Geotechnical and Geological Engineering (2006) 24: 1821–1833
DOI 10.1007/s10706-006-7127-6

River bank erosion control by soil nailing

SATYENDRA MITTAL[1,★] and A.K. BISWAS[2]
[1]*Department of Civil Engineering, Indian Institute of Technology, Roorkee, 247 667, India*
[2]*Bangladesh Water Development Board, Dhaka, Bangladesh*

(Received 7 October; accepted 2 February 2006)

Abstract. A study has been done for analysing soil nailed cuts with circular type wedge failure by friction circle method. Various parameters such as nail length, nail diameter, nail inclination, wall inclination and angle of internal friction of soil have been considered to determine the factor of safety of nailed open cuts. The study shows that for cohesionless soil nailed cut, factor of safety increase with increase of parameters like angle of internal friction of soil, length of nail (L) versus height of cut (H) ratio, cohesion of soil and nail inclination (upto 15°) with horizontal. The study revealed that nails grouted with cement perform better than driven nails. A case study further confirms the analytical findings.

Key words. erosion control, factor of safety, friction circle method, nailed cut, shotcreting.

1. Introduction

The soil nailing is a method of reinforcing the soil with steel bars or other materials. The purpose is to support the tensile and shear stresses in soil and restrain its lateral displacements. The nails are either placed in drilled bore holes and thereafter grouted along their length to form grouted nails or simply driven into the ground as driven nails. The technique permits stabilization of both natural slopes and vertical or inclined excavations. Slope. The construction proceeds from 'top to bottom'. This process creates reinforced section to retain the soil around it. Nails provide tensile strength to the soil mass. The soil–nails composition also increase apparent soil cohesiveness through its ability to carry tensile load. A construction facing is usually required and generally shotcrete reinforced by welded wire mesh or chicken mesh is used. For permanent walls, the shotcrete construction facing may be covered by cast-in-place concrete facing. Erosion due to rainfall is quite common in those areas where soft soil is available and where there are chances of landslides. It is seen that the nailing technique is useful for making underground cut and also for stabilization of the loose soil subjected to erosion.

2. Review of Literature

In India, at I.I.T. Roorkee, a comprehensive research work and model studies are going on since last 3 years. Some investigators have contributed works on soil

★ Corresponding author: Department of Civil Engineering, Indian Institute of Technology, Roorkee, 247 667, India. e-mail: smittfce@iitr.ernet.in

nailing (Juran et al., 1988; Jewell and Pedley, 1990; Juran and Elias, 1991, 1992). Some of the design steps suggested by Juran and Elias (1991) for design of nailed soil structures are: (1) For the specific structure geometry (depth and cut slope inclination), ground profile and surcharge loading, estimate working nail forces and location of potential sliding surface. (2) Select the reinforcement type and verify local stability at each reinforcement level i.e. verify that nail resistance (strength and pull out capacity) is sufficient to withstand the estimated working force with an acceptable factor of safety. (3) Verify that the global stability of the nailed soil structure and the surrounding ground is maintained during and after excavation with an acceptable factor of safety. (4) Estimate the system of forces acting on the facing and design the facing for specified architectural and durability criteria. (5) For permanent structures, select corrosion protection relevant to site condition. (6) Select the proper drainage system for ground water movement. The available design methods for soil nailed retaining structures can be broadly classified into two main categories e.g. (1) Limit equilibrium design methods of modified slope stability analyses which are used to evaluate the global safety factor of the nailed structures with respect to a rotational or translational failure along potential sliding surfaces taking into account the shearing, tension or pull out resistance of the inclusions crossing the potential failure surface. (2) Working stress design methods which are used to estimate the tension and shear forces generated in the nail during construction under the design loading conditions and evaluate the local stability at each level. Juran and Elias (1991) presented field observations during and after construction of instrumented full scale nailed soil-retaining structures. They observed a significant post construction increase in both facing displacement and nail forces. Juran et al. (1988) used small-scale model to investigate the effect of construction method on the behaviour of reinforced soil and nailed soil structure. The effect of nail inclination and nail bending stiffness on the behaviour of nailed soil retaining structure was also investigated. The reinforcement used was 0.1 mm thick flexible aluminum strips and 0.2 mm thick relatively rigid channel shaped polystyrene strips. In both the cases the maximum displacement of model wall was about 1.2% of wall height. Plumelle and Schlosser (1990) tested a full-scale soil nailed wall to failure progressively by saturating the reinforced soil mass. The nails, soil and wall were instrumented and pullout tests were performed to determine the soil nail lateral friction. Jewell and Pedley (1990) conducted long term tests on a 15 m high-nailed wall in a cohesive soil. The main findings of their study were: The top nail did not substantially contribute to the retaining force of the wall system, nail force increases for a short duration during construction and remains almost constant thereafter and the main deformation occurred at the top of wall.

Davis et al. (1993) investigated the behaviour of steel reinforced slopes by conducting a series of model tests in clayey sand soils. In the model, the nailed embankment was loaded to failure and the failure surface was identified by viewing through the side glass wall of the test tank, and found that it was more effective in sandy slope for longer reinforcement. The reinforcement effect was compared in terms of a reinforcement ratio which is defined as ratio of failure load for reinforced soil to failure load for unreinforced soil. Patra and Baudhar (2001) presented an overview of experimental and theoretical studies leading to the development of various methods of soil nailed structures. Gupta (2002) conducted model tests on nailed wall on coarse sand and the wall (facing element) was made of aluminium sheet of 1 mm thickness. The height of wall was 1.0 m and the length of backfill was 1.5 m. He found that a minimum length of nail should be 0.70 m and length of nail upto 0.8 times the height of wall yields maximum factor of safety. He further concluded that tor steel performs better as compared to plain steel bar in nailed open cuts. Saran et al. (2006, accepted for publication) presented a Pseudo-static analyses design of nailed vertical excavations in sands.

3. Present Analytical Study

Figure 1 shows a section of nailed open cut (wall) and the various forces acting there. Here, W = weight of wedge, α = angle made by wedge at centre, β = angle made by

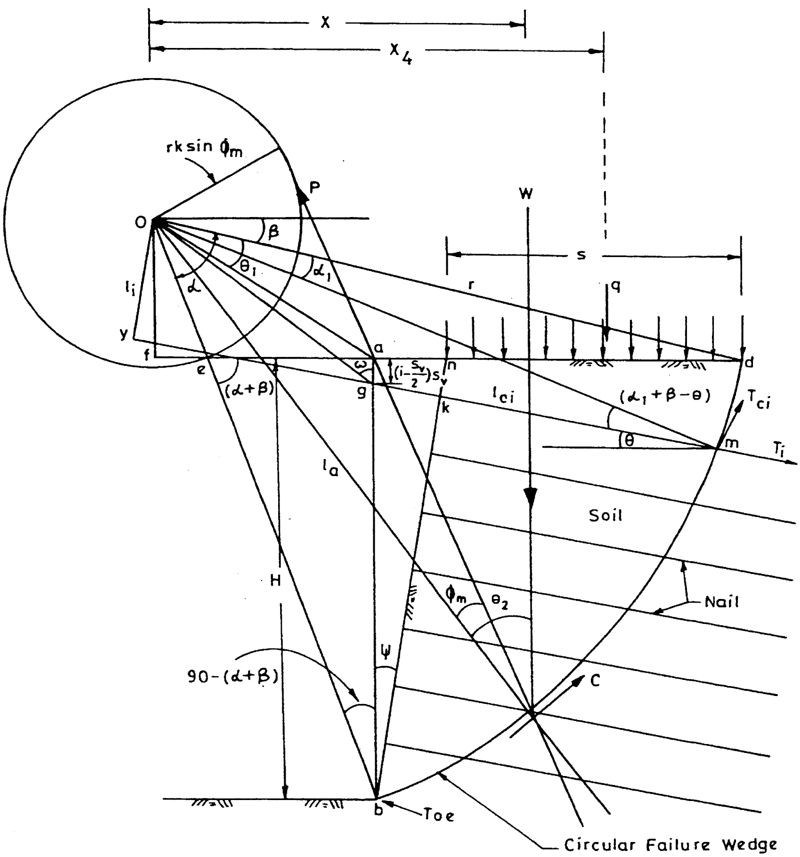

Figure 1. Nailed soil wall showing all the forces.

radius of wedge with horizontal, c = soil cohesion, ψ = angle of nailed cut with vertical, θ = nail angle with horizontal, H = height of cut/wall.

Friction circle method has been adopted for analysis. The assumptions made in the study are: (1) The failure is along a surface defined by the radius of a spiral wedge passing through the toe. The centre of the spiral is located on a straight line which rises at an angle β to the horizontal and passes through the point where the failure surface meets the ground as shown in Figure 1. (2) Only internal stability is considered. (3) While considering force equilibrium in the vertical direction, nail axial force has not been considered. (4) The analysis is based on moment and force equilibrium. (5) The shear resistance of the nail due to nail bending stiffness is taken care by using the plastic analysis method suggested by Jewell and Pedley (1990). (6) The deformation of the soil in the active zone is sufficient to fully mobilize the shear strength of the soil over the entire failure surface. (7) The internal failure mode of the wall is either by pull out or excessive bending leading to the formation of a plastic hinge in the nail whichever is critical. (8) Mobilized soil and nail interface friction angle (δ) is assumed to be two third of the value of angle of internal friction (Φ) of soil.

A computer program was prepared in C-language to determine the factor of safety of the nailed cut for various combinations of parameters. The range of values of the different parameters were considered as given below:

Sl. No.	Parameter	Value range	Interval
1.	H (height of cut/wall)	6 m	(Fixed value taken)
2.	Φ (angle of internal friction, Deg.)	25–40	2
3.	S_h, S_v (horizontal and vertical spacing of nail, respectively)	0.05H–0.08H	0.01H
4.	d (nail diameter, mm)	20–40	5
5.	D (grout hole diameter, mm)	4 d	
6.	Ψ (inclination of wall with vertical, Deg.)	0–30	5
7.	θ (inclination of nail with horizontal, Deg.)	0–30	5
8.	L/H (here, L is length of nail)	0.5–0.9	0.1
9.	f_y (yield stress of steel), kN/m^2	200,000–400,000	50,000
10.	c (unit cohesion of soil, kN/m^2)	10–75	5
11.	q (Surcharge load kN/m^2)	45	Nil (fixed value taken)

4. Results and Discussion

Figure 2 shows that for cohesionless soil nailed cut, factor of safety (FOS) increases with the increase of angle of internal friction and also increases with the increase of L/H ratio. Figure 3 indicates that for cohesive soil nailed cut, FOS increases with

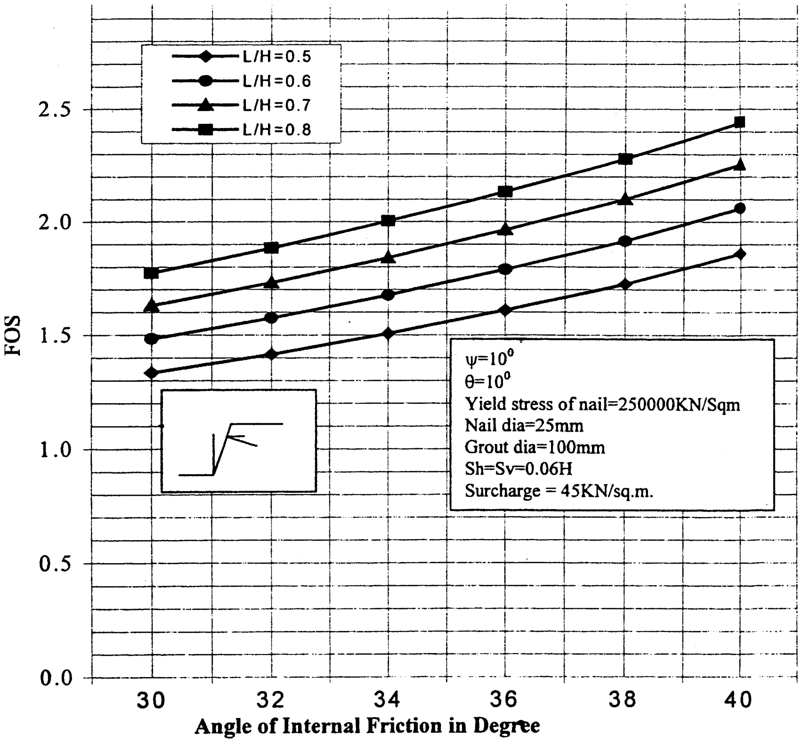

Figure 2. FOS versus angle of internal friction (for $c = 0$).

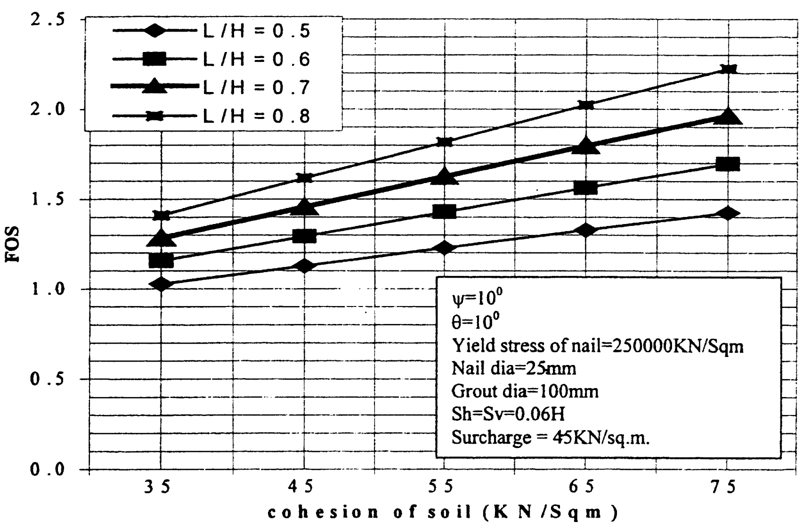

Figure 3. FOS versus cohesion (for $\phi = 0$).

the increase of cohesion of soil and also L/H ratio. Figure 4 indicates that for a soil nailed vertical cut, FOS initially increases with the increase of nail inclination for L/H ratio equal to 0.8, with horizontal (upto 15°) after which it decreases. Figure 5 illustrates a typical case for inclined nail cut where also FOS increases upto 15° nail inclination with horizontal for L/H ratio equal to 0.8, beyond which it decreases.

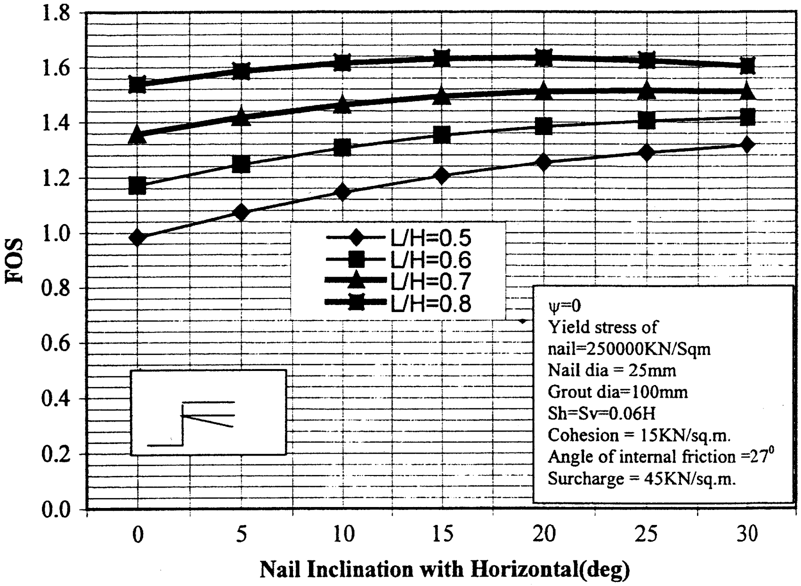

Figure 4. FOS versus nail inclination (for vertical wall/cut).

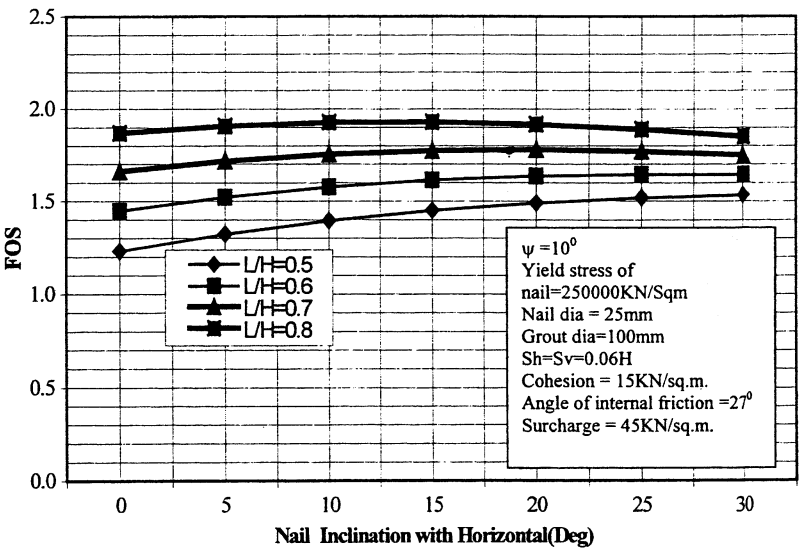

Figure 5. FOS versus nail inclination (for inclined wall/cut).

Figure 6 illustrates that for inclined cut (or wall), FOS increases with increase in nail diameter. Figure 7 shows a comparison in vertical wall and inclined wall. It shows that for an inclined wall, FOS is more as compared to vertical wall. Further,

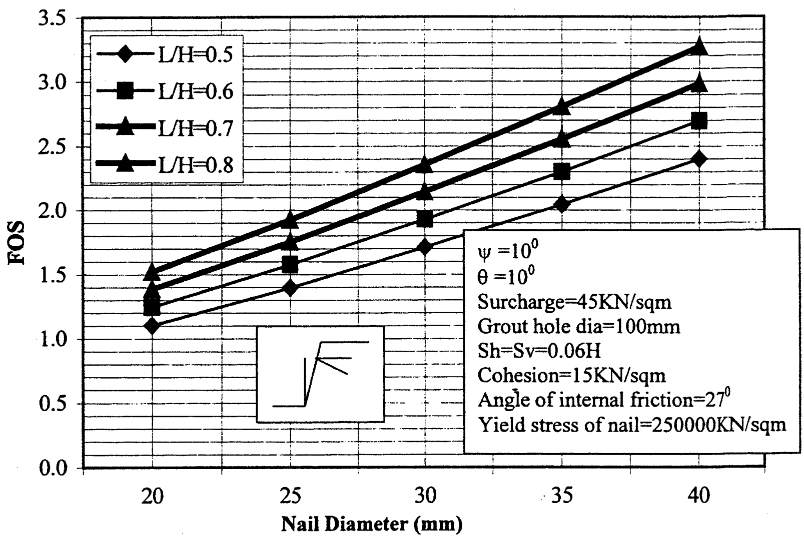

Figure 6. FOS versus nail diameter (mm).

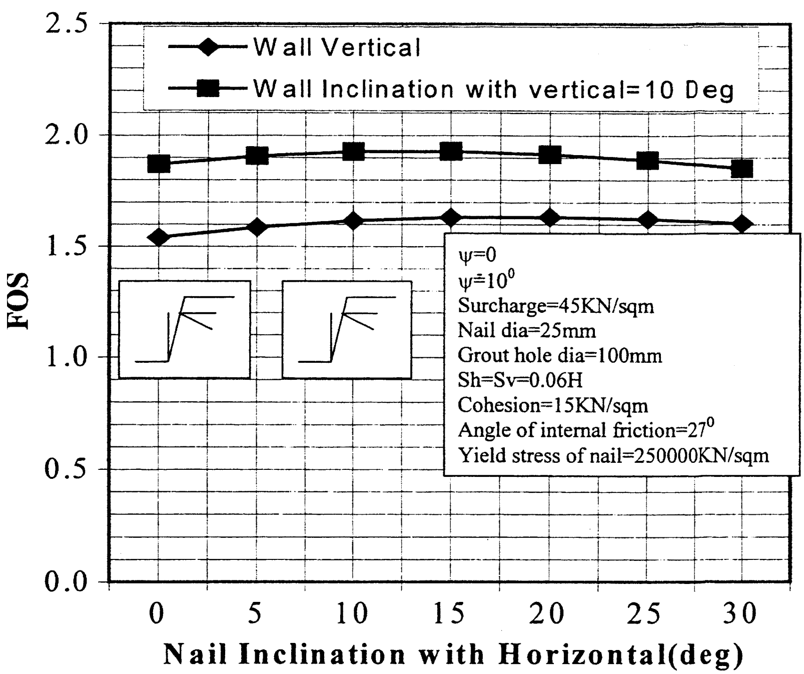

Figure 7. FOS versus nail inclination ($L/H = 0.8$).

the FOS increases upto 15° nail inclination with horizontal but beyond that it has declining trend. The declining trend is more in case of inclined wall. This is a typical case for one particular value of L/H ratio as 0.8. Figure 8 illustrates a typical case of nail inclination ($\theta = 10°$) with horizontal, where FOS increases with wall inclination with vertical. Rate of increase is uniform upto 20° beyond which rate of increase is high. This is a typical plot for angle of of internal friction as 27°. Figure 9 shows that for horizontal nail also, FOS increases uniformly with increase

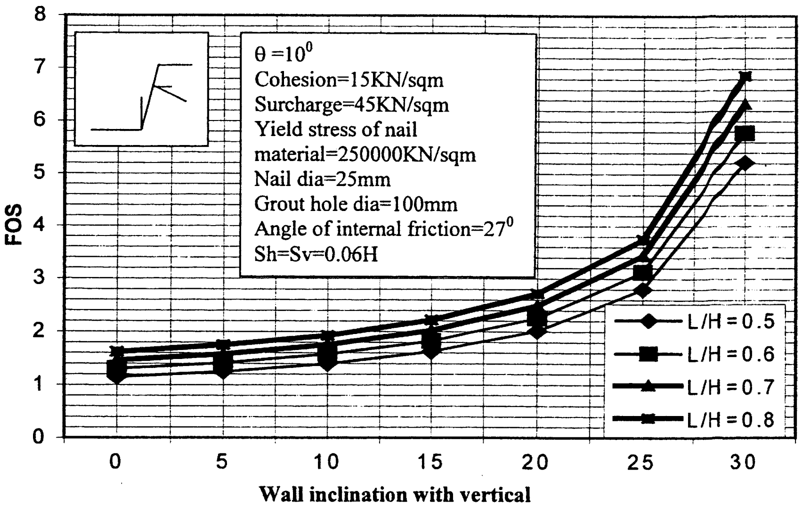

Figure 8. FOS versus wall inclination (for inclined nail).

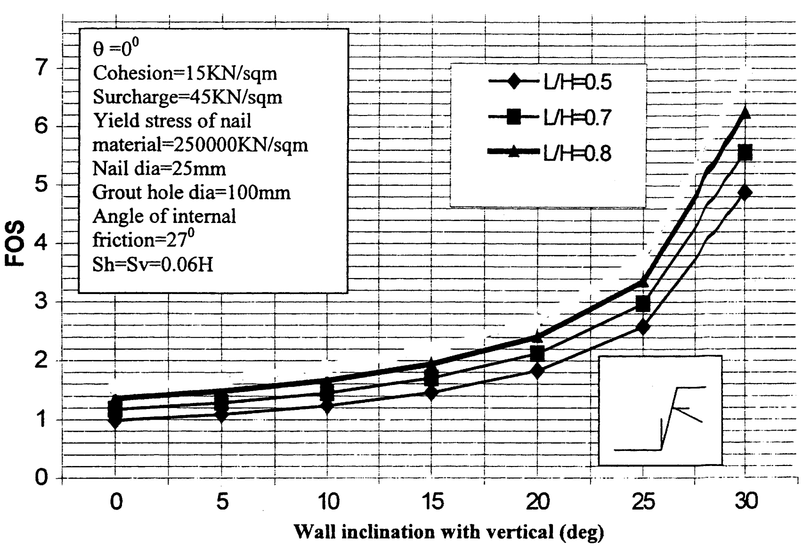

Figure 9. FOS versus wall inclination (for horizontal nail).

is wall inclination upto 20° with vertical, beyond which the rate of increase is high. Figure 10 illustrates that in a nailed wall where nail is inclined, FOS is more than that with nail laid horizontally and it coincides at about 25° wall inclination with vertical.

Figure 11 illustrates that FOS is more for nail grouted with concrete than that for driven nail. Further, this trend linearly increases upto L/H 0.8, beyond which the increase in FOS is very nominal. Figure 12 illustrates that FOS increases with L/H ratio. The other important finding of the study is that nails grouted with cement give more FOS as compared to driven nails.

5. Field Study of Rainfall Erosion Control

Erosion due to rainfall is quite common in those areas where loose soil is available and where there are chances of landslides. It is indicated in the review of literature that the nail is useful for constructing stable underground cuts and also for stabilization of the loose soil *in situ*. A field study was made by using the nails along some

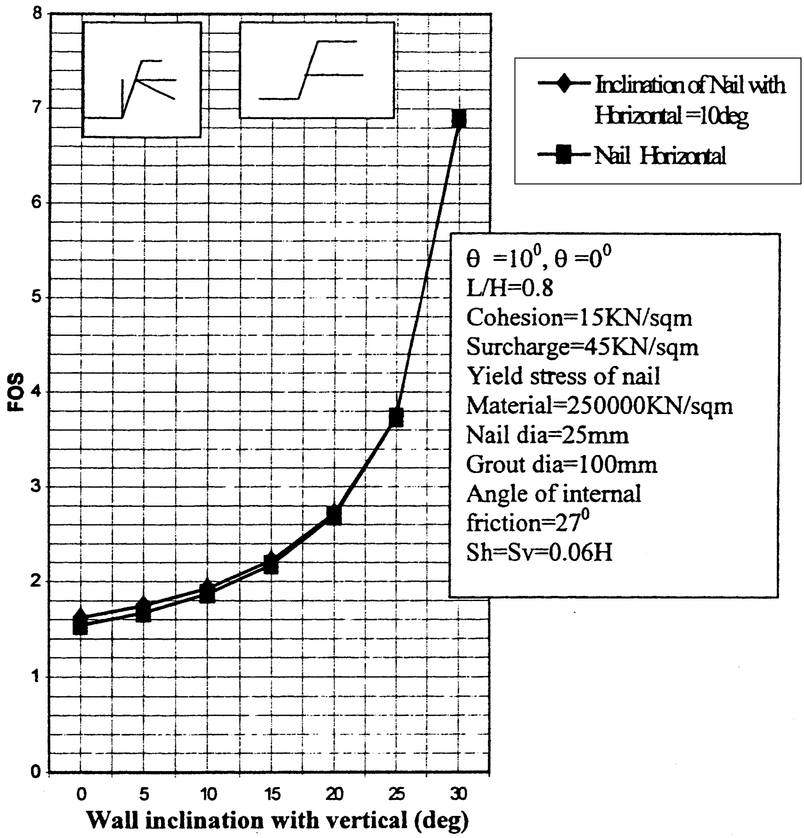

Figure 10. FOS versus wall inclination.

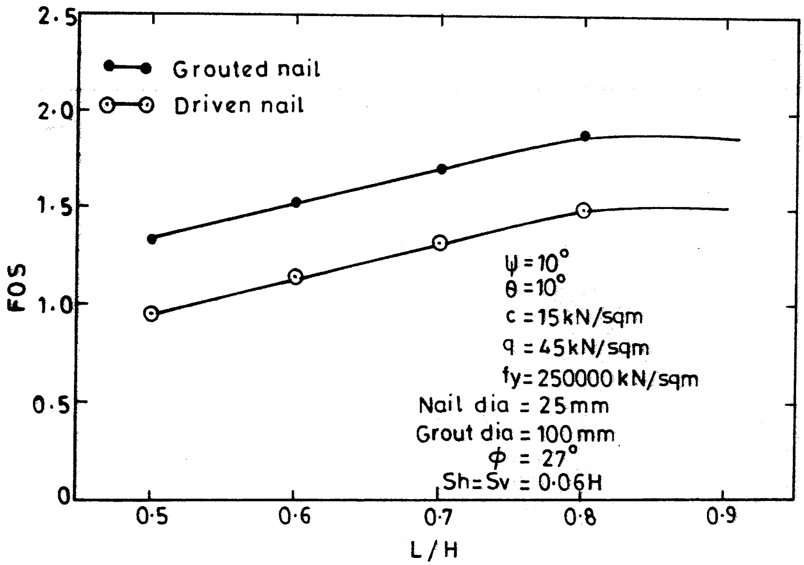

Figure 11. FOS versus L/H ratio.

length of slope of river cross-section in a river. To compare the performance of driven and grouted nail, a continuous patch of 10 m was selected in the free board area of river bank. In first 5 m, the nails (tor steel bars of 25 mm diameter) were directly driven into the soil and in rest 5 m length, the nails were grouted in the soil by making bore holes in the soil. Tensile stress of the steel bars was 250,000 kN/m^2. Grouting hole diameter was 100 mm i.e. 4 times the diameter of nail, Nail length was 0.72 m (i.e. L/H ratio as 0.8) and it was driven at an angle of 10° with horizontal (Figure 12). To ensure the perfect driving of nail at designed angle, an arrangement was made by centrally welding a hollow G.I. pipe of 38 mm diameter and 300 mm length with a steel plate of 100 mm width with 38 mm diameter hole in its centre. The pipe was welded at an angle of 10° with horizontal. While driving the nail, the nail was passed through this hollow pipe before inserting into the soil and was gradually slipped into the soil medium with the help of hammer. This ensured the nail angle of 10° with horizontal into the soil medium. For remaining 5 m length, the nail grouting was done by making a bore hole into the soil with the help of an auger. To ensure that the hole is made at an angle of 10° with the horizontal, another system was prepared (on the pattern of driven nail case) where the hollow pipe was of 150 mm diameter through which an auger of 100 mm was passed to make a bore hole of 100 mm diameter. After making the bore hole, the nail was centrally placed and the concreting was fired into the bore hole. A concrete mix of 1:2:4 proportion was used for grouting. A 50 mm thick shotcreting was done after driving the nails into the soil medium in both the cases. A wire mesh was put on natural soil covering the nail heads exposed in free board area. The wire mesh was kept in place by fixing U-shaped steel hooks through mesh into the soil. Thereafter the concrete was put manually on the wire

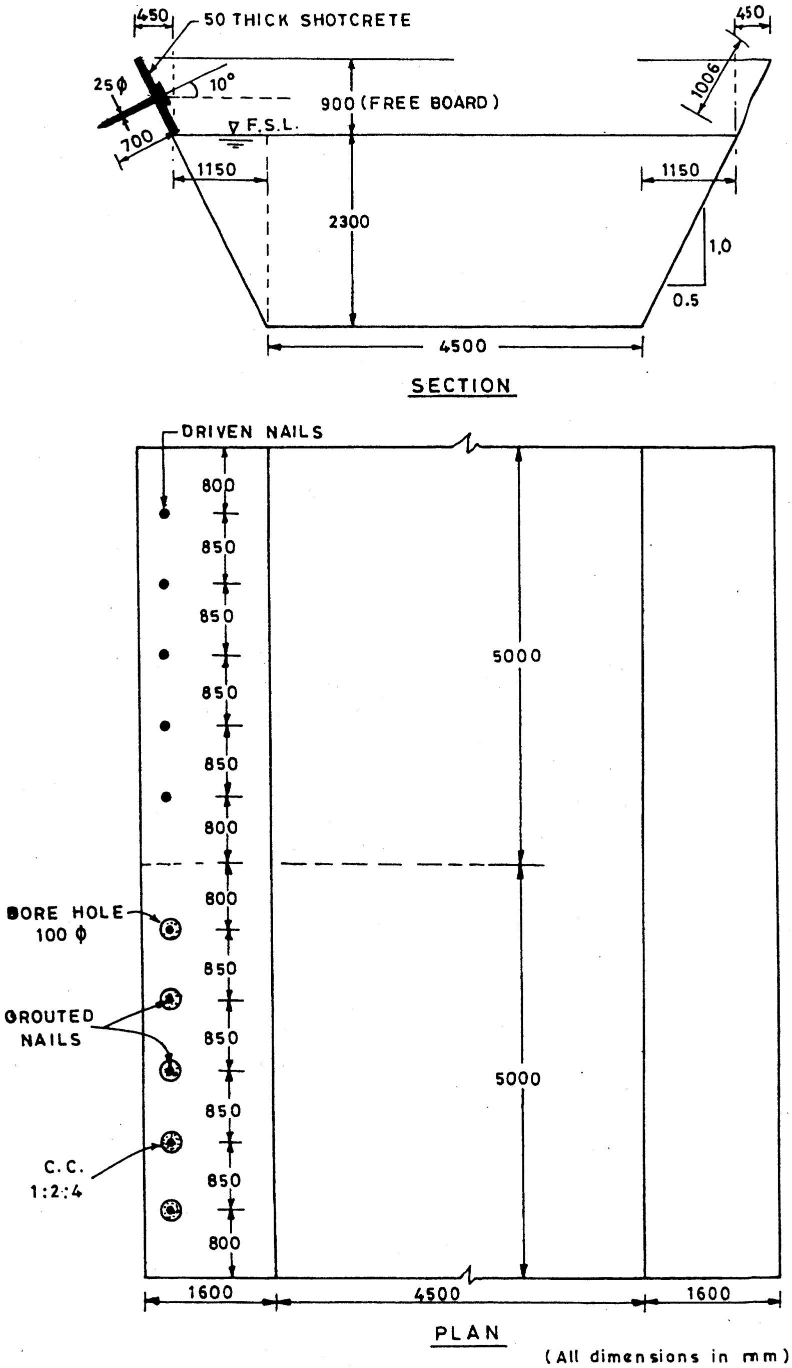

Figure 12. Schematic of soil nailing in river section.

mesh (due to non-availability of concrete pump, the concrete cover was laid by manual operation only) thus, covering the entire nailed area. The horizontal spacing of the nail was kept as 900 mm, thus, a total of 5 nails were driven into the ground as shown in Figure 12. The work was done before the monsoon period.

After driving the nails, the site was left for performance evaluation. After monsoon period it was seen that bank with grouted nail was fully intact whereas the bank with driven nails was about less eroded. This erosion was compared with the untreated length of bank just adjoining to treated length. The erosion was towards the river bed in untreated length of bank. This field observation also suggests that in high rainfall areas, nails grouted with cement concrete may be adopted for rainfall erosion control.

6. Conclusions and Recommendations

From the study, following conclusions can be drawn:

1. The soil nailing is a useful method for protection of loose soil and slopes from rainfall induced erosion.
2. The friction circle method may be adopted for design of nailed open cuts.
3. For L/H 0.7 and 0.8, the factor of safety increases with nail inclination with horizontal upto 15°, beyond which the factor of safety decreases, however, for L/H 0.5 and 0.6, the FOS increases, though marginally, beyond nail inclination of 15° with horizontal.
4. Nails grouted with cement are more effective than driven nails into the ground.
5. The nail length upto 0.8 times the height of cut is a reasonable length for providing a stable cut, minimum nail length of 0.7 m performs well in field (as also shown by Gupta (2002) in field.
6. The soil nailing method does not require any skilled labour or sophisticated tools. Hence it may be adopted at sites where soil stabilization is necessary.

References

Davis, M.C.R., Jacobs, C.D. and Bridle, R.J. (1993) An Experimental Investigations of Soil Nailing, Retaining Structures, Thomas Telford, London, pp. 587–598.

Gupta, R.P. (2002) A study on soil nailing with respect to open excavation and slopes, M-Tech. Dissertation, IIT, Roorkee.

Jewell, R.A. and Pedley, M.J. (1990) Soil Nailing Design: The Role of Bending Stiffness, Ground Engg, March, pp. 30–36.

Juran, I., Baudrand, G., Farrag, K. and Elias, V. (1988) Kinematics limit analysis approach for the design of nailed soil retaining structures, International Geotechnical Symposium on Theory and Practice of Earth Reinforcement/Fakuoka Japan.

Juran, I. and Elias, V. (1991) Soil Nailing for Stabilization of Highway Slopes and Excavation, Federal Highway Administration Publication No.FHWA-RD-89-193.

Juran, I. and Elias, V. (1992) Ground Anchor and Soil Nailing in Retaining Structures, Found. Engg, Handbook, Van Nostrand Company, 2nd ed., pp. 868–905.

Patra, C.R. and Basudhar, P.K. (2001) Nailed soil structure: an overview, *Indian Geotechnical Journal*, **31**(4), 322–362.

Plumelle, C. and Schlosser, F. (1990) A French national research project on soil nailing: Clouterre, performance of reinforced soil structure, Proc. of Int. Reinforced Soil Conference, Glasgow, pp. 219–223.

Saran, S., Mittal, S. and Gosavi, M. (2006) Pseudo Static Analyses of Nailed Excavations in Sands, Accepted for publication in Indian Geotechnical Journal.