SEISMIC RESPONSE OF STEEP NAILED SOIL SLOPES – SHAKING TABLE TESTS AND ANALYSIS

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by

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To My Family

CERTIFICATE

This is to certify that the thesis entitled "**Seismic response of steep nailed soil slopes – shaking table tests and analysis**" being submitted by **Ms. Smrutirekha Sahoo** to the **Indian Institute of Technology Delhi** is a record of bonafide research work carried out by her under our supervision and guidance. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any university or Institute for the award of any degree or diploma.

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ABSTRACT

The seismic performance of nailed soil structures is of great importance especially for the earthquake prone zones. Most of the literature on nailed soil structures stresses on the design of structures and the reinforcement mechanism under static load only. However, only limited studies are available to evaluate the seismic response of nailed soil slopes. Therefore, the seismic resistance and failure mechanism of nailed soil slopes are worthy of investigation with a view to understand the seismic behaviour of steep nailed slopes and design accordingly.

The model testing using a shaking table is one of the few ways to study the behaviour of reinforced slopes under seismic condition in the laboratory. So in the present investigation, an attempt has been made to understand the seismic behaviour of model soil slopes without and with nails with the help of shaking table tests and numerical studies. The testing program has been implemented to evaluate the effects of various nail and slope arrangements on the seismic response of model soil slopes using shaking table tests at the Heavy Structures Laboratory (HSL), Department of Civil Engineering at Indian Institute of Technology (IIT) Delhi.

Shaking table tests on 44 nos. of 0.4 m high model slopes were conducted to investigate the effects of various important parameters such as slope angle, nail length, nail inclination, effect of facing on the behaviour of the soil slopes with proper instrumentation under a particular seismic condition viz., 1989 Loma Prieta earthquake having the peak ground acceleration (PGA) of 0.57*g* recorded at Los Gatos presentation center. Out of total 44 nos. of model slopes, four are unreinforced slopes i.e., without nailing, twenty are nailed slopes without facing and the rest twenty are nailed slopes with facing. The important parameters considered for the present investigation consists of a combination of four different slope angles (45°, 60°, 75° and 90°) which have been used for three different nail inclinations (i = 0°, 15° and 30°) and three nail lengths (0.2 m, 0.3 m and 0.4 m).

Additionally, Finite element (FE) analyses were also performed on all the model slopes to examine their response to seismic loading. Three-dimensional numerical models were developed to simulate the model slopes by finite element software, MIDAS/GTS (2013). The FE results such as maximum lateral displacements at various elevations of the facing, acceleration amplification at the crest, crest settlement, axial forces developed along the length of the nails and variation of nail forces developed with time as the seismic loading progresses are compared with the shaking table test results to confirm the findings of the shaking table tests on all model slopes and to establish some useful guidelines for predicting the failure pattern of nailed soil slopes and distribution of nail forces for various combination of slope angle, nail length, nail inclination and facing condition under the seismic loading condition. The seismic response and failure mechanism of both unreinforced and reinforced soil slopes without and with facing are evaluated in detail.

The study reveals that the nature of response accelerations was not uniform throughout the soil mass due to the base excitation irrespective of the slope and/or nail arrangements. The unreinforced slopes responds to seismic excitation too early as compared to the reinforced slopes which can be the main contributing factor in destabilization of the unreinforced slopes in the early phase of seismic excitation. The magnitude of slope face displacement at all the measured points of unreinforced slopes is higher than that of the reinforced slopes. A combination of translational and rocking movement is found in reinforced model slopes with both types of slope facing but in case of unreinforced model slopes, translational movement is more predominant. The effect of slope angle on the seismic resistance of steep nailed soil slopes is quite significant. The magnitude of facing displacement increases with decrease in nail length. The minimal magnitude of facing displacement is obtained with horizontally placed nails and with nail inclination of 15° in case of reinforced model slopes without facing and in reinforced model slopes with facing respectively. The development of maximum axial nail force in each of the nails of reinforced model slopes with facing has been obtained at a distance of around two-third of the nail length from the slope face, whereas in case of the nails of reinforced model slopes without facing, it is obtained at the slope facing itself, and diminishes steadily toward the end irrespective of any slope and nail arrangements. The magnitude of maximum axial nail force, maximum shear force and bending moment in each of the nails of reinforced model slopes without facing is 5 to 10 times, 10 to 15 times and 25 to 30 times higher than that in case of the reinforced model slopes with facing respectively.

सारांश

किसी न किसी मिट्टी संरचनाओं के भूकंपीय प्रदर्शन विशेष रूप से भूकंप प्रवण क्षेत्रों के लिए काफी महत्व की है। किसी न किसी मिट्टी संरचनाओं पर साहित्य का सबसे संरचनाओं के डिजाइन और स्थिर भार केवल तहत सुदृढीकरण तंत्र पर जोर दिया। हालांकि, केवल सीमित पढ़ाई किसी न किसी मिट्टी ढलानों के भूकंपीय प्रतिक्रिया का मूल्यांकन करने के लिए उपलब्ध हैं। इसलिए, भूकंप प्रतिरोध और किसी न किसी मिट्टी ढलानों की विफलता तंत्र तदनुसार खड़ी किसी न किसी ढलानों और डिजाइन के भूकंपीय व्यवहार को समझने की दृष्टि से जांच के योग्य हैं।

मॉडल एक मिलाते हुए तालिका का उपयोग कर परीक्षण प्रयोगशाला में भूकंप शर्त के तहत प्रबलित ढलानों के व्यवहार का अध्ययन करने कुछ तरीके से एक है। वर्तमान जांच में तो, एक प्रयास के बिना और मेज परीक्षण और संख्यात्मक पढ़ाई झटकों की मदद से nail के साथ मॉडल मिट्टी ढलानों के भूकंपीय व्यवहार को समझने के लिए बनाया गया है। परीक्षण कार्यक्रम भारी संरचनाएं प्रयोगशाला (एचएसएल), भारतीय प्रौद्योगिकी संस्थान (आईआईटी) दिल्ली में सिविल इंजीनियरिंग विभाग में मेज परीक्षण मिलाते हुए का उपयोग कर मॉडल मिट्टी ढलानों के भूकंपीय प्रतिक्रिया पर विभिन्न nail और ढलान व्यवस्था के प्रभाव का मूल्यांकन करने के लागू किया गया है ।

44 नग पर तालिका परीक्षण हिलती। 0.4 मीटर की उच्च मॉडल ढलानों इस तरह ढाल कोण, nail की लंबाई, nail झुकाव, मिट्टी के व्यवहार पर का सामना करना पड़ के प्रभाव एक विशेष भूकंपीय

हालत अर्थात के तहत उचित उपकरण के साथ ढलान के रूप में विभिन्न महत्वपूर्ण मापदंडों का प्रभाव की जांच को आयोजित की गई।, 1989 Loma Prieta भूकंप Los Gatos प्रस्तुति केंद्र में दर्ज 0.57*g* के शिखर जमीन त्वरण (पीजीए) हो रही है। कुल 44 ओपन स्कूल से बाहर। मॉडल ढलानों के, चार unreinforced ढलानों यानी, का सामना करना पड़ और बाकी बीस का सामना करना पड़ के साथ ढलानों किसी न किसी रहे बिना व्यवस्थित करना, बीस किसी न किसी रहे ढलानों बिना कर रहे हैं।महत्वपूर्ण पैरामीटर वर्तमान जांच के लिए विचार चार अलग अलग ढलान कोण (45 डिग्री, 60 डिग्री, 75 डिग्री और 90 डिग्री), जो तीन अलग अलग कील हठ (0 डिग्री, 15 डिग्री और 30 डिग्री) और के लिए इस्तेमाल किया गया है का एक संयोजन के होते हैं तीन nail लंबाई (0.2 मीटर, 0.3 मीटर और 0.4 मीटर)।

साथ ही, परिमित तत्व (FE) विश्लेषण भी भूकंपीय लोड हो रहा है के लिए उनकी प्रतिक्रिया की जांच करने के सभी मॉडल ढलानों पर प्रदर्शन किया गया। तीन आयामी संख्यात्मक मॉडल विकसित किए गए परिमित तत्व सॉफ्टवेयर द्वारा मॉडल ढलानों अनुकरण करने के लिए, MIDAS / GTS (2013)।इस तरह के संपर्क वाले के विभिन्न ऊँचाइयों पर अधिकतम पार्श्व विस्थापन के रूप में एफई परिणाम, शिखा, शिखा निपटान में त्वरण प्रवर्धन, अक्षीय बलों nail और nail बलों की भिन्नता समय के साथ विकसित की लंबाई के साथ के रूप में भूकंपीय लोड हो रहा है प्रगति के साथ तुलना में कर रहे हैं विकसित तालिका परीक्षण के परिणाम मिलाते हुए सभी मॉडल ढलानों पर

और करने के लिए मिलाते हुए मेज परीक्षण के निष्कर्षों की पुष्टि करने किसी न किसी मिट्टी ढलान और ढाल कोण, nail की लंबाई, nail झुकाव के विभिन्न संयोजन के लिए nail बलों के वितरण की विफलता पैटर्न की भविष्यवाणी और भूकंप लोड हो रहा है शर्त के तहत हालत का सामना करना पड़ के लिए कुछ उपयोगी दिशा निर्देशों की स्थापना। भूकंप प्रतिक्रिया और दोनों unreinforced की विफलता तंत्र और बिना और का सामना करना पड़ विस्तार से मूल्यांकन किया जाता है के साथ मिट्टी ढलानों को मजबूत बनाया।

अध्ययन से पता चलता है कि प्रतिक्रिया त्वरण की प्रकृति के आधार उत्तेजना ढलान और / या nail की व्यवस्था पर ध्यान दिए बिना के कारण मिट्टी जन भर एक समान नहीं था।unreinforced ढलानों भूकंपीय उत्तेजना के रूप में प्रबलित ढलानों जो भूकंपीय उत्तेजना के प्रारंभिक चरण में unreinforced ढलानों की अस्थिरता में मुख्य योगदान कारक हो सकता है की तुलना में बहुत जल्दी प्रतिक्रिया करता है। unreinforced ढलानों के सभी मापा बिंदुओं पर ढलान चेहरा विस्थापन की भयावहता प्रबलित ढलानों की तुलना में अधिक है। अनुवादकीय और कमाल आंदोलन का एक संयोजन ढलान का सामना करना पड़ के दोनों प्रकार के साथ प्रबलित मॉडल ढलानों में पाया जाता है लेकिन unreinforced मॉडल ढलानों के मामले में, अनुवादकीय आंदोलन अधिक प्रमुख है। खड़ी किसी न किसी मिट्टी ढलानों के भूकंप प्रतिरोध पर ढाल कोण के प्रभाव काफी महत्वपूर्ण है। विस्थापन का सामना करना पड़ की भयावहता nail लंबाई में कमी के साथ बढ़ जाती है। विस्थापन

का सामना करने की कम से कम परिमाण का सामना करना पड़ के बिना और क्रमशः का सामना करना पड़ के साथ प्रबलित मॉडल ढलानों में क्षैतिज रखा nail के साथ और मजबूत बनाया मॉडल ढलानों के मामले में 15 डिग्री के झुकाव के साथ nail प्राप्त की है। अधिकतम अक्षीय nail के विकास प्रबलित मॉडल के nail में से प्रत्येक में बल ढलान के साथ संपर्क वाले का सामना करना पड़ बिना प्रबलित मॉडल ढलानों के nail के मामले में ढाल चेहरे से nail की लंबाई के चारों ओर दो-तिहाई की दूरी पर प्राप्त किया गया है, जबकि, यह कम से प्राप्त किया जाता है ढलान ही सामना करना पड़ रहा है, और अंत में किसी भी ढलान और nail की व्यवस्था पर ध्यान दिए बिना की ओर तेजी से कम हो। का सामना करना पड़ बिना अधिकतम अक्षीय nail बल, अधिकतम कतरनी बल और प्रबलित मॉडल ढलानों के nail में से प्रत्येक में झुकने पल की भयावहता प्रबलित मॉडल ढलानों के मामले में 5 से 10 गुना, 10 से 15 गुना तक और 25 से 30 गुना तुलना में अधिक है क्रमशः झेल रहे हैं।

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Description	**Notation**	**Unit**
Acceleration due to gravity	g	m/sec^2
Angle of internal friction in soil	ϕ	Degree (°)
Angle of internal friction between soil and nail	ϕ_n	Degree (°)
Bulk modulus	K	MPa
Cohesion	c	kPa
Damping coefficient for the primary axis	C_p	-
Damping coefficient for the secondary axis	C_s	-
Density of aluminum	ρ	kg/m^3
Diameter of nail	D	Meter (m)
Elastic modulus	E	MPa
Facing plate	f	-
Inclination of nail	i	Degree (°)
Length of nail	l	Meter (m)
Maximum axial nail force	A	Newton
Maximum bending moment	M	Newton-meter
Maximum shear force	F	Newton
Maximum dry unit weight	$\gamma_{d_{max}}$	kN/m^3
Minimum dry unit weight	$\gamma_{d_{min}}$	kN/m^3

Nail	N	-
Normal stiffness modulus	K_n	kN/m^2
Poisson's ratio	v	-
Pull-out resistance	q_s	kN/m^2
Relative density	D_r	%
Scaling factor	λ	-
Shear modulus	G	MPa
Shear stiffness modulus	K_s	kN/m^2
Slope angle	β	Degree (°)
Strain	ε	-
Strain gauge	S	-
Stress	σ	kN/m^2
Tensile strength of nail	F_y	MPa
Time	t	seconds
Yield strength	T_y	MPa
Uniformity coefficient	c_u	-

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The technology of ground reinforcement has been familiar to mankind throughout civilization. Even though the technique of reinforcing the ground with other materials providing additional strength is known and practiced, it is in 1966 when Vidal introduced the method of reinforced earth. Since then the technology of ground reinforcement became a much studied and well used technique and many types of ground improvement and reinforcing techniques have been developed, including that of soil nailing. The fundamental concept of soil nailing is to strengthen the excavations and slopes by reinforcing with closely spaced steel bars which are called as ‘nails’. This process makes a reinforced structure which is stable by itself and capable of retaining the ground around it. The soil-nail composition is capable of carrying tensile loads through which it increases the apparent cohesion of the soil. Though soil nailing is an advanced area of research in the field of Civil Engineering, a number of model and large field tests have been conducted in past by various researchers to understand the behavior of nailed slopes. The large-scale field tests on virtually vertical nailed cuts and/or slopes in cohesionless soil were conducted by Stocker et al. (1979), Gassier and Gudehus (1981). A number of small-scale model tests on reinforced slopes have been conducted by Kitamura et al. (1988), Gutierrez and Tatsuoka (1988) in which the tensile (reinforcement) forces and developed strain were measured. The small-scale models were used by Juran et al. (1988) to investigate the effect of construction method on the behavior of nailed soil structures. A full-scale test has been conducted by Schlosser (1991) on a nailed soil wall in which the reinforced soil mass was made saturated leading it to fail progressively. A 15 m high nailed soil wall made up of cohesive soil was tested by Pedley (1992) for a longer period of time. The behavior of steel reinforced slope were investigated by Davis et al. (1993) by a series of model tests conducted in clayey sand.

During the 1989 Loma Prieta Earthquake in the San Francisco Bay, it was observed that many of the nailed soil structures were subjected to considerable levels of shaking which has been reported by Barar et al. (1990). One of the reinforced slopes (La Honda Slope) had deformed about 20 mm laterally as compared to pre-earthquake inclinometer measurements. Thirty four reinforced structures were reported (Kutter et al., 1990) to suffer from distress and significant damage was observed in a 4.5 m high reinforced wall. However no details were available from the observations made from the 1989 Loma Prieta Earthquake to identify damages for the other failed reinforced structures. During the Northridge Earthquake in California (1994), the performances of a number of reinforced soil structures were documented (Sandri, 1994; Stewart et al., 1994; Bathurst and Cai, 1995; White and Holtz, 1996). The wall face of a 16 m wall experienced bulging of 460 mm (Sitar at al., 1997).

Tanata wall moved about 300 mm and also suffered spalling and cracking of the facing panels during the Hyogoken-Nanbu (Kobe) Earthquake in Japan (1995). Earthquake caused outward movement of the top of a 9 m high reinforced wall by about 150 mm and similar damage patterns were observed in two other reinforced earth walls (Tatsuoka et al., 1997).

It was observed from the 1999 Chi-Chi Earthquake in Taiwan that several steep slopes experienced severe damages which has been reported by Lin et al. (2004) and also several reinforced soil structures collapsed. Assessments of the stability of highway slopes following the earthquake revealed that approximately 350 number of slopes out of more than 500 failed slopes were steep (60° or more from the horizontal). Several reinforced soil structures also collapsed. The seismic performance of nailed soil structures especially for the earthquake prone zones is of great importance. A 3.4 m high reinforced wall was observed to displace about 1.6 m laterally at the toe of the wall which is quite unacceptable from the stability point of view of a reinforced wall. Another 40 m high geogrid reinforced slope collapsed during the earthquake (Huang, 2000; Ling et al., 2001).

The documentation related to seismic response of the reinforced soil slopes obtained from the literature confirmed the need for a further comprehensive investigation of the seismic performances of reinforced soil slopes to have a clear insight into it.

Soil nailing is one of the important reinforcing techniques for protecting slopes especially steep slopes against such catastrophic failure because of earthquakes. It stabilizes the entire slope by providing the soil confinement. Most of the literature on nailed soil structures stresses on the design of structures and the reinforcement mechanism under static load only. Therefore, the seismic resistance and failure mechanism of nailed soil slopes are worthy of investigation with a view to understand the seismic behaviour of steep nailed slopes and design accordingly. The failure or distress reported in the literature (Bathurst and Alfaro, 1996) due to earthquakes showed how vulnerable the nailed soil structures are to ground motions. An extensive description of the soil nailing technology and design methods is reported by Hussin et al. (1997). However, few studies are available to evaluate the seismic responses of nailed soil slopes and corresponding failure mechanism of nailed soil slopes.

The coherent and flexible nature of nailed soil structure make them inherently capable of resisting larger deformation under dynamic loading conditions. However the failure mechanism and the seismic resistance of nailed soil slopes during an earthquake event are not distinctly understood and hence proper comprehensive investigation is needed. The instrumentation and monitoring of actual structures is the best way to study their performance during earthquakes. However due to lack of such data, model tests in the laboratory are the only way to study the seismic behaviour of nailed slopes and excavations.

The first well-documented shaking table study of unreinforced slopes was performed by Clough and Pirtz (1956). Seed and Clough (1963), Goodman and Seed (1965), and Arango and Seed (1974) also used shaking table tests to study the earthquake resistance of embankment slopes and dams. But a very limited investigation has been done related to shaking table tests on reinforced soil slopes. Some of them include Hong et al (2005) and Giri and Sengupta (2009) used shaking table tests to study the earthquake resistance of reinforced (nailed) slopes. But in their investigation also, the details related to the development of nail forces under earthquake loading was limited which is an important parameter in understanding the seismic behaviour of nailed soil slopes.

The model testing using a shaking table is one of the few ways to study the behaviour of reinforced slopes under seismic condition in the laboratory. Therefore, in the present investigation, an attempt has been made to understand the seismic behaviour of model soil slopes without and with nails with the help of shaking table tests and numerical studies. The seismic excitation of the model slopes was carried out using the input time history of 1989 Loma Prieta earthquake having the peak ground acceleration (PGA) of 0.563*g* recorded at Los Gatos presentation center. This particular seismic time history has been chosen for the present study as it is a very well-known and standard seismic history recorded in the past and usually a preferred seismic history considered for research purposes (Felio et al., 1990, Keefer, D.K., 2000, Khazai and Sitar, 2004, Wasowski et al., 2011, Zhang and Zhao, 2008). The testing program has been implemented to evaluate the effects of various nail and slope arrangements on the seismic resistance of model soil slopes using shaking table tests at the Heavy Structures Laboratory (HSL), Department of Civil Engineering at Indian Institute of Technology (IIT) Delhi.

1.2 OBJECTIVES OF THE PRESENT STUDY

The primary objectives of the present study are to understand the seismic behaviour of model soil slopes without and with nails with the help of shaking table tests and numerical studies. The following are the specific objectives of the present study:

1. To carry out laboratory shaking table tests to study the seismic behaviour of model soil slopes without and with nails under a particular seismic loading condition.

2. To establish 3D finite element models for the simulation of the shaking table tests carried out on the model soil slopes under seismic loading condition.

3. To compare the shaking table test results with the predicted results from finite element analyses on the model soil slopes.

4. To develop the failure mechanism of both unreinforced and reinforced soil slopes and delineate the effect of slope angle, nail inclination, nail length and slope facing on the behaviour of model soil slopes under the seismic loading condition.

5. To study the maximum lateral displacements at various heights of the facing, maximum crest settlement and acceleration amplification at crest for both unreinforced and reinforced soil slopes under seismic loading.

6. To examine the development of maximum nail forces and the variation of the nail forces along the nail length with time at various stages of the seismic load.

The findings of this work will establish a pioneering, scientific and rational framework for the design of soil slopes without and with nails to cope with the earthquake loading condition. This research will also contribute to establish some useful guidelines for predicting the failure pattern of nailed soil slopes and distribution of nail forces for various combination of slope angle, nail length and nail inclination under seismic loading condition.

1.3 SCOPE OF THE PRESENT STUDY

The scope of the present study is stated in the following points:

1. Shaking table tests on 44 nos. of 0.4 m high model slopes were conducted to investigate the effects of various important parameters such as slope angle, nail length, nail inclination,

effect of facing on the behaviour of the soil slopes with proper instrumentation under a particular seismic condition, i.e., 1989 Loma Prieta earthquake having the peak ground acceleration (PGA) of 0.57*g* recorded at Los Gatos presentation center. Out of total 44 nos. of model slopes, four are unreinforced slopes, i.e., without nailing, twenty are nailed slopes without facing and the remaining twenty are nailed slopes with facing.

2. The important parameters considered for the present investigation consists of a combination of four different slope angles (β = 45°, 60°, 75° and 90°) which have been used for three different nail inclinations (i = 0°, 15° and 30°) and three nail lengths (l = 0.2 m, 0.3 m and 0.4 m) under a particular seismic condition.
3. Finite element analyses were also performed for the validation of all the shaking table test results performed on both unreinforced and reinforced model slopes. Seismic analyses were carried out on three-dimensional numerical models to simulate the model slopes by finite element software, MIDAS GTS (2013).
4. The finite element results such as maximum lateral displacements at various heights of the facing, acceleration amplification at the crest, crest settlement, axial forces developed along the length of the nails and variation of nail forces developed with time as the seismic loading progresses are compared with the shaking table test results to confirm the findings of the shaking table tests on all model slopes.

Some useful guidelines are also established for predicting the failure pattern of nailed soil slopes and distribution of nail forces for various combination of slope angle, nail length and nail inclination under the seismic loading condition.

1.4 ORGANIZATION OF THE THESIS

The thesis is organized under seven different chapters as given below.

Chapter 1 describes an introduction to the soil nailing concept, outlines the need of the present study and presents detailed objectives and the scope of the present study.

Chapter 2 gives preliminary information on soil nailing technique, its installation techniques, various components associated with it, factors affecting soil nailed slopes, advantage and disadvantage of soil nailing. The chapter then comprises of literature review of relevant research papers on soil nailing, shaking table tests and corresponding numerical analyses and points out the research gaps in available literature, thus establishing the need of the present study.

Chapter 3 outlines the details of the experimental investigation that was carried out to find out different material properties of the soil and the nail associated with the shaking table test. The chapter also gives detailed description of preparation of models and the shaking table test procedure. The modeling considerations regarding selection of materials used in model tests, test box dimensions, shaking table, adopted scaling law, loading conditions etc. are also covered.

Chapter 4 constitutes the details of the results obtained from shaking table tests on model slopes.

Chapter 5 presents the features of the finite element software Midas/GTS (2013) to simulate the laboratory shaking table tests. The numerical results obtained from the finite element analyses on the model slopes are also presented.

Chapter 6 consists of the results and discussions on the results obtained from shaking table tests and the finite element analyses. The results of finite element analyses are compared with the shaking table test results. Finally the result interpretation has also been done in terms of various important parameters to achieve the objectives of the present study.

Chapter 7 presents the general conclusions drawn on the seismic behavior of model soil slopes based on the results of shaking table tests and numerical studies. The chapter also proposes scope for the future studies in this area.

A list of references is given at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The first field application of soil nailing originated in Versailles of France in 1972. A typical cut slope was successfully reinforced by grouting a number of closed spaced bars into ground (Clouterre, 1991). This typical project led to a wide application of soil nailing as an effective reinforcement technique for excavations, slopes and retaining walls. In the following decades, a number of large scale research programs were carried out all over the world to explore several critical aspects of soil nailing. The origins of soil nailing are often reported as a development from the New Austrian Tunneling method (NATM), Mitchell and Villet (1987). The technique of NATM utilizes passive inclusions installed in a radial pattern in the ground around a tunnel to reduce load on the tunnel lining and its supports. Passive inclusions were extensively applied as fully bonded rock bolts (passive anchors) for tunnel support during the 1950's and 60's, leading to the use of rock bolts in weaker rocks. This then progressed to trials in soils such as silt, gravel and sands. In 1970 a small metro tunnel in Frankfurt was constructed using the technique in soil, Bruce and Jewell (1987). In conjunction with the developments towards stabilizing tunnels in weak rock and soil, the use of dowels and bolts to stabilize rock slopes was well established. In 1961 a retaining wall using anchored bars faced with reinforced concrete was constructed in schist for an overflow spillway at Notre-Dame-de-Commiers, reported in Clouterre (1991). The two applications appear to converge into a form considered as soil nailing in 1972 when a cut slope of 70º in heavily cemented Fontainbleu sand was constructed near Versailles, in France, Clouterre (1991). This was one of the early applications where the method of retention of existing soil had moved from primarily being a retaining wall assisted by the inclusions, to the passive inclusion being the primary form of support. After the success of this method, a number of soil nailing stabilization and excavation projects followed in France, North America and Germany and in 1975 the first major research project was undertaken to develop an understanding of the mechanisms of soil nailing, Gassier and Gudehus (1981).

2.2 BASIC INFORMATION ON SOIL NAILING

The technology of ground reinforcement has been familiar to mankind throughout civilization. Ingenious techniques have been known to be applied to ancient structures as far back as 2100 B.C. in the construction of ziggurats and other monuments (Kerisel, 1987) which involved layering of materials bearing tensile strength interbedded with compressive materials like soil and gravel to form a reinforced composite. Even though the technique of reinforcing the ground with other materials providing additional strength is known and practiced, it is in 1966 when Vidal introduced the method of reinforced earth that the technology of ground reinforcement became a much studied and well-used technique. Since then many other types of ground improvement and reinforcing techniques have arisen, including that of soil nailing. Ground reinforcement techniques may be classified broadly into two main categories (Juran and Schlosser, 1979):

- In-situ soil reinforcement
- Remoulded soil reinforcement

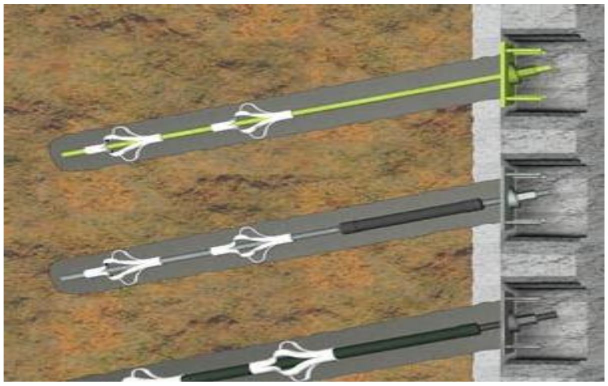
The above mentioned reinforced earth techniques follow the second method where the soil is built up together with the reinforcement, which may comprise of geogrids, geotextiles or steel strips. However, since many geotechnical applications require reinforcement that needs to be placed in-situ, such as excavated walls or slopes, rather than built up structures, such as embankments, the former category has been developed in recent times to be an important aspect of ground reinforcement. Such techniques like soil nailing and dowelling, have received tremendous development over the last 35 years.

2.2.1 Soil Nailing Technique

Soil nailing is a reinforcement technique in which retaining walls, soil slopes and/or excavations are passively reinforced by inserting relatively slender elements (viz., steel reinforcing bars, tubes, etc.). Such a structural element which transfers load to the ground (which otherwise could have driven the slope and/or excavation to fail) in reinforcement application is called nail (Figure 2.1). Soil nails are mainly subjected to tensile stresses and are generally placed at an inclination of 10 to 20 degrees with horizontal. Soil nailing is generally used to strengthen and/or to increase the stability of existing slopes or excavations in which top-to-bottom construction is advantageous as compared to the other retaining wall systems. As construction proceeds from top to bottom, shotcrete or spraying concrete is also applied on the slope or excavation face to provide a smooth continuous finish. Figure 2.2 depicts cross section of a grouted nailed wall along with a typical soil nail application in the field.

Figure 2.1 Soil nail with centralizers

(www.williamsform.com/Ground_Anchors/Soil_Nails_Soil_Nailing/soil_nail_soil_nailing.html)



(a) (b)

Figure 2.2 (a) Cross-section of a grouted soil nailed wall, (b) Typical Soil nailing method (Maunsell.Geotechnical ltd ,2003) (www.williamsform.com/Ground_Anchors/Soil_Nails_Soil_Nailing/soil_nail_soil_nailing.html)

Ortigao (2004) noted that the first use of the soil nailing application was in 1972 and now this method is a well-established technique around the world. Sometimes, soil nailing can combine different type of retaining methods such as soil nailing on retaining walls and with greening surfaces. Soil nailing can provide a cost efficient, quick and standard technique for slope improvement solution.

2.2.2 Types of soil nailing

The different types of soil nailing methods which are employed in the field are as follows (FHWA-IF-03-017, 2003):

2.2.2.1 Driven nail

This type of nails are driven mechanically to the wall during excavation. This type of nails are generally used as temporary nailing. This type of soil nails can be installed very fast; however, it does not provide protection against corrosion.

2.2.2.2 Grouted nail

First holes are drilled in the slope/wall face after excavation and then the nails are inserted in the pre-drilled holes. Finally, the cement grout is injected in the drill holes.

2.2.2.3 Jet-grouted soil nail

Jet grouting is used for creating the hole in the slope/wall face by eroding the ground and then the steel bars are installed in the created holes. The grouting of this type of soil nails provides good corrosion protection for the nail.

2.2.2.4 Self-drilling soil nail

First the hollow bars are driven in to the slope/wall face and then grout is injected simultaneously through the hollow bars during the drilling process. This type of nails exhibit better corrosion protection than the driven nails and the procedure is faster than the grouted nailing method.

2.2.2.5 Launched soil nail

Bars are inserted into the slope/wall face using firing mechanism at very high speed involving compressed air. The installation of this type of soil nails is very fast; however, the length of penetration of the bar into the ground is difficult to control.

2.2.3 Components of nailed structure

The different components of a soil nail are presented in this section (FHWA-IF-03-017, 2003). A typical cross-section of a soil nailed wall is shown in Figure 2.3. Some of the field photographs of the various components of a soil nail are shown in Figure 2.4.

2.2.3.1 Steel reinforcing bars

The main components of the soil nail wall system are the solid steel reinforcing bars. These bars are placed in pre-drilled holes and then grouted in place. During subsequent excavation activities, tensile stress is applied passively to the nails in response to the deformation of the retained materials.

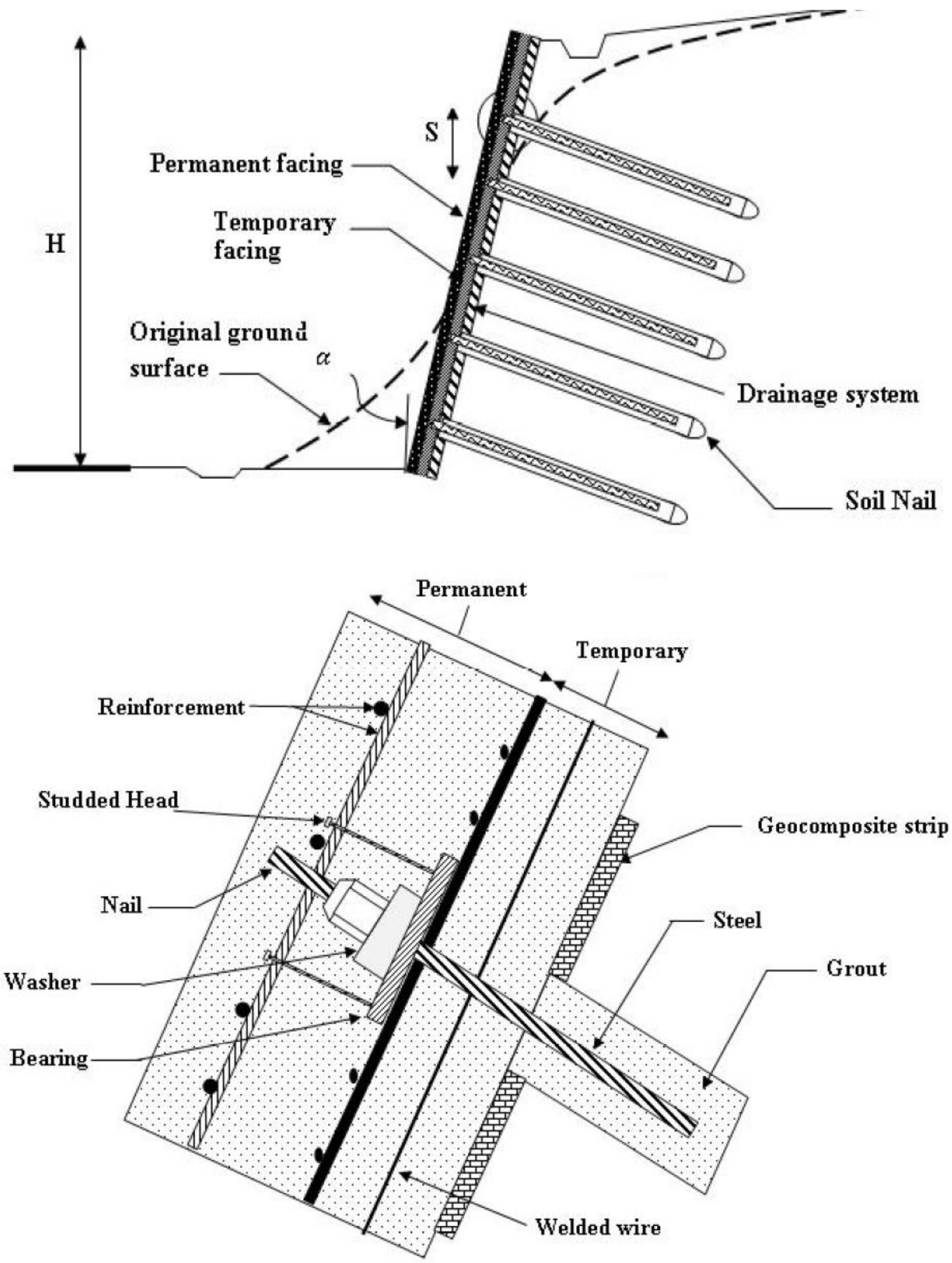


Figure 2.3 Typical cross-section of a drilled soil nail wall (www.rdso.indianrailways.gov.in)