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Seismic analysis of Bored and Driven Soil Nailed Structures

by

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ABSTRACT

Soil nails serve as passive reinforcement components inserted horizontally into the ground to stabilize unstable soil masses and various subterranean or surface excavations. There are different types of soil nailing techniques, categorized based on their installation methods. In the case of driven nails, they are directly pushed into the structure during excavation. On the other hand, drilled and grout-type soil nails involve initially drilling a hole in the excavated soil face, followed by the installation of nails, which are subsequently filled with grout at low pressure. The design process of the soil nail structure hinges on upon its limit state of safety and serviceability. Soil nailed wall are designed based on two main methods. The first is the limit equilibrium method, and the other method is by using finite element analysis.

In this study, we discussed the effects of 2D and 3D analyses of soil nailed structures and the differences in the outputs given by those analysis. The results of the 2D and 3D analysis in in various outputs in which the design of soil nailed walls depends upon like the global factor of safety, horizontal displacement at the top of the soil nailed wall, axial tension in nail, skin friction developed in the various construction stages is found out using a the PLAXIS 3D software. Further seismic inputs of Barpak and Kobe earthquake were used to study the dynamic behavior of the soil nailed structure.

Results show that for both drill-grout nails and driven nails maximum displacement predicted by 2D analysis is more compared to 3D and more prominent difference was seen in driven nails compared to drill-grout nail. The maximum axial forces were found to be maximum at soil nails installed at a depth of about 2/3H from the top of the wall in both drill-grout nails and driven nails. Maximum displacement decreases as the L/H ratio increases for static loadings whereas in dynamic loadings L/H ratio seems to have little contribution for controlling displacement at lower values (less than 1). Maximum axial force developed in the soil nail decreases with the increase in magnitude of earthquake loading. The values of maximum skin friction developed in the soil nail increases with the increase in the L/H ratio in both static and dynamic loading. As the L/H ratio increases the global FoS of the structure increases due to increase in the depth of the slip surface. Seismic analysis shows that the maximum amplification was found at about L/H ratio of about 1 and decrease as L/H ratio increases.

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075MSGtE005

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
Ag	Area of Grout
An	Area of Nail
c	Cohesion of the soil
DoLI	Department of Local Infrastructure
DoR	Department of Road
E	Youngs Modulus of Elasticity
Eeq	Equivalent Modulus of Elasticity
EA	Axial Stiffness
EI	Bending Stiffness
FEM	Finite Element Method
FHWA	Federal Highway Administration
FoS, FS	Factor of Safety
ICIMOD	International Centre for Integrated Mountain Development
LEM	Limit Equilibrium Method
MBT	Main Boundary Thrust
MCT	Main Central Thrust
MSE	Mechanically Stabilized Earthen Wall
SRN	Strategic Road Network
STDS	South Tibetan Detachment System
USCS	United Soil Classification System
α	Vertical face Angle
β	Horizontal Backslope angle
δ	Deformation of Wall
γ	Unit weight of soil
φ	Angle of Internal Friction of Soil
σn	Normal Strength
τ	Shear Strength
ʋ	Poisson’s Ratio

1. INTRODUCTION

1.1 Background of the Study

1.1.1 Geology of Nepal

Nepal lies in south east Asia, the central part of the Himalayan region that stretches from Myanmar in the east to Afghanistan in the west. This Himalayan area are defined by the presence of tall, steep mountains and its ongoing seismic activity. This seismic activity is the result of the collision between the Indian plate and the Tibetan Plate. Following this collision, the Indian plate continues to move beneath the Tibetan plate through a process known as subduction, and this subduction process is still ongoing.

Geologically, Nepal is divided into 5 different regions namely Indo-Gangetic Plain, Sub-Himalaya, Lesser Himalayas, Higher Himalaya, and Inner Himalaya from South to the North (Dhakal, 2014). Each of these systems is separated by the major fault system existing in between them. Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT) and South Tibetan Detachment System (STDS) are the major thrust line from south to north in the Nepalese Himalayas (Hashash et al., 2015).

Landside, earthquakes, flood, Glacial Lake Outburst Flood (GLOF) are the common natural hazards associated with the geology of Nepal. Siwalik region consists of the young and fragile sandstone and mudstone which are highly susceptible to the weathering due to which there is a high chance of the landslide and slope failure which includes plane, wedge and toppling failure. Lesser Himalayan consists of the highly jointed meta-sedimentary rock along with the high concentration of the fault and folds. Deep seated landslides along the highway frequently occurred in this region. One of the great examples is the Krishnabhir landslide in the Prithvi Highway in Chitwan district. Higher Himalayan region consists of the severely weathered rock with the great potentiality of large-scale landslides. River passing through this region has a high risk of landslide damming as was in the case seen in Jure landslide of Sindupalchowk.

1.1.2 Infrastructure Development

Infrastructure development and connectivity is key for any country to develop and be prosperous. For the proper planning, design, construction, maintenance of the Road network, overall road network of the Nepal is classified by the Nepal Road standard 2070 as:

- National Highway: Connecting the length and width of the country
- Feeder Roads: Connecting the important trade centers and district headquarters from national highways
- District roads: Connecting the trade centers and district headquarters
- Urban roads: Roads within city area
- Rural roads: Roads that provide access to settlements and agricultural areas.

National Highway and Feeder roads fall under the strategic road networks (SRN) which are under the direct supervision of the Department of Road (DoR), the apex body under Ministry of Physical Infrastructure and Transport responsible for supervision and construction of the major roads in the nation. These roads consist of the major road of the country which comprises nearly one third of the total road length of the country.

1.1.3 Understanding the Background of Study

Nepal is characterized by its young and fragile geology dissected by around 6000 rivers and streams along with the high frequently of seismic activities. This has set out the many constraints in the construction, maintenance and operation of the highways along the Nepalese hills and mountains which covers 80% of the land and more than 50% of the population of Nepal.

More than seventy five percent of the strategic road network under DoR is either in construction process or planning phase to pass through these. So, sustainable roads within economic constraints and the use of local manpower has become the challenges to the transportation authority of this Country. The Standard specifications For Road and bridge works 2073 along with its amendments under Section 300: Soil improvement has clearly mentioned soil nailing as an efficient way for soil slope stabilization. DoR and other government agencies are still mostly relying on large gravity structures for road construction process.

Slope protection works are one of the important steps in sustainable road planning. The current state of the practice of the slope protection work done by DoR and other public entities revolves around the bio-engineering work and use of conventional gravity retaining structures. This can mostly be credited due to the lack of sufficient design data and lack of practice among the designers, engineers and contractors and other bodies. Modern methods of slope protection include the application of the soil anchoring, soil nailing, shotcreting, and use of geosynthetic reinforcement methods. Although these methods seem to be modern, most of these methods are economical and can be performed with the locally available manpower and material.

Soil nailing has the principal function of resistance against the tension with secondary function of resistance against the shearing and bending which makes them more suitable for the steep slopes rather than the soil anchoring with primary function of shearing. Similarly, Reinforced earth is also another technique to stabilize the slope but the limitation of reinforced earth lies in its construction procedure as it can be performed only by “bottom-up” approach whereas soil nailing can be performed by both “bottom-up” and “top-down” approach according to the requirement of the site.

The current research on slope stabilization technology primarily focuses on safer and efficient design of soil nailed structures that is suitable for the unique geological conditions and slope characteristics in Nepal. Since most of the areas of Nepal are prone to the effects of earthquakes and thus to address this issue, a comprehensive numerical analysis is being conducted, exploring various factors related to slope, soil, and nail properties and their affect in the seismic response of the soil nailed walls. This analysis aims to establish the relationships between these parameters and the strength and stability of slopes.

1.2 Objective of study

1.2.1 General objective

The general objective of this study is to carry out seismic analysis of the soil nail wall by varying the nail and geometric parameter by dynamic analysis and to suggest the results.

1.2.2 Specific objective

The specific objective of this research work are as follows:

- To perform the 2D and 3D analysis in drill and grout and driven nails by using Plaxis and compare the results.
- To carry out the dynamic analysis of the soil nailed wall using 3D analysis.
- To verify the results of FEM with similar verified studies.

1.3 Study area

The study area is located in Bandipur, Tanahun district, Gandaki Province, Nepal. Study area lies the Lesser Himalayan Zone and is located at a distance of about 70 kms from the epicenter of 2072 Barpak earthquake. Soil parameters used in the numerical modeling is taken from a site in Bandipur of Tanahun district where the culture centre wanted to built is building. Study is performed by the consultant hired by the culture center and various field and lab tests were performed. This specific site was found to have an average cohesion value of 0 kN/m^2 and friction angle 31.6 degrees. (Soil Investigation Report,Bandipur, 2022)

Subsurface exploration was done using Percussion Drilling of 100mm nominal diameter. Conducting the laboratory tests on selected disturbed / undisturbed soil samples. Direct shear tests results were used to find out the engineering properties of soil. The details of the soil reports used in this study have been attached in the annex. (Soil Investigation Report,Bandipur, 2022)

Figure 1-1-1 Photo of Bandipur site (Soil Investigation Report,Bandipur, 2022)

Figure 1-1-2 Site exploration being done (Soil Investigation Report,Bandipur, 2022)

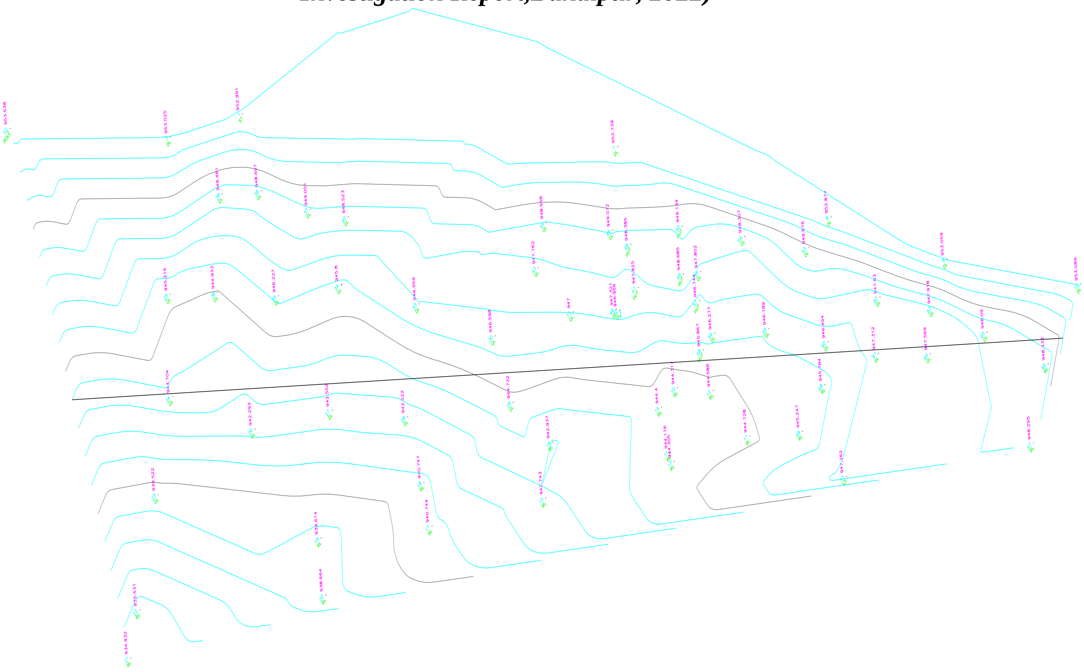


Figure1-1-3 Autocad profile of proposed site (Soil Investigation Report,Bandipur, 2022)

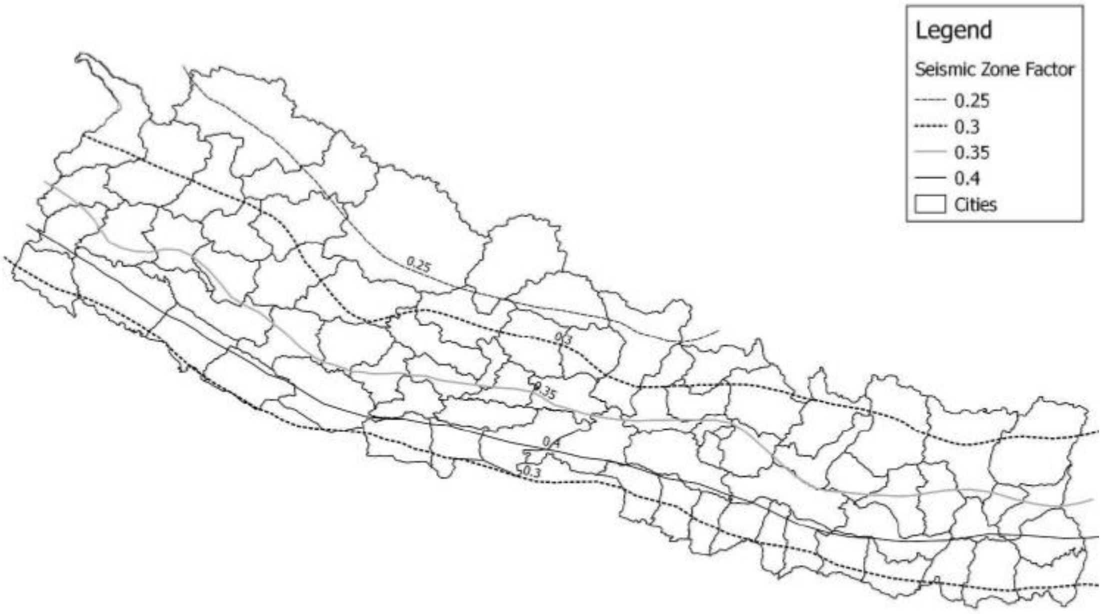


Figure 1-1-4 Seismic Map of Nepal (modified after NRA, 2020)

1.4 Scope of study

To determine the proper parameter range for the numerical analysis, a literature review is conducted. In Plaxis 3D, a finite element analysis in three dimensions is carried out to determine the impact of changing various parameter values. Using a suitable nail wall geometry and nail characteristics, the finally impact of dynamic loadings on the soil nail structure is investigated.

1.5 Limitations of study

The limitations of study are listed below:

- Soil particles are assumed to be isotropic and homogeneous.
- Study does not include all types of soil available over Nepal. Only the modeling is done in the soil obtained from the study area.
- Different parameters not available from the field and lab test results have been approximated using available suitable literatures.
- Real model construction, stagewise field measurement of deformations, pull out test and other field tests weren’t possible to conduct.

2. LITERATURE REVIEW

According to (Munro, 2018) retaining structures are those built as part of the civil infrastructure with the intention of retaining either earth or water. Water retaining structures include dams, flood walls, and other similar constructions. The constructions known as "earth retaining structures" are those that hold onto the earth materials that are next to other civil structures like buildings, bridges, and so forth. The primary goal of an earth retaining structure is to protect the infrastructure from a level of strength and service that exceeds its capacity. The slope and embankment's ability to maintain stability and be safe from collapse is made possible by the earth retaining structure, which increases the soil mass's resistance to instability. Retaining structures like piles, retaining wall, buttresses, counter fort wall, prestress anchor enhance the resisting force through external (active) mechanism whereas other retaining structures like reinforced earth, soil nail, soil dowels enhance the resisting force through the internal (passive) mechanism.

Soil nailing is considered as a modified form of the “New Austrian Tunneling Method”, whose application has been highly useful in various underground and slope protection works. Their economies, flexibility of adopting technology, structural flexibility, and use of light construction equipment during construction, environment friendly nature are the reasons behind its wider scope of its application (Kulczykowski et al., 2017). Currently, soil nail wall is applied to slope stabilization retaining wall and earthwork in filling (Babu, 2009; Ma et al., 2011; Alsubal, Harahap, & Babangida, 2017). A practice of soil nailing technique is also widening even to the conservation of the ancient monuments and buildings of historical importance (Kulczykowski et al., 2017). Kerry D. Stauffer found out that 3D FEM analysis may predict lower FoS values than using a conventional technique and concluded that fully modeled slopes using a 3D FEM approach is superior to the other approaches.

Stabilizing slopes and excavations through soil nailing is considered a practical approach. The performance of reinforced soil structures is influenced by several factors, including the site's geometry, soil density, and mechanical properties, as well as on placement of nail tendons. Numerous studies have indicated the significance of these parameters in determining the behavior of such structures

Hong et al. (2005) conducted experiments using a shaking table to explore how the length and angle of nails impact the seismic stability of slopes. The results indicated that slopes reinforced with nails exhibited a flexible response to strong vibrations. The nail angle was found to influence slope displacement, although it had a negligible impact on the overall seismic stability of the slopes. In a study by Barar and Liu (2010), seismic stability was examined, revealing that the displacement of the mass prone to slipping is more pronounced in far-fault earthquakes compared to near-fault earthquakes. Another investigation by Papazafeiropoloulos et al. (2009) focused on the dynamic interaction of soil nailed structures, revealing that soil-structure interaction enhances system stiffness, leading to a reduction in the amplification factor.

Gazetas *et al*. (2004) conducted a numerical simulation to explore the dynamic response in flexible retaining walls which pointed out that vertical forces of seismic loadings have negligible impact on the lateral pressure distribution on the soil nailed wall. Additionally, Majid Yazdandoust (2010) investigated the dynamic response of soil nailed walls through experiments conducted on a 1g shaking table.

2.1 Origin/History and State of Practice in Nepal

Soil nailing technique for the soil stabilization developed from the support technique used in supporting the Underground excavation method in New Austrian Tunneling Methods(Lazarte et al., 2003). The evidence of the application of the concept of the soil nailing i.e. used of passive reinforcement steel with the shotcrete to stabilize the rock slope found in the 1960s. Soil Nailing technique was firstly used in 1972's railway widening project near Versailles, France. After that it became more popular in the other countries of Europe.

Soil nailing technique has become popular in Europe in the 70s decade and its popularity has also extended to North America in 1980s. Then after, soil nailing has been used in the many soil and rock slopes in Asia too. In Hong Kong soil nailing is firstly used to provide the support on the deeply weathered rock zones (Murthy et al., 2002). This technique was extensively used in Japan in late 90s, around 4000km length of the soil nailing structure along the expressway were built in the Japan. We can also find the soil nail retaining wall to stabilize the roadway and railway slope in India(Murthy et al., 2002).

Figure 2-1 Soil Nailing works being done at Pasang Lambhu Highway

Soil nailing has also become popular in Nepal too. Though not used extensively to the extent in which it should have been it can be found in the many road side slopes in the context of Nepal. It has been found effectively used to stabilize the road side slope in the Narayanghad-Muglin road extension project (Dhakal & Prasad, 2019). DoR is currently performing soil nailing works in various sections of. A study has also been carried to stabilize the failed and critical slope using the soil nailing technique in the Nepalthok-Khurkot section(Sharma & Prasad, 2017) . A Finite Element Modelling and Study of Soil Nailed Slope in case of Silty Sandy Slope at Khadkadil, Bhaktapur has also been conducted (Dahal and Pudasaini). Currently soil nailing practice is performed in the Ring Road of the Kathmandu valley, Narayanghad-Muglin road, Pasang Lambu highway, Fast track and many others road and hydropower projects.

2.2 Components of Soil Nail Wall

Soil Nail Wall structure consists of nail components like nail/tendons, grout, facing plate, corrosion protection structure and facing components like temporary facing and permanent facing. Some nail walls consist of other components like connection components and drainage systems. The component of the soil nail wall is shown on Figure 2.2.

Reinforcement bars (Nail or Tendon)

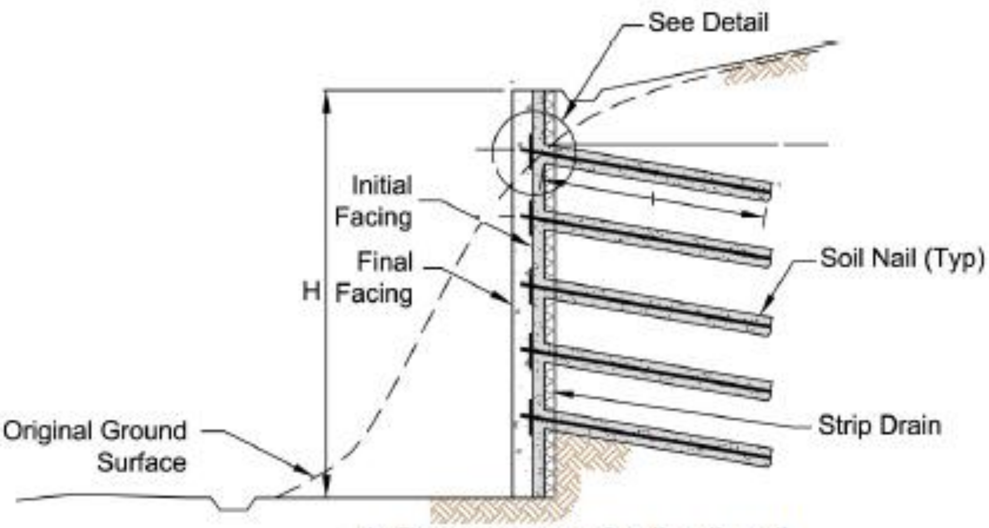
The tension-bearing component, or tendon, should be composed of high-strength steel reinforcing bars with a tensile strength of 415 MPa or greater, and it may have threading at one extremity. The suggested minimum diameter for the reinforcing bar (tendon) is 16 mm.

Grout

Grout is the cement- water slurry which is poured in the predrilled hole after the insertion of the slender tendon member. Grout mix shall be prepared in accordance with IS : 9012. And have a minimum 28 days characteristic strength of 20 MPa. Its main function is to transfer the stress between the soil element and tendon.

Nail Head

The nail head shall comprise of following main components: the bearing plate, hex nut, and washer, and the headed-stud. Its main function is to provide the reaction to the tendon element so that tensile force is mobilized in the tendon. For temporary walls, the bearing plate shall be on the outside face of the shotcrete facing.



a) Components of soil nail wall

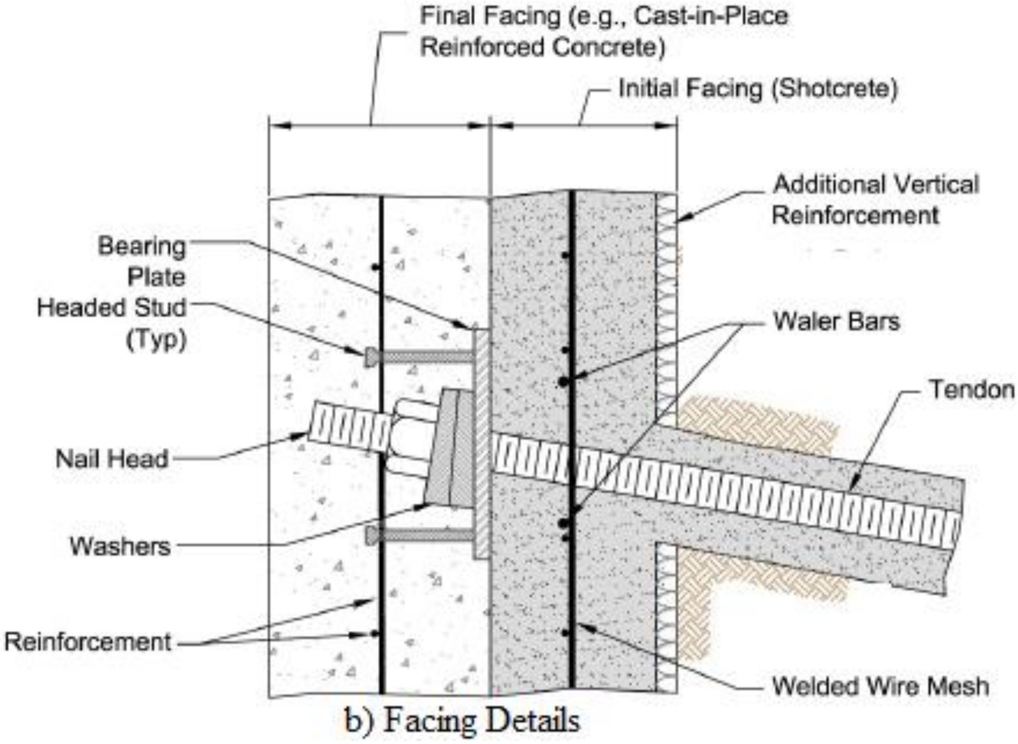


Figure 2-2 Different Component of Soil Nail Wall (modified after FHWA, 2015)

Facing

Facing is the external part of soil structure which provides structural connectivity to the structure and protects the wall from the erosion caused by the water. Facing are of two types, they are Permanent facing and Temporary facing.

Drainage System

Drainage system consists of vertical geo-composite drain which is placed in between the temporary facing and excavation surface in order to drain off the water which may develop the water pressure behind the wall. It is provided with the weep holes and horizontal foot drain.

Connectors

Connectors are the element provided to connect the tendons together within the drill hole. Connectors may be of couplers, couplers with thread, coupler with shear bolts etc.

2.3 Construction of Soil Nail Wall

Construction procedure of the soil nail wall is shown in Figure 2.3. The general steps of construction are.

Excavation

Initial excavation of 1 to 2 m depth is carried out. Excavated surface has the capacity to withstand the surface without failure for up to 24 to 48 hours.

Drilling

Holes are drilled on the excavated surface up to the required depth for the installation of the tendon member. The diameter of the hole, inclination of the hole is determined as per design specification.

Nail Installation and Grouting

Nail is inserted into the pre-drilled hole. A grout pipe is placed with the nail which allows the passage of the grout. Low pressure grouting or gravity grouting is performed to fill the drill hole with the grout.

Construction of the Subsequent levels

After the construction of the temporary reinforcement up to the first lift step 1 to step 4 as shown in the figure 2.3 is repeated to the required height. After the construction of each lift required drainage should also be laid up to that depth.

Construction of the Permanent Facing

After the excavation, drilling, installation of tendon, grouting, construction of the temporary lift is completed up to the required depth final facing is constructed in the soil nail wall.

Construction of the driven soil nail wall started with the initial excavation of the 1 to 2m depth where the nail tendon member is directly driven up to the required depth after that a suitable temporary facing is provided and then these three steps are repeated until the required depth and then final permanent facing is provided.

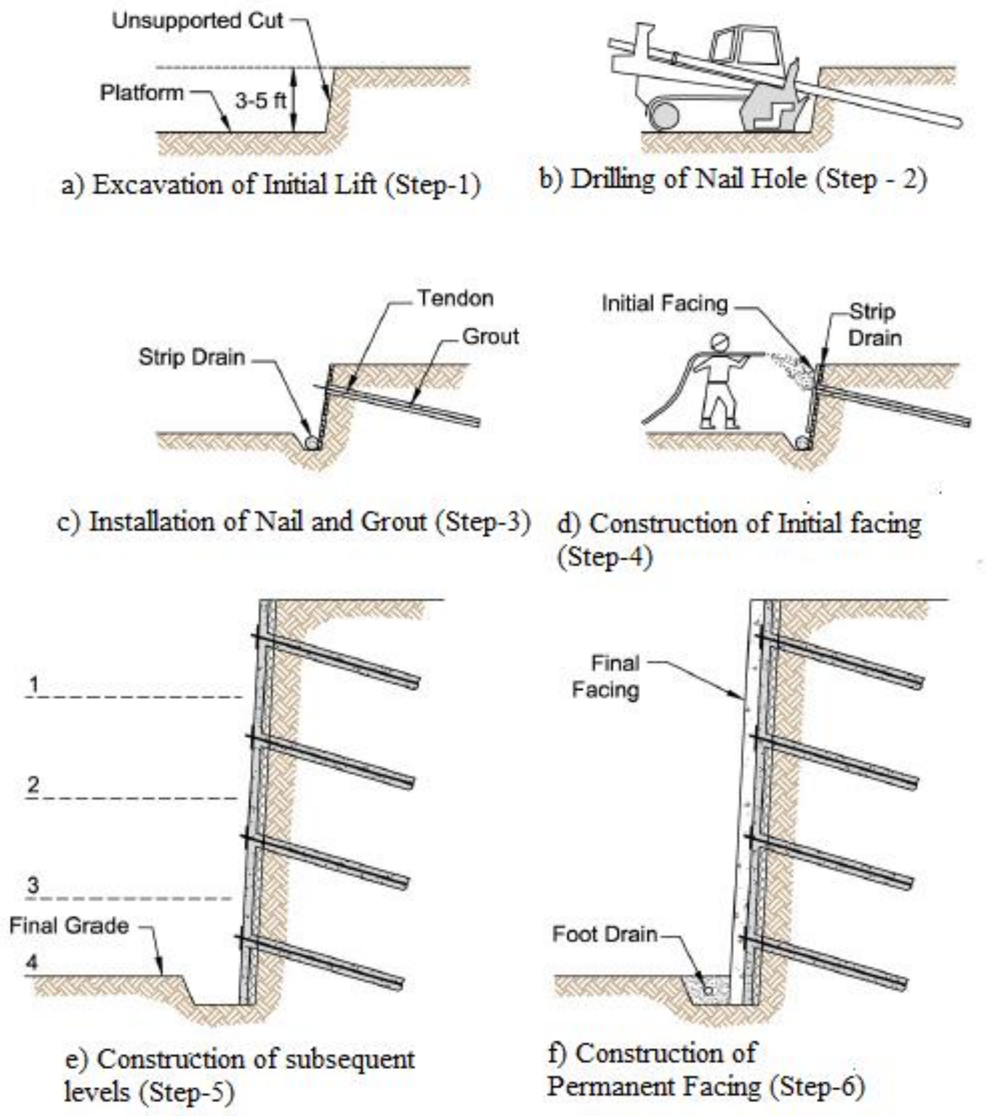


Figure 2-3 Construction Sequence of Soil Nail Wall modified (modified after FHWA, 2015)

2.4 Different types of Soil Nailing methods

Drill and Grouted Soil Nailing Technique

It is the mostly used type of soil nailing method where a nail is pushed into the hole which is drilled prior and after that hole is filled by the grout at minimum pressure. It is suitable in both temporary and permanent purpose. Grouted nailing is performed for a nail wall with the height more than 7m for the both temporary and permanent purpose.

Driven Soil Nailing Technique

In this method nails are driven into the structure as the excavation proceeds. This method of nailing technique is generally done for temporary purposes. This method is not corrosion resistive. Driven nails can be performed when the wall height is less than 7m for the temporary purpose (DoR, 2073).

Self-Drilling Soil Nail Method

In self-drilling soil nail method grouting operation is performed simultaneously along with the driving of the tendon. Tendon used in this method consists of the hollow bar. This self-drilling soil nailing method is faster than the drill grouted method. It is more corrosion resistive than driven soil nailing technique.

Jet Grouted Nailing Method

In jet grouted method water jets are used to drill holes in the surface followed by the installation of the nail bar and then grouting.

Launched Soil Nail Method

In this method compressive air is used to drive into the soil in a single shot. Installation of nails is faster in this method but it is difficult to penetrate the long nail into the ground.

2.5 Application of Soil Nailing Methods

2.5.1 Slopes

Soil nailing methods are commonly used to stabilize and strengthen the new cut slopes, embankment slopes and existing slopes. When ground has to be cut in a steeper profile than its safe inclination angle soil nailing is preferred for the stabilization of new cut slope. Sometimes existing slopes may tend to fail due to the effect of the erosion, seepage, surcharge loading, sudden drawdown, rainfall, earthquake, construction activities and gravitational forces in order to strengthen such slope soil nailing is found to be effective. Some of the works related to the slope stabilization using soil nail walls include (Rajak & Gui, 2021).

2.5.2 Retaining Walls and Embankments

Soil nailing technique has been found to be successfully used for the stabilization of the retaining walls and existing embankments in many railway and highway projects. Retaining walls like stone retaining wall, brick retaining wall, concrete retaining wall are found to be strengthened by using soil nails. Different old and vulnerable embankments are found to be retained by the soil nailing technique. Some examples of stabilization of retaining walls and embankments using soil nail walls are found on (Perry et al., 2003; Phear, 2005; FHWA, 2015).

2.5.3 Urgent Repair and Maintenance Work

Soil nailing can be used for the stabilization of the urgent repair and maintenance work of the deformed and unstable slopes, embankment wall, landslide scars, excavation and embankments.

2.6 Mechanism of Soil Nail Wall

The basic principle of the soil nail retaining structure is that the soil nail transfers the stress to the deeper stable layer behind the deformed (active) layer. Soil nails provide the reinforcement to the slope by following two effects which are shown in Figure 2.4.

- Soil nails withstand some of the applied shear load and reduce the portion of the applied shear stress of the soil mass.
- Soil nails also help to increase the applied normal stress on the soil nail structure due to which the strength of the soil nail structure is increased.

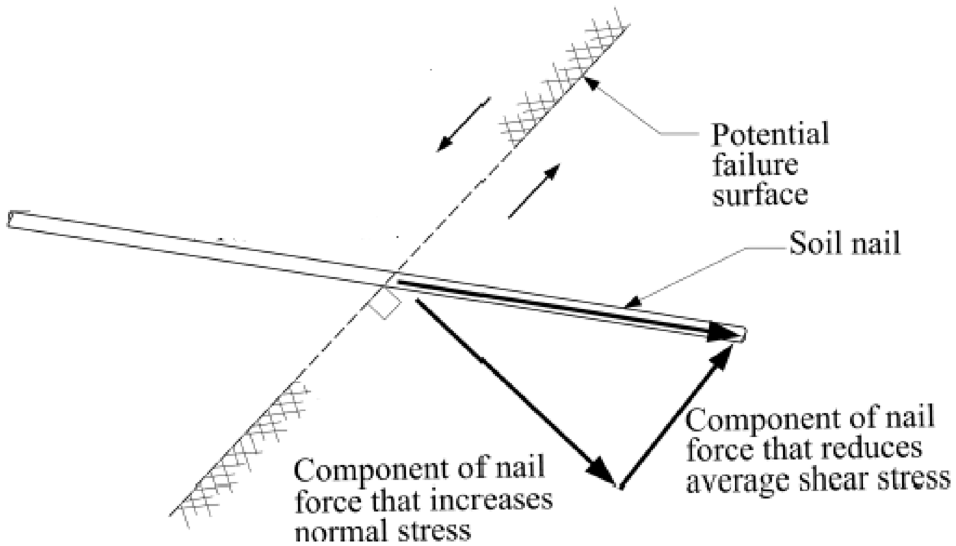


Figure 2-4 Reinforcement Effect of Soil Nail (modified after Geoguide, 2008)

When the soil surface is subjected to the excavation or reduction in the lateral pressure either by the excavation or any factors, a slip surface will be formed on the soil structure. The portion of the soil structure in front of the slip surface will tend to move outwards forming the active condition and the portion beyond the slip surface will remain intact with the parent soil mass at passive condition. The function of the soil nail is to tie the deformed active structural portion to the intact passive portion. As the deformation of the soil nail structure increases more stress is mobilized to resist deformation as a result tension of the soil nail also increases.

2.7 Failure of Soil Nail Wall

Different types of the failure of the soil nail wall were discussed by (Clouterre, 1991) which are described below and shown in Figure 2.5.

2.7.1 External Failure Mode

In external failure mode the potential slip surface does not meet the soil nail wall. It passes behind the soil nail wall. There are three types of potential external failure modes which are Shown in 2.5(a-c).

2.7.2 Internal Failure Mode

In internal failure mode there will be a failure in the load transferring mechanism between the soil, nail and grout. Deformation caused during the excavation tends to mobilize the bond strength along the soil nail structure. Different type of internal failure mode are shown in figure 2.5(d – g) respectively.

2.7.3 Facing Failure Mode

Facing failure are the failure at the Nail- Head connection. The common types of the facing failure are shown in the figure 2.5(h-j) respectively.

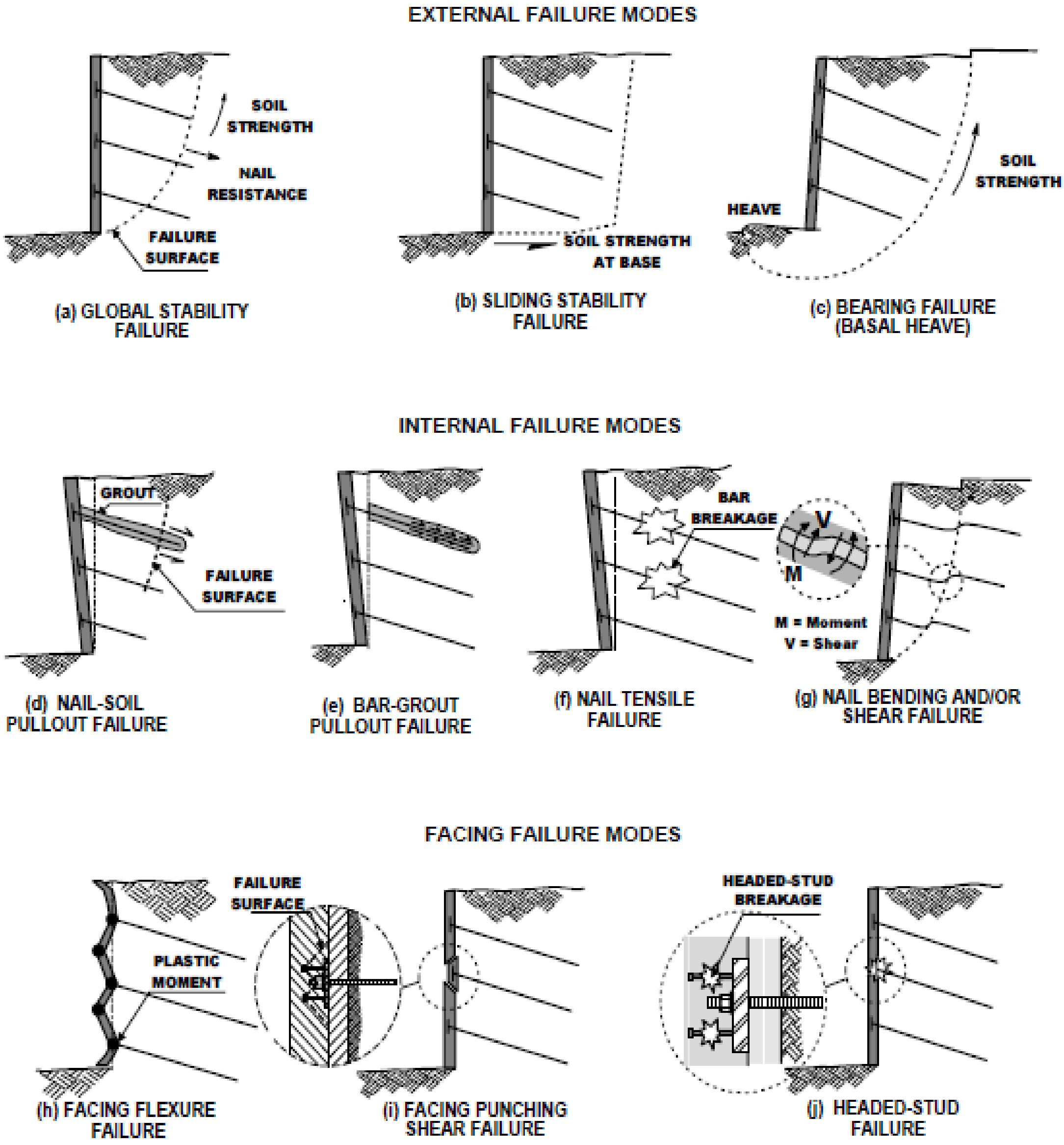


Figure 2-5 Principle Mode of Failure of Soil Nail Wall (modified after Clouterre, 1991)

The minimum Factor of Safety for the Safe design of the soil nail wall is given in FHWA Soil Nail Wall reference manual(FHWA, 2015). Summary of the factor of safety is given in the Table 2.1

Table 2-1 Factor of Safety against Different Failure

Failure Mode	Failure Type	Symbol	Minimum Recommended FOS	
			Seismic	Static
	Global stability	FS_G	1.1	1.5

External stability	Sliding stability	FS_{SL}	1.1	1.5
Internal Stability	Pull-out resistance	FS_P	1.5	2
	Nail bar tensile strength	FS_T	1.35	1.8
Facing Failure	Facing flexure	FS_{FF}	1.1	1.5
	Facing punching failure	FS_{FP}	1.1	1.5

2.8 Design Aspects of Soil Nail Wall

Soil nail is subjected to the tensile force after the deformation has occurred along the slope. This tensile force is developed on the Soil Nail as a effect of the frictional interaction between the ground and soil nail. This developed tensile force reduces the shear force which allows the more shear stress to play along the shearing zone. Besides this soil nail head and facing provide the confinement in a direction normal to the soil surface. Practically, Soil nail model is classified into the two zones i.e. active and passive zones which are distinguished by the failure surface and tied by the soil nail. Active zone lies in front of the slip surface whereas the zone located behind the failure surface is classified as the passive zone.

Soil nail system consists of the combination of the soil nailing, facing and the drainage structure. Soil nail consists of the prestressed tendon member, grout and the corrosion protection. Tendon members may be of the solid or hollow steel bar according to their suitability. The recent development in this field leads to the development of the fiber reinforced plastic (FRP) soil nail(Cheng et al., 2009). According to the method in which soil nails are installed and setup, soil nail are categorized into the various types such as : Grouted soil Nail, Driven Nail, Jet Grouted Nail and Launched Nail(Dey & Kong, 1996). Facing used in the soil nailing structure consists of the two types: Temporary facing which consists of the welded wire mesh which is fixed in the surface of the soil nailing where as other type of the facing include the permanent type which includes the use of reinforced concrete or shotcrete or either use of the precast panels. Facility of the proper drainage is one of the important serviceability requirements. For proper drainage a suitable drainage system is placed behind the temporary facing wall.

The soil nail retaining wall is failed by the various modes which are categorized mainly on three as mentioned in section 2.8. A designed soil slope should be checked under all of these modes for the better use however most of the design focuses considering only the tensile and shear failure mode(Seo et al., 2014).

2.9 Analysis of Soil Nail Wall

2.9.1 Limit Equilibrium Method of Analysis of Soil Nail Wall

Limit equilibrium method is one of the common methods of evaluating the global safety of the Soil Nail Walls which considers the shearing, tension, pull-out resistance of the nail. Different methods of evaluating safety using limit equilibrium method includes. Force elements used to find the global factor of safety using limit equilibrium method is shown in the figure 2.6.

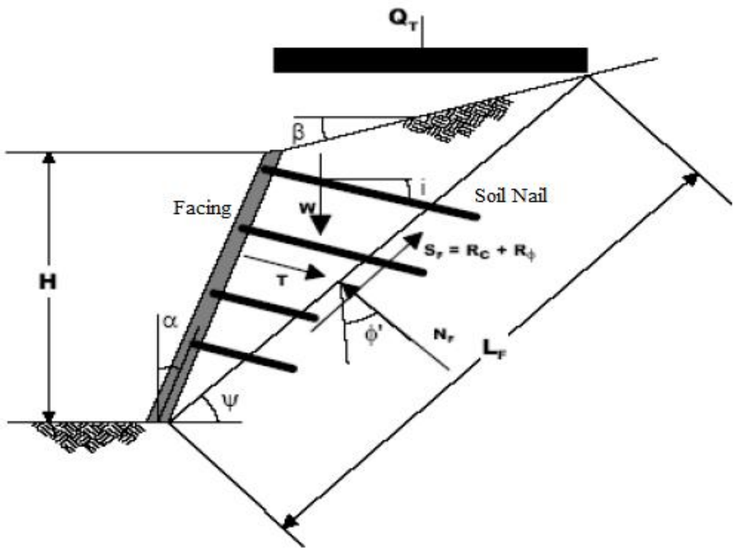


Figure 2-6 Forces used in Limit Equilibrium Method of Analysis (modified after Clouterre, 1991)

Where

W = weight of the sliding mass.

Q_T = surcharge load

H = Height of the soil nail wall

α = Slope face angle

β = Backslope angle

i = angle of inclination of soil nail wall

T_{EQ} = Equivalent Nail Tensile Force

S_F = Shear Force on Failure Surface

N_F = Normal Force on Failure Surface

Φ' = effective frictional angle of soil

c' = effective cohesion of soil

Ψ = angle made by failure line with horizontal

L_F = Length of potential slip surface

R_C = Cohesive Component of S_F

R_φ = Frictional Component of S_F

Factor of Safety against global failure (FS_G) using the limit equilibrium method is the ratio of the resisting force to the driving force acting to the potential failure surface.

$FS_G = (\Sigma \text{resistinng force})/(\Sigma \text{driving force})$ (2.1)

Normal and Tangential force on a failure plane are

Σ Normal Forces = $(W + Q_T) \cos\psi + T_{EQ} \cos(\psi - i) - N_F = 0$ (2.2)

Σ Tangent Forces = $(W + Q_T) \sin\psi + T_{EQ} \sin(\psi - i) - N_F = 0$ (2.3)

Where,

$S_F = R_c + R_f = C_m L_s + N_F \tan\varphi_m$ (2.4)

$\tan\varphi_m = \frac{\tan\emptyset'}{FS_G}$ (2.5)

$c_m = \frac{c'}{FS_G}$ (2.6)

where,

φ_m = mobilized friction angle

C_m = mobilized cohesion angle

2.9.2 Finite Element Method of Analysis of Soil Nail Wall

As the limit equilibrium method is unable to predict the deformation of the soil nail wall structure nowadays finite element method is used to predict the deformation of the soil nail wall. Different software like PLAXIS, ABACUS, PHASE etc. are the common Finite Element Software to simulate the soil nail wall. Singh and Babu performed the 2D numerical analysis of the soil nail wall using different soil models in Plaxis 2D (Singh & Babu, 2010). Rawat and Gupta also performed a numerical analysis in the Finite Element Method to find out FOS of a slope and compared it with the limit equilibrium methods(Rawat & Gupta, 2016). Similarly Jayanandan and Chandrakaran performed the numerical simulation of the soil nail wall to know the effect of the soil nail installation on the deformation of the soil nail wall(Jayanandan & Chandrakaran, 2015).

2.9.3 Deformation of the Soil Nail Wall

Deformation on a soil nail wall occurred during and after the construction. The horizontal deformation of the soil nail wall is found to be decreased along with the toe of a wall and vertical displacement of the wall is found to be in the same order of magnitude along with the horizontal displacement(Clouterre, 1991). Displacement in the soil nailed wall is depended on following factors:

- Height of the Wall
- Geometry of the Wall
- Soil type
- Spacing of nail and excavation of lifts
- Global FoS
- Nail Length to Wall Height Ratio
- Inclination of the nail
- Surcharge Load

Empirical formula to predict the maximum long term deformation of the wall for the soil nail wall with L/H ratio between 0.7 and 1.0., having a global factor of safety 1.5 is given by(Clouterre, 1991).

$$\delta_h = \left(\frac{\delta_h}{H}\right)_i \times H \tag{2.7}$$

Where,

$$\left(\frac{\delta_h}{H}\right)_i = \text{ratio dependent of soil condition i indicated in table2.2}$$

Table 2-2 Values of (δ_h/H) and ((δ_v/H) and C under given Conditions

Variable	Weathered rock and Stiff Rock	Sandy-Soil	Fine Grained Soil
$\left(\frac{\delta_h}{H}\right)$ and $\left(\frac{\delta_v}{H}\right)$	1/1000	1/500	1/333
C	1.25	0.8	0.7

Zone of influence where noticeable ground deformation (D_{DEF}) may takes place is shown in figure 2.6 and formula is given by equation 2.8

$$D_{DDF} = HC(1 - \tan\alpha) \quad (2.8)$$

Where,

C = coefficient indicated in Table 2.2

α = Face batter angle

H = Wall Height

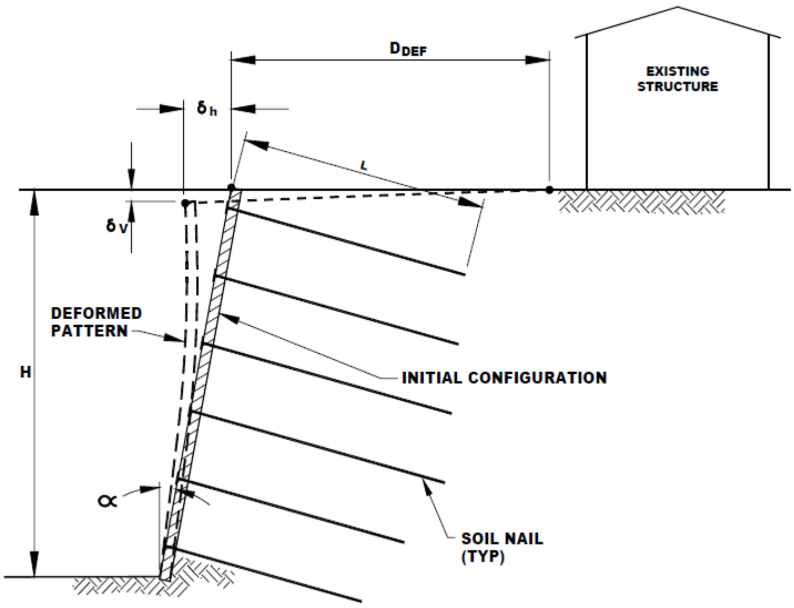


Figure 2-7 Deformation of the Soil Nail Wall (modified after Byrne et al., 1996)

2.10 Numerical Modeling of Soil Nail Wall

Previously various lab testing with different scale models was done in order to check the stability of the soil nail wall. Different conventional techniques are also used in the analysis of the soil nail retaining structure. Most of these include limit equilibrium methods of the slice like Janbu, Bishop, Morgenstern Price and Spencer method. This limit equilibrium method does not provide any information about the deformation which is the key factor during construction and stability of the soil nailed structure.

The information related to the deformation can be obtained through the different other methods like Finite Element Method and Finite Difference Methods(Yanpeng et al., 2008; Singh et al., 2021). The common finite element method (FEM) tools include PLAXIS, ABACUS, ANSYS and finite difference method (FDM) tools include FLAC for the analysis of the slope stability The two dimensional finite element is further upgraded to the three dimensional analysis which is found to be more accurate but consume more time than the two dimensional analysis (Zhou et al., 2013). Using the two dimensional finite element tool several parametric analysis is conducted and the influence of the several factors like properties of the soil nail, layout and dimension of the soil nail, strength parameters of the soil materials on the force applied on soil nail was observed (Yan, 2012;Caliendo et al., 1994;Fan & Luo, 2008).

A research on the stability of the slope by changing spacing of soil nail reinforcements showed that stability decreased as the spacing between the nails grew larger (Alsubal et al., 2017). Some of the numerical analyses are also performed to suggest the application of the hybrid reinforcing technique to improve the stability of the slope. Cheuk, Lam and Ho carried out the numerical analysis and showed that use of hybrid nails consisting of two different orientations limits the slope movement and increases robustness of the structure (Cheuk et al., 2013).

2.11 Seismic studies

In numerical dynamic modeling for the behavior of ground properties and inhibit of alteration that might be pronounced because of wave distribution, it is essential that the biggest dimension of elements used in our model be limited to a certain length. Kuhlmeyer and Lysmer (1973) proposed in their study to limit the dimension of any elements to not more than $\lambda/8$. Appropriate boundary conditions are defined considering the soil to behave as a semi-infinite medium. Absorbent boundaries to the lateral sides and standard fixities, earthquake boundaries were applied to the model. Effect of boundary conditions was diminished by choosing an appropriate width. For considering damping properties of the material, the Rayleigh damping coefficients were used, which was found by the following equation:

$$C = \alpha M + \beta K \tag{2.9}$$

where C = damping,

K is stiffness,

M = mass

α and β are Rayleigh factors,

$$\alpha + \beta \omega_i^2 = 2 \omega_i \xi_i \tag{2.10}$$

where ξ_i is the critical damping ratio, which is 0.05 for all materials, and ω_i is the angular frequency in two vibration modes.

3. METHODOLOGY

The general methodology consists of performing a literature review in order to find the general principle and current state of practice on the design and existing results of the similar previous study. In addition to this, soil nail guidelines used in different countries are reviewed to know the geometrical and nail parameters of the soil nail walls. The flowchart of the general methodology is given in Figure 3.1.

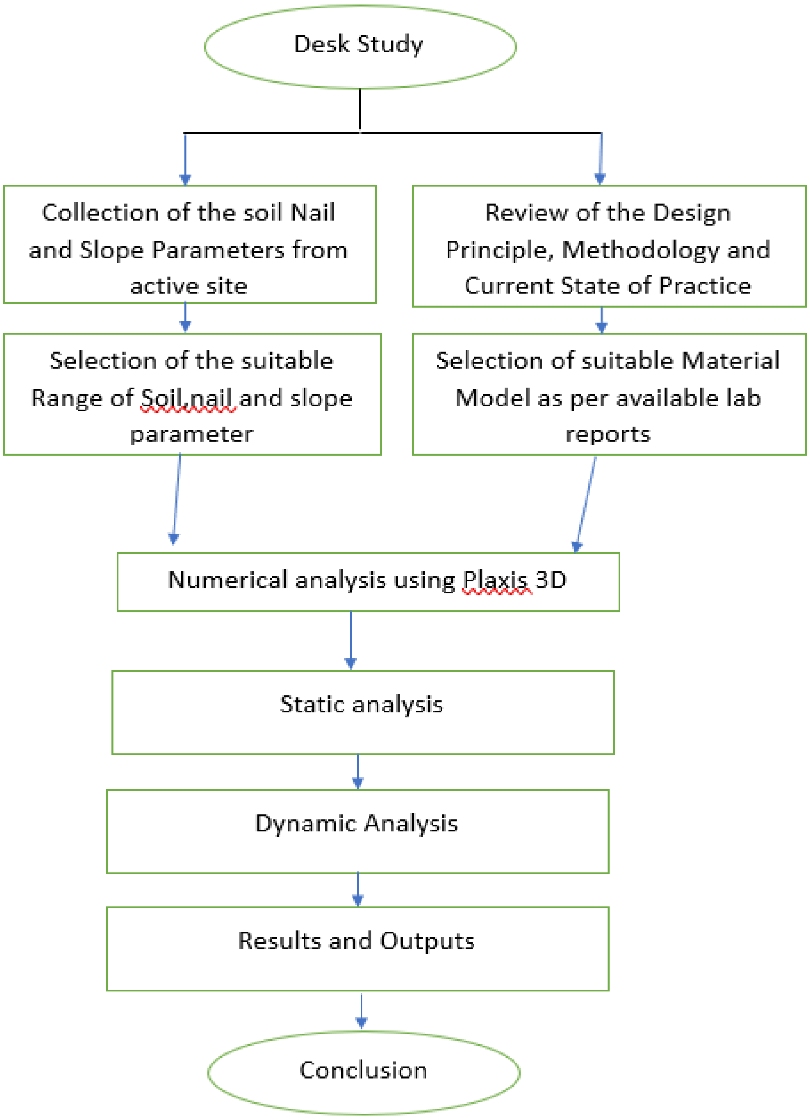


Figure 3-1 Flowchart of the Methodology

3.1 Literature Review

Available literature including previous thesis, text books, journal papers, conference papers, guidelines, etc. are reviewed to know the general principle and working mechanism of the soil nail interaction. A general idea on the methodology of the analysis and current state of practice is also obtained through the different available literature. The brief description of the finding of literature review is provided in the previous chapters.

3.2 Review of Existing Guideline

Different guidelines related to the soil nailing application and slope stability analysis and application are used in several countries which gives the general idea about the basic technique for the site investigation, design, construction and monitoring of the soil nail wall. The common guidelines used for investigation, design, construction and monitoring of the soil nail retaining structure includes:

- Design and Construction Guideline for the Soil Nail Wall System(G. E. Manual & Bureau, 2013).
- Standard Specification for Road and Bridge Works published by Department of Roads, 2073
- Mountain Risk engineering Handbook Subject Background Part I(Deoja Bhaskar, Thapa., International Centre for Integrated Mountain Development., 1989).
- Soil Nail Wall Reference Manual(FHWA, 2015).
- GEOTECHNICAL ENGINEERING CIRCULAR NO. 7 Soil Nail Wall (Lazarte et al., 2003)

3.2.1 Soil Parameter

For the analysis the value of the soil parameters for both types of soil nail wall was as per the lab results obtained from samples collected from Bandipur site which is given below. Subsurface exploration was done using Percussion Drilling of 100mm nominal diameter and laboratory tests were conducted on selected disturbed/undisturbed soil samples. Direct shear tests results were used to find out the engineering properties of soil.

Table 3-1 Soil Parameter used for Analysis of Soil Nail wall

Parameter	Value
Cohesion, c (kN/m2)	0
Friction angle φ (deg)	31.6
Dilatancy angle ψ (deg)	0
Unit weight γ (kN/m3)	17
Modulus of Elasticity of the Soil (kN/m2)	30000
Poisson ratio (ʋ)	0.3

Reference from soil test reports.

3.2.2 Nail Parameter

Different soil nail wall design guideline is reviewed and various parameters are selected for analysis. The suitable value of the nail parameters like spacing, length and inclination of the nail is obtained through the generalization of the suggested value in four major guidelines: Soil Nailing for Stabilization of Steep Slope Near Railway Tracks (Prashant & Mukherjee, 2010), Soil Nail Wall Reference Manual (FHWA, 2015), Guide to Soil Nail Design and Construction (Geoguide 7, 2008) Standard Specification for Road and Bridge Works (DoR, 2073). The diameter of the soil nail parameter used for the analysis in bored soil nail is based on the size of the soil nail wall available on the market which are given in the Appendix A of (FHWA, 2015) and also guidelines form the DoR. Different nail parameter used for the analysis in bored and driven nail is listed as:

For Drill and Grout Nail

- Length of the soil nail is varied from 0.8 times to 1.2 times of the total depth of excavation (12m) i.e. from 9.6 to 14.4m.
- Spacing of the soil nail is a value of 1.5m is taken in both horizontal and vertical directions.
- Diameter of the soil nail taken as 25 mm.
- Inclination of the soil nail wall is taken as 15 degrees.

For Driven Soil Nail

For the driven soil nail, Standard Specification of the Road and Bridge Works (DoR, 2073) is reviewed to select the parameters for the soil nail wall.

- Length of the soil nail is taken equal to height of excavation i.e 6 m.
- Spacing of the soil nail is taken as 0.6 m in both horizontal and vertical directions.
- Diameter of the soil nail taken for analysis is taken as 32 mm as per DoR guidelines.
- Inclination of the soil nail wall is taken as 0 degrees for both static and dynamic loading.

3.2.3 Model Parameters

Table 3-2 Parameter for Nail

Nail Parameter (Standard)	Drill and Grout Nail	Driven Nail
Diameter of reinforcement d(mm)	25	32
Nail Length L (m)	12	6
Inclination with horizontal i(deg)	15	15
Spacing Sh × Sv (m × m)	1.5×1.5	0.6×0.6
Element used in Model	Embedded Beam Row	Embedded Beam Row
Elasticity modulus of reinforcement En (Gpa)	200	200
Unit weight of the reinforcement (kN/m3)	78.5	78.5

Table 3-3 Wall Geometrical Parameter

Wall geometrical Parameter	Drill and Grouted Nail	Driven Nail
Height of the wall H (m)	12	6
Face batter α (deg)	15	0
Back slope angle β (deg)	0	0
Nailing type	Grouted	Driven
Grouted nails and Facing		
Material model	Elastic	Elastic
Yield strength of reinforcement fy (Mpa)	415	415

Elasticity modulus of reinforcement En (Gpa)	200	200
Elasticity modulus of grout concrete Eg (Gpa)	22	22
Drill Hole diameter DDH (mm)	100	-
Live load during Construction	8kN/m^2	8kN/m^2

Table 3-4 Standard Shotcrete Facing Parameter

Plate Element (Standard)	**Value**
Elasticity modulus of grout E_g (kN/m2)	22000000
Facing thickness t (mm)	200
Axial Stiffness EA (kN)	6600000
Bending Stiffness EI (kNm^2)	22000
Poisson's ratio of Shotcrete (ʋ)	0.25

Table 3-5 Values of skin friction used for Analysis of Soil Nail wall

Skin Friction Parameter	**Value**
Driven nail below 8m (kN/m)	28.15
Driven nail above 8m (kN/m)	17.32
Drilled nail (kN/m)	43.32

3.2.4 Dynamic Analysis using data from real earthquake data

In the present study, the time acceleration plot of Barpak earthquake and Kobe earthquake have been used for dynamic analysis. Barpak earthquake has a spectral acceleration of 0.18 g whereas Kobe earthquake has a spectral acceleration of 0.8g. The accelerograms have been shortened at the time where the earthquake loading is maximum as recorded by the instruments. This is due to the time required for the computer to complete the dynamic analysis of the entire time period of earthquake loading.

Amplification factor is found out by dividing peak horizontal ground acceleration of the top of the wall by peak acceleration of lower layer where dynamic surface displacement is applied in time domain of dynamic analysis. Selecting various nodes at the different values in the z axis helps find out the amplification factors at various depths.

The seismic loading is given in the form surface displacement at the base of the model where the static displacements in all the directions are set to zero and dynamic displacement in y directions was given as per the accelerogram. Earthquake loading and dynamic analyses are carried out after the achievement of full excavation depth.

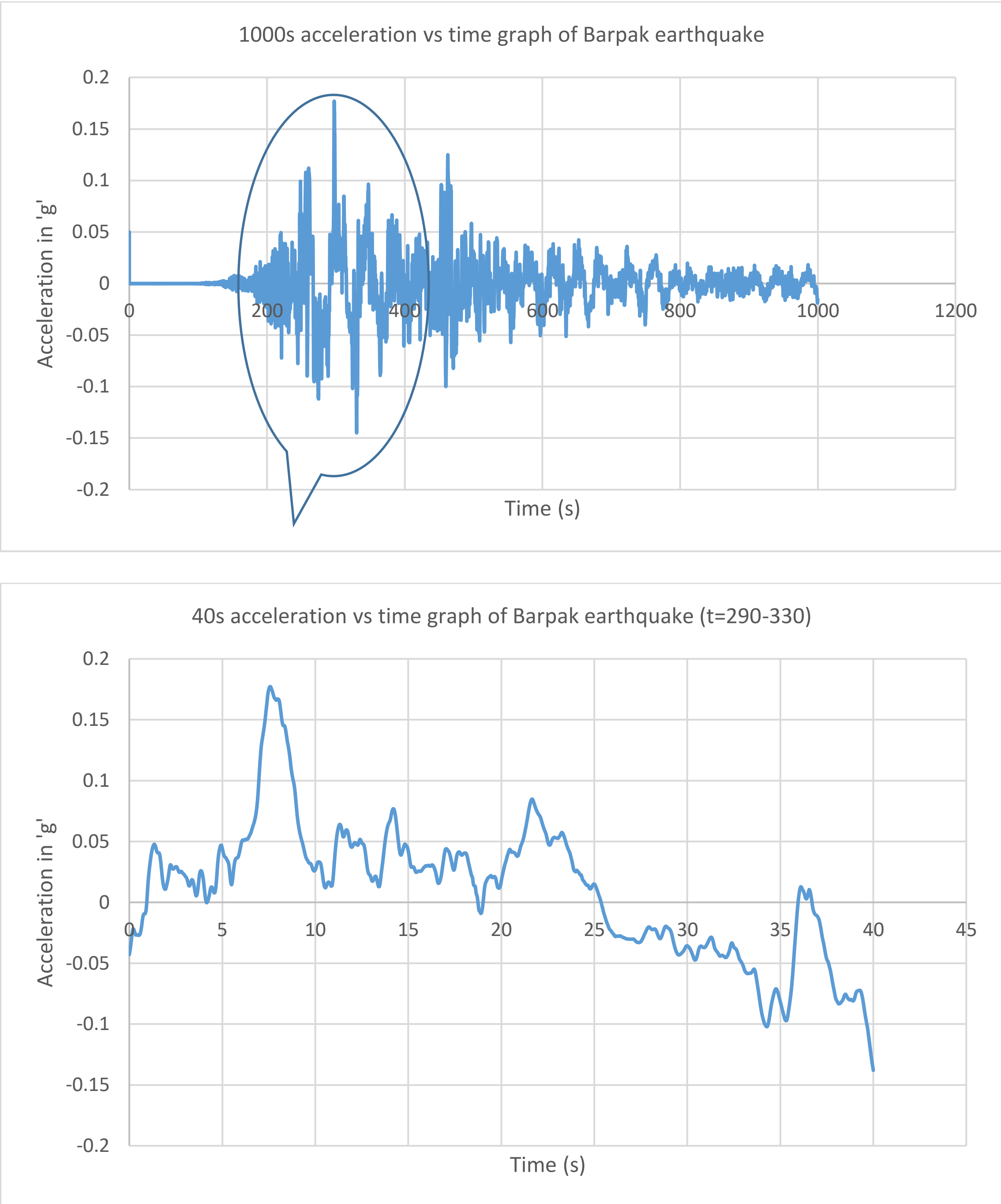


Figure 3-2 a) 1000s time vs acceleration plot for Barpak earthquake b) Reduced 40 s time vs acceleration plot for Barpak earthquake

From Barpak earthquake time history the 40 seconds maximum vibration was used for the analysis (time t=290-330).

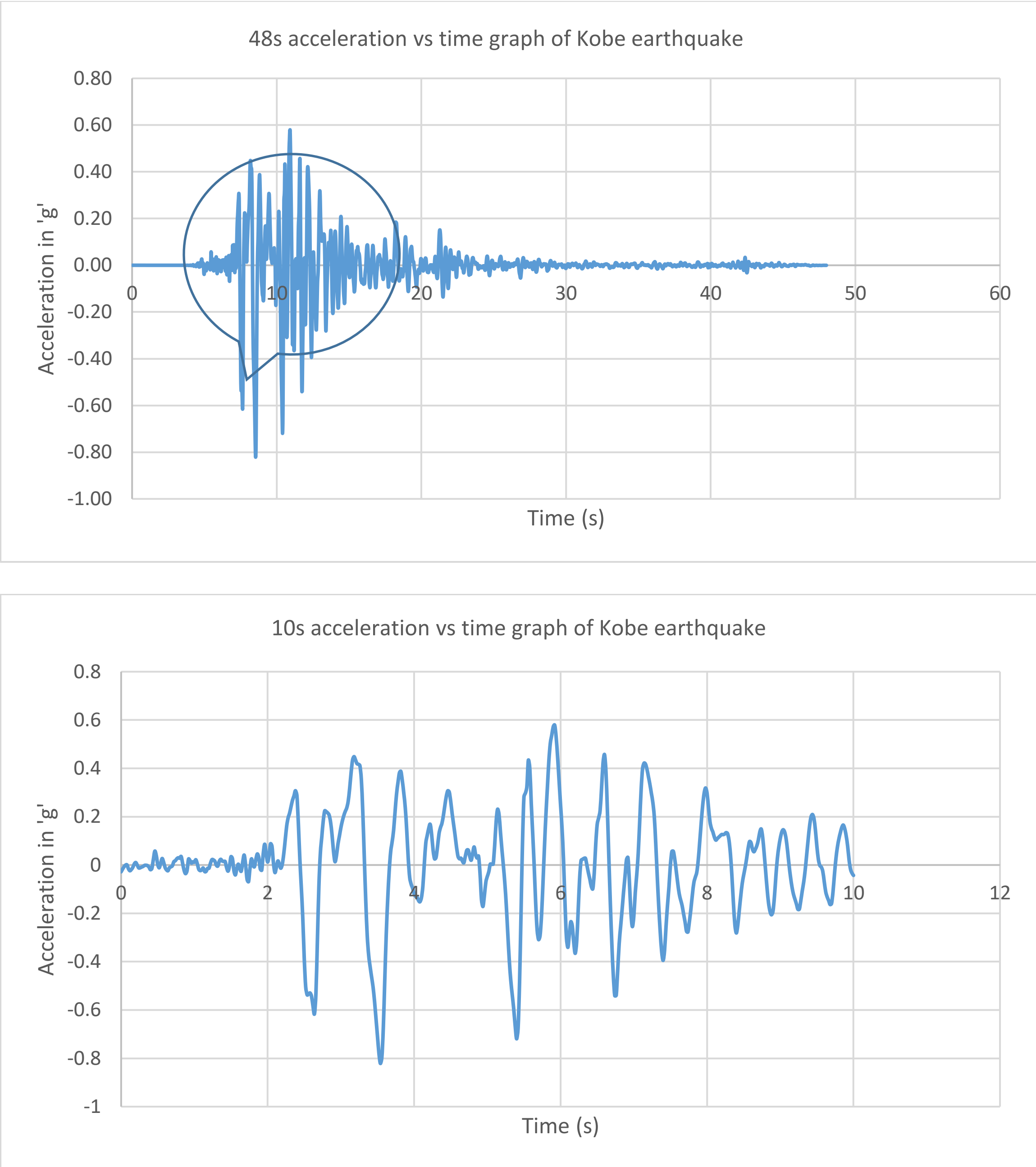


Figure 3-3 1000s time vs acceleration plot for Barpak earthquake b) Reduced 40 s time vs acceleration plot for Kobe earthquake

From Kobe earthquake time history the 10 seconds maximum vibration was used for the analysis (time t=5-15sec).

3.3 Numerical Analysis

PLAXIS is a numerical analysis tool based on the principles of FEM which is available with both 2D and 3D modelling options. It is developed for analysis of displacement, stability and other parameters in several geotechnical problems.

"Plaxis 3Dv20" is used to perform the numerical analysis for this study. Plaxis provides the use of the 6-noded and 15-noded triangular element for the analysis under the plane strain condition. Fifteen nodded triangular elements are used for the simulation in this study. Plaxis-2D can perform an analysis by taking soil models in fifteen different models from linearly elastic Hook model to the sophisticated UBC-3D PLM model (ULT) (Manual, 2020). Evaluation of the parameters required for the simulation of the Numerical model in different soil-models required more sophisticated laboratory experiments which makes research more expensive. So, a simple Mohr-Coulomb model is taken for the simulation of the Material model. Linearly elastic perfectly plastic model (Mohr-Coulomb Model) is used in the analysis of the soil nail structure. Many literature like (Rawat & Gupta, 2016), (Jayanandan & Chandrakaran, 2015): (Dhakal & Prasad, 2019) etc. show the use of the Mohr Coulomb model. Simulation of a material using plain strain analysis required to determine the five parameters which are shown in Table 3.6.

Table 3-6 Parameter Required for Mohr Coulomb Analysis

Symbol	Description	Unit
E	Young's Modulus	[kN/m^2]
υ	Poisson's ratio	[-]
c	Cohesion	[kN/m^2]
φ	Friction angle	[°]
ψ	Dilatancy angle	[°]

Plane strain analysis is unable to take account of the cylindrical and radial element directly. Cylindrical soil nail element should be converted to the plane strain condition for the simulation under the plane strain condition. Various studies have shown the use of the drill and grouted soil nail element as a Geogrid type and Plate type for the numerical simulation. The main advantage of taking drill and grouted soil nail as a plate element over the geogrid elements is that plate elements consider the condition of both axial and bending stiffness whereas geogrid elements only consider the axial stiffness. So, plate elements are taken for the analysis of the drill and grouted soil nail. The significance of the soil nail as a plate element in the numerical simulation of the soil nail wall was shown in the article of the Singh and Babu 2009 (Singh & Babu, 2010). For the simulation of the nail element as a plate two parameters axial stiffness (EA) and flexural rigidity (EI) need to be calculated. Facing element is also considered as the plate element.

For the grouted nails the equivalent modulus of elasticity is needed to calculate the axial stiffness and flexural rigidity. Equivalent modulus of elasticity (E_{eq}) is calculated using the elastic stiffness of both grout material and nail material. E_{eq} is given in Equation 3.1.

$$\mathrm{Eeq} = \mathrm{En}\left(\frac{\mathrm{An}}{\mathrm{A}}\right) + \mathrm{Eg}\left(\frac{\mathrm{Ag}}{\mathrm{A}}\right) \tag{3.1}$$

Now Axial Stiffness and Bending stiffens:

$$\text{Axial stiffness EA [kN/m]} = \frac{E_{eq}}{Sh}\left(\frac{\pi D_{DH}^2}{4}\right) \tag{3.2}$$

$$\text{Bending stiffens EI [kNm}^2\text{/m]} = \frac{E_{eq}}{Sh}\left(\frac{\pi D_{DH}^4}{64}\right) \tag{3.3}$$

Where: Sh = Spacing of the Nail

Skin friction is the important parameter that governs the stability and design of the driven soil nail. In order to consider the effect of the skin resistance in the driven nail, the driven nail is simulated as an embedded row element. The theoretical value of the bond resistance for the driven nail is obtained from the Table 3-5(FHWA, 2015).

PLAXIS provides a range of nonlinear native and UDSM (User Defined Soil Models) options for earthquake analysis. While all native models in PLAXIS can be utilized with dynamic analysis, it's crucial to understand the limitations of each model. Several models are commonly employed in seismic analysis. Additionally, the manipulation and adjustment of input accelerograms play a vital role in earthquake analysis. These accelerograms can be easily converted and displayed in various forms such as Fourier amplitude spectrum, Power spectrum, PSA (Peak Spectral Acceleration), and Arias

Intensity. Furthermore, a dynamic calculation can automatically apply drift correction to rectify displacement drift caused by instrument or background noise.

The generated curves in the time domain can be automatically converted to the frequency domain using Fast Fourier Transform (FFT). The output curves enable the creation of a PSA spectrum, aiding in the identification of the predominant period. Additionally, Relative Displacement Response Spectrum, Amplification Factor, and Arias Intensity plots can be generated to assess response magnification, ground motion strength, and dynamic phase characteristics. Plots for extreme accelerations, velocities, and displacements during dynamic phases can also be produced.

A surcharge load equals to 8kN/m^2 on the top of the wall to 8m beyond is applied to simulate the effect of live load due to the operation of the construction equipment during soil nail construction procedure. A width of 5 m of the soil nail structure is used to simulate the 3D analysis. A global medium mesh is chosen for the analysis; however, the mesh is refined to half of the global mesh size in the vicinity of nail structure. The top boundary is set free in both the horizontal and vertical direction, right and left boundaries are fixed only in the horizontal direction and bottom boundary is set fixed in both directions. Now, a required number of stages for the analysis are defined which is analogues with the field construction procedure. The standard numerical model used for the analysis is shown in Figure 3.2.

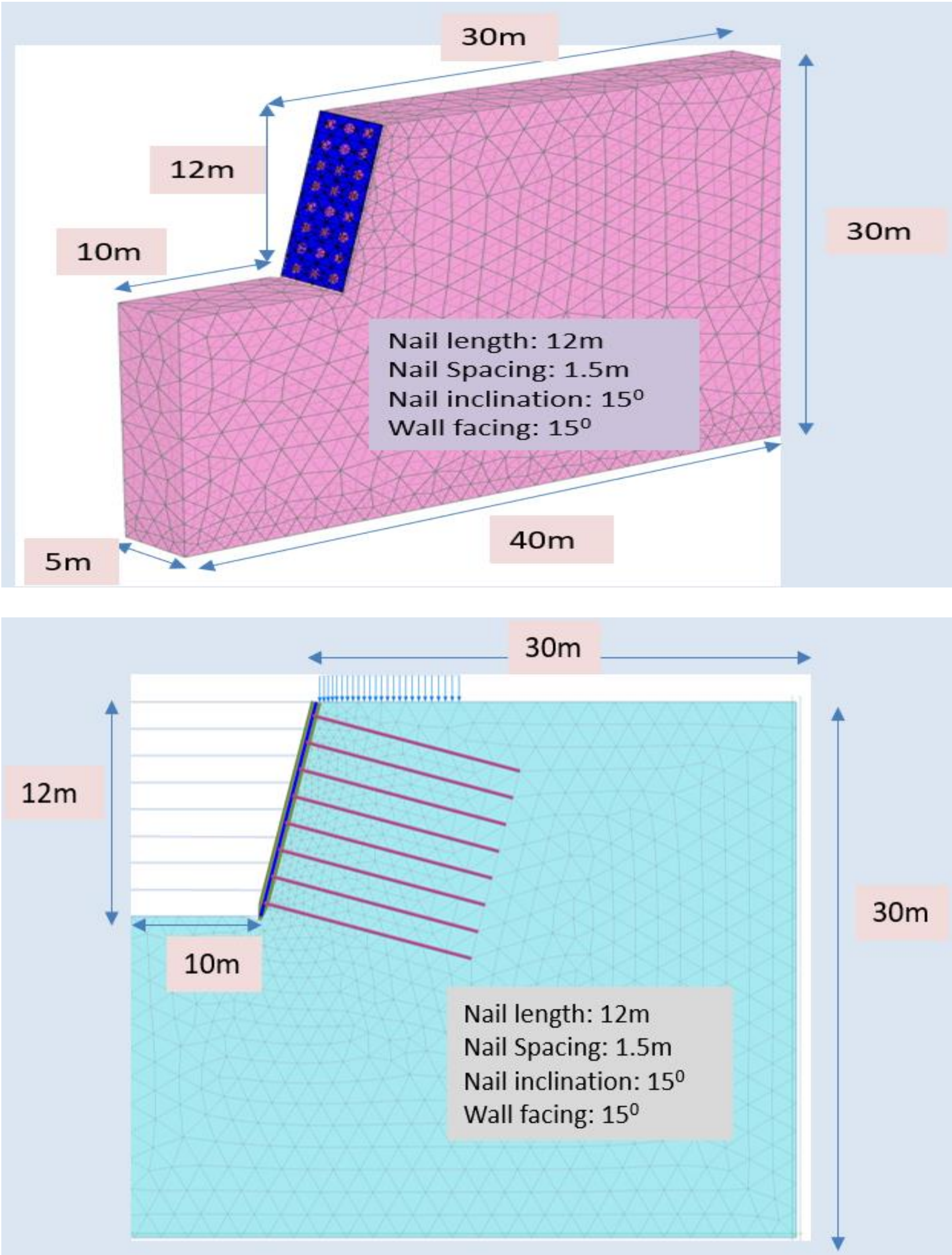


Figure 3-4 Model Used for Analysis of Drill and Grout Nail (2D and 3D models)

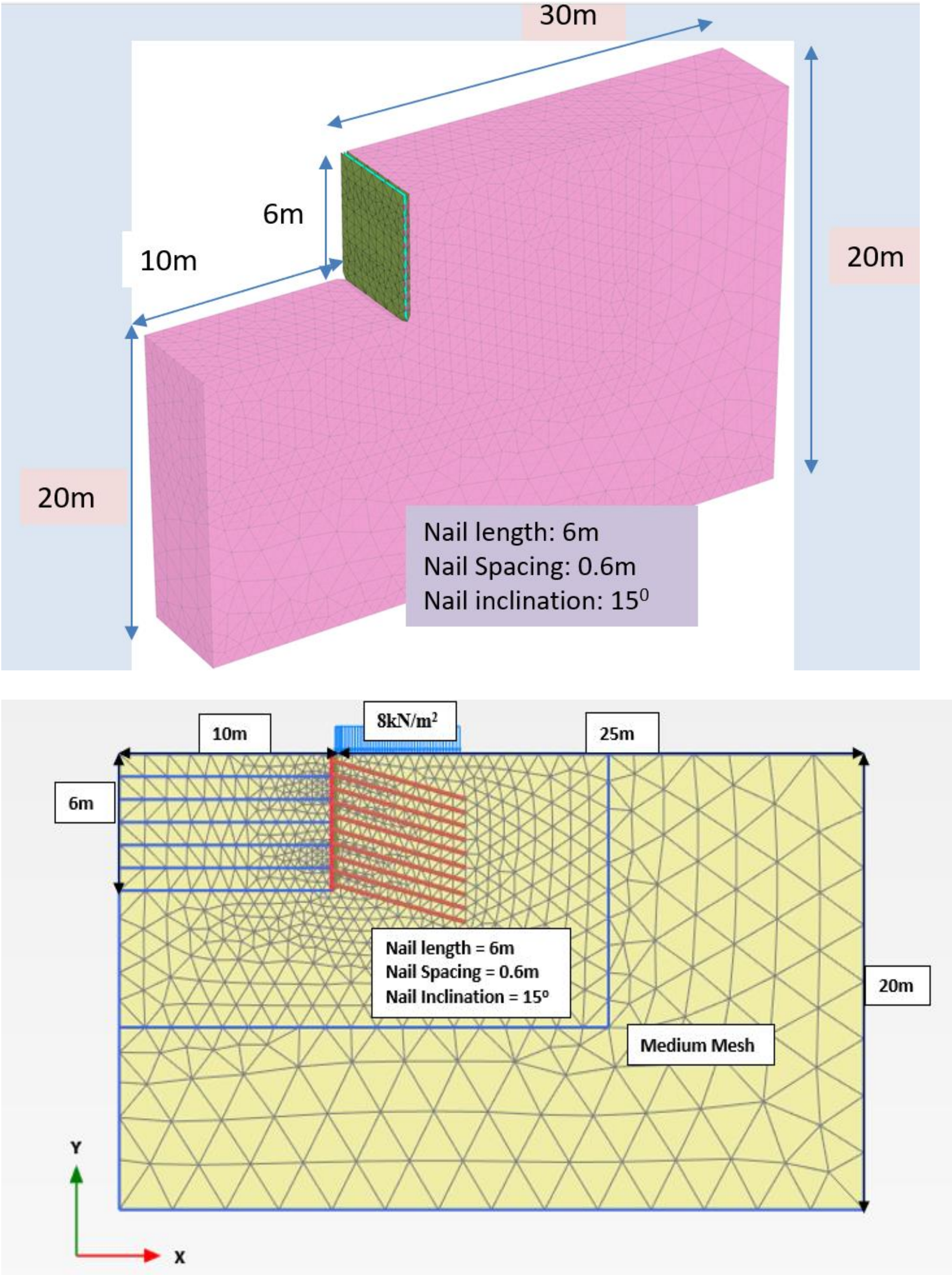


Figure 3-5 Standard Model Used for Analysis of Driven Nail (2D and 3D models)

Now to simulate the stage wise construction, at first initial condition is simulated in the Ko procedure, then the stage wise construction is performed under ‘plastic type’ calculation methods up to the required level. Safety calculation is performed to know the factor of safety as per requirement. Global factor of safety is performed at the end of the simulation process. If it is necessary to calculate the intermediate factor of safety then safety calculation is performed by following the required stage. Point at the top of the wall is selected to know the lateral deformation on the wall due to the excavation process.

For the plastic type calculation maximum number of steps used in the calculation is 1000 with the tolerated error of 0.01. Maximum number of the iterations performed in each step of analysis is 60. For the safety type calculation, the maximum number of steps used is 100 with the tolerated error of 0.01 and. Maximum number of iterations performed for the calculation is 60. For the dynamic analysis as well, the maximum number of steps used is 100 with the tolerated error of 0.01 and. Maximum number of iterations performed for the calculation is 60.

4. RESULTS AND DISCUSSION

4.1 Comparison between the 2D and 3D analysis in case of drill and grout nails

4.1.1 In case of drill and grout nails

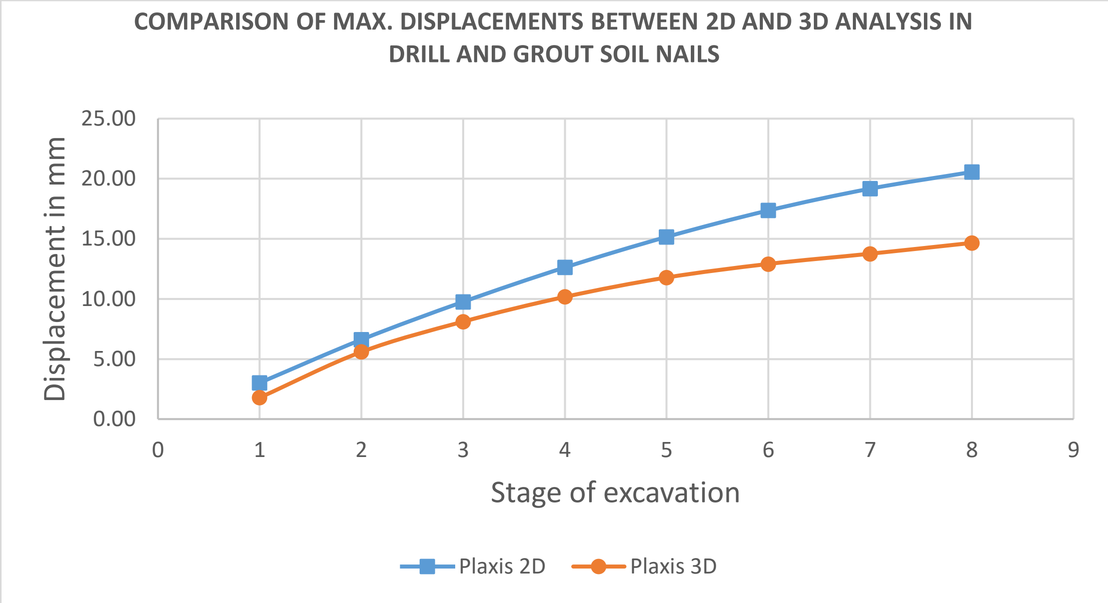


Figure 4-1 Comparison of max. displacements between 2D and 3D analysis in drill and grout soil nails

4.1.2 In case of driven nails

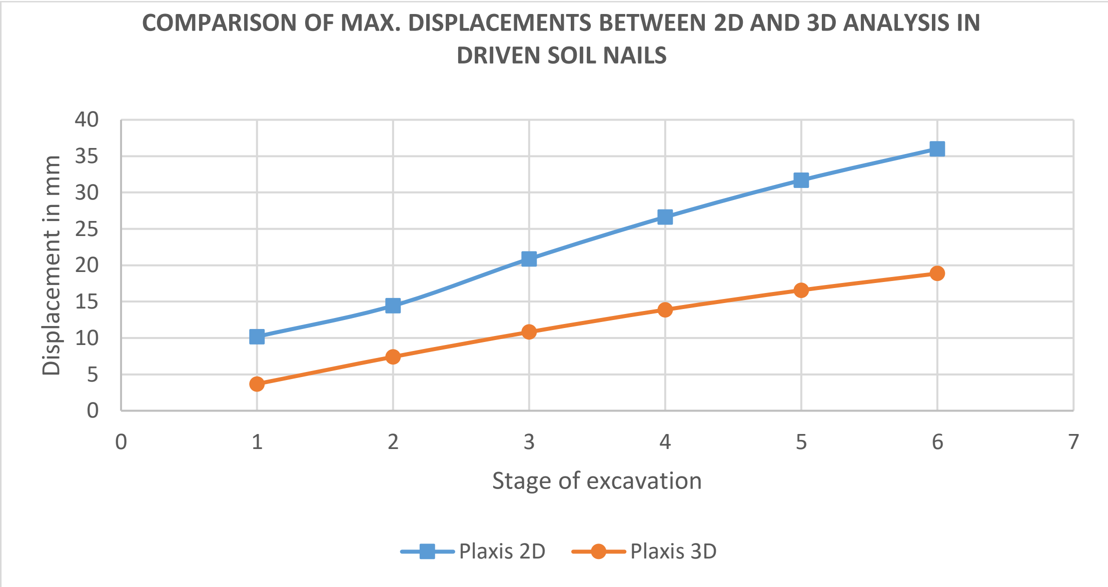


Figure 4-2 Comparison of max. displacements between 2D and 3D analysis in driven soil nails

From the analysis in Plaxis 2D and 3D of the same arrangement for both drilled and grout and driven nails we observed that the maximum displacement shown by 2D analysis is more in comparison to the 3D analysis and this difference in maximum for later stages of excavation i.e as the depth of excavation increases.

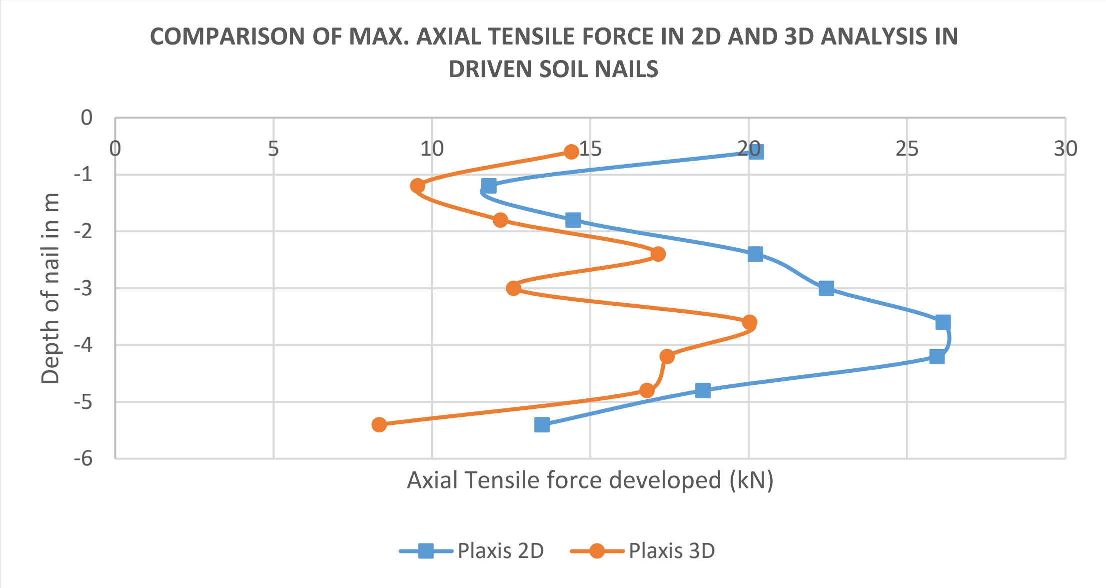


Figure 4-3 Comparison of max. axial tensile force developed between 2D and 3D analysis in driven soil nails

In case of driven nails the axial forces developed in 2D analysis is greater than that predicted by 3D analysis by around 25 %.The maximum axial forces were found to concentrate at soil nails installed at a depth of about 2/3H from the top of the wall.

4.2 Comparison between the static and dynamic analysis

After the 100 % achievement of construction stage dynamic analysis is carried out along after the static analysis for each construction step is completed. For both conditions the maximum horizontal nail displacements and maximum axial force in each nail is recorded. For dynamic analysis, the accelerograms given in fig 3.3 and 3.4 of Barpak earthquake and Kobe earthquake are used.

4.2.1 For L/H=0.8

S.N	Depth	Static			Dynamic barpak			Dynamic kobe		
		u	axial t	skin f	u	axial t	skin f	u	axial t	skin f
1	-0.75	2.982	6.951	36.57	3.062	7.206	37.390	3.635	7.013	36.970
2	-2.25	3.501	8.161	22.77	3.576	8.361	23.070	4.385	7.581	22.240
3	-3.75	4.498	26.69	14.09	4.610	26.86	14	5.466	25.79	15.09
4	-5.25	6.545	36.39	17	6.662	36.45	16.96	7.544	34.69	18.78
5	-6.75	8.701	16.77	6.643	8.823	16.78	6.757	9.717	13.65	10.43
6	-8.25	11.120	44.86	12.63	11.250	44.84	12.85	12.220	41.33	16.85
7	-9.75	13.460	24.31	20.89	13.600	23.81	20.84	14.610	18.52	16.49
8	-11.25	16.780	40.4	13.35	16.930	41.36	14.55	18.130	37.67	19.74

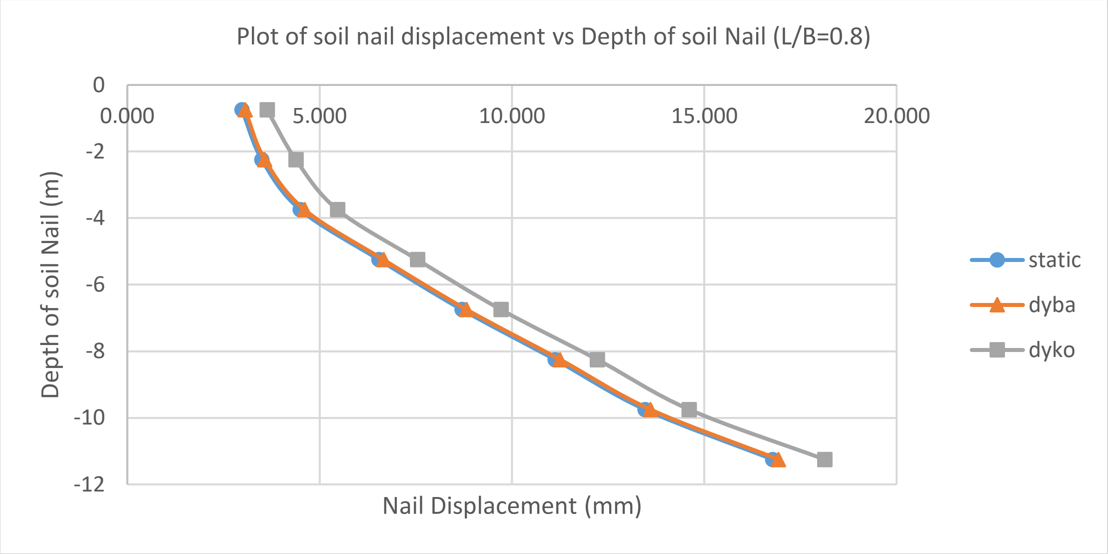


Figure 4-4 Plot of maximum nail displacement vs Depth of soil Nail in Drill and grout nail(L/B=0.8)

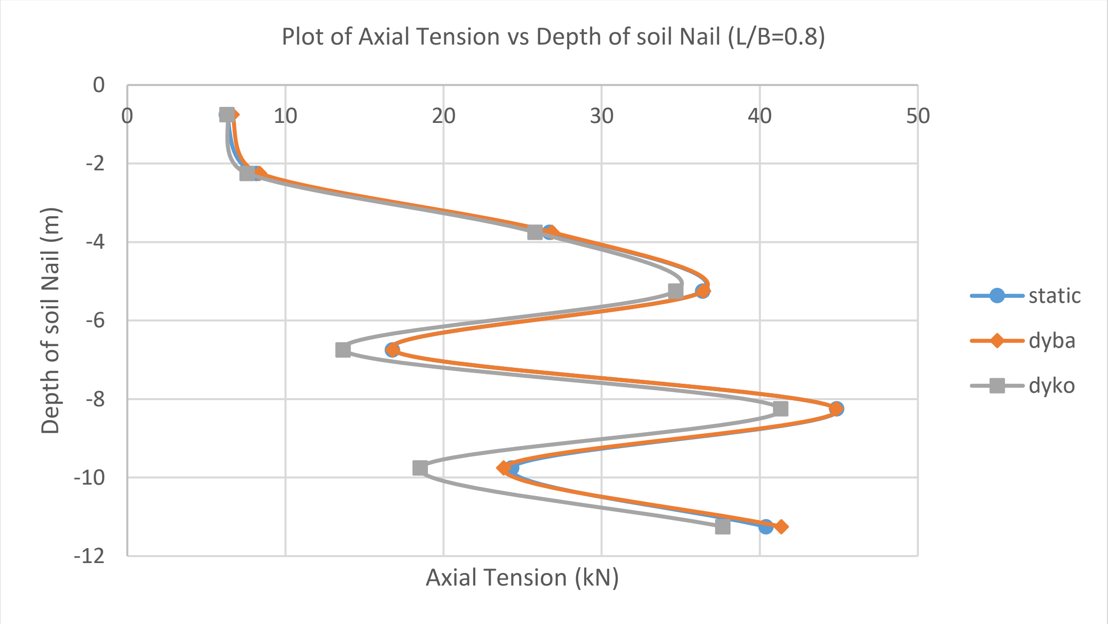


Figure 4-5 Plot of Axial Tension vs Depth of soil Nail in drill and grout nail (L/B=0.8)

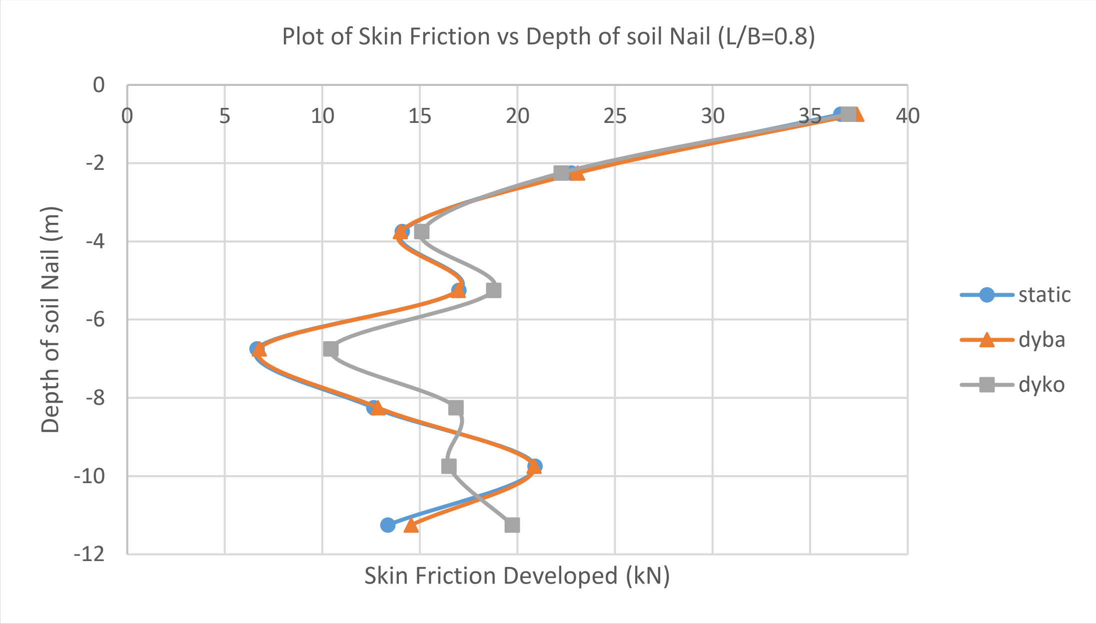


Figure 4-6 Plot of Skin Friction vs Depth of soil Nail in drill and grout nail (L/B=0.8)

4.2.2 For L/H=1

S.N	Depth	Static			Dynamic barpak			Dynamic kobe		
		u	axial t	skin f	u	axial t	skin f	u	axial t	skin f
1	-0.75	2.980	6.257	36.57	3.062	6.626	37.39	3.635	6.309	36.97
2	-2.25	3.501	8.161	22.77	3.576	8.361	23.07	4.385	7.581	22.24
3	-3.75	4.498	26.69	14.09	4.610	26.86	14	5.466	25.79	15.09
4	-5.25	6.545	36.39	17	6.662	36.45	16.96	7.544	34.69	18.78
5	-6.75	8.701	16.77	6.643	8.823	16.78	6.757	9.717	13.65	10.43
6	-8.25	11.120	44.86	12.63	11.250	44.84	12.85	12.220	41.33	16.85
7	-9.75	13.460	24.31	20.89	13.600	23.81	20.84	14.610	18.52	16.49
8	-11.25	16.780	40.4	13.35	16.930	41.36	14.55	18.130	37.67	19.74

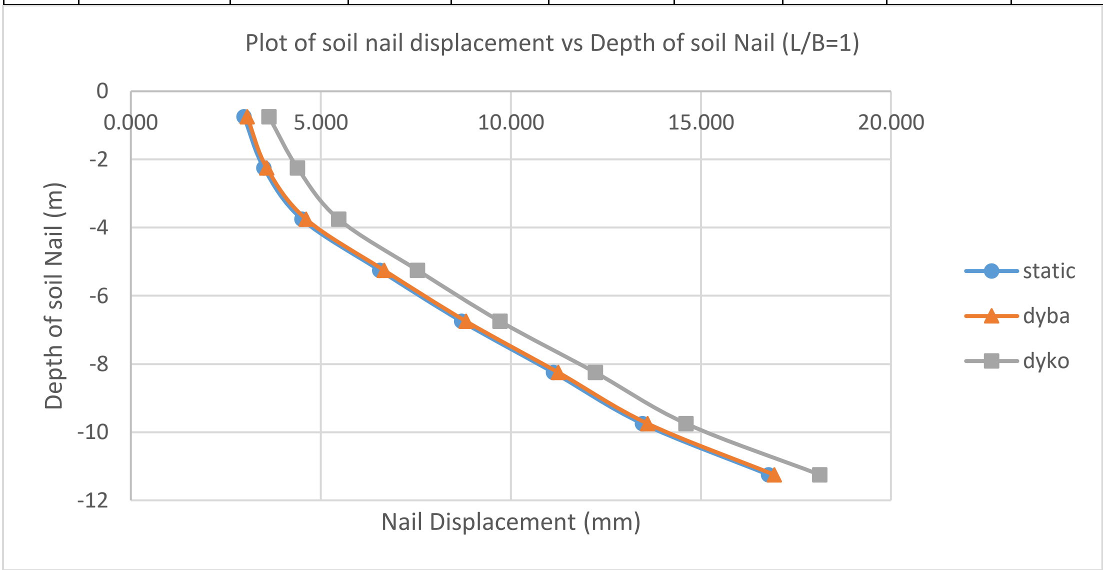


Figure 4-7 Plot of maximum nail displacement vs Depth of soil Nail in Drill and grout nail(L/B=1)

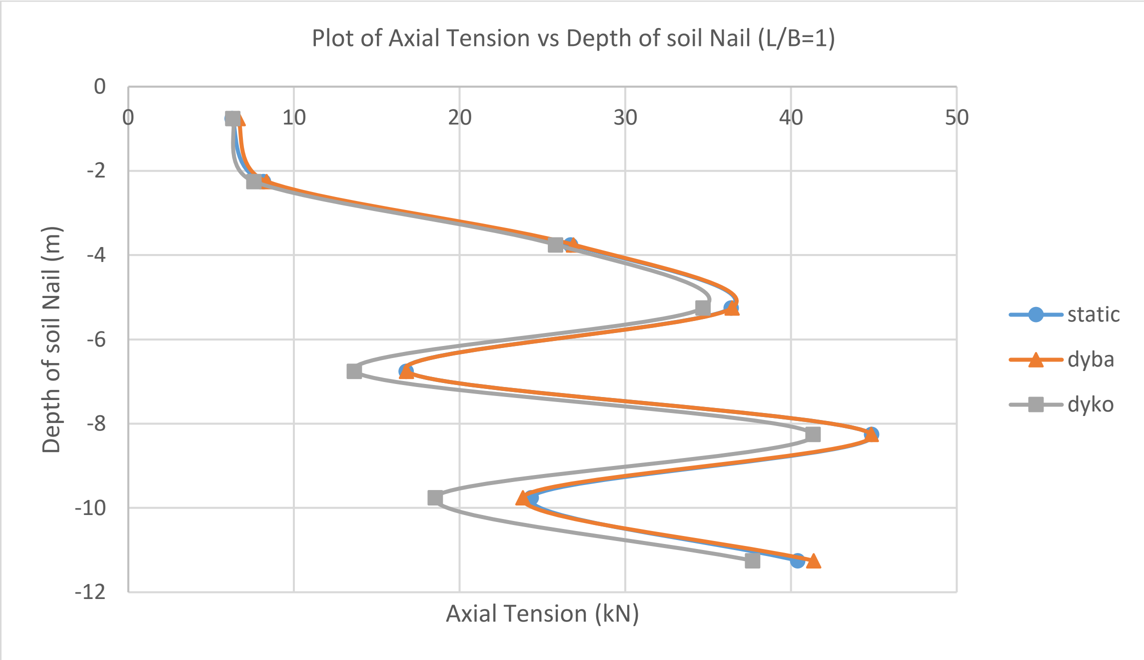


Figure 4-8 Plot of Axial Tension vs Depth of soil Nail in drill and grout nail (L/B=1)

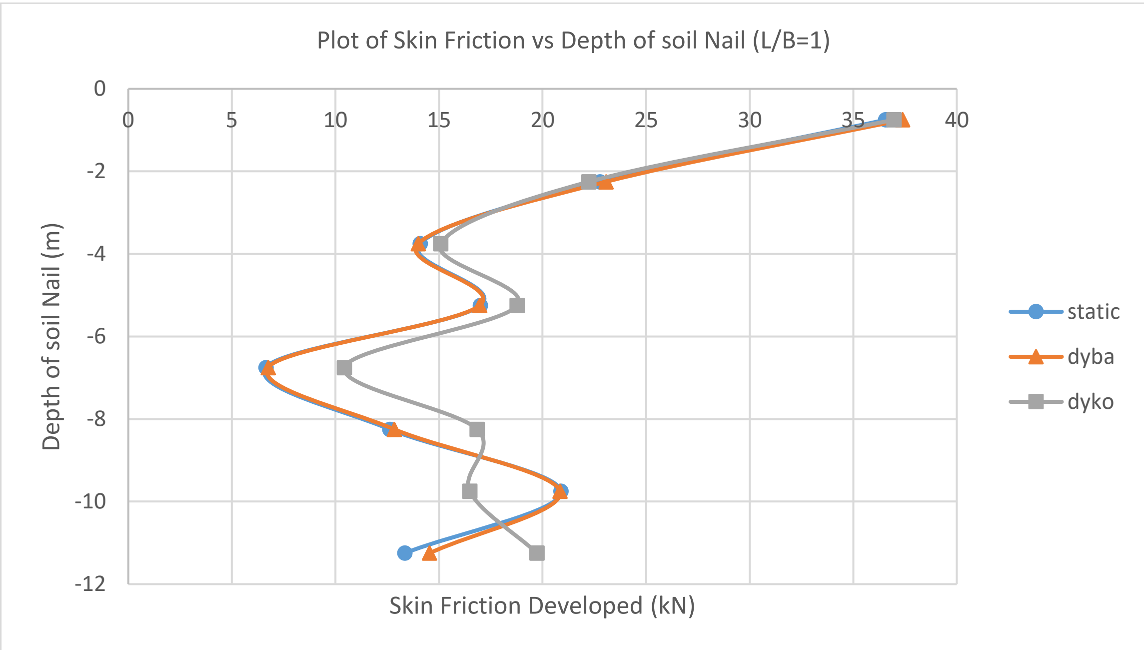


Figure 4-9 Plot of Skin Friction vs Depth of soil Nail in drill and grout nail (L/B=1)

4.2.3 For L/H=1.2

S.N	Depth	Static			Dynamic barpak			Dynamic kobe		
		u	axial t	skin f	u	axial t	skin f	u	axial t	skin f
1	-0.75	2.805	6.398	37.93	2.877	6.666	38.7	3.446	6.642	38.79

2	-2.25	3.297	13.06	22.16	3.401	13.47	22.54	4.215	12.41	21.7
3	-3.75	4.253	26.3	8.535	4.365	26.51	8.48	5.232	25.84	9.622
4	-5.25	6.274	35.31	9.223	6.392	35.37	9.217	7.290	34.24	11.61
5	-6.75	8.572	26.1	32.34	8.695	26.12	32.36	9.603	23.99	30.48
6	-8.25	11.110	46.11	13.86	11.240	46.09	14.13	12.230	41.95	18.37
7	-9.75	13.380	21.07	12	13.520	20.44	11.95	14.560	13.82	12.4
8	-11.25	16.520	40.4	21.58	16.680	41.39	24.11	17.880	41.23	37.12

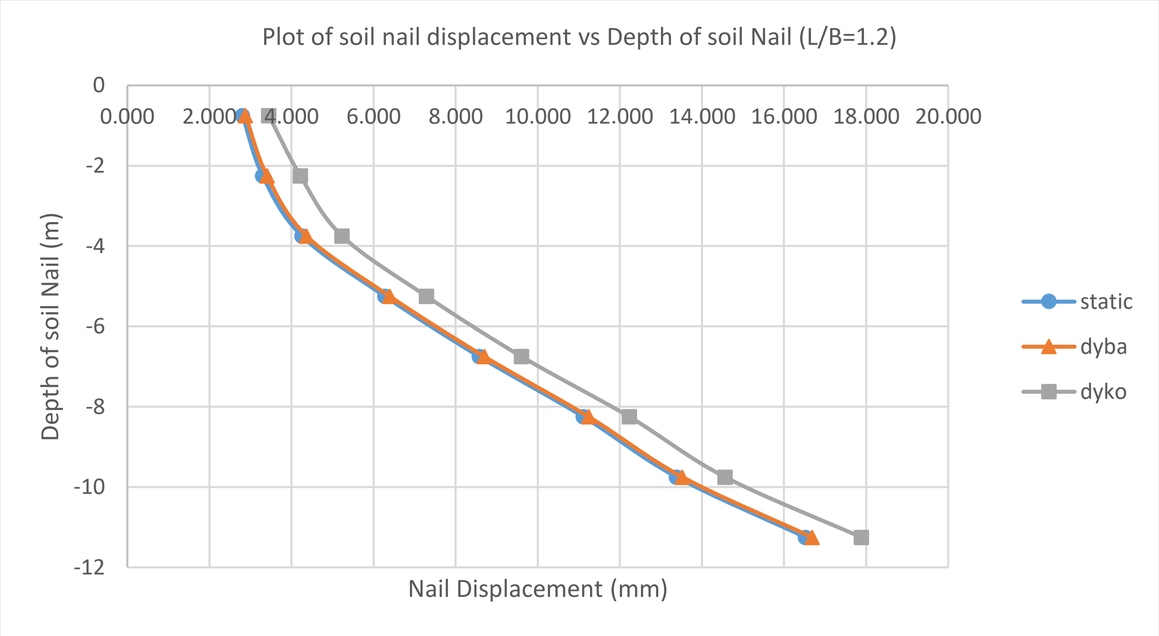


Figure 4-10 Plot of maximum nail displacement vs Depth of soil Nail in Drill and grout nail(L/B=1.2)

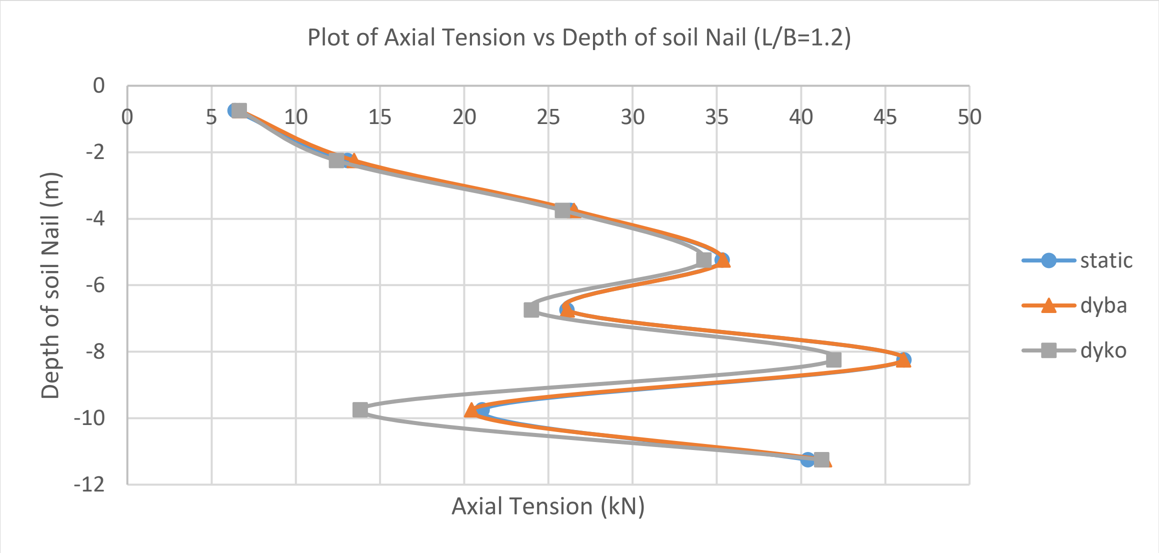


Figure 4-11 Plot of Axial Tension vs Depth of soil Nail in drill and grout nail (L/B=1.2)

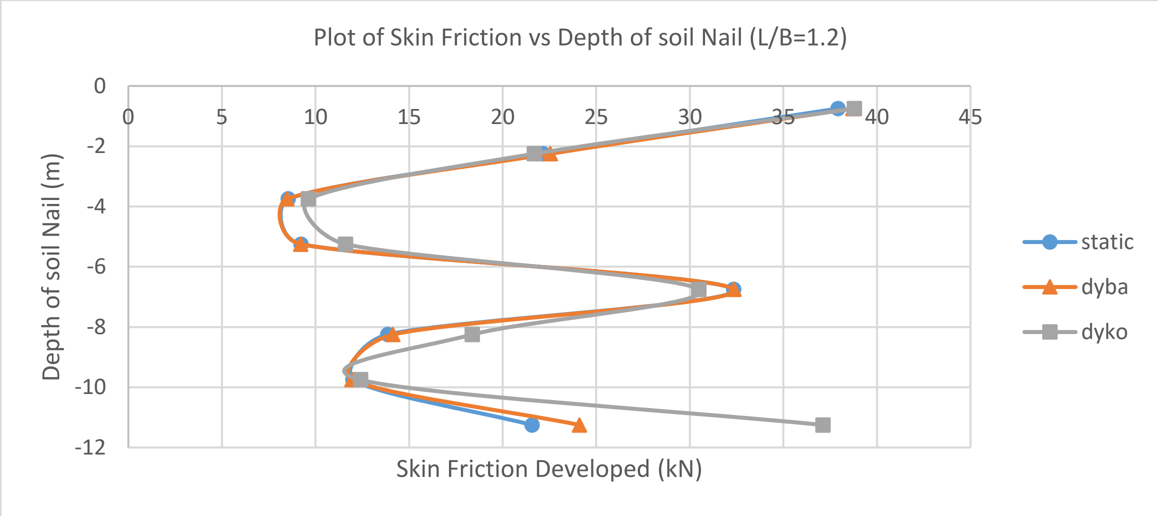


Figure 4-12 Plot of Skin Friction vs Depth of soil Nail in drill and grout nail (L/B=1.2)

4.3 Effect of L/H ratio

4.3.1 Maximum displacement of soil nail

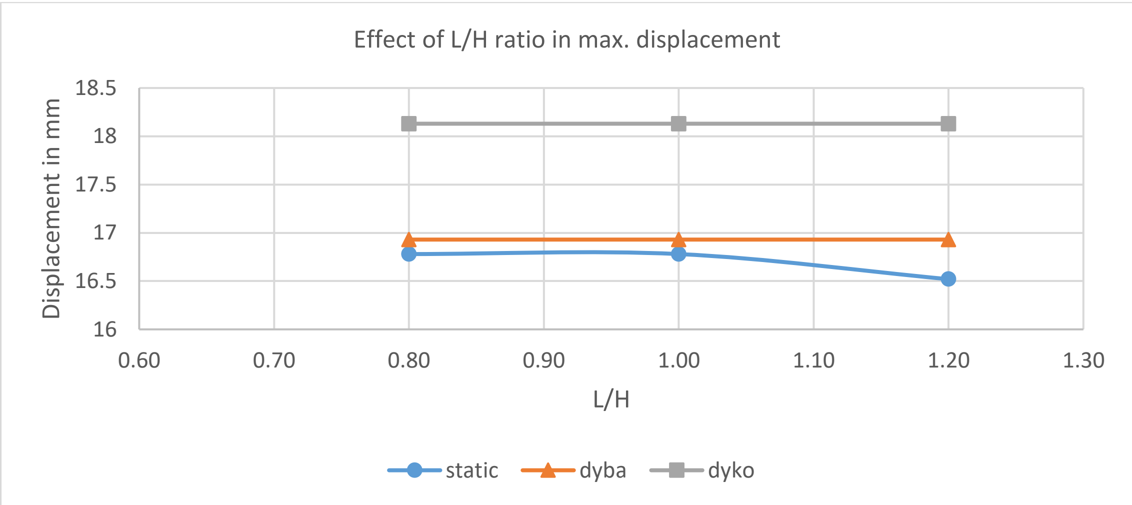


Figure 4-13 Plot of maximum displacement vs L/H ratio in drill and grout nail

- L/H ratio has little contribution for controlling displacement in case of dynamic loading at lower values.
- The maximum displacement of the wall increases as the magnitude of earthquake loadings increases.
- The maximum displacement of the wall decreases as the L/H ratio increases for static loadings.

4.3.2 Maximum axial force developed in soil nail

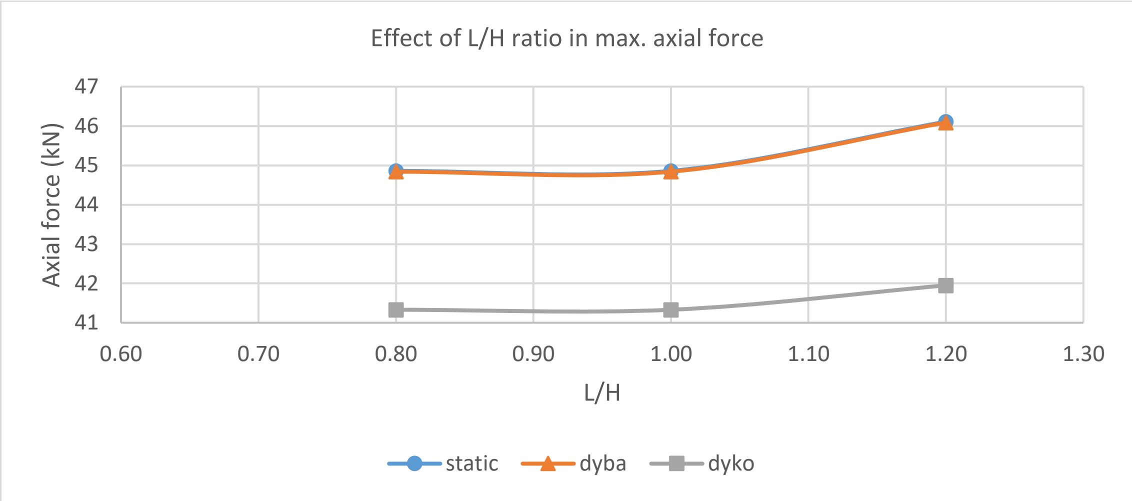


Figure 4-14 Plot of maximum axial force in nail vs L/H ratio in drill and grout nail

- The value of maximum axial force is constant at lower L/H ratio and increase as the L/H ratio increases from unity.
- Value of maximum axial force developed in the soil nail decreases with the increase in magnitude of earthquake loading.
- Axial forces developed in soil nails in static conditions are more than that developed during dynamic conditions.

4.3.3 Maximum skin friction developed

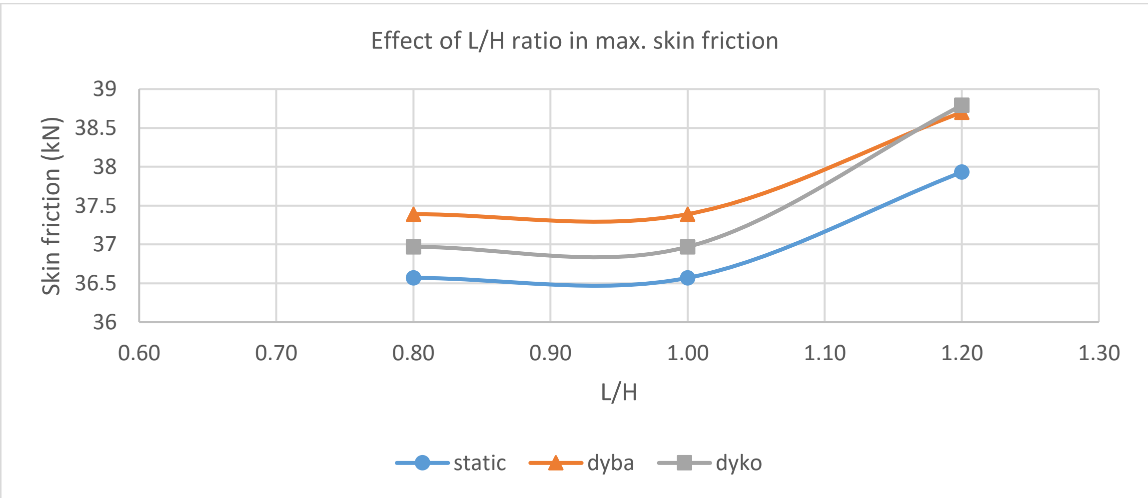


Figure 4-15 Plot of maximum skin friction vs L/H ratio in drill and grout nail

- The values of maximum skin friction developed in the soil nail increases with the increase in the L/H ratio in both static and dynamic loading.

- Value of maximum skin friction developed in the soil nail decreases with the increase in magnitude of earthquake loading.
- The values of skin friction is found to increase in seismic conditions in comparison to static loading conditions.

4.3.4 Amplification factor

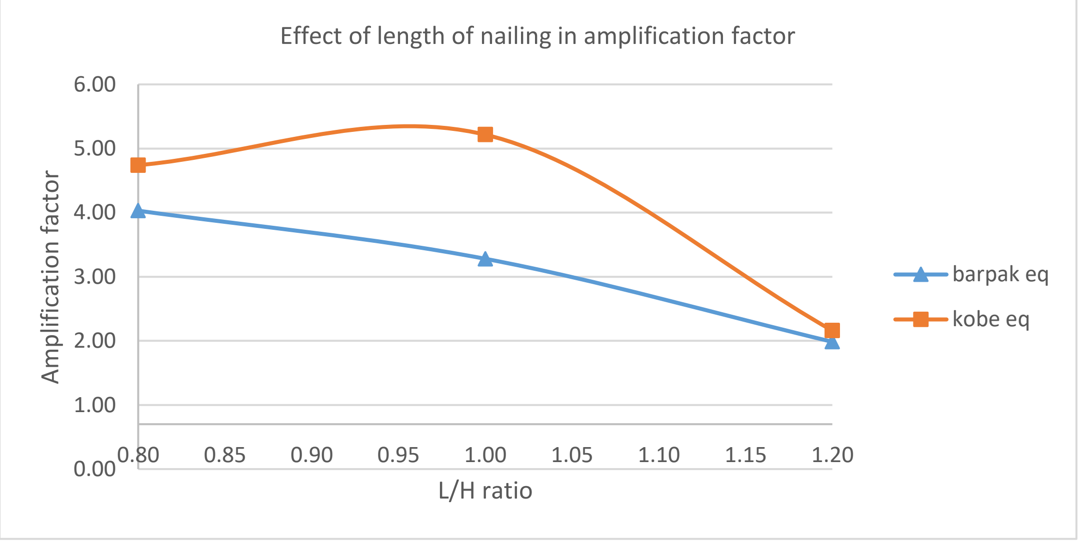


Figure 4-16 Plot of maximum amplification vs L/H ratio in drill and grout nail

As the L/H ratio increases the amplification factor increases in the first gains a maximum value at L/H nears to 1 and then decreases gradually. The amplification factor for both seismic inputs converges at higher L/H ratio.

4.3.5 Factor of safety

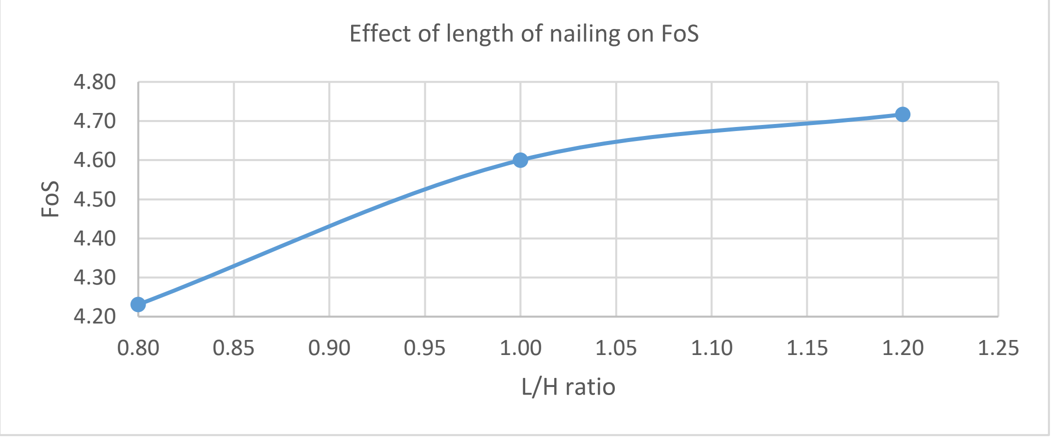


Figure 4-17 Plot of FoS vs L/H ratio in drill and grout nail

As the L/H ratio increases the global FoS of the structure increases due to increase in the depth of the slip surface. Presence of nails on the slip surface cause the tangential forces of the nail and prevents its rupture in turn increasing the stability of the soil nail walls.

4.4 Verifications

Following are the literature that have confirmed with the results of our numerical analysis:

- Stauffer (2015) shows similar results for the maximum displacement and tensile forces incase of 2D and 3D analyses of soil nailed structures.
- Nájar (2009) suggest that 2D models are modelled too rigid due to the approximation of nails by planar inclusions and should be gradually replaced by 3D models for better results.
- Singh et al. (2010) shows similar results for the lateral wall displacement and maximum tensile forces for soil nailed structures.
- Tavakoli et al. (2019) shows similar results for type of factor of safety, effect of L/H ratio in amplification factor, effect of magnitude of earthquake loading in the amplification factor and effect of L/H ratio in the maximum displacement.

5. CONCLUSIONS

Following conclusion are drawn from this study.

1. From 2D and 3D analyses of the same arrangement for both drilled and grout and driven nails we observed that, the maximum displacement shown by 2D analysis is more compared to 3D for each construction stage with an average value of 24.68 % in case of grouted nails and 50 % in case of driven nails which suggests more prominent difference in driven nails compared to drill and grout nail.
2. The maximum displacement of the wall decreases as the L/H ratio increases for static loadings. In case of dynamic loadings L/H ratio seems to have little effect for controlling displacement especially at lower values.
3. The maximum axial forces were found to be maximum at soil nails installed at a depth of about 2/3H from the top of the wall in both 2D and 3D analysis in both drill-grout and driven nails.
4. Value of maximum axial force developed in the soil nail decreases with the increase in magnitude of earthquake loading. The value of maximum axial force is constant at lower L/H ratio and increase as the L/H ratio increases from unity value in case of static loading.
5. The values of maximum skin friction developed in the soil nail increases with the increase in the L/H ratio in both static and dynamic loading. The values of skin friction is found to increase slightly in seismic conditions in comparison to static loading conditions but this value decreases with the increase in magnitude of earthquake loading.
6. As the L/H ratio increases the global FoS of the structure increases due to increase in the depth of the slip surface. Presence of nails on the slip surface

cause the tangential forces of the nail and prevents its rupture increasing the stabilizing forces.

7. Seismic analysis shows that the maximum amplification was found at about L/H ratio of about 1 and decrease as L/H ratio increases. As the magnitude of the earthquake loading increases the amplification factor also increases especially at lower L/H values.
8. Amplification depends on the various parameters of soil nailed structures and soil-structure interaction and thus should be considered while designing soil nailed structures in seismically active places.

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ANNEX : SOIL INVESTIGATION AND LAB REPORTS

(Courtesy of Bandipur Culture Center)