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HOUSING CONSTRUCTION ON INCLINED CUTS

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ABSTRACT

In order to meet the housing needs with the constraints of meager space available for development, new construction methodology is to be evolved. Soil Nailing is one of the emerging technologies which can help civil engineers for underground construction, slope stability, housing construction on inclined or vertical cuts etc. The literature available on this techniques reveals findings based on experimental and empirical studies only. The empirical studies made by various investigators are mostly made by assuming circular, parabolic and straight line rupture surfaces only. In the present study an attempt has been made to develop design of nailed open cuts by assuming log-spiral rupture surface. In the study the tensile force in the nail material has been determined with strength property of nail material. All the possible variables. e.g. nail angle, nail length, nail's structural geometry, nail's spacing (horizontal & vertical), method of nail installation, type of loading, nail materials etc have been incorporated in the study. It has been found that the optimum nail angle with the perpendicular to the face and excavation lies between 0 to 10^{o} The optimum length is between 0.6 to 0.9 H, H being the height of cut. Grouted nails are found to exhibit more factor of safety as compared to driven nails. The plastic modulus of the nail material also plays an important role; higher the plastic modulus, more the factor of safety. For construction at the inclined cuts, design charts have also been developed in the present study.

Keywords: inclined cuts, house construction, soil nailing, grouted nails, driven nails, slope stability

1. INTRODUCTION

Housing construction is gaining momentum to meet needs of increasing population. In India alone, more than 1 million houses are constructed per year by government to provide shelter to people. But due to paucity of land in urban areas, the houses are sometimes constructed in rural or remote areas where land available may not be leveled. For those areas which have

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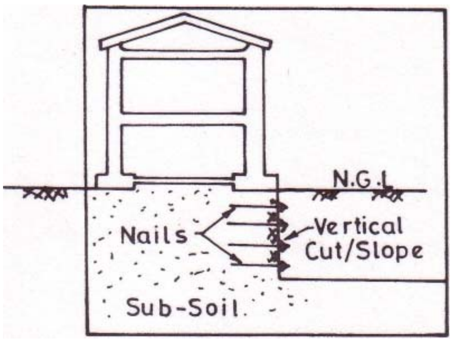
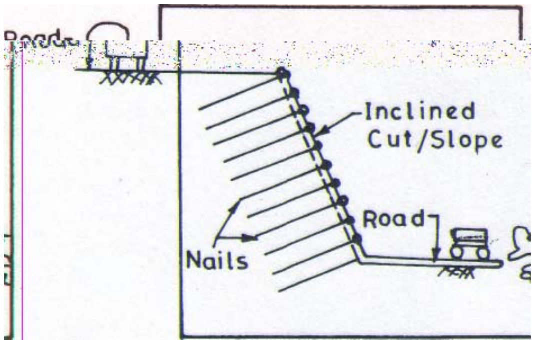
mountainous topography, the ground slopes sometimes may not permit housing construction as the slopes may not be stable enough to withstand the stresses caused by dwelling units. In such cases, one has to construct retaining walls to sustain the earth pressures. The construction of retaining walls requires adequate space on ground and also involves substantial expenditure. The soil nailing technique stablises the slope insitu by inserting nails into inclined ground surface. The technique may also be used for underground construction. Some of the possible locations soil nailing are given in Figure 1. (a, b & c).



(a)



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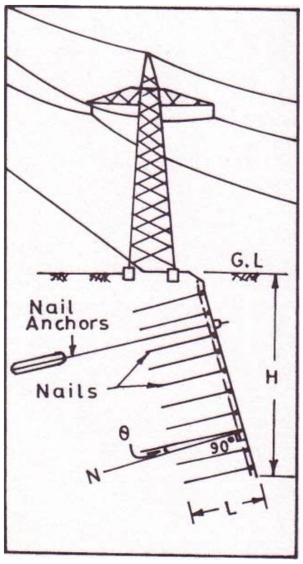

(c)

Figure 1. (a) Housing construction on cut/slopes (b) Laying of roads on cut/slopes
(c) Transmission tower foundations

Soil nailing is a method of reinforcing the soil with steel bars or other materials. The purpose is to increase the tensile and shear strength of the soil and restrain its displacements.

The nails are either placed in the drilled bore holes and grouted along their length or simply driven into the ground (called as 'driven nails'). The technique permits stabilization of both natural slopes and vertical or inclined excavations. The applications of the technique for new constructions include : construction of buildings, underground car parks, cut and cover construction for metro transport system, open cast mining, slope stabilization, stabilizing tunnel portals and shafts etc. Soil nailing has also been used for remedial works [1] including repair of unstable old masonry gravity retaining walls, stabilization of failed soil slopes, repair of reinforced soil walls etc [1].

Small scale model tests [3,9,12] and large scale model tests [2,3,8] have been conducted by various researchers in the past in the area of soil nailing. Various forms of failure surface have been assumed in design, for example bi-planar [12], parabolic [11], circular [10] and log-spiral [5].

Excavations with a vertical face are the most common. As soil nailing technique functions through the friction or adhesion mobilized at the nail-soil interface, frictional soils with a trace of cohesion are considered ideal. Though in Singapore and South East Asia, this technique had been applied successfully even in cohesive soils also. The L/H ratios (L, being the length of nail and H, being the height of cut) used in practice varied widely from less than 0.4 to greater than 1. High values of L/H (>1.0) were used mainly for repairing of existing structures. The commonly used L/H ratio lies in the range of 0.5 to 0.8. Most of the nails were installed at inclination (θ) between 10^0 to 20^0, to the perpendicular to the face of cut [7]. The facing element is meant only to support the soil in between the nails and tends to be thicker for larger nail spacing. It is usually proportioned based on the earth pressure acting on it. In most cases, the ratio of the facing thickness to the vertical nail spacing are between 0.1 to 0.15.

2. ANALYSIS OF NAILED SOIL WALL

The log-spiral mechanism has been used by early investigators for study of nailed slopes [5]. The analysis by log spiral mechanism takes into account the nail stiffness. The design charts developed [5] were based on local stability at each nail location. The results were conservative because they were based on the maximum value of width of failure zone at the top and nail force. The simplified analysis developed in the present study is based on the following assumptions: (1) The deformation of the soil in active zone is sufficient to fully mobilise the shear strength of the soil over the entire failure surface (2) The failure is along a surface defined by the arc of a logarithmic spiral passing through the toe and intersecting the ground at right angles. The center of the spiral is located on straight lines, which makes an angle ϕ at the point where the failure surface meets the ground as shown in Figure 2, Ref. [3].

The shear resistance of the nail due to nail bending stiffness is taken care by using the plastic analysis method [6]. The shear resistance mobilised in the nail is calculated by limiting the soil bearing pressure to the safe value (4) The normal stress on the nail surface in the horizontal direction is assumed to be K_a times the normal stress in the vertical direction, where K_a is the coefficient of active earth pressure (5) The internal failure mode of the wall is either by pull-out or rupture or excessive bending leading to the formation of plastic hinge in the nail whichever is critical. (6) There is a possibility of the nailed zone behaving monolithic to undergo block sliding or overturning. The soil nailed walls, being in-situ structures, do not impose any additional load on the foundation. Hence the bearing capacity failure mode of foundation is ruled out and (7) The analysis is based on moment equilibrium.

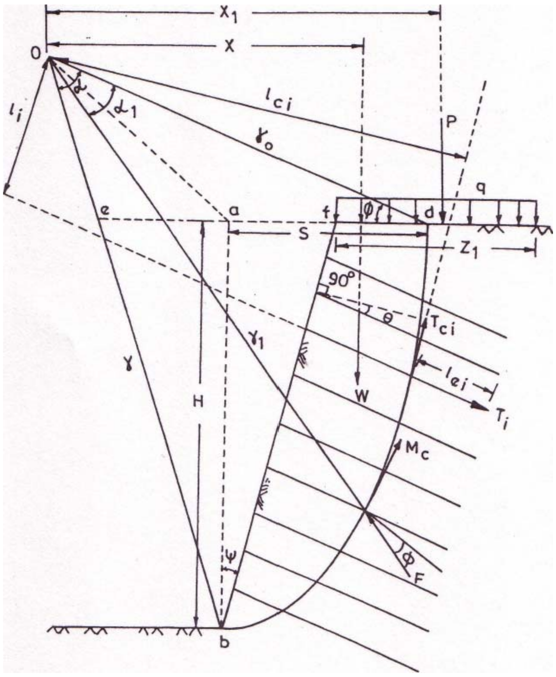

Figure 2. Log-spiral failure mechanism

3. WEDGE STABILITY

The various forces acting on the sliding wedge bounded by the logarithmic spiral arc are shown in Figure 2. Here, W = weight of the soil wedge ‘fbd’, P = force due to surcharge ‘q’ on the surface of ground, F = reaction along the sliding surface ‘bd’, c = soil cohesion, T_i = tensile force or pull out capacity (whichever is small) of the i^{th} nail, T_{ci} = maximum shear force mobilised in the i^{th} nail due to bending stiffness. For moment equilibrium of the sliding wedge, the sum of moments of the forces acting on the wedge about the point ‘O’ must be equal to zero. Hence:

$$WX + PX_1 = T_i l_i + M_c + T_{ci}\, l_{ci} \quad (1)$$

Where X, X_1, l_i and l_{ci} are the lever arms of the respective forces about O as shown in Figure 2.

WX = (Moment of the weight of log-spiral wedge 'obd' about O) – (Moment of the weight of triangle 'oed' about O) – (Moment of the weight of the triangle 'abe' about O)– (Moment of weight of triangle 'abf' about O).

= M1 – M2 – M3 – M4

The values of M1, M2, M3 & M4 can be calculated by using geometry of the figure, and are given as under:

$$M1 = \frac{\gamma r_o^3}{3(1+9\tan^2\phi)}\left[e^{3\alpha\tan\phi}\{3\tan\phi\cos(\alpha+\phi)+\sin(\phi+\alpha)\}-4\sin\phi\right]$$

$$M2 = \frac{1}{6} r_o \sin\phi\left[H\cot(\phi+\alpha)+S\right].\left[2r_o\cos\phi-\{H\cot(\phi+\alpha)+S\}\right]$$

$$M3 = \left\{\frac{1}{2} H \times H\cot(\phi+\alpha).\gamma\right\}.\{ro\ \cos\phi - S - \frac{1}{3}\ H \cot(\phi+\alpha)\}$$

$$M4 = \frac{1}{2} H.H\tan\psi.\gamma.\ (ro\ \cos\phi - S) + \frac{H\tan\psi}{3}$$

Where ψ = angle of wall inclination with vertical. For vertical wall, $\psi = 0$.

The value of M_c is determined by considering cohesion along the face of the log-spiral and is given as follows –

$$M_c = \frac{c}{2\tan\phi}\left[r_1^2 - r_0^2\right] \quad (2)$$

The derivations of equations of M1, M2, M3, M4 and M_c are given elsewhere [4].

The other parameters e.g. S, r_o, H, ϕ, α etc. are shown in Figure 2.

From Δ Ode,

$$\frac{S}{H} = \frac{\operatorname{cosec}(\phi+\alpha)\sin\alpha}{[\sin(\phi+\alpha)e^{\alpha\tan\phi}-\sin\phi]} - \cot(\phi+\alpha) \quad (3)$$

and

$$r_o = \frac{\left[H\cot(\phi+\alpha)+S\right]\sin(\phi+\alpha)}{\sin\alpha} \quad (4)$$

After substituting various values in Eq. (3), the value of S (where log –spiral cuts the ground surface) can be calculated for a particular value of α. On putting the values of S and α in Eq. (4), r_o can be calculated and hence the value of M1, M2, M3, M4, can be determined.

The value of axial force in nail can be determined by

$$T_i = (c + \sigma_{ni}\tan\delta)\ P_i\ l_{ei}\ /\ S_h \quad (5)$$

where,

σ_{ni} = normal stress at mid depth of i^{th} nail along its length, δ = mobilized soil/nail interface friction angle, S_h = horizontal spacing between nails, P_i = perimeter of i^{th} nail, l_{ei}= length of i^{th} nail behind the failure surface. The value of σ_{ni} can be calculated by the following expression:

$$\sigma_{ni} = \frac{\sigma_y \cos^2\theta - \sigma_x \sin^2\theta}{\cos 2\theta + \sin 2\theta \tan\delta} \tag{6}$$

σ_x and σ_y are horizontal and vertical stresses acting on soil element respectively, θ is the nail inclination with perpendicular to the face of excavation.

σ_y = unit weight of soil x depth of nail from ground level , σ_x = K_a x σ_y

l_{ei} can be calculated from Figure 3, which illustrates the forces acting on the failure surface.

From Figure 3, in Δ Oad,

$$\frac{r_o}{\sin(\phi+\theta_1)} = \frac{S}{\sin\theta_1} = \frac{oa}{\sin\phi}$$

From above,
$$\frac{r_o}{\sin(\phi+\theta_1)} = \frac{S}{\sin\theta_1}$$

or
$$\theta_1 = \cot^{-1}\left[\frac{\frac{r_o}{S} - \cos\phi}{\sin\phi}\right]$$

and
$$Oa = \frac{r_o \sin\phi}{\sin(\phi+\theta_1)}$$

In Δ oag,

$$\frac{Oa}{\sin m} = \frac{Og}{\sin(90+\theta_1+\phi)} = \frac{(i-0.5)S_v}{\sin(180-90-\theta_1-\phi-m)}$$

From the above relationships,

$$\cot m = \frac{(i-0.5)S_v}{oa} + \tan(\phi+\theta_1)$$

and
$$Og = \frac{Oa\cos(\phi+\theta_1)}{\sin m}$$

In Δ OgM,

$$\frac{r_o e^{\alpha_1 \tan\phi}}{\sin(90+m)} = \frac{Og}{\sin(\phi+\alpha_1)} = \frac{gM}{\sin(180-90-m-\phi-\alpha_1)}$$

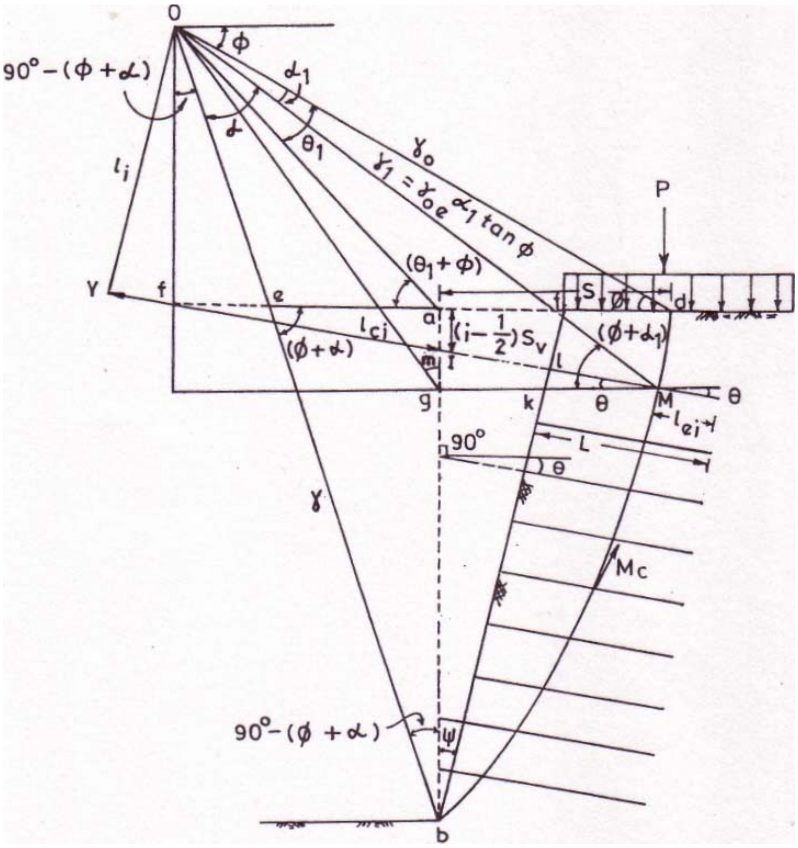

Figure 3. Forces acting on failure wedge

where $r_1 = r_0 e^{\alpha_1 \tan\phi}$ (as per equation of log –spiral)

From above relations, the value of α_1 can be determined by iteration. From second and third ratios, the value of gM may be determined.

Thus,

$$gM = \frac{Og \times \cos(m + \phi + \alpha_1)}{\sin(\phi + \alpha_1)}$$

$$= Og\left[\cos m \times \cot(\phi + \alpha_1) - \sin m\right]$$

From Figure 3, kM = gM-gk

or, $kM = gM - \{H - (i - 0.5) \times Sv\} \times \tan\psi$

where i is the number of nail rows.

Length of nail within the log-spiral, $\ell M = kM \times \cos\theta$

Length of nail behind failure surface, $l_{ei} = L - \ell M$ (7)

where L is the overall length of nail

From Δ OMY (Figure 3)

$OM = r_1 = r_0\, e^{\alpha_1 \tan\phi}$, $OY = l_i = r_1 \sin(\phi + \alpha_1 - \theta)$, $MY = l_{ci} = r_1\cos(\phi+\alpha_1-\theta)$

The mobilized shear T_{ci} in the 'i'th nail which acts normal to the nail axis at its intersection with the slip surface is given as under [6]:

$$T_{ci} = \frac{CM_P}{l_{si} S_h}\left[1 - \left(\frac{T_i}{T_P}\right)^2\right] \tag{8}$$

Here, C is a constant of proportionality between nail shear and maximum moment and is equal to 4 for inclined nails, M_P = plastic moment capacity of nail (depends on the shape and material property of nail) and l_{si} = shear width (It is the distance between the points on the reinforcement on either side of the reinforcement on the either side of the shear plane in the soil that experiences the maximum moment). The l_{si} is given by -

$$l_{si} = \sqrt{\frac{8M_P}{\sigma_b d} \times \frac{d}{D}\left(1 - \frac{T}{T_P}\right)^2} \tag{9}$$

T = axial force in the nail at the point of maximum bending moment

= σ_v x 2w (dL) tanδ, w= width of inclusion of nail, dL = length of an element of inclusion, T_P = plastic axial force = Nail yield stress (σ_y) x cross sectional area = $\frac{\pi}{4}d^2$, d = diameter of nail, D = grout hole diameter.

For grouted nails, $D \neq d$.

For driven nails, D = d

The safe estimate of the bearing stress σ_b as a function of the soil internal friction angle ϕ and the overburden stress σ_v assuming a punching shear failure of the soil around the bar is determined as under [6]:

$$\sigma_b = \sigma_V\left(\frac{1+K_a}{2}\right)\tan\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\exp\left[\left(\frac{\pi}{2}+\phi\right)\tan\phi\right] \tag{10}$$

Here, σ_v = γ x depth of nail from the top

The σ_b is calculated at the intersection of the nail with the slip surface.

3.1 Moment due to surcharge load

Let surcharge load of intensity q (kN/m^2) is acting over a length of z_1 (Figure 2).
Hence, moment of forces about O,

$$PX_1 = q \,.\, z_1\,(r_o \cos\phi - S + 0.5 \,.\, z_1) \tag{11}$$

The factor of safety (FOS) is defined as:

$$= \frac{\sum_{i=1}^{n} T_i l_i + \sum_{i=1}^{n} T_{ci} l_{ci} + M_c}{WX + PX_1} \quad (12)$$

Providing different widths to the slip surface by varying log-spiral angle, the minimum value of factor of safety is determined. Due to apparently more complex geometry of the log-spiral, the process of finding the minimum value of FOS is determined with the help of computer program made in C plus language.

4. PARAMETRIC STUDY

The following parameters were used for soil and nail. The horizontal and vertical spacings of nails (S_h and S_v repectively) were taken as equal in the study:

wall height, H (m)= 4,6,8,10,12, density of soil, γ =16.5 kN/m^3, soil friction angle ϕ =30^o,35^o,40^o, soil cohesion, c = 0,10 kN/m^2, nail diameter, d = 25mm, grout hole diameter, D = 100mm, q = 30,60 KN/m^2, nail yield stress, f_y = 2.5x10^5 kPa, nail inclination, θ =0^o,10^o,15^o,20^o, nail length = 0.5 H to 0.9 H

A computer program "NAILEDCUTS" had been developed as per flow chart (Figure 4) in order to study the behaviour of nailed open cuts by varying the above said parameters. The representative charts of factor of safety versus length of nails for grouted nails and driven nail are illustrated vide Figures 5 and 6 respectively. More details are given elsewhere [4]. The effect of nail inclination and yield stress of nail material are given vide Figures 7 and 8. For intermediate values, linear interpolation can be made.

5. EFFECT OF NAIL GEOMETRY

Comparison of square and circular nail:

For same cross sectional area (As) of two nails, $\frac{\pi}{4}d^2$ = b2 Or, d = $\frac{2b}{\sqrt{\pi}}$

Now, (Mp)sqr = $\frac{b^3}{4}$; (Mp)circular = $\frac{d^3}{6}$

Here, M_p = plastic modulus of nail.

$$\frac{(M_p)_{sqr}}{(M_p)_{circular}} = \frac{3b^3}{2d^3} = \frac{3\pi\sqrt{\pi}}{16} > 1.0$$

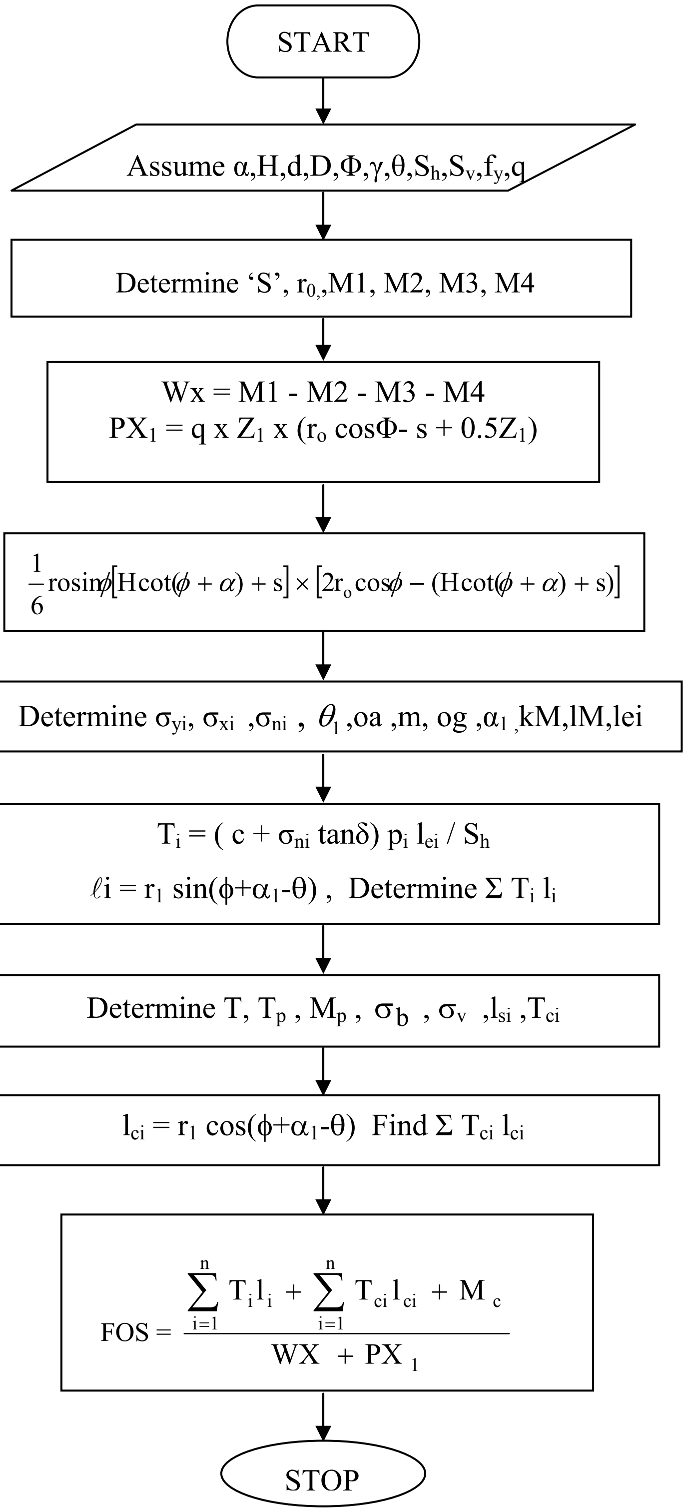

Figure 4. Flow chart

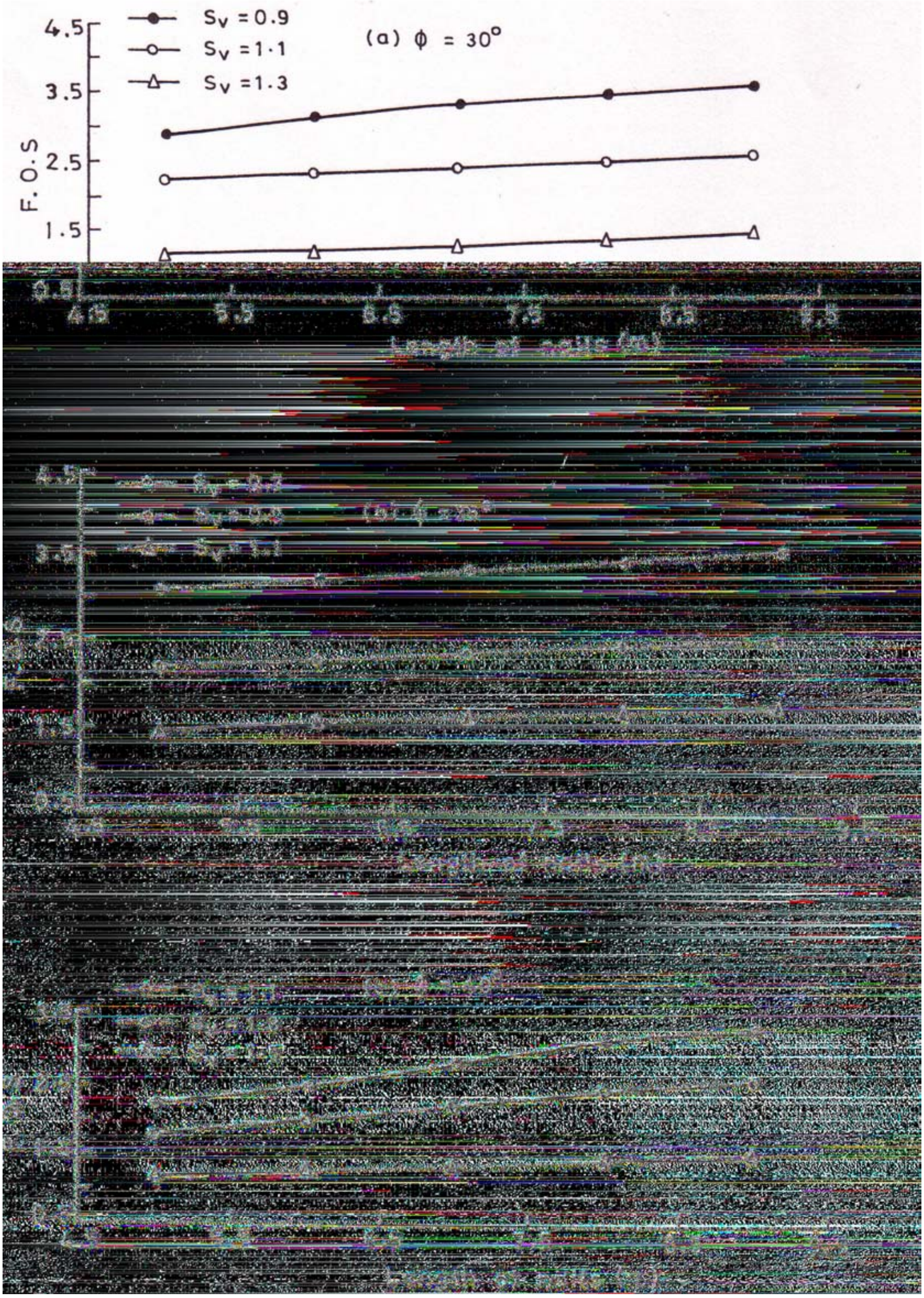

Figure 5. Factor of safety v/s length of nails for grouted nails for vertical cut (H=10m), $c=10kN/m^2$, $p=45kN/m^2$

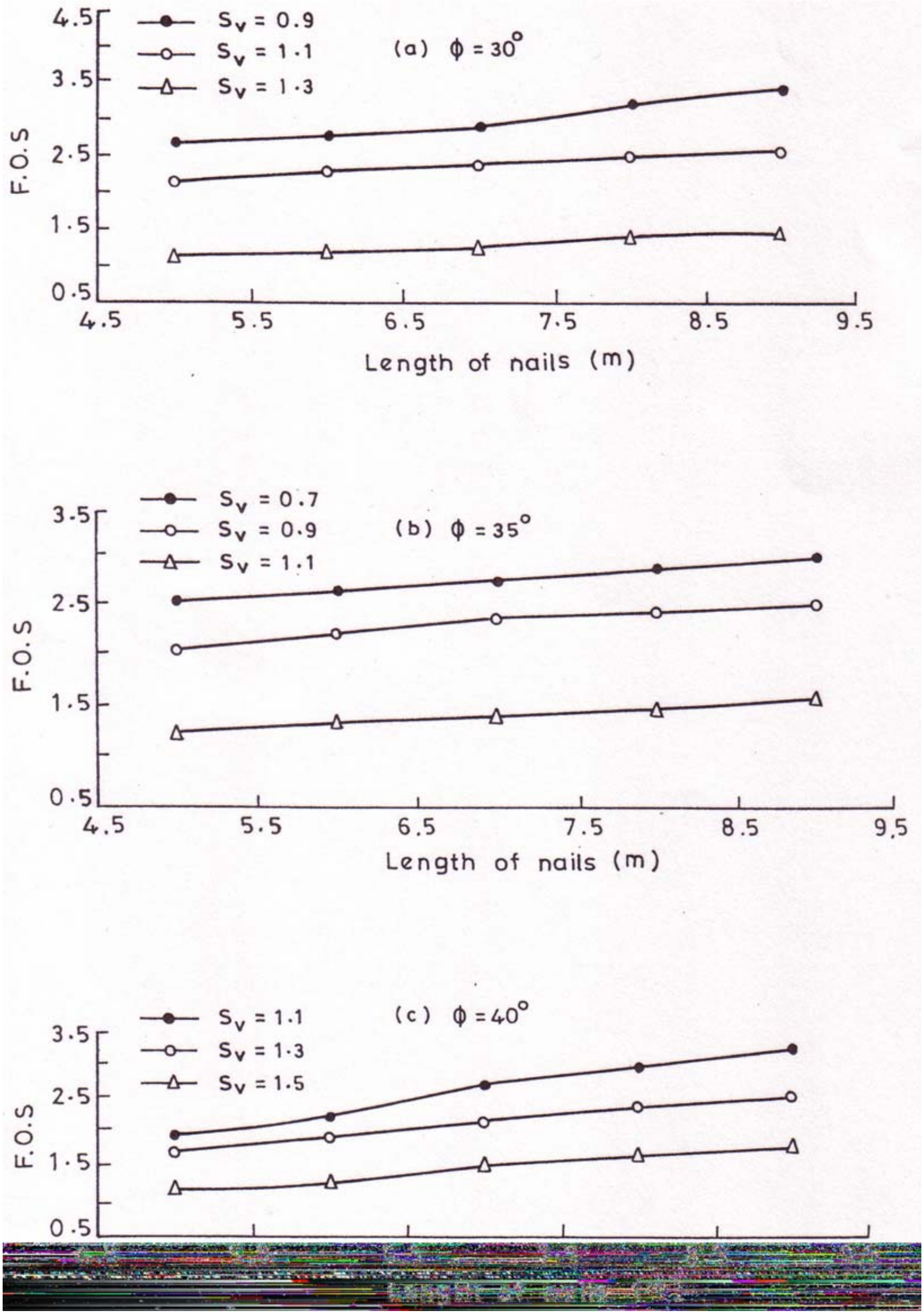

Figure 6. Factor of safety v/s length of nails for driven nails for vertical cut (H=10m), c=10kN/m^2 , p=45kN/m^2

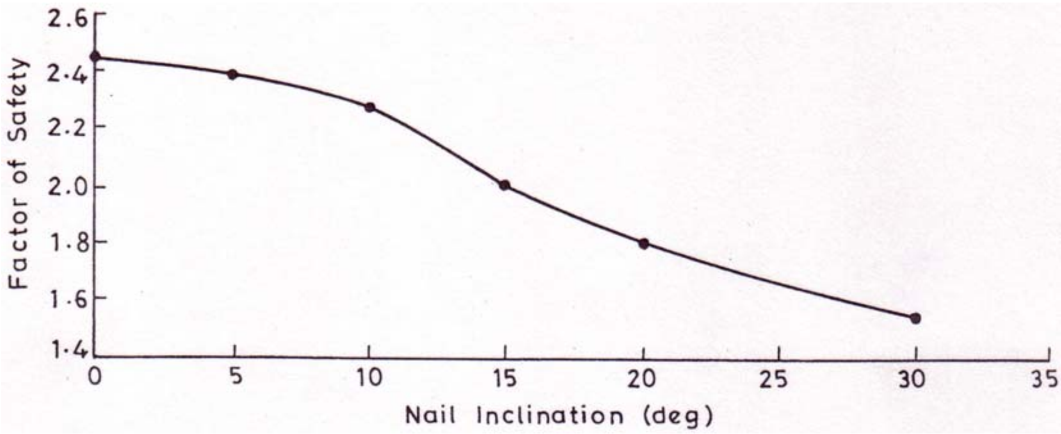

Figure 7. Effect of Nail inclination

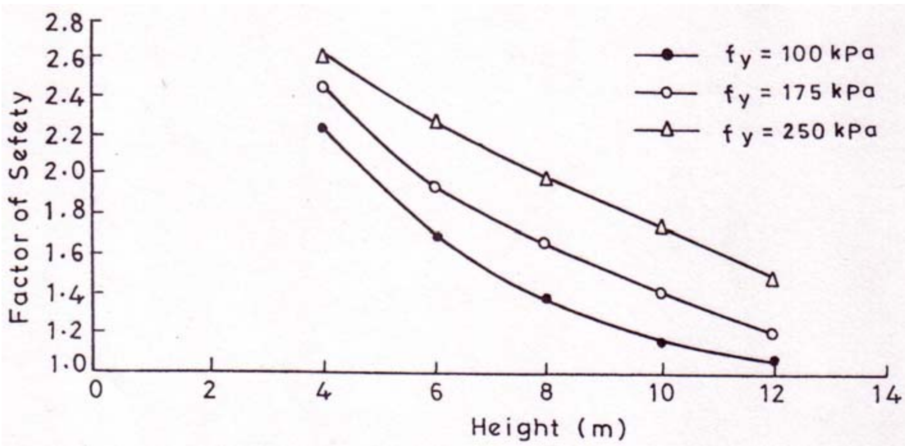

Figure 8. Effect of yield stress of nails

It is seen that plastic modulus of square nail is higher, therefore, square section will give higher value of factor of safety as compared to circular bar.

6. DESIGN EXAMPLE

Problem: To ensure stability of a vertical nailed soil retaining structure 10 m high supporting surcharge load of a house construction. The soil has following properties :

Soil properties: density (γ) = 16.5 kN/m^3, ϕ = 30^o, c = 10 kN/m^2

surcharge intensity (q) = 50 kN/m

Nail properties: Diameter of bar = 25 mm ,

yield stress of steel (f_y) = 2.5 x 10^5 kPa

***Solution*:**

Referring Figures 5(a) and 6(a), and adopting a factor of safety =1.5,

(a) For grouted nail	(b) For driven nail
Nail length = 8.5m	Nail length = 8 m
Nail spacing = 1.3 m	Nail spacing =1.3m

7. CONCLUSIONS

Following conclusions are drawn from the study :

1. Housing construction activity can be undertaken on inclined cuts by using soil nailing techniques.
2. Factor of safety increases appreciably upto the length of nails between 0.6H to 0.9 H, H being the height of excavation. Beyond 0.8 H, the increase in factor of safety is marginal.
3. The factor of safety decreases with increase in nail inclination with the perpendicular to face of excavation. Beyond 10^0, the factor of safety decreases drastically. The optimum range of placement of nails is between 0^0 to 10^0 with the perpendicular to face of excavation.
4. The factor of safety decreases with increase in nail spacing (vertical as well as horizontal).
5. Factor of safety decreases with decreases in yield stress of nail material.
6. The factor of safety is more for grouted nails as compared to driven nails.

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LIST OF NOTATIONS

c = Soil cohesion

d = Nail bar diameter

D = Grout hole diameter

F = Soil reaction „@

„˜þ Æass

f_y = Yield stress of nail material

H = Nailed wall height

K_a = Active earth pressure coefficient

L = Overall length of nail

l_{si} = Shear width of failure zone for i^{th} nail

l_{ei} = Effective nail length of the 'i'th nail

l_i = Lever arm of 'i'th row of nail tensile force

l_{ci} = Lever arm of 'i'th row of maximum nail shear force

M_c = Moment of cohesive force along rupture wedge

M_P = Plastic moment capacity of the nail

M1,M2,M3,M4 = Moments about 'O'

P = Force on the active wedge due to surcharge

P_i = Perimeter of i^{th} nail

q = Intensity of surcharge

r_o = Initial radius of log-spiral

r_1 = Radius of log-spiral at the toe of wall

S_h = Horizontal nail spacing

S_v = Vertical nail spacing

T = Axial force in nail at the point of maximum bending moment

T_{ci} = Maximum nail shear force

T_i = Tensile nail force in the 'i'th nail

T_p = Plastic axial force

w = Width of the inclusion

W = Weight of soil wedge in the nailed zone

Z_1 = Distance

θ = Nail inclination with perpendicular to the face of excavation
α = Log Spiral angle
δ = Soil/nail interface friction angle
ϕ = Soil internal friction angle
ψ = Angle of wall inclination / cut with vertical
γ = Soil unit weight
σ_v = Vertical stress
σ_{ni} = Normal stress on i^{th} nail
σ_x = Horizontal stress on a soil element in x-direction
σ_y = Normal stress on a soil element in y- direction
σ_b = Bearing stress