\frac{\text{Resisting Forces}}{\text{Driving Forces}} \quad (4.22)$$

FOS=25.236/8.198=3.08

Similarly, the analysis was carried out for 12m wall height. Fig 4.6 shows the slip circle and factor of safety associated with it for 12m wall height.

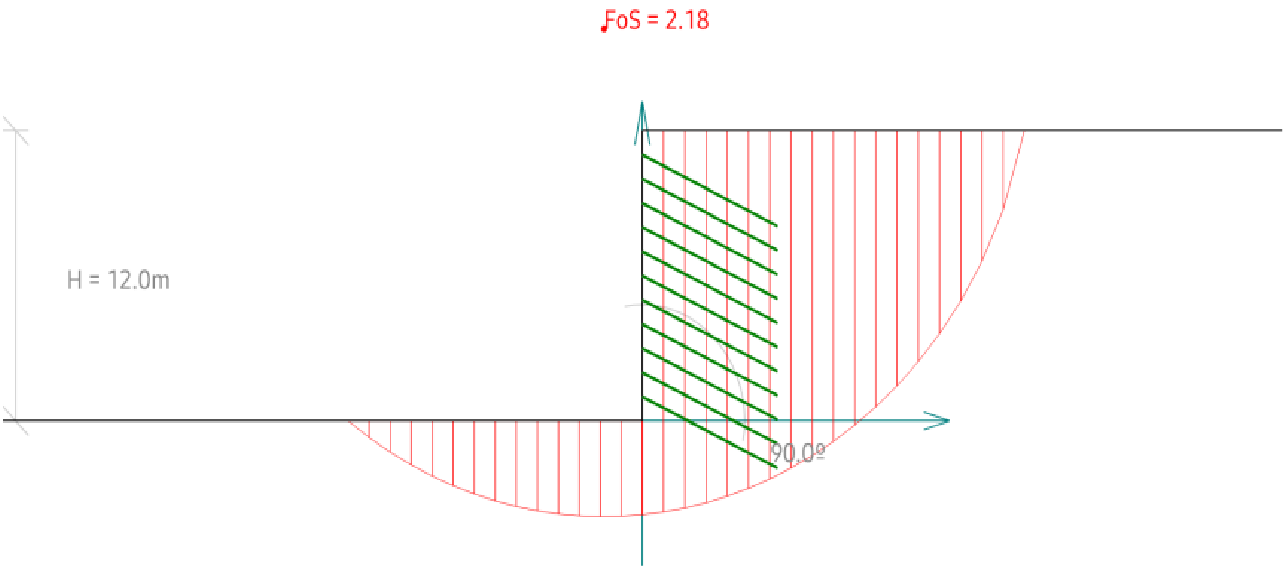

Fig 4.6 Slip circle for slope (H=12m)

Table 4.10. Calculation table(H=12m)

Slice	**Area (m^2)**	**Weight (kN)**	**Base Inclination (^{0})**	**Driving Force (kN)**	**Resisting Force (kN)**
1	0.3379	6.386	-27.5	-2.949	12.725
2	0.9731	18.392	-27.5	-8.493	24.106
3	1.5314	28.943	-27.5	-13.365	34.107
4	2.0199	38.176	-25.1	-16.196	41.154
5	2.4442	46.195	-22.04	-17.338	46.227
6	2.8086	53.083	-19.05	-17.327	50.093
7	3.1167	58.905	-16.11	-16.346	52.977
8	3.3711	63.713	-13.21	-14.564	55.039
9	3.5739	67.546	-10.35	-12.137	56.397
10	3.7267	70.434	-7.51	-9.211	57.137
11	3.8306	72.399	-4.7	-5.927	57.322
12	3.8865	73.456	-1.89	-2.421	56.997
13	3.8948	73.612	0.91	1.174	56.191
14	3.8555	72.869	3.72	4.726	54.923
15	0.0	0.0	3.91	0.0	0.0
16	0.0002	0.0	5.46	0.0	0.003
17	15.75	297.675	6.55	33.938	207.175
18	15.6111	295.049	9.4	48.212	203.623
19	15.4211	291.459	12.29	62.021	199.971
20	15.1786	286.876	15.2	75.216	196.191
21	14.8816	281.261	18.15	87.637	192.249
22	14.5273	274.566	21.16	99.114	188.104
23	14.1126	266.728	24.23	109.46	183.7091

Slice	Area (m^2)	Weight (kN)	Base Inclination (^{0})	Driving Force (kN)	Resisting Force (kN)
24	13.6331	257.666	27.37	118.471	179.004
25	13.0834	247.278	30.61	125.912	173.914
26	12.4567	235.432	33.96	131.514	168.338
27	11.7436	221.954	37.45	134.955	162.14
28	10.9319	206.612	41.11	135.84	155.131
29	10.0044	189.083	44.98	133.666	147.026
30	8.9363	168.896	49.15	127.754	137.382
31	7.6889	145.32	53.7	117.119	125.439
32	6.1955	117.095	58.83	100.186	109.744
33	4.3193	81.634	62.5	72.411	83.222
34	1.631	30.825	62.5	27.342	35.573
sum		4639.522		1610.394	3503.333

$$FOS = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

$$FOS = \frac{3503.333}{1610.394} = 2.18$$

This concludes the analysis of our soil nail wall. The values obtained from different methods for factor of safety are listed in Table 4.11

Table 4.11 Summary of safety factors from different methods

Method	FOS(H=8m)	FOS(H=12m)
Conventional method FHWA(2003)	1.36	1.02
PLAXIS	3.96	3.28
Bishop's Method	3.08	2.18

Chapter 5: Results & Discussion

The conventional design was based on the assumption that a wedge failure would occur. The wall was designed for minimum safety factor of 1.35 and the global safety value of wall of 8m height after consideration of nail parameters was found 1.36, which shows that the conventional design was safe against global stability of the structure. While the wall of 12m height provided the value of 1.02. The wall is safe but the design should be revised so to attain minimum safety factor suggested. The plaxis method provided safe values with safety factor of 3.96 and 3.28 against wall of height 8m and 12m respectively. The Bishop's method also provided safe values of 3.08 and 2.18 against wall of height 8m and 12m respectively. Figure 4.7 shows the trend of global factor of safety with different methods adopted for the study.

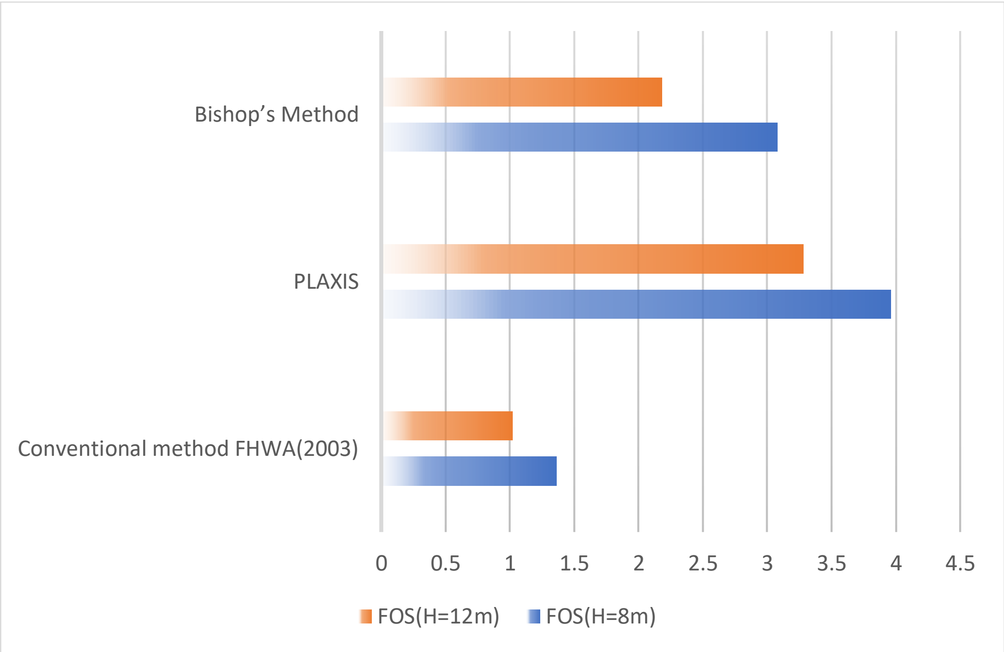

Fig 4.7 Trend of safety factors from different methods

This can be observed that with the depth of excavation the global factor of safety reduces. Since, the conventional method is designed for minimum factor of safety values the results obtained are very conservative than numerical analysis carried out by Plaxis, which does not account for such adoption of minimum factor of safety in calculation.

The internal safety of the wall is governed by soil nail failure. The soil nail pullout failure and soil nail tensile failure. The values obtained for soil nail tension failure are more than the recommended minimum values from both the methods.

The safety against soil pullout failure from numerical simulation is 3.11 and 1.89 for wall of height 8m and 12m respectively. While it is 1.82 and 0.77 for 8m and 12 m wall from conventional method. The conventional method provided almost safe value for 8m wall height whereas for 12m wall height the result shall be revised to attain minimum safety factor value.

The soil nail wall is also checked for facing failures.The Results obtained in Table 4.4 and 4.8 shows that the safety values against facing flexure failure and facing punching failure calculated from both conventional method and as well as numerical simulations are more than the minimum recommended values.

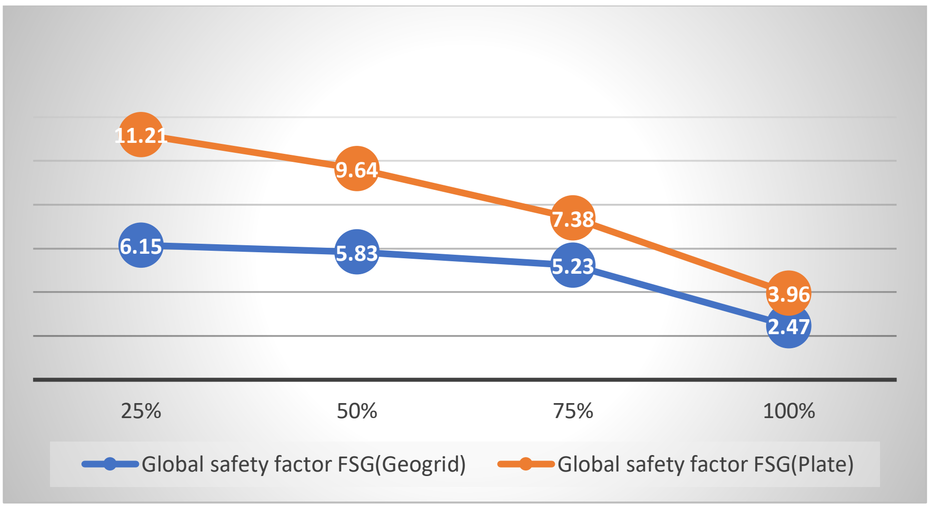

Fig 4.8 Trend of a global factor of safety

Literature shows that the soil nails are not only subjected to axial forces but the bending moment is acted upon them too. This allows user to simulate the soil nails with various models. In this study soil nail element was simulated by geogrid element and also with the plate element.. The factor of safety trend of both the element after every construction stage is shown in Fig4.8.

Chapter 6: Conclusion

In this study, soil nail wall has been designed conventionally and numerical simulation was performed. The values obtained after the design suggests that the conventional method adopted in this study provides a safe but conservative design.

The result shows that with the plate element the factor of safety of 3.96 was recorded and with geogrid element, the factor of safety of 2.47 was recorded. The geogrid nail element shows 37% less value as compared with plate element.This shows that contribution of shear and bending stiffness of nail is significant for overall stability of the wall. This can be concluded that best approach to simulate soil nail is using it as plate element rather than geogrid element.

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