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Effect of Soil Nailing On Stability of Slopes

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Abstract: In the present experimental work, the behaviour of the unreinforced and soil nailed slopes under different static surcharge load is carried out experimentally. The slopes are constructed of sand size soil at presumed soil slope angle of 60° with the horizontal plane. Different static load is applied on the bearing plate mounted on the crest of soil slope to observe the load vs. settlement behaviour. These soil slopes are then reinforced by installing aluminium hollow tubes as soil nails at three different inclinations of 0°, 15° and 30° with the horizontal plane keeping the horizontal and vertical spacing = 0.1m. The effect of soil nail pattern with in the soil slope is also analysed in the present study. Nails are installed in square, diamond and staggered arrangements. Stress and strain produced in the nails installed at different positions has been also found out in the present study with the help of strain gauges during the subsequent stages of loading. It is observed that nails inserted at 0^0 are more efficient in providing the stability to the slopes as compared to nails inserted at 15^0 and 30^0. Also nails installed in staggered pattern were found to be most efficient.
Keywords: Static load, nail inclination, nail pattern, static loading.

I. INTRODUCTION

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.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).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.

In the present experimental work, the behaviour of the unreinforced and soil nailed slopes under different static surcharge load is carried out experimentally. The slopes are constructed of sand size soil at presumed soil slope angle of 60° with the horizontal plane. Different static load is applied on the bearing plate mounted on the crest of soil slope to observe the load vs. settlement behaviour. These soil slopes are then reinforced by installing aluminium hollow tubes as soil nails at three different inclinations of 0°, 15° and 30° with the horizontal plane keeping the horizontal and vertical spacing = 10 cm. The effect of soil nail pattern with in the soil slope is also analysed in the present study. Nails are installed in square, diamond and staggered arrangements. Stress and strain produced in the nails installed at different positions has been also found out in the present study with the help of strain gauges during the subsequent stages of loading.

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II. EXPERIMENTAL SET UP

A. Wooden Box

A box of dimension 0.60m x 0.40m x 0.30m is fabricated by using plywood sheetas 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.

Fig.1 Wooden Box

B. 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 usedas 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).

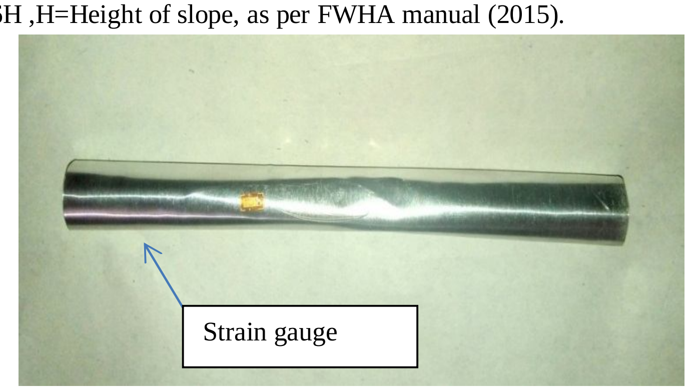

Fig.2 Nails used in the project

C. 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.

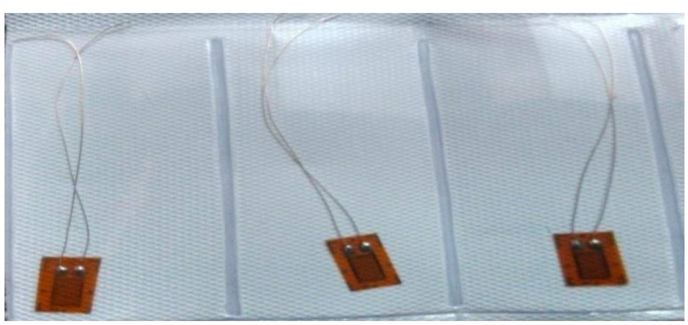

Fig.3 Strain gauges

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D. 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.

E. 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. 4 Mild Steel Bearing Plate

F. Dial Gauge

Dial gauge of least count0.01 mm is used in order to find the settlement of bearing plate during the subsequent loading.

G. Backfill Material

The backfill material used for the construction of slopes is taken from Delhi Technical University campus,Delhi. Preliminary tests of soil identification are carried out in the laboratory to determine the backfill properties. Theproperties of the backfill is given below:

TABLE I
PROPERTIES OF BACKFILL MATERIAL

Properties	Results
Material type	Sand
Grain size distribution	Poorly graded sand
Value of cohesion,c	4.85 N/m^2
Angle of internal friction,Φ	31^0
Maximum dry density	15.053 KN/m^3

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II. PREPARATION OF SLOPES

A .Preparation Of Unreinforced Slopes

Sand size soil in its dry state is used to prepare slopes at predetermined slope angles of 60° . The slope is prepared in layers of thickness 70mm each . A layer 30 mm 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 70 mm. The procedure is repeated till a complete height of 300 mm is achieved. A crest width of 400 mm and the base width of 600 mm 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

Fig.5 Unreinforced soil slope(60^0)

B. 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 the help of a protractor. 9 hollow nails, each of length 16 cm are inserted at the face of the slope in an arrangement of 3 rows x 3columns. The horizontal spacing is kept 10 cm whereas the vertical spacing is kept 10 cm (for square nail pattern only). Before the nails are inserted into the slope face, strain gauges are glued to the nails with super glue Z-70 and connections are made with connecting wires by soldering process.

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Fig.6 Nail Installation

III. 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.7 Soil nailed slope before loading

Fig.8Loading on unreinforced soil slope.

In addition to the load – settlement measurement, the deflection of 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 on 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.

$$\epsilon = \Delta R_g/(R_g \times G.F.) \quad (1)$$

Where, G.F. = gauge factor of 2.00

Rg= resistance of strain gage unstrained,

ΔRg= change in resistance from unstrained to strained condition, and

∈ = strain.

After calculating strain, stress- strain graphs are plotted for nails at 0°. The maximum stress on the nail is determined for top , middle and bottommost nail inserted below the bearing plate

IV. TEST RESULTS

A. Test Results For Different Nail Inclination

The results show 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

Table IIi
Failure Load And Final Settlement For Different Nail Inclination

Nail inclination	Failure load(N)	Final settlement(mm)
Unreinforced	1020	6.75
0^0	1560	5.19
15^0	1500	5.75
30^0	1460	6.08

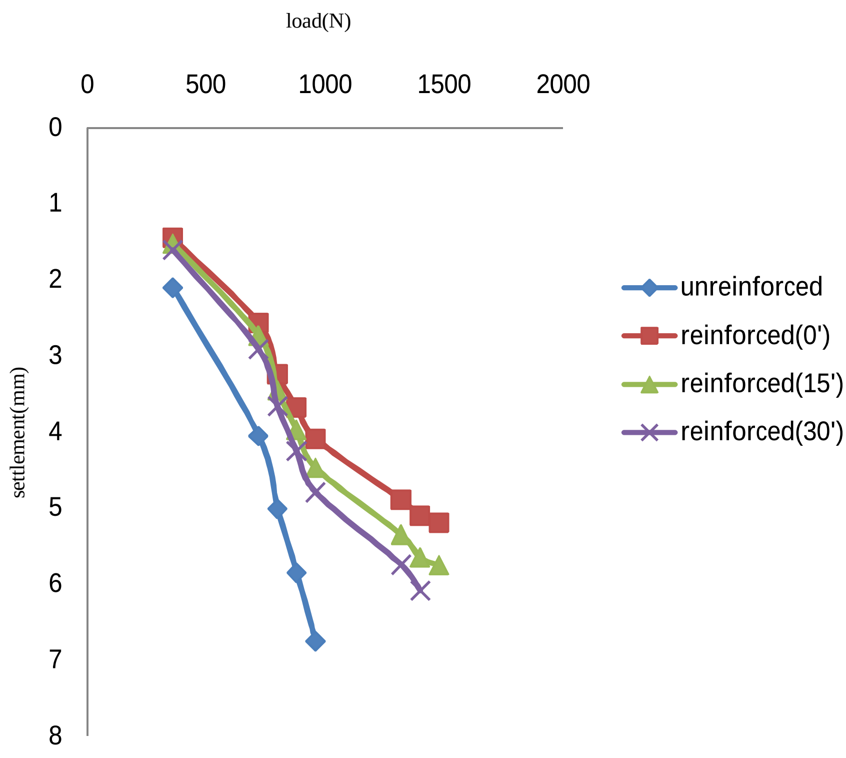

Fig.9 Load vs settlement curve for different nail inclination

. 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.

B. Test Results for Soil Nailed Slope with DifferentNail Pattern

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 .

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Nails are arranged in square, diamond and staggered or triangular pattern keeping the horizontal and vertical spacing equal as per FWHA manual(2015). Load is then applied on the bearing plateand settlement corresponding to the load is noted down.

Table IIIii
Failure Load And Final Settlement For Different Nail Pattern

Nail Pattern	Failure load(N)	Final settlement(mm)
Unreinforced	1020	6.75
Square	1560	5.19
Diamond	1420	6.05
Staggered or Triangular	1600	4.75

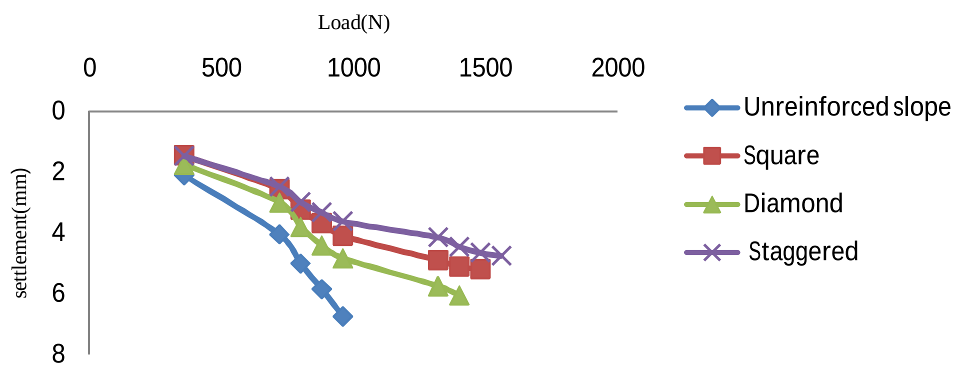

Fig.13 Load vs settlement curve for different nail pattern

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.

Different Types Of Nail Pattern Within The Soil Slope

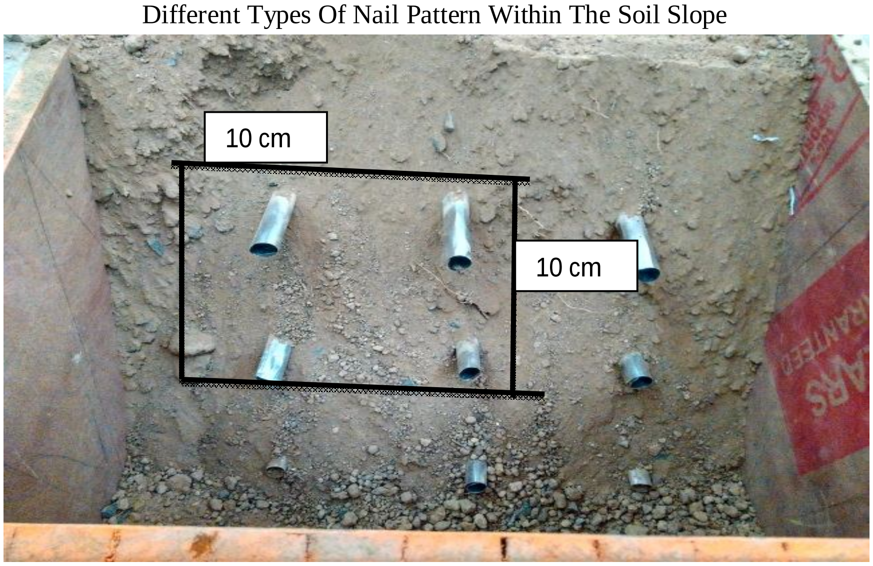

Fig.10 Square Nail Pattern

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Fig.11 Staggered or Triangular Nail Pattern

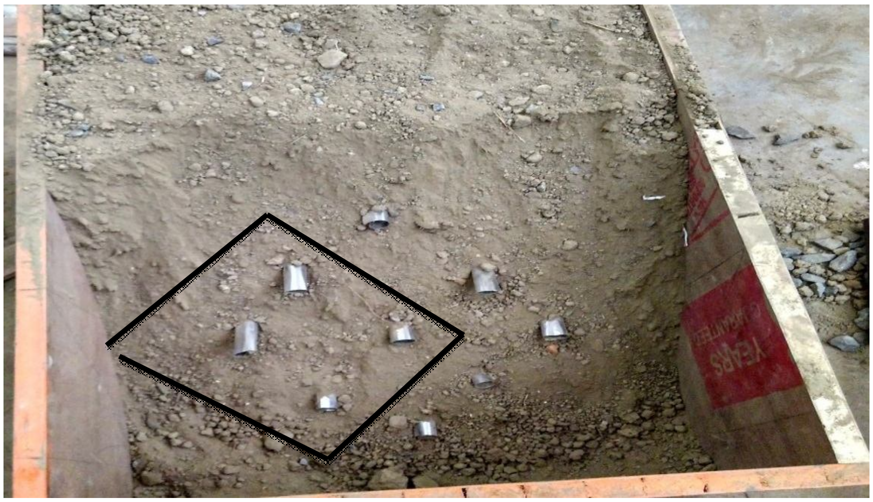

Fig.12 Diamond Nail Pattern

C. Variation Of Strain In The Soil Nails During Different Stages Of Loading

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

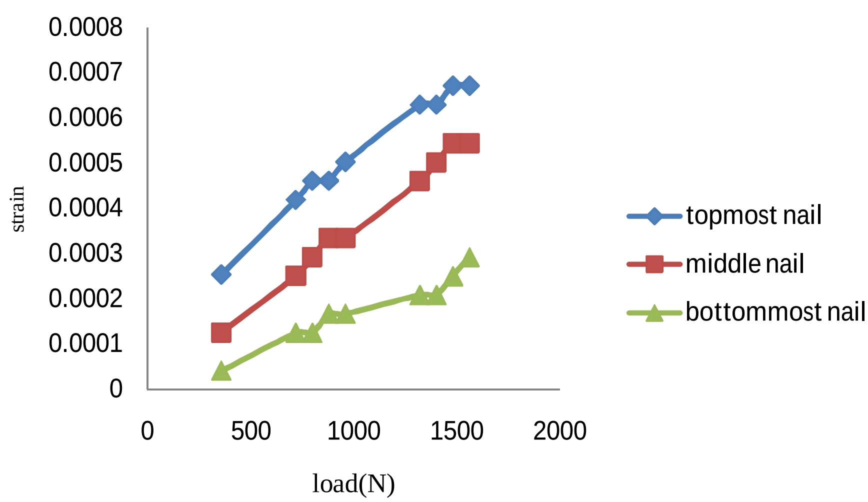

Fig.13 variation of strain in nails during loading

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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.

V. 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 throug the toe of the slope. Let AB be any probable slip plane. The wedge ADB is in equilibrium under the action of 3 forces:

Weight of wedge(W)

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

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

Factor of safety = Resisting force/ Driving force

Resisting Force = c.L + W cosϴtanΦ

Driving Force = W sinϴ

Hence, the factor of safety,

F = c.L + W cosϴtanΦ/ W sinϴ------------------- *(2)* as per Culmann(1866).

By using geometry, W = ϒLH cos(β-ϴ)/ 2cosβ

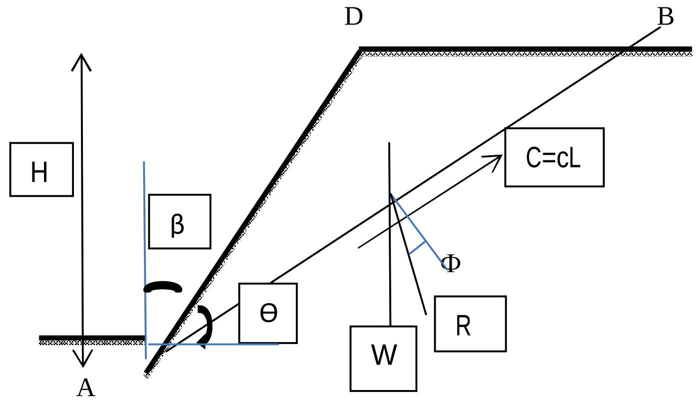

Fig.14 Unreinforced soil slope

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 IVv Factor Of Safety For Unreinforced Soil Slope Having 60^0 Slope Angle(B= 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 "Soil Nailing for Stabilization of Steep Slopes Near Railway Tracks" submitted to Research Designs and Standard Organisation(RDSO),LucknowbyDr. Amit Prashant department of civil engineering IIT Kanpur. 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)

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

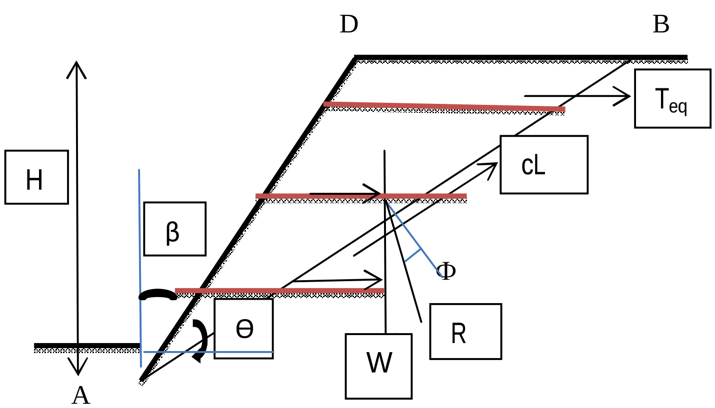

Fig.15 Soil nailed slope with nail inclination angle 0^0

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 V

Factor Of Safety For Reinforced Soil Slope Having 60^0 Slope Angle(B= 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

C. 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.

Table Vi
Allowable Load For Reinforced And Unreinforced Soil 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

D. 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:

Table Vii
Failure Load Comparison

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 ultimate bond stress may not have achieved between the nails-soil interfaces.

E. 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 = $c.L + W \cos\Theta \tan\Phi + \dot{\eta} T_{eq} \cos\Theta$

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

Hence modified equation for factor of safety,

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

Where $\dot{\eta}$ = Reduction Factor

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

VII. CONCLUSIONS

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

B. 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.

C. 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.

D. 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.

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

F. 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.

G. 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.

H. It is observed from the above analysis that the mobilised bond stress developed between the nail-soil interfaces 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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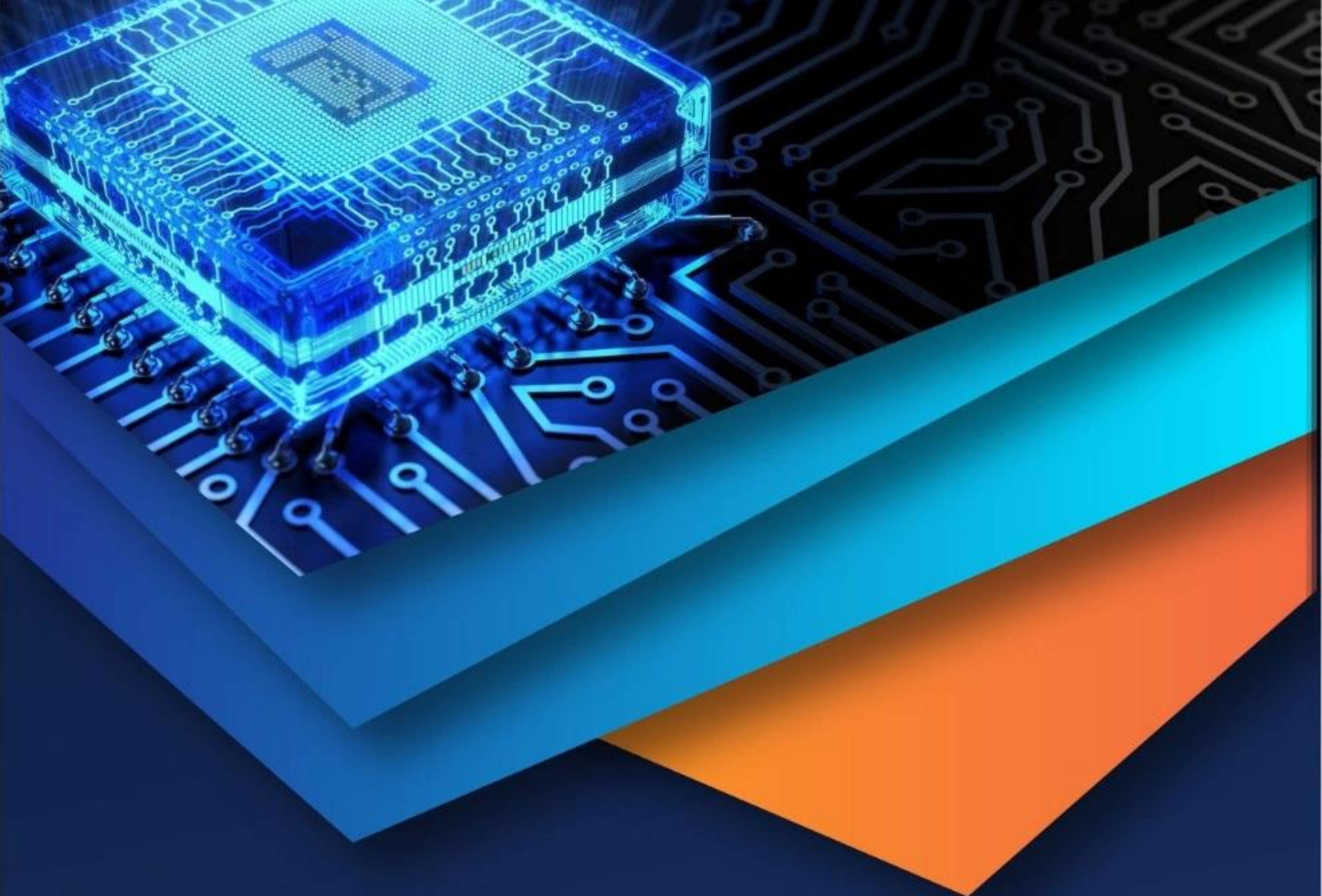

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