SOIL NAILING FOR STABILITY OF THE SLOPES

A DISSERTATION

Submitted to

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In partial fulfilment of the requirement for the award of the degree of

Master of Technology

In

Geotechnical Engineering

Submitted by

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CANDIDATE'S DECLARATION

I do hereby certify that the work presented is the report entitled **" SOIL NAILING FOR STABILITY OF SLOPES"** in the partial fulfilment of the requirements for the award of the degree of "Master Of Technology in Geotechnical Engineering" submitted in the department of Civil Engineering, Delhi Technological University, is an authentic record of our own work carried from January'1 to june'30 under the supervision of Dr.A.K. Shrivastava, Department of Civil Engineering.

I have not submitted the matter embodied in the report for the award of any other degree or diploma.

Date :30-june-2017 Surender Singh

. (2k15/GTE/18)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

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CHAPTER 1

INTRODUCTION

1.1 General

Soil nailing is a soil stabilization technique which is used as a remedial measure in order to treat the unstable natural or artificial soil slopes. This technique is also used in order to allow the safe over-steepening of new or existing soil slopes.

In this method of slope stabilization, a relatively slender reinforcing element is driven into the soil slope. Reinforcing elements generally used in this technique generally consists of HYSD steel bars or steel hollow tubes depending upon the requirement.

The nails used for soil nailing are generally driven into the slope at an angle of 10^0 to 20^0 with horizontal plane. Due to the application of surcharge load by various means, the backfill material starts deforming which in turn passively produces the tensile stresses in the nails.

The method of installation is different for solid and hollow bars. Solid bars are generally installed into the pre-drilled holes. These bars are grouted into place simultaneously using separate grout line. Hollow bars are drilled and grouted simultaneously with the help of sacrificial drill bit.

When bars are inserted into the soil slope by using drilling technique ,then they are fully grouted and are installed at a slight downward inclination. Centralizers are used in order to keep the nails at its exact position. In order to provide the stability a rigid facing usually of pneumatically applied concrete (shotcrete) is applied. In some cases isolated nail head plates can be also used for this purpose.

In few cases a flexible reinforcing mesh is held against the soil slope face under the head plates. In case if environmental conditions are not adequate, then rabbit proof wire mesh and environmental erosion control fabrics are used in addition with flexible mesh facing.

1.2 Various Types of Soil Nailing

Prashant, A. (2010). “Soil Nailing for Stabilization of Steep Slopes Near Railway Tracks”. Research Designs and Standard Organisation(RDSO), Lucknow, India. Suggest various types of soil nailing methods that are employed in the field are as follows:

1. Grouted Nails – In this method holes are first drilled into the slope face and then nails are inserted in the pre-drilled holes. At the end drill holes are filled with cement grout.

2. Driven Nails-In this type of method nails are driven mechanically into the slope face. As holes are not drilled in this method therefore it is a fast method of soil nailing. The major disadvantage of this method is that it does not provide a good corrosion protection. This type of soil nailing is generally used for temporary nailing.

3. Self- Drilling Soil Nails- This type of method involves driving the hollow bars into the soil slope along with the injection of grout simultaneously during the drilling. This method of soil nailing is much faster than the grouted nailing and it also provides better corrosion protection than the driven nail.

4. Jet-Grouted Soil Nails- This method of soil nailing use jet grouting to erode the ground. The reinforcing elements are thus placed on the holes created by grouting.

5. Launched Soil Nail- in this method a firing mechanism involving compressed air is used to launch the bars into the soil slope. This method of installation is very fast.

1.3 Favourable Ground Conditions for Use of Soil Nailing

As per FWHA manual (2015), soil nailing is generally suited for the following types of soiling:

- Stiff to hard clays
- Clayey silts
- Sandy clays
- Sandy silts
- Very dense granular soils with some apparent cohesion

1.4 Unfavourable Ground Conditions for Use of Soil Nailing

As per FWHA manual (2015), soil nailing is not suitable for following types of soils:

- Dry and poorly graded cohesion less soils
- Soils with cobbles and boulder (as in this case it is difficult to drill)
- Highly corrosive soils
- Soils with high ground water table

1.5 Soil Nail Configuration

a) Soil Nail Length:

It has been found from the previous studies that the length of nail required for preliminary design can be taken as 0.7H, where H is the height of soil slope/soil nail wall. The length of nails for the battered soil walls is normally lesser than the vertical wall. According to the FWHA manual (2015) for a batter of 10% there is a reduction of (10-15) % in the length of soil nails, with all other conditions same.

b) Soil Nail Inclination:

As per the FWHA manual (2015) for soil nail walls, soil nails are installed at an angle of 10^0-20^0 from the horizontal plane. This is due to the reason that the grout can easily flow at these inclination from the bottom of the drill hole to head.

c) Soil Nail Spacing:

As per FWHA manual (2015) for soil nail walls,

Preferred nail pattern for soil nailing = staggered or triangular pattern

Horizontal spacing, S_h = (1.2-1.8)m

Vertical spacing, S_v = (1.2-1.8)m

Minimum spacing = 1m

The spacing can be checked such that $S_H \times S_V$ is less than approximately (3.34 –3.90) m^2.

1.6 Construction Procedure for Nailed Structure

It has Soil nailed structures are generally constructed in stages and it involves following steps:

A) Soil is excavated till the depth where nails are to be installed

B) Drilling of nail holes

C) Installation of nails along with grouting.

D) Construction of temporary shotcrete facing.

A

B

C

C

D

Fig1.1 construction of soil nailed slope
(source:http://www.wmplanthire.com/slope_stabilisation.htm)

1.5 Objectives of Project

Stability of slopes is nowadays required in almost every construction work. Soil nailing technique is most frequently used in order to stabilise railways embankments, road embankments, retaining walls etc. So by noticing the importance of soil nailing for a geotechnical engineer, I decided to carry a study on various aspects of this techniques. The objectives of my study are as follows:

- Physical modelling of a slope (Angle of inclination with horizontal plane= 60°)
- To study the effect of nail inclination(with horizontal plane) on stability of slope.
- To study the effect of spacing and various different pattern of nails (e.g. rectangular, triangular, diamond) on stability of slopes.
- To study the strain produced in the nails during different stages of static loading.

CHAPTER 2
LITERATURE REVIEW

A nailed slope can be regarded as a composite structure with elements of nails, gout, facing walls and soil. Because of difficulty of research on soil nailing comes from complex interaction among these elements, most of the previous research work has concentrated on one or some of the elements.

1. **Nail Parameters, Spacing and Orientation effects on Soil Nailing :**

A nail is fundamental element in soil nailing and estimation of nails (lengths and spacing) forms the major parts of the design procedure for soil nailing. It is widely known that a nail force, by friction or bond to surrounding soil, can decrease the principal strain in soil and hence improve the stability and decrease the displacements of the soil (Mc Gown et al., 1978). It is therefore, of great importance that the interaction mechanism between soil and nail are understood, and the effects of the interaction on improving the slope stability are fully clarified. Jewell (1980) carried out a series of direct shear tests of reinforced soil to study how a wide range of reinforcements modified the mechanical response of the soil to the applied stress. He showed that the most efficient use of reinforcement is achieved when the direction of the reinforcements coincides with that of minimum normal strain in the soil.

Kitamura et al. (1988) studied the effect of steel bar reinforcement in vertically loaded reinforced sand slopes. A number of small-scale model tests of reinforced slopes are conducted by (Gutierrez and Tatsuoka 1988) to measure the tensile reinforcement forces and strain fields. Similarly a series of model tests are performed by (Hayashi et al. 1990) to investigate the failure mechanism of steel bar reinforced cut slopes.

Heymann et al. (1992) reported increased normal stress in dense sand when reinforcement with rough surface is pulled out. Long et al. (1990) studied the importance of variables like shape of assumed failure surface, wall height, length of nails, inclination and global stability of nailed soil wall. Huang and Tatsuoka (1994) analysed the results of a series of plane strain model tests for both reinforced and unreinforced sand slopes loaded with a 10 m wide strip footing. Researchers have employed kinematical limit analysis to study the failure surface, load transfer mechanism of the soil nailed slopes (Juran et al., 1992).

A comparison between the kinematical limit equilibrium and the model test has also been carried out which resulted in study of parameters like nail stiffness, nail inclinations, soil stiffness and boundary conditions (Juran et al., 1992). A new approach to analyze soil nailed walls using a trial wedge method is presented by (Sheahan and Carlton ,2003) on the Amherst Test wall in clay and the Clouterre test wall in sand. Study of circular wedge type failure in soil nailed cuts by friction circle method is done by (Biswas et al., 2006).

Finite element model has been also used to study the slope failures which occurs `naturally' through the zones in which the shear strength of the soil is insufficient to resist the shear stresses (Griffiths and Lane, 1999). Sengupta et al. (2011) studied the effect of earthquake forces on the stability of 8m high vertical wall by assuming the failure plane to be either planar or circular. Hassan and Nadir (2012) studied the effect of nail inclination and nail spacing on stability of soil nailed wall by using hollow reinforcing element. The study showed the best nail inclination angle ranging from (10-25) degrees and nail spacing equal to 1m.

Jaya and Annie (2013) studied the effect of nail length on stability of soil slope and found decrease in settlement of slope crest with increase in length of nails. FWHA manual (2015) came up with various design requirements for soil nailed wall. The manual recommended various values for nail orientation, nail spacing, nail length, nail pattern etc.

2. Effect of Grouting on Soil Nailing:

The grout, which is usually made of cement or cement mortar, is injected directly into the borehole not only to ensure a good bond between the soil and a nail but to protect the nail from corrosion.

Synder (1979) showed that the ratio of the diameters of the borehole and of a nail directly affects the maximum pull-out force of nail. Plumelle (1987) concludes that considerably larger in situ pull out forces can be obtained by increasing the pressure of grout injection.

Schlosser and Juran (1983) reported that the maximum pull out force of nail in the field is not proportional to the vertical depth of nail from the upper ground surface. Gassler (1988) showed that beyond a maximum depth of 2.5m, the value of limit bond stress becomes nearly constant.

3. Effect of Soil Type on Soil Nailing:

Soil nailing is not possible for all types of soil. Various scholars have studied the regarding the soil suitable for soil nailing. Palmeira and Milligan (1989) reported the influence of stiffness of a reinforcement and soil in developing the full interaction mechanism. When a nail is pulled out in dense sand, restrained dilatency of the sand will occur, and the normal stress acting on the nail may be increased.

Jaya and Annie (2013) studied the effect of relative density of soil on the stability of soil slope. Study showed a decrease in settlement of soil wall with increase in the relative density.

FWHA manual (2015) also suggested several favourable and unfavourable soils for soil nailing. Soil nailing is generally suited for stiff to hard clays, clayey silts, sandy clays, sandy silts, very dense granular soils with some apparent cohesion. Soil nailing is not suitable for dry and poorly graded cohesion less soils, soils with cobbles and boulder (as in this case it is difficult to drill), highly corrosive soils, soils with high ground water table.

CHAPTER 3

METHODOLOGY

3.1 Experimental Set Up

1. Wooden Box

A box of dimension 0.60m x 0.40m x 0.30m is fabricated by using plywood sheet as these are easy to handle and provide sufficient restrain. The dimension of the box is chosen so that the dead load can be easily applied on the crest of slope by concrete beams and cubes.

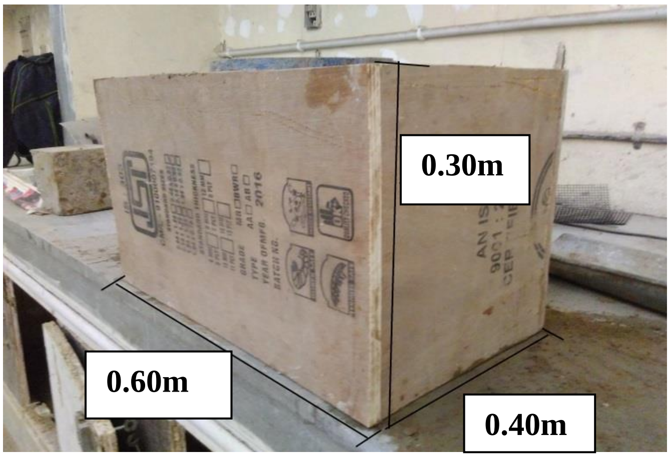

Fig3.1 Wooden Box

2.Nails Used

As the load sustained by the slope in the box will not be too high due to its dimensions hence hollow aluminium tubes are used as a reinforcing material as they can produce strain at low load. Dimensions of these hollow tubes are specified as below:

Diameter(D) = 0.001m

Length of nails(L) = 0.016m (0.6H ,H=Height of slope, as per FWHA manual (2015).

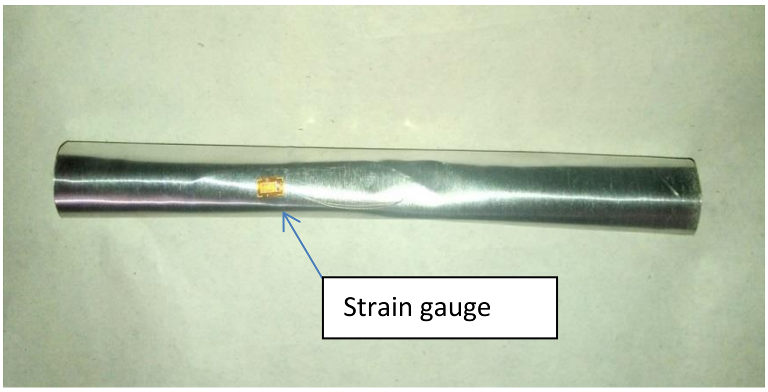

Fig 3.2 Nails used in the project

3. Strain Gauges : Strain gauges of gauge length 3mm and resistance 120 ohm are used in order to calculate the strain produced in the steel bars and soil during the loading.

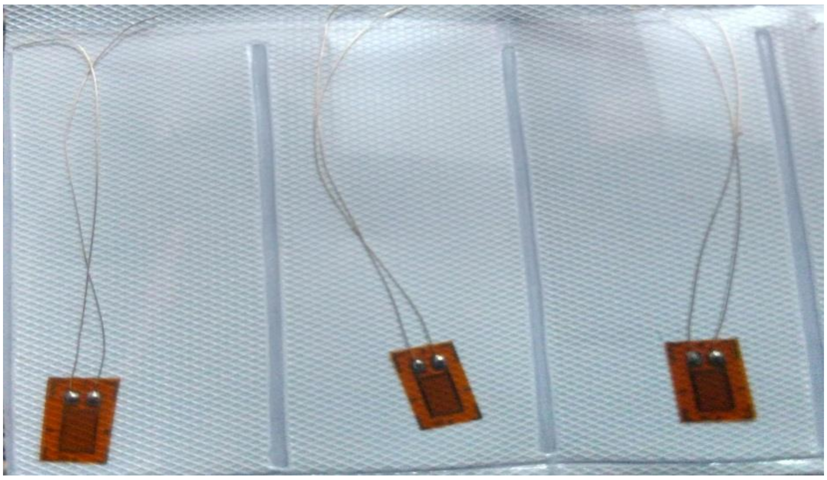

Fig 3.3 Strain gauges

4. Digital Multimeter: 3 digital multimeter are used in order to obtain the change in resistance during the loading. This change in resistance is then used to determine the strain produced in the nails during loading.

5.Bearing Plate: A rectangular bearing plate of dimension (0.16 X 0.08 X 0.035)m is used. The dimension of bearing plate is selected considering the effect of rigid wall of box. The effect of stress can be observed nearly upto 1.5B in either direction for rectangular footing. The above concept is taken from the textbook, Principles of Foundation Engineering (seventh edition) by B.M. Das. Thus in the present case the width of plate is such chosen so that the edge of footing is at a distance of 2B from either direction, where B is the width of footing. Thus the stress will be distributed well within the wall and hence wall will not affect the stress distribution.

Fig 3.4 Mild Steel Bearing Plate

Fig 3.5 Digital Multimeter

6.Dial Gauge: Dial gauge of least count 0.01 mm is used in order to find the settlement of bearing plate during the subsequent loading.

7.Backfill Material

The backfill material used for the slopes is Poorly Graded Sand. Preliminary tests of soil identification are carried out in the laboratory to determine the backfill properties.

The properties of the backfill material are as follows

a)Soil Type

Table3.1 sieve analysis (as per IS:2720 (Part.4) 1985. Grain size analysis)

S.No.	Sieve Size(mm)	Wt. Retained(g)	% Retained	% Finer
1	4.75	68.84	6.88	93.11
2	2.36	128.81	12.88	80.23
3	1.18	205.66	20.56	59.66
4	0.600	142.72	14.27	45.39
5	0.425	138.7	13.87	31.52
6	0.150	281.27	28.12	3.4
7	0.075	28.62	2.86	.53
8	PAN	5.38	0.53	0

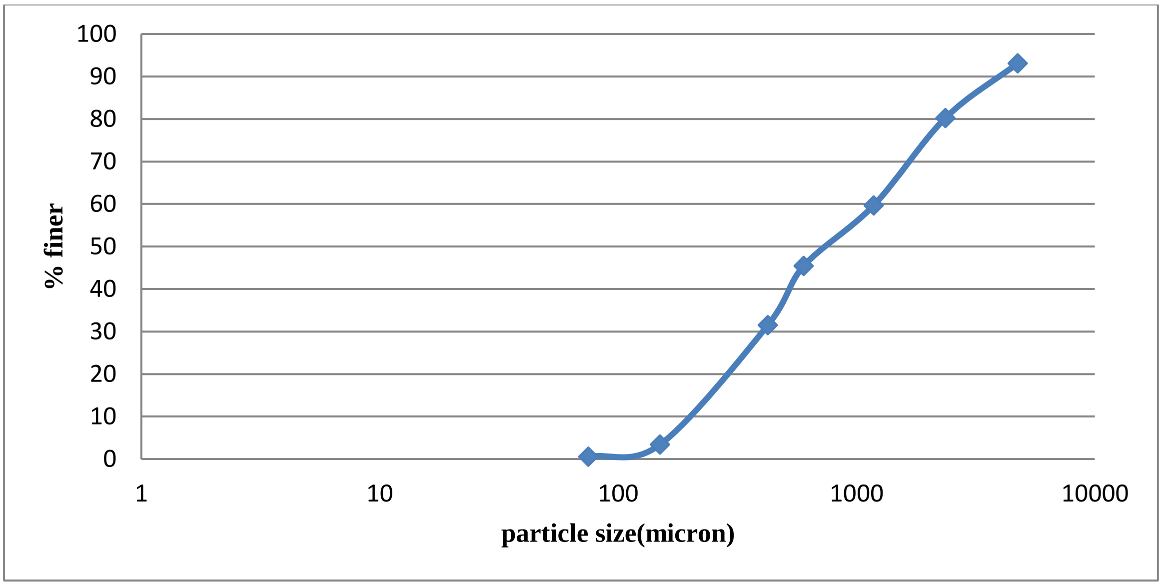

Fig 3.6 Particle size distribution curve

D_{10}= 0.12 mm, D_{30}= 0.33 mm, D_{60}=1.3mm C_{C} = 0.698 , C_{u} = 10.83
Hence the soil used is **Poorly Graded Sand (SP).**

b) Dry Density: In order to obtain optimum moisture content Standard proctor test is performed as per IS: 2720 (Part. VII) 1980. Determination of water content - dry density relation using light compaction.

Table 3.2 Observation table for standard proctor test (as per IS: 2720 (Part. VII) 1980

S.No	Mass of soil + mould(Kg)	Mass of soil(kg)	Bulk density (KN/m^3)	Water content(%)	Dry density(KN/m^3)
1	5.70	1.50	15.87	7.3	14.79
2	5.75	1.55	16.40	9.0	15.04
3	5.80	1.60	16.93	11.0	15.25
4	5.85	1.65	17.51	15.0	15.23
5	5.79	1.59	16.82	17.0	14.38

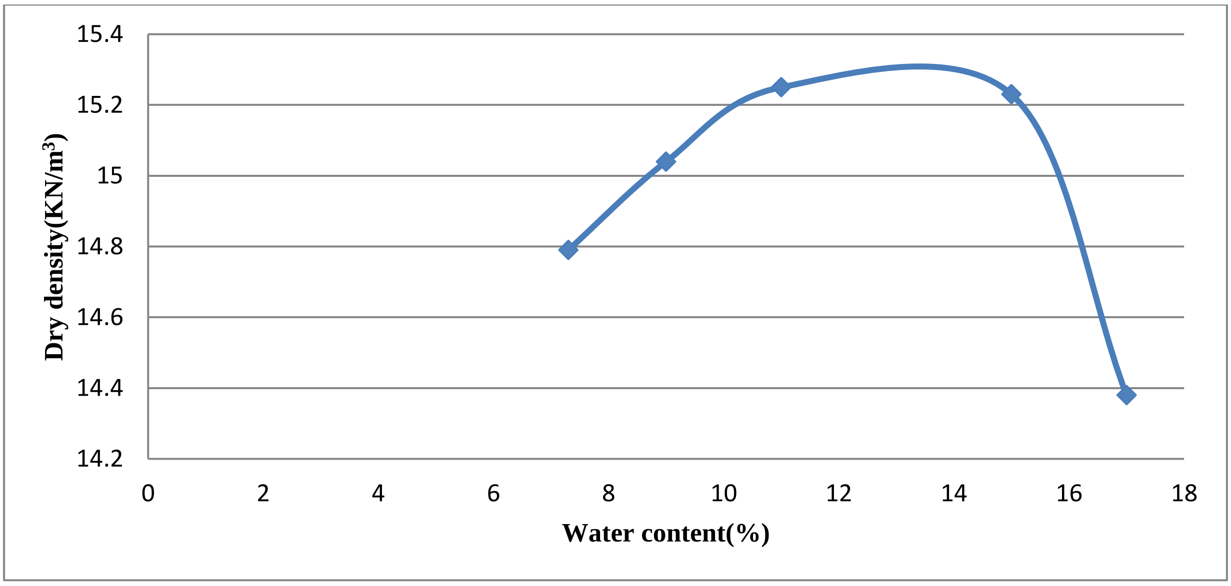

Fig3.7 Dry density vs water content curve

Weight of empty mould =4.2kg
Vol. of standard proctor mould=945 x 10^{-3} m^3
Max. dry density(from fig 3.7)=15.058KN/m^3
Optimum moisture content(from fig3.7)=13.5%

c) Shear Parameters(C and φ) : Direct shear test is performed in order to calculate the value of cohesion and angle of internal angle. The test is performed as per IS: 2720 (Part. XIII) 1986. Direct shear test.

Table 3. Observation table for direct shear test (as per IS: 2720 (Part. XIII) 1986)

S.No.	Normal Stress(KN/m^2)	Max. Shear Stress(KN/m^2)
1	13.88	0.48
2	29.43	0.65
3	49.05	0.76

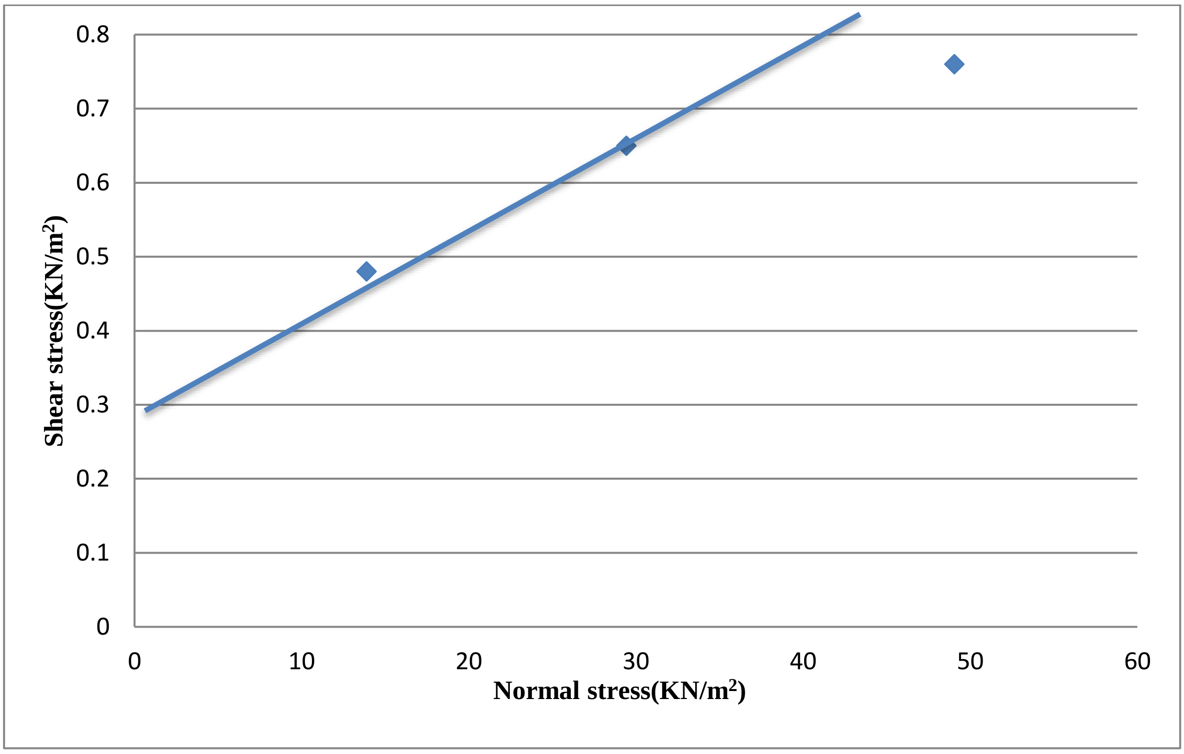

Fig 3.8 Max. shear stress vs normal load graph

From the above graph, cohesion (c) = 0.298KN/m^2

Angle of internal friction (φ) =31^0

3.2 Preparation of Unreinforced Slopes

Sand size soil in its dry state is used to prepare slopes at predetermined slope angles of 60°. The soil slope angle is selected by preliminary tests performed for different slope angle. It was found that slopes with angle greater than 60^0 become unstable at very small dead load and the slopes with angle less than 60^0 require high dead load which was not possible due to lack of loading arrangement.

The slope is prepared in layers of thickness 0.07m each. A layer 0.03m thick is made as the base layer completely along the length of model. The layer is formed by placing soil in box and lightly compacting it after every 0.07m. The procedure is repeated till a complete height of 0.30m is achieved. A crest width of 0.40m and the base width of 0.60 m is maintained for all the slope angles. The soil is such compacted so as to maintain the dry density of soil equal to 14.00 KN/m^3. Bearing plate is placed over the crest of the slope and load is then applied over it during loading stage.

Fig 3.9 Unreinforced soil slope(60^0)

3.3 Preparation of Reinforced Slopes

The procedure for preparation of reinforced soil slope is same as that for unreinforced soil slope except that the nails are installed at their respective position during the process. The nails are installed at predetermined inclination of 0°, 15° and 30°with horizontal plane with the help of a protractor. As per FWHA manual (2015), soil nails are installed angle ranging from (10-20) degrees with horizontal plane in downward direction. Hence nails are installed at 0°, 15° and 30° in in order to study the effect of nail inclination on the failure load.

9 hollow nails, each of length 0.16 m are inserted at the face of the slope in an arrangement of 3 rows x 3 columns. The horizontal spacing is kept 0.10 m whereas the vertical spacing is kept 0.10 m (for square nail pattern only). The spacing of nails are decided as per the recommendations given by United States Department Of Transportation Federal Highway Administration, FWHA (2015).

Before the nails are inserted into the slope face, strain gauges are glued to the nails with super glue Z-70. Before the installation of strain gauge surface of nail are properly cleaned with sand paper. Sometimes a suitable solvent can be used to clean the surface. Then super glue is applied on both strain gauge as well as surface of nails and the interface is pressed with thumb for few minutes (depending upon the time required for curing of super glue). After the strain gauge is installed over the surface, connections are made with connecting wires by soldering process.

Fig 3.10 Nail Installation

3.4 Arrangement of Nails Within The Soil Slope

Staggered nail pattern has been recommended by FWHA manual(2015) for arrangement of nails with in soil slope. In this work, three nail pattern has been used and their results has been compared. Following are the different nail arrangement with in the soil slope:

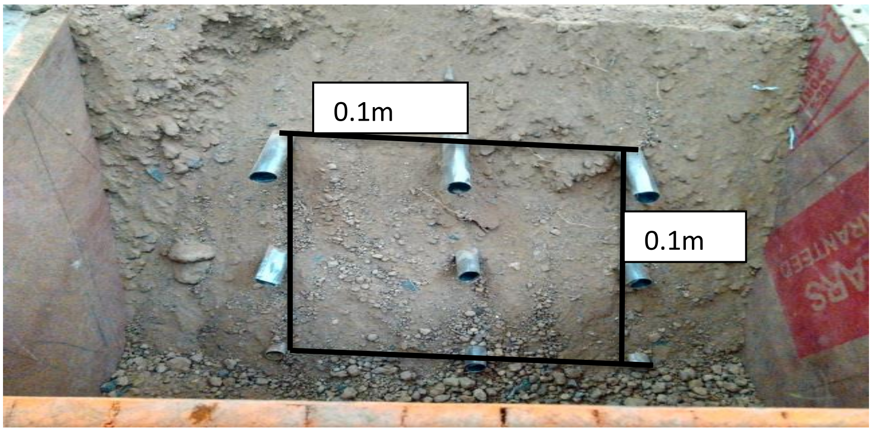

Fig 3.11 Square Nail Pattern

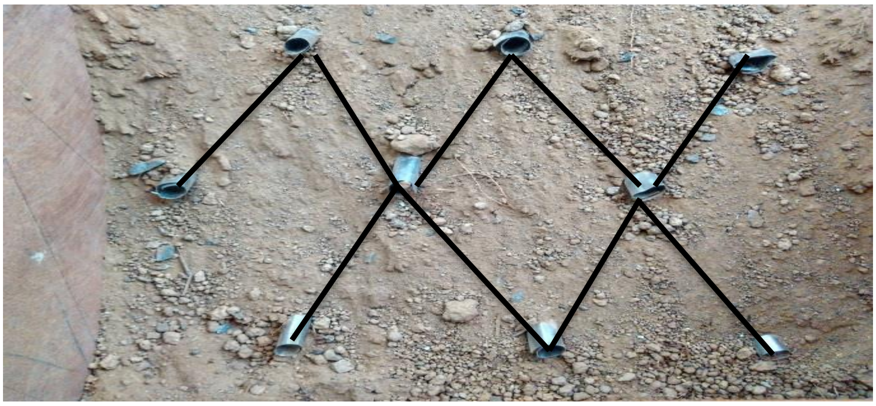

Fig 3.12 Staggered or Triangular Nail Pattern

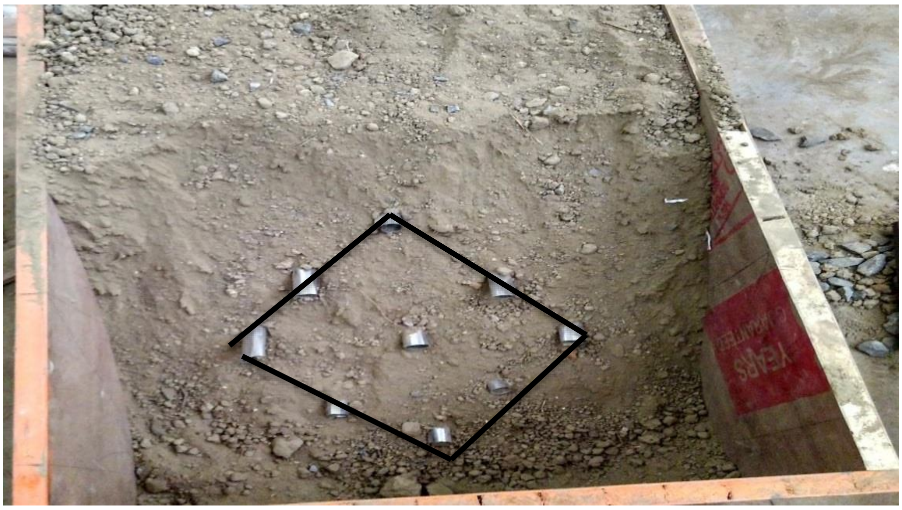

Fig 3.13 Diamond Nail Pattern

3.5 Testing Procedure

A rectangular bearing plate of dimension 0.016m x .008m is placed on the crest of slope . A series of dead load is applied on the plate. Dead load used in this case consists of precast beams and cubes. A beam is first placed over the plate and settlement corresponding to that is observed. The value of settlement is taken when the dial gauge starts showing constant reading. The load and the corresponding settlement of the crest at which the slope fails is observed from the dial gauge installed. The slope considered to be failed when it collapse down at a particular load.The slopes are then installed with nails at different inclinations and load is applied at the crest.

Fig 3.14 Soil nailed slope before loading

Fig 3.15 Loading on unreinforced soil slope.

In addition to the load – settlement measurement, the strain produced in the nails under the increasing dead load is also measured. For finding the strain in nails on loading, multimeters are used which measure the resistance from strain gages glued to nails in unstrained and strained positions. The increase in dead load is found to induce tensile forces in nails and a change in nail strains is observed, which is detected by strain gauges. For the calculation of nail forces, a strain on nails is measured in unstrained and strained positions. After measuring resistances in strain gages, the following formula is used to calculate strain as given by.

$$\epsilon = \Delta Rg / (Rg \ X \ G.F.) \text{-------------------------------------} (1)$$

The above equation was used by Rawat and Gupta(2015). "An Experimental and Analytical Study of Slope Stability by Soil Nailing". Electronic Journal of Geotechnical Engineering .vol 21

Where, G.F. = gauge factor of 2.00 (for the strain gauge used in this project)
Rg = resistance of strain gage unstrained,
ΔRg = change in resistance from unstrained to strained condition, and
∈ = strain.

CHAPTER-4

TEST RESULTS

4.1 Test Results for Soil Nailed Slope with Different Nail Inclination

a) $+0^0$ Nail Inclination: The first series of test is performed on unreinforced soil slope. After that load tests are performed on reinforced slope which is prepared by installing nails at $+0^0$ with the horizontal plane. Load is then applied on the bearing plate and settlement corresponding to the load is noted down.

Table4.1 Observation table for load and settlement + 0^0 nail inclination.

Load(N)	Settlement(mm) Unreinforced slope	Settlement(mm) Nail inclination= $+0^0$
360	2.1	1.45
720	4.05	2.57
800	5.01	3.24
880	5.85	3.68
960	6.75	4.09
1020	failure	-
1320	-	4.89
1400	-	5.10
1480	-	5.19
1560	-	Failure

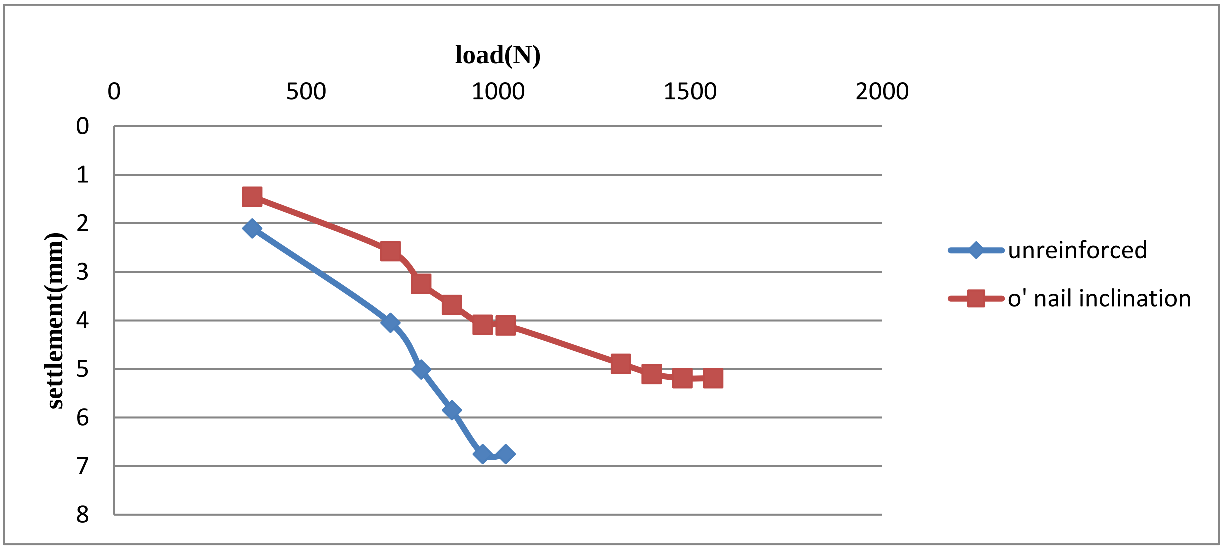

Fig 4.1 load vs settlement curve for unreinforced and reinforced slope ($+0^0$nail inclination)

b)+15^0nail Inclination: After the completion of load test for soil nailed slope having nail inclination equal to +0^0, load test are performed with nail inclination equal to +15^0. The box is emptied first and then soil slope is prepared same as explained earlier with subsequent installation of nails at +15^0. Load vs settlement plot are then prepared by using following observations.

Table4.2 Observation table for load and settlement + 15^0 nail inclination

Load(N)	Settlement(mm) Nail inclination= +15^0
360	1.52
720	2.73
800	3.45
880	3.97
960	4.47
1320	5.35
1400	5.65
1480	5.75
1500	Failure

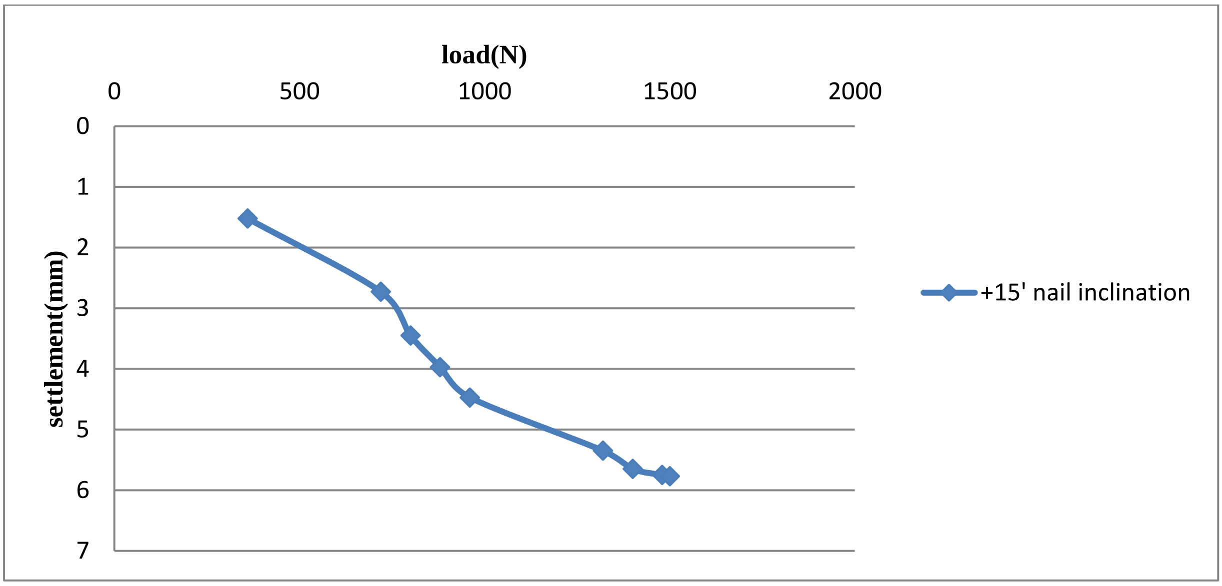

Fig 4.2 load vs settlement curve for unreinforced and reinforced slope (+15^0nail inclination)

Failure load for soil slope with nailed inclined at +30^0=1500N

Final settlement for soil slope with nailed inclined at +30^0=5.75mm c)+30^{0}Nail Inclination: After the completion of load test for soil nailed slope having nail inclination equal to +15^0, load test are performed with nail inclination equal to +30^0. The box is emptied first and then soil slope is prepared same as explained earlier with subsequent installation of nails at +30^0 with the horizontal plane. Load vs settlement plot are then prepared by using following observations.

Table4.3 Observation table for load and settlement + 30^0 nail inclination

Load(N)	Settlement(mm) Nail inclination= +30^0
360	1.61
720	2.91
800	3.66
880	4.25
960	4.79
1320	5.74
1400	6.08
1460	Failure

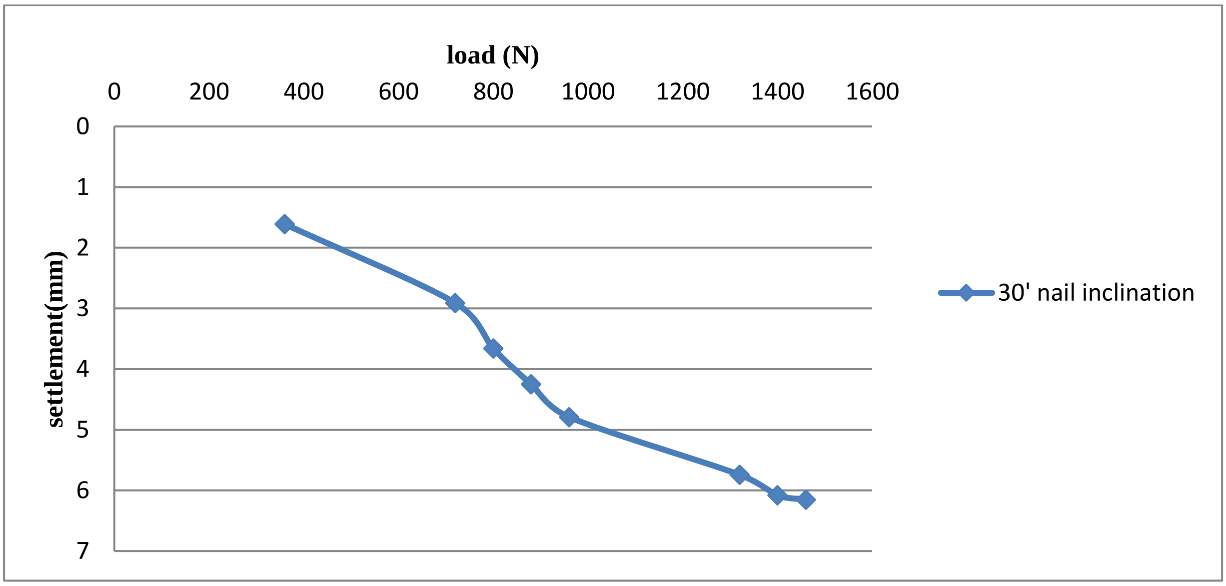

Fig 4.3 load vs settlement curve for unreinforced and reinforced slope (+30^{0}nail inclination)

Failure load for soil slope with nailed inclined at +30^0=1460N

Final settlement for soil slope with nailed inclined at +30^0=6.08mm

4.2 Comparison between Unreinforced and Reinforced Slope (With Different Nail Inclination)

As the load vs settlement curve has been already plotted above for unreinforced and reinforced slope, now to make a comparison all these plots are merged into single graph.

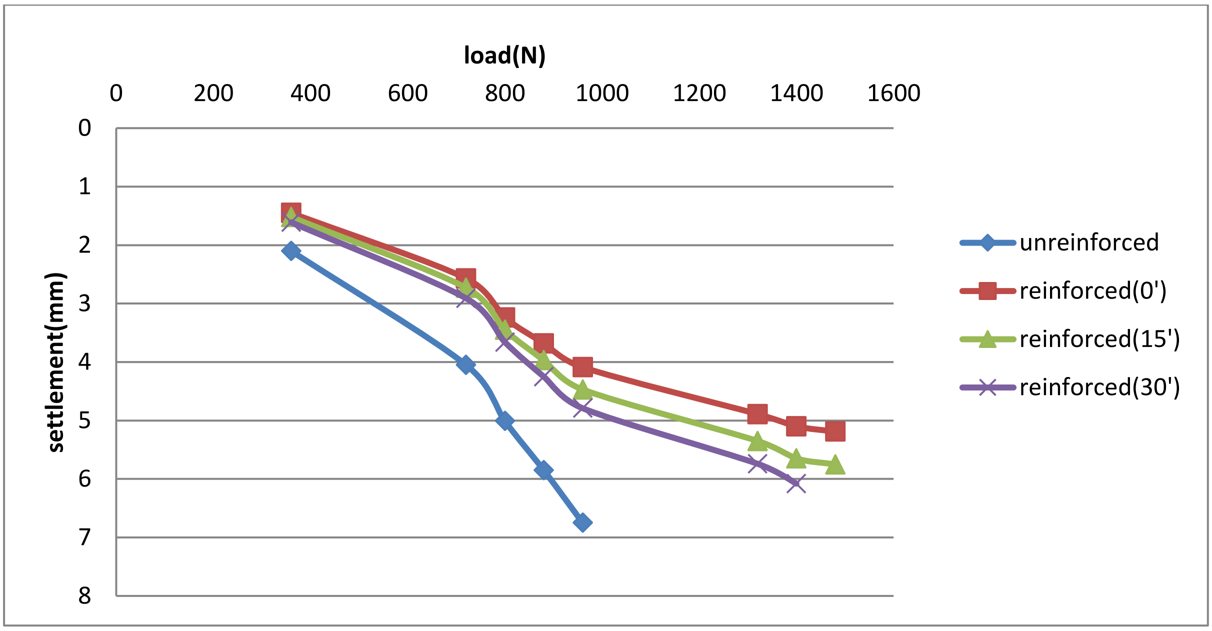

Fig 4.4 Load vs settlement curve for different nail inclination

From the above it is quite clear that soil slope in which nails are installed at $+0^0$ with horizontal plane can sustained the maximum load before failure.

Also soil slope with nail inclination of $+0^0$ with horizontal plane have least final settlement as compared to soil slope with nail inclination of $+15^0$ and $+30^0$.

Fig 4.5 Aluminium hollow tubes inserted at 0^0 to horizontal plane

4.3 Test Results for Soil Nailed Slope with Different Nail Pattern

a) Square Nail Pattern: After studying effect of nail inclination on stability of slope, effect of nail pattern on stability of soil slope is studied here. In first case nails are arranged in square pattern keeping the horizontal and vertical spacing equal as per FWHA manual(2015). Load is then applied on the bearing plate and settlement corresponding to the load is noted down.

Table 4.4 Observation table for load and settlement for square nail pattern

Load(N)	Settlement(mm)
360	1.45
720	2.57
800	3.24
880	3.68
960	4.09
1320	4.89
1400	5.1
1480	5.19
1560	Failure

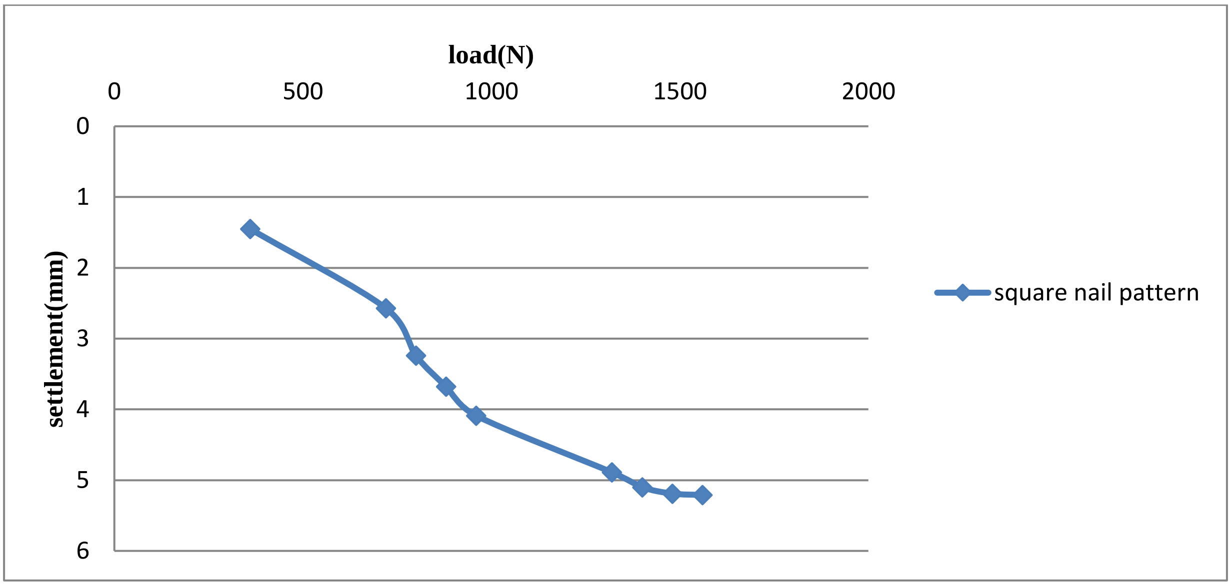

Fig 4.6 load vs settlement curve for square nail pattern

Failure load for soil slope with square nail pattern=1560N

Final settlement for soil slope with square nail pattern =5.19mm

b) Diamond Nail Pattern: In this case nails are arranged in diamond pattern in which 3 nails are installed at mid depth, followed by 2 nails and 1 nails in either directions. Load is then applied on the bearing plate and settlement corresponding to the load is noted down.

Table 4.5 Observation table for load and settlement for diamond nail pattern

Load(N)	Settlement(mm)
360	1.76
720	3.00
800	3.80
880	4.41
960	4.84
1320	5.75
1400	6.05
1420	Failure

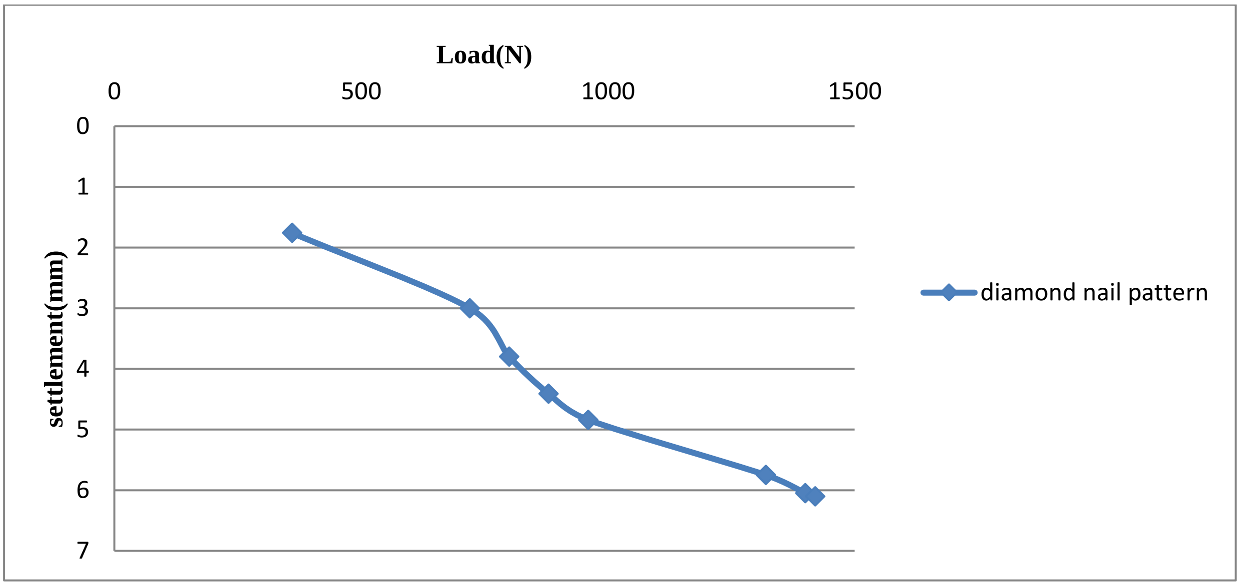

Fig 4.7 load vs settlement curve for diamond nail pattern

Failure load for soil slope with square nail pattern=1420N

Final settlement for soil slope with square nail pattern =6.05mm

c) Staggered Nail Pattern: In this case nails are arranged in staggered or triangular pattern keeping the horizontal and vertical spacing equal as per FWHA manual(2015). Load is then applied on the bearing plate and settlement corresponding to the load is noted down.

Table 4.6 Observation table for load and settlement for staggered nail pattern

Load(N)	Settlement(mm)
360	1.47
720	2.47
800	2.98
880	3.32
960	3.62
1320	4.14
1400	4.45
1480	4.65
1560	4.75
1600	Failure

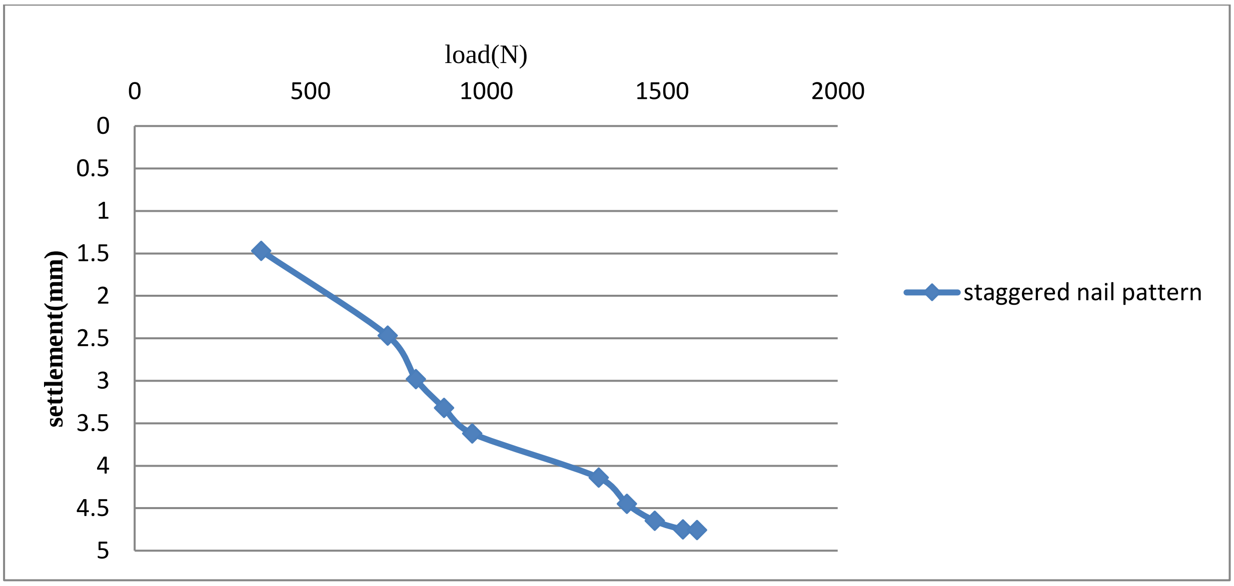

Fig 4.8 load vs settlement curve for diamond nail pattern

Failure load for soil slope with square nail pattern=1600N

Final settlement for soil slope with square nail pattern =4.75mm

4.4 Comparison between Load Sustained by Different Nail Pattern

In order to compare the effectiveness of nail arrangement in stabilising the soil slope, load vs settlement curve for all nail pattern are merged together.

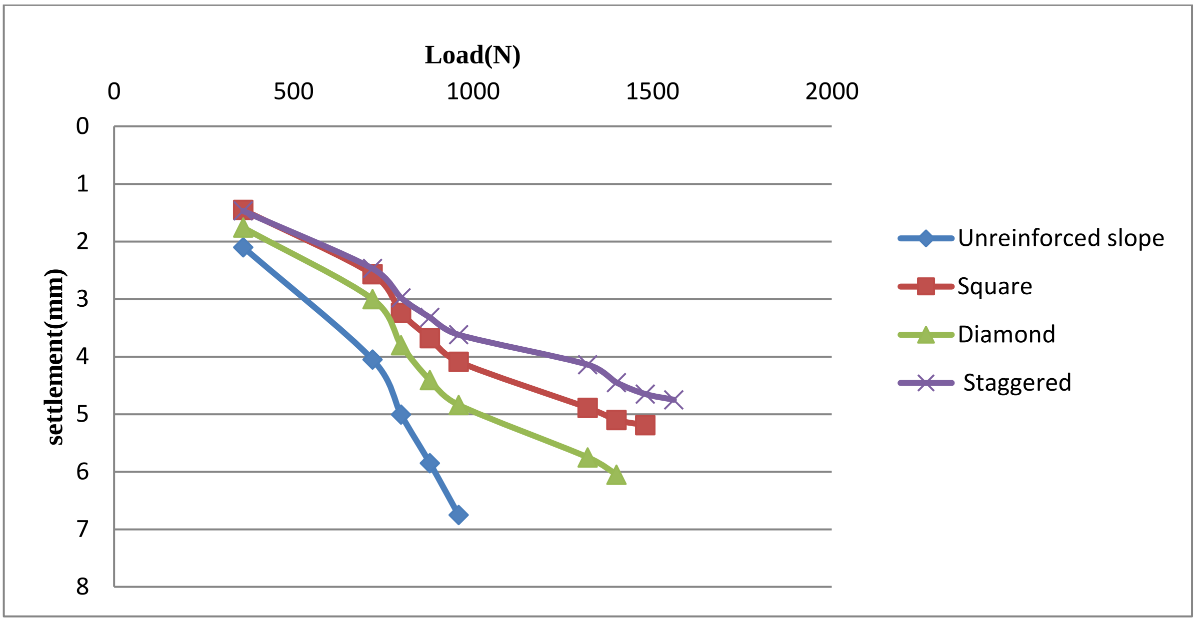

Fig 4.9 Load vs settlement curve for different nail pattern

From the above it is quite clear that soil slope in which nails are arranged in staggered pattern can sustain greater load as compared to nail arranged in diamond and square nail pattern. This may be due to the reason that in staggered arrangement nails are arranged more uniformly whereas in diamond arrangement nails are installed in confined area.

Also soil slope with staggered nail pattern have least total settlement followed by square and diamond nail pattern respectively.

4.5 Test Results for Strain produced in Nails

a)For Topmost Nail:Stresses produced by nails during loading are calculated only for the square nail pattern. Strain gauges are installed on the surface of topmost, middle and bottommost nails. These strain gauges are then connected with the digital multimeter in order to obtain the strain produced in the nails during the different stages of loading.

Initial resistance shown by multimeter in unstrained condition, Rg = 119.20 Ω

Gauge Factor = 2(depends upon the type of strain gauge used)

Table 4.7 Observation table strain produced in the topmost nail

Load(N)	Change in Resistance(ΔRg)(Ω)	Strain value $\epsilon = \Delta Rg/(Rg\ X\ G.F.)$
360	0.06	2.54×10^{-4}
720	0.10	4.19×10^{-4}
800	0.11	4.61×10^{-4}
880	0.11	4.61×10^{-4}
960	0.12	5.03×10^{-4}
1320	0.15	6.29×10^{-4}
1400	0.15	6.29×10^{-4}
1480	0.16	6.71×10^{-4}
1560	0.16	6.71×10^{-4}

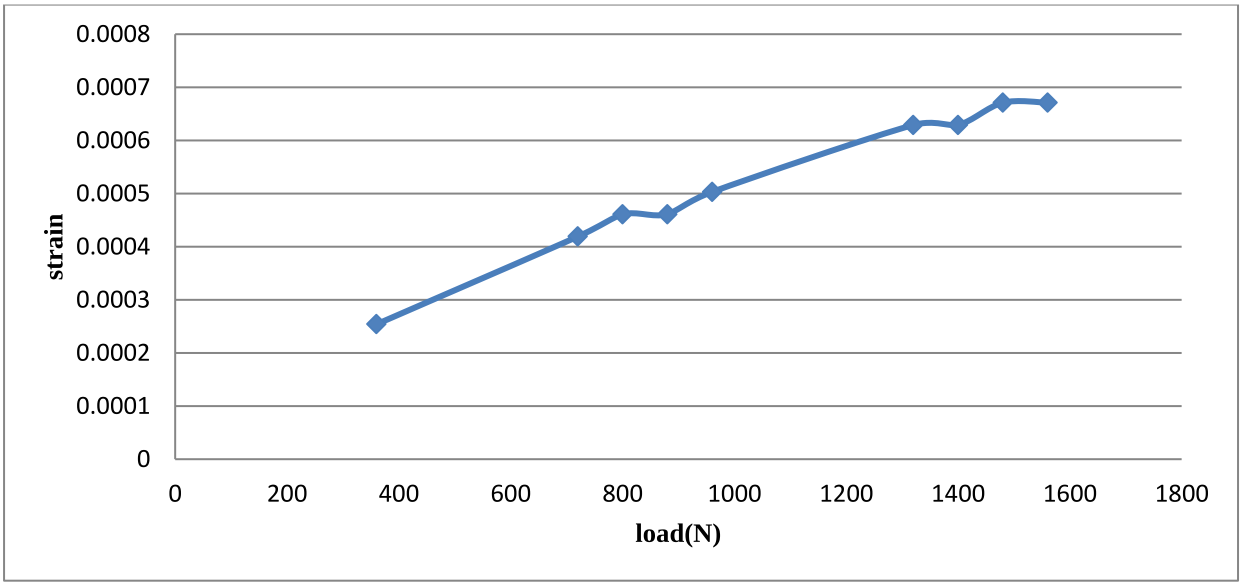

Fig 4.10 strain produced in the topmost soil nail during loading.

Maximum strain is produced in the topmost nail. As the loading increases strain in the nail also increases. Maximum strain in the nail is achieved just before the failure of slope.

b)For middle Nail: Strain produced in nails during loading are calculated only for the square nail pattern. Strain gauges are installed on the surface of topmost, middle and bottommost nails. These strain gauges are then connected with the digital multimeter in order to obtain the strain produced in the nails during the different stages of loading

Initial resistance shown by multimeter in unstrained condition,Rg = 119.30 Ω

Gauge Factor = 2.00(given for particular type of strain gauge)

Table 4.8 Observation table for strain produced in the middle nail

Load(N)	Change in Resistance(ΔRg)(Ω)	Strain value $\epsilon = \Delta Rg/(Rg\, X\, G.F.)$
360	0.03	1.25×10^{-4}
720	0.06	2.51×10^{-4}
800	0.07	2.93×10^{-4}
880	0.08	3.35×10^{-4}
960	0.08	3.35×10^{-4}
1320	0.11	4.61×10^{-4}
1400	0.12	5.02×10^{-4}
1480	0.13	5.44×10^{-4}
1560	0.13	5.44×10^{-4}

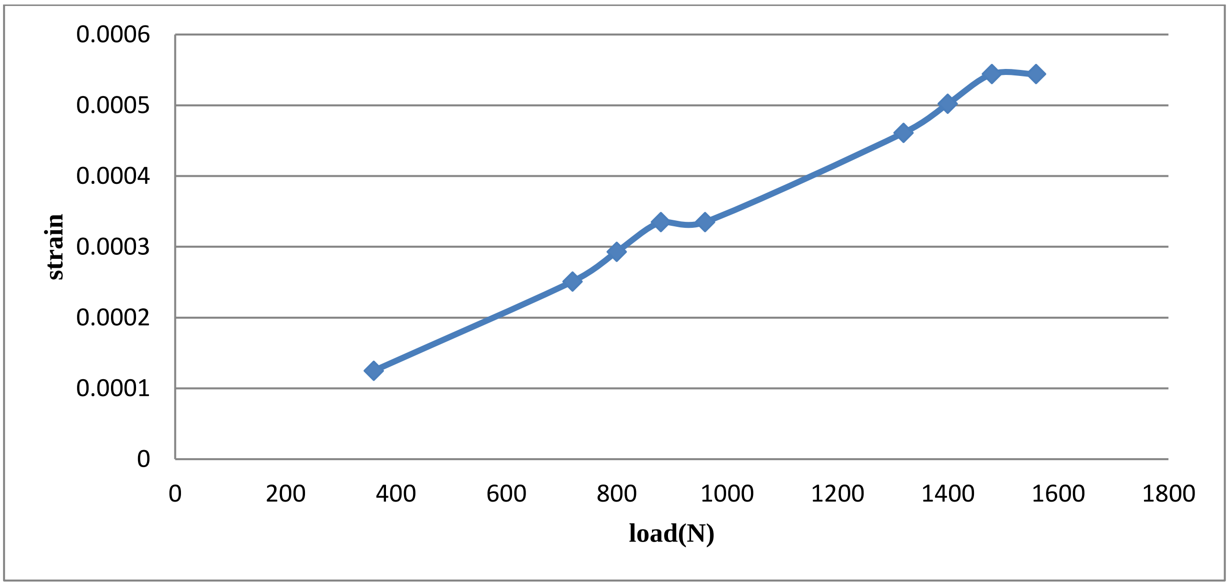

Fig 4.11 strain produced in the middle soil nail during loading.

b)For bottommost Nail: Strain produced in nails during loading are calculated only for the square nail pattern. Strain gauges are installed on the surface of topmost, middle and bottommost nails. These strain gauges are then connected with the digital multimeter in order to obtain the strain produced in the nails during the different stages of loading

Initial resistance shown by multimeter in unstrained condition, Rg = 119.34 Ω

Gauge Factor = 2(given for particular type of strain gauge)

Table 4.9 Observation table for strain produced in the bottommost nail

Load(N)	Change in Resistance(ΔRg)(Ω)	Strain value $\epsilon = \Delta Rg/(Rg\ X\ G.F.)$
360	0.01	0.41×10^{-4}
720	0.03	1.25×10^{-4}
800	0.03	1.25×10^{-4}
880	0.04	1.67×10^{-4}
960	0.04	1.67×10^{-4}
1320	0.05	2.09×10^{-4}
1400	0.05	2.09×10^{-4}
1480	0.06	2.51×10^{-4}
1560	0.07	2.93×10^{-4}

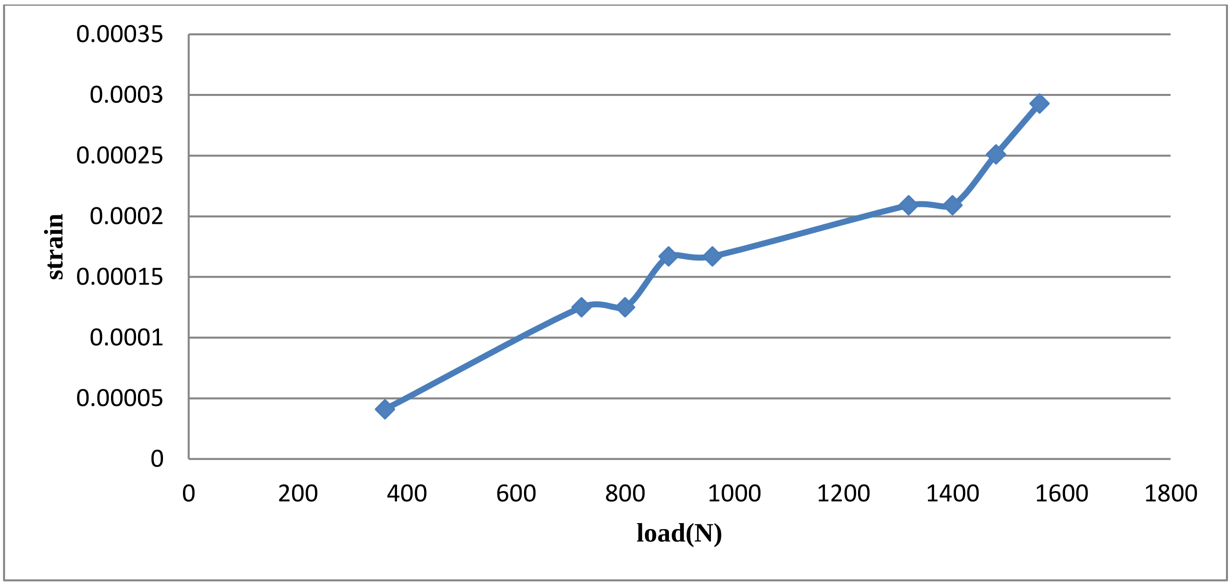

Fig 4.12 strain produced in the bottommost soil nail during loading.

4.6 Comparisons Between the Strains Produced in Topmost, Middle and Bottommost Nail During Loading.

In order to make comparison between the strains produced in topmost, middle and bottommost nail during loading**,** all above curves are merged together.

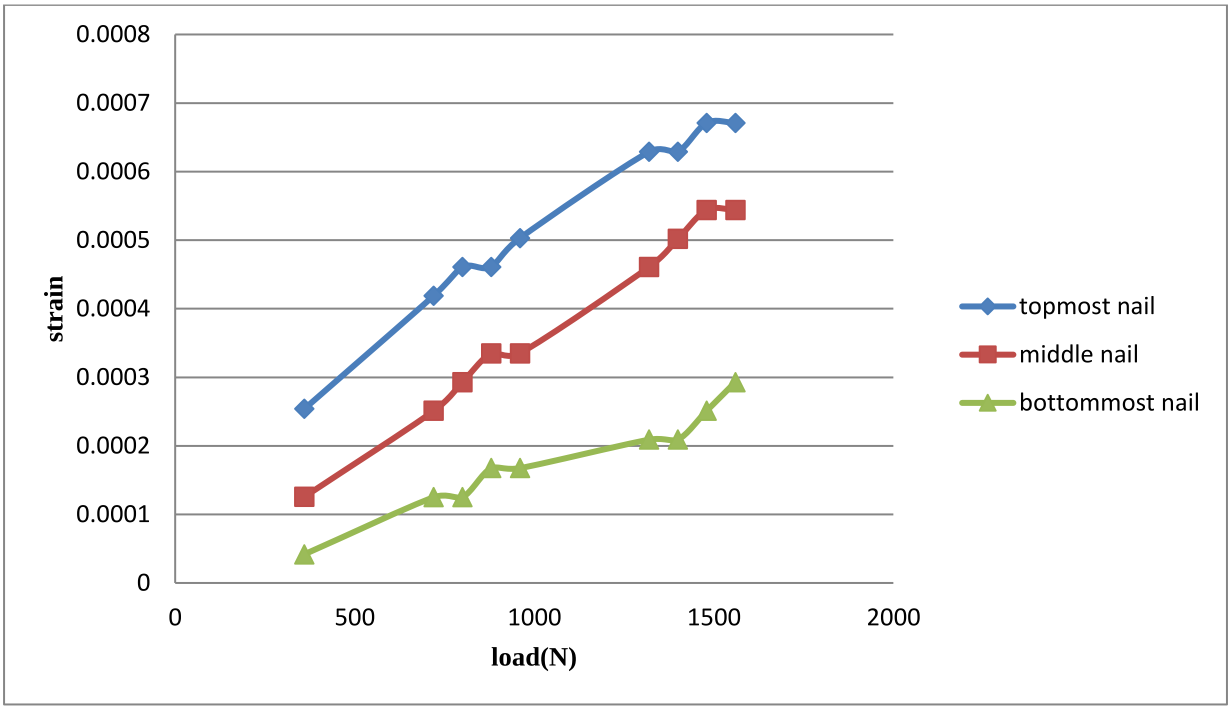

Fig 4.13 variation of strain in nails during loading

From the above graph, it can be observed that maximum strain is produced in the topmost nail as load is firstly transferred through the topmost nail. As the depth increases the load is taken by larger area which may consist of more nails due to which small strain are produced in the middle and bottommost nails.

4.7 Factor of Safety for Soil Slope

a) For unreinforced slope: Factor of safety for unreinforced slope is calculated by using Culmann's method. Culmann(1866) considered a simple failure mechanism of a slope of homogeneous soil with plane failure surface passing through the toe of the slope. Let AB be any probable slip plane. The wedge ADB is in equilibrium under the action of 3 forces:

i) Weight of wedge (W)

ii) Cohesive force C along the surface AB, resisting motion = cL

iii) The reaction R, inclined at an angle Φ to the normal.

Factor of safety = Resisting force/ Driving force

Resisting Force = $c.L + W \cos\Theta \tan\Phi$

Driving Force = $W \sin\Theta$

Hence, the factor of safety,

$F = c.L + W \cos\Theta \tan\Phi / W \sin\Theta$ --------------------(2) as per Culmann(1866).

By using geometry, $W = \Upsilon L H \cos(\beta-\Theta)/ 2\cos\beta$

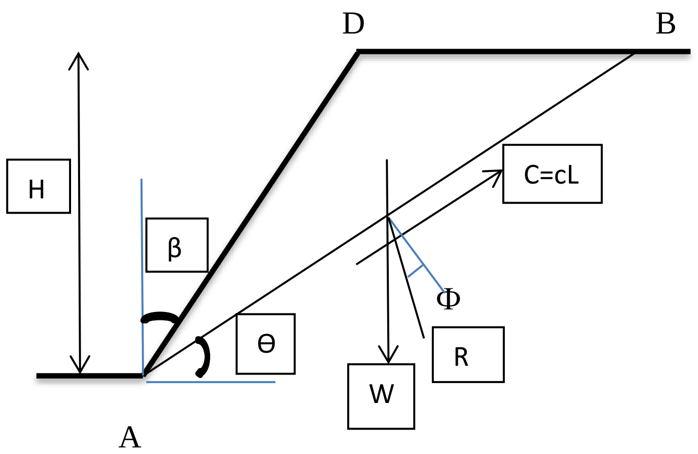

Fig.4.14 Unreinforced soil slope

Where W= weight of wedge

L= length of slip plane

ϴ = angle made by slip plane with horizontal

Φ = internal angle of friction of soil.

β = angle made by slope face with the vertical

c = soil effective cohesion

ϒ = unit weight of soil

H = height of slope

Table.4.10 factor of safety for unreinforced soil slope having 60^0 slope angle(β= 30^0)

Weight of failure wedge, W(N)	Length of failure plane, L(m)	Angle made by slip plane with horizontal, ϴ(degrees)	Factor of safety
218.4	0.39	45	1.306
331.1	0.45	40	1.262
414.0	0.43	35	1.360
596.7	0.55	30	1.509

b) For reinforced slope: The procedure for the calculation of factor of safety for soil nailed slope is given in a report Prashant, A.(2010). "Soil Nailing for Stabilization of Steep Slopes Near Railway Tracks". Research Designs and Standard Organisation(RDSO. The factor of safety is calculated for the reinforced slope in which nails are installed at an angle of 0^0 with the horizontal plane.

As per the report, factor of safety = Resisting force/ Driving force

Resisting force = $c.L + W \cos\Theta \tan\Phi + T_{eq} \cos\Theta$

Driving force = $W \sin\Theta - T_{eq} \cos\Theta$

Where, T_{eq}= equivalent nail tensile force

To find the value of equivalent nail tensile force the above mentioned report suggested the following equation:

$T_{eq} = \sum_{j=1}^{n} Tj$ --(3)

$T_j = (c + \sigma_v \tan\delta)\pi dl / s_h$ --(4)

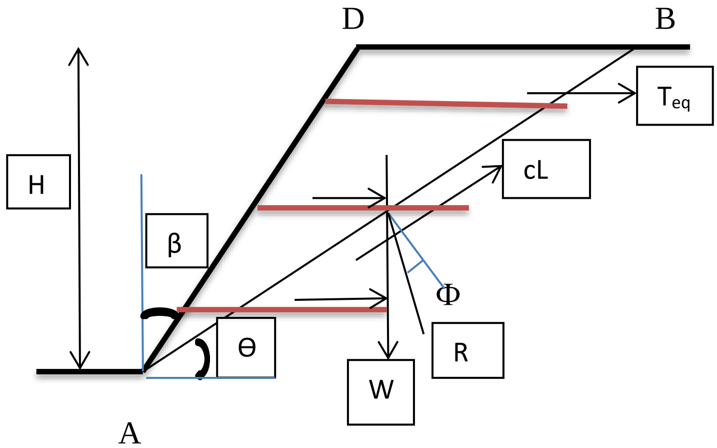

Fig.4.15 Soil nailed slope with nail inclination angle 0^0

Where, T_j = tensile force in j^{th} nail.

d = diameter of nail

n = number of nails used

l = length of nail used

s_h = horizontal spacing of nails

δ = soil-nail interface friction angle

σ_v = overburden pressure at depth where nail is installed.

Table.4.11 factor of safety for reinforced soil slope having 60^0 slope angle($\beta = 30^0$).

Weight of failure wedge, W(N)	Length of failure plane, L(m)	Angle made by slip plane with horizontal, Θ(degrees)	Equivalent tensile force on nail, T_{eq}(N)	Factor of safety (F.O.S)
218.4	0.39	45	44.98	1.889
331.1	0.45	40	44.98	1.638
414.0	0.43	35	44.98	1.694
596.7	0.55	30	44.98	1.767

4.8 Allowable Load for Soil Slope

The minimum factor of safety recommended by FWHA manual (2003) is 1.35 for soil nailed wall. Factor of safety calculated for different failure plane are greater than the minimum recommended value. Hence assuming the factor of safety to be 1.638 from the above calculations, we can calculate the allowable load that can be sustained by the unreinforced and soil nailed slope.

Slope type	Failure load(N)	Nail inclination angle(degrees)	Factor of safety, F	Allowable load(N) = Failure load/F
Unreinforced	1020	-	1.638	622.71
Reinforced	1560	0^0	1.638	957.26

4.9 Comparison of Results with Previous Studies

The results obtained in present experimental work has been compared here with research carried by Rawat and Gupta (2015). "An Experimental and Analytical Study of Slope Stability by Soil Nailing". The following table compares the results of both work:

Properties	**Present Work**	**Work Done by Rawat and Gupta (2015)**
Soil Type	Poorly Graded Sand(SP)	Well Graded Sand(SW)
Mould Dimensions	(0.6 x 0.4 x 0.3)m	(0.5 x 0.25 x 0.35)m
Bearing Plate dimensions	(0.16 x 0.08 x 0.035)m	(0.15 x 0.075 x 0.004)m
Nail Material	Hollow Aluminium Tubes	Hollow Aluminium Tubes
Preferred Nail Inclination	$+0^0$(with horizontal plane)	$+0^0$(with horizontal plane)
Preferred Nail Pattern	Staggered	Square
Loading Type	Static Loading	Gradual Increasing Load (By UTM)
Failure load for unreinforced slope(KN/m^2)	79.68	103.11
Failure load for Soil Nailed Slope slope(KN/m^2)	125.00	153.77

4.10 Failure Load Comparison (Experimental Work vs Analytical Analysis)

Failure load for slope has been already calculated above experimentally as well as analytically. The failure load for slope in case of analytical method will be equal to that of resisting force (calculated above for the determination of factor of safety of slope). The following failure loads are expressed per metre width for different types of soil slopes:

Slope type	Failure load(N) (Analytical)	Failure load(N) (Experimental)
Unreinforced	1096	1020
Reinforced (+0^0nail inclination)	1909	1560

From above table it is observed that failure load calculated by analytical approach is greater than that of failure load calculated experimentally. The difference in failure load calculated experimentally and analytically is more for reinforced slope as compared to unreinforced slope as mobilised bond stress may not have fully developed between the nails-soil interface. Hence analytical approach over predicts the bond stress developed. It can be noticed from the above analysis that the mobilised bond stress developed between the nail-soil interface is about 81.71% of the ultimate bond stress. Hence a modified equation has been proposed to calculate the factor of safety by analytical approach.

Modified equation proposed for calculating factor of safety

As explain above that the mobilised bond stress calculated experimentally is 81.71% of the bond stress calculated by analytical approach. Thus the analytical approach over predicts the bond stress developed between nail-soil interface.

Factor of safety = Resisting force/ Driving force

Modified Resisting force = $c.L + W \cos\Theta \tan\Phi + \grave{\eta} T_{eq} \cos\Theta$

Driving force = $W \sin\Theta - \grave{\eta} T_{eq} \cos\Theta$

Hence modified equation for factor of safety,

$F = (c.L + W \cos\Theta \tan\Phi + \grave{\eta} T_{eq} \cos\Theta)/ (W \sin\Theta - \grave{\eta} T_{eq} \cos\Theta)$------------------------------------(5)

where $\grave{\eta}$ = Reduction Factor

$\grave{\eta}$ = 81.78% for Aluminium hollow tubes soil nails and Poorly Graded Sand(SP)

CHAPTER-5

CONCLUSION

Based upon the above analysis, following conclusion has been drawn:

1. It is observed that the unreinforced soil slopes initially have a settlement of the crest which ultimately leads to the failure of the slope.

2. It is clear from the above observations that there is increase in the load sustained by the soil slope due to the installation of aluminium nails. Moreover there is a considerable decrease in the final settlement of the crest due to soil nailing.

3. The above study clearly shows the effect of nail inclination on the load sustained by the slope. Nail inclination also affects the final settlement of crest of the slope before failure. It was found from the above experiments that the nail driven at 0^0 to horizontal plane are the most efficient in stabilising the soil slope followed by nails inclined at 15^0 and 30^0 respectively.

4. The arrangement of soil nails within the soil slope also affects the overall stability of soil slope. It has been found from the above study that nails arranged in staggered pattern shows best results followed by square nail pattern and diamond nail pattern.

5. The maximum strain is obtained for the topmost nail followed by the middle and bottommost nail respectively.

6. The maximum allowable load by assuming the factor of safety equal to 1.638 is found to be 957.26 N for soil slope in which nails are inserted at angle of $+0^0$ with the horizontal plane and 622.71N for unreinforced soil slope.

7. Failure load calculated by analytical approach is greater than that of failure load calculated experimentally. It is also observed that the difference in failure load calculated experimentally and analytically is more for unreinforced slope as compared to reinforced slope.

8. It is observed from the above analysis that the mobilised bond stress developed between the nail-soil interface is about 81.71% of the ultimate bond stress. Hence the analytical approach over predicts the mobilised bond stress between nail-soil interface.

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