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Nailed Soil Structure : An Overview

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Introduction

In-situ soil reinforcing by passive bars called "Nailing", is generally adopted to retain excavation, construct in-situ nailed soil-retaining structures and stabilize unstable slopes and is increasingly being finding wide acceptability all over the world. The reinforcements are placed either in predrilled bore holes and grouted along their whole length or may be driven or fired into the ground (generally by vibro-percussion system) with desired inclination. Model and large-scale field tests have been undertaken for proper understanding of the behavior of nailed slopes. The knowledge and experience gained from these studies helped in developing various design and analysis methods based on limit equilibrium, limit analysis and finite element technique for stability computations of such slopes.

An effort is made in this paper to collate the available information in a concise manner on the subject at one place for easy accessibility.

State of the Art

Here a brief review of literature pertaining to the successful application of the nailing technique for in situ ground modification (Fig.1) under very adverse and trying conditions is presented. The gist of the cases presented in the Table-1 is enough to provide confidence to use nailing as an alternative to the expensive cantilever, counterfort type of earth retaining structures and tie back walls. An overview of experimental and theoretical studies leading to the development of various methods of analysis of soil-nailed structures is presented as follows.

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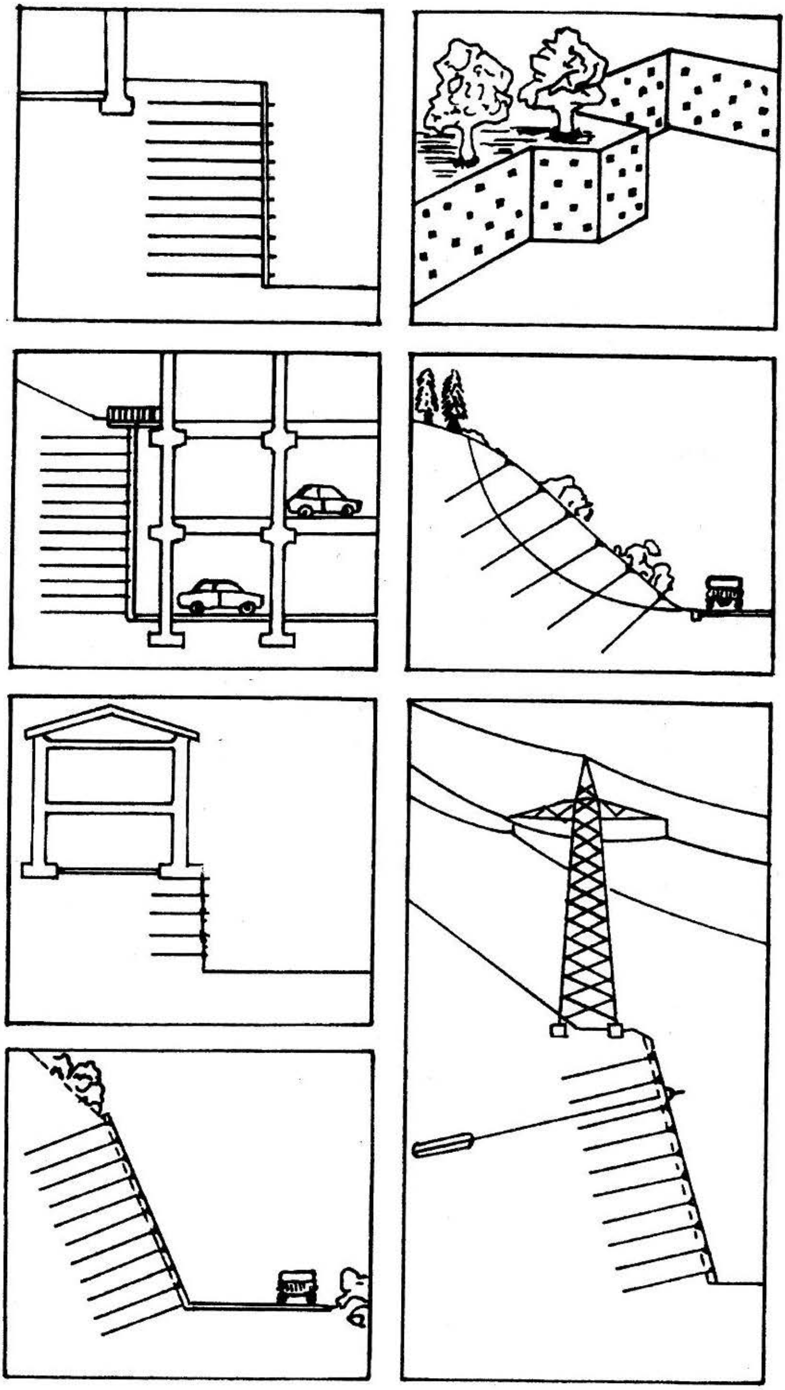

FIGURE 1 : Examples of Soil Nailing Applications (The BAUER System Schrobenhausen)

TABLE 1 : Nailed Slope : Case Studies

Site	Objective	Construction	Authors
At Lor. Terigu Bukit Timah Diversion Canal-Phase I, Singapore	To stabilize a failed slope (about 24 m high and 100 m in length) along the canal by nailing	First stabilized by sheet piles, then by nailing	Tan et al. (1988)
Near Singapore General Hospital	To stabilize a steep slope near Singapore General Hospital	The slope has been rein forced with 8m long nails at 2 m c/c.	Tan et al. (1988)
Pennsylvania, U.S.A.	Stabilization of road cut into steep hillside along the bench of a river.	Inserts placed to provide maximum width at top.	Schnabel (1991)
Cumberland Gap, Border of Kentucky and Tennessee, U.S.A.	Replacing the steep grades and present road, resulting in 12 m high nailed wall.	Excavating in lifts of 1.5m with sequential installation of shotcrete and nails.	Schnabel (1991)
Easton, PA, U.S.A.	Construction of 14.4 m high permanent nailed wall	Construction began with excavation of a shallow cut.	Schnabel (1991)
Phoenix, Arizona	Construction of a deck by nailing, which allows for the protection of adjacent property.	A cut was required to be made adjacent to a Row of bushes and palm trees.	Schnabel (1991)
San Francisco, CA, U.S.A.	To underpin heavily loaded structures by soil nailing.	Concrete piers, soil nails and shotcrete were adopted.	Schnabel (1991)
Phoenix, Arizona	Stabilize a cut required to install a 2.5m pipe 19.8 m below grade.	No sufficient room to slope the cut by retaining wall.	Schnabel (1991)
Monroeville, Pennsylvania, U.S.A.	For the construction of a parking lot for commercial development in a hillside.	In-situ nailing adopted as an alternative to costly cantilevered retaining wall.	Schnabel (1991)

TABLE 1 : Continued

Site	Objective	Construction	Authors
Bypass Channel, Walnut Creek, California, U.S.A.	For the excavation of a 15.25 m wide by 6.1 m deep drainage within a few feet of existing building, for the bank protection.	Buildings were under pinned by drilling through the footings. Reinforced horizon-tally with soil nails.	David (1991)
Phoenix, Arizona	Protection of street and utilities nearby an excavation to install a drainage tunnel junction and avoid high cost of drilling soldier beam.	Soil nailing was installed in 1.5 m lifts by placing wire mesh and shotcrete to exposed surface.	David (1991)
Fredericksburg, Virginia, U.S.A.	Stabilization of a 9.6 m cut action of tiebacks with soil nails called TEN Wall (tied back element nailed wall).	Seven rows of nails and one row of tie backs were installed by pressure – injected grout method.	David (1991)
Marine Training Facility, Near Coleville, California, U.S.A.	To retain the slope above a bench cut 6.1 m high, for a water storage tank; nailing was adopted to avoid aesthetically undesirable over excavation required for a conventional retaining wall.	Wire mesh was welded to bars & nails were installed in 10 cm diameter drilled holes.	David (1991)
Pullman, Washington	Building a soil-nailing support system needed to excavate a 12.2 m cut for a new chemistry building of Washington State Univ.	The system could be constructed rapidly with short steel tendons and shotcrete that are readily available	Schnabel (1991)
Pullman, Washington University, Washington, U.S.A.	For building an extension to the chemistry building at Washington State University the protection to the excavation on four sides (7.6 m to 13.7 m deep), soil nailing was adopted because of the quick start up time and shorter construction duration.	Soil nails were installed with a hollow-stem auger to prevent the drill hole from collapsing. Vertical drains, wire mesh and shotcrete were applied to each lift while excavating in a spiral fashion.	David (1991)

TABLE 1 : Continued

Site	Objective	Construction	Authors
St. Peter Port, Guernsey, U.K.	For the construction of a new office and residential development, where an existing 20 m high 53° slope was to be re-graded to 70° over the lower 10m and below the base of slope a basement was constructed.	Nails installed at 20° below horizontal. Corrosion protection was provided by a corrugated P.V.C. sheath. A geogrid was rolled over the surface of the slope.	Pedley (1992)
Denholme Clough, Bradford, U.K.	To stabilize existing retaining walls, which exhibited bulging and collapse in the road crossing an open hillside.	Soil nails installed at 15° inclination with steel mesh positioned on face of the wall with gunite sprayed over the wall.	Barley (1993)
Cymsiflog, Glamongan, U.K.	To stabilize an existing masonry wall exhibiting cracks, bulging and movement and thus endangering a school building.	Corrosion protection was provided by continuous corrugated plastic duct.	Barley (1993)
Beaufort Road, Bristol, U.K.	To stabilize an existing masonry wall retaining ground plus an upward 50% slope ground for the construction of a new building at top.	Nails were installed on a grid pattern at 20° inclination working from top to bottom.	Barley (1993)
Amphthill Road, Bedfort, U.K.	To stabilize an existing high gravity brick wall supporting trunk road in the approach to a road over a rail bridge as some movement in the wall appeared.	Nail lengths ranged from 8.5 to 12.5 m at 10° to 20° inclinations.	Barley (1993)
Birmingham, U.K.	For stabilizing a steep face up to 8 m in height for building construction.	Construction in a downward progression with shotcrete facing.	Barley (1993)

TABLE 1 : Continued

Site	Objective	Construction	Authors
Between Chirg and Glyn Ceirog in North Wales, U.K.	To stabilize a steep embankment (100% gradient and maximum height of 12 m) having a main road at below and minor road at top.	The nail steel consisted of high yield bar complete with galvanized plates and nuts at the head.	Barley (1993)
Lakeside, Thurrock, U.K.	To stabilize a 500 m long, 15 m high face, for of a modern shopping complex within an extensive disused chalk quarry.	Stabilization was carried out by installation of bolts threaded with cables to support galvanized mesh.	Barley (1993)
Cantareira Water Supply Project, Sao Paulo, Brazil	For stabilization of a 30 m high slope in a tunnel portal of the water supply project.	Nails of equal length inclined downward.	Ortigao et al. (1995)
Paulista Railway Lines, Brazil	For the stabilization of 26 m high abutment of a Railway bridge in soil consisting of residual soil.	Stabilized by steel bar nails in boreholes inclined backwards at an angle of 75°.	Ortigao et al. (1995)
Tabaao da Serra, Brazil	To protect the slope near an existing building. Slope height is 12 m.	Nail length varied from 8.5 m at top to 4.5 m at bottom.	Ortigao et al. (1995)
Salvador, Brazil	To stabilize a slope, height of 18.3 m excavated to steeper slope for a building construction.	Nail length varied from 7 m at top to 5m at bottom positioned normal to slope face.	Ortigao et al. (1995)

Stocker et al. (1979) carried out model tests and large-scale field tests for nailed-soil walls and measured deformations within the reinforced soil, surface deformations of the nailed ground along with the forces and strains in the nails. They observed two kinds of failure mechanisms governed by the location of the loading. Where loads are closer to the edge of the slope, a simple failure mechanism with one slip line has been observed. But when loads are away from the edge of the slope a composite mechanism of two blocks, consisting of a triangular soil block under the load and trapezoidal nailed soil mass separated from each other by a secondary slip line was observed.

Shen et al. (1981a, 1981b) reported the performance of a lateral earth support system (in-situ-earth reinforcement) at the two sites. The predictions from finite element analysis agree with the field measurements indicating that the analytical procedure so developed can predict correctly the field behavior.

Gassler and Gudehus (1981), Gassler (1988) conducted four large scale field tests on nearly vertical nailed cuts in cohesionless soils and analyzed various failure mechanisms based on their field and model tests. Only tensile capacity of the reinforcement has been taken care of while determining the stability of the reinforced soil mass. They adopted kinematically admissible failure mechanism of rigid bodies to find the minimum factor of safety varying the inclinations of slip planes and suggested four failure modes such as, translation of a rigid body, translation of two rigid bodies, rotation of one rigid body and rotation of two rigid bodies. The results obtained from the above failure modes are in good agreement with model and field test results and the translation mechanism of one or two bodies and the simple rotation mechanism are found to be more relevant to practical design.

Schlosser (1982) developed a multi-criteria based design method for nailed soil structure, considering soil- reinforcement friction and the normal earth pressure on the nail and used the method of slices. He suggested that the consideration of the principle of maximum plastic work enables one to estimate the shear and tensile forces mobilized at failure in each nail. He reported that the predictions made by using his design method are in good agreement with observed values for a large number of reinforced structures.

To avoid the difficulties associated with drilling large diameter piles, Guilloux et al. (1983) proposed installation of nails over the original Berlin wall proposal for the construction of retaining wall in very dense moraine soil. They considered the effect of dilatancy resulting in the parabolic shape of the Mohr-coulomb envelope and investigated the effect of swelling due to heavy frost during winter in both the walls. The movements in nailed wall was lesser compared to that of the Berlin wall.

Gassler and Gudehus (1983) proposed a statistical approach for the design of nailed slopes where the parameters like unit weight, friction angle of soil, pull out resistance of nails and surcharge stress are introduced as stochastic variables. With the partial safety factors of 1.1 for friction and surcharge, and 1.3 for nail forces, the design yields negligibly low value of probability of failure (P_f).

Juran et al. (1983) conducted direct shear tests on nailed soil mass and carried out theoretical analysis to study the mechanism of interaction between the soil and nails. They carried out finite element analysis also and investigated the relative influence of different parameters such as normal stress, on the failure surface, rigidity, number of the nails and the efficiency of reinforcements. Very small displacements are sufficient to generate friction at the soil/nail interfaces and to mobilize high tensile forces in nails. Whereas, relatively large displacements are necessary to mobilize the passive lateral earth thrust on the reinforcements and to generate the bending moments in the nails.

Blondeau et al. (1984) developed a computer program (TALREN) to calculate the internal and external stability of various reinforced soil systems like soil nailing, prestressed anchors and reinforced earth works. Considering interaction between the inclusion and the soil, they analyzed the tensile and shearing forces, bending moments developed in the inclusions. The comparison between the actual behavior (in some of the failed structures) and the theoretical safety factor values are in good agreement.

Sano et al. (1988) reported briefly the design and construction of reinforced cut slope and excavation of reinforced earthwork. The design is based on the past experiences or on the stability analysis depending on the scale of expected failure. Up to 2m depth the design is based on the past experience. They have suggested that stability analysis should be done based on circular slip failure, wedge type slip failure depending on the type of sliding surface expected.

Kitamura et al. (1988) conducted model tests to study the effect of steel bar reinforcement in vertically loaded reinforced sand slopes. They concluded the following: (i) The maximum and minimum effect of the reinforcement is obtained respectively for the horizontal and the inclined upward placement of the nails. The inclined downward reinforcement is less effective compared to the horizontal one, the difference in the results being only 2%. (ii) Bending and shearing resistance of steel bars do not contribute significantly to the reinforcement effect. (iii) Location of the largest increase of axial stress at each loading step is in between the slip surfaces of reinforced and unreinforced slopes.

Nagao et al. (1988) conducted large-scale field loading tests on natural earth slope reinforced with steel bars to study the mechanism of stability of reinforced earth. Loading tests were simulated using two and three-dimensional FEM analyses and opined that the two-dimensional plain strain FEM analysis is very effective.

Gutierrez and Tatsuoka (1988) conducted a number of small-scale model tests of reinforced slopes and measured tensile reinforcement forces and strain fields. The results were analyzed by using limit equilibrium method modifying the ordinary method of slices incorporating the inclined reinforcement forces and the inclined footing pressure. They found the method to be simple and accurate.

Matsui and San (1988) formulated a finite element method of analysis for a reinforced cut slope and indicated that there exists a minimum inclusion length beyond which the performance cannot be significantly improved.

Treating the reinforced soil as macroscopically homogeneous material Sawicki et al. (1988) analyzed the mechanical behavior of a steep nailed slope by FEM to predict stresses in the reinforcement assuming that slippage on the interfaces between both the constituents is negligible. Data corresponding to real field problems were used for the same. A good agreement between theory and experiment has been obtained.

Tan et al. (1988) reported the stabilization of a large slope failure at Lorong Terigu and the cut slope at the Singapore General Hospital (part of the Central Express way project) by soil nailing. A design methodology for soil nailing was presented by modifying Bishop's simplified method, which was developed in PWD, Singapore using the multi-failure criterion proposed by Blondeau et al. (1984). They concluded that the factor of safety of a nailed slope be calculated by considering shear and pull out effects. Consideration of pull out capacity only is generally adequate.

Juran and Chen (1989) developed strain compatibility approach for the design of reinforced earth walls. It is fundamentally based on the analogy between the plain strain shear mechanisms that develops along a potential failure surface in the actual structure and the response of the reinforced soil material to direct shearing. In order to verify the model/design assumptions, numerical simulations of the construction process are compared with at-failure observations on reduced scale laboratory model walls as well as with tension forces measured in reinforcements of both reduced scale model walls and full scale structures. The assumption that the construction process does not have a significant effect on the maximum tension forces generated in reinforcements of actual structure seems to be more consistent with the observed structure behavior and should be adopted in design purposes.

Juran et al. (1990a) developed a kinematical limit analysis for design of soil-nailed structures. It allows for the evaluation of the effect of main design parameters (inclination and bending stiffness of the nails, embankment slope, facing inclination, and soil -strength characteristics) on the magnitude and location of the maximum nail forces and on the structure stability. This design procedure enables one to estimate nail forces and thereby to evaluate local stability at the level of each nail, which can be significantly more critical than the global stability. Their design method has been evaluated through the analysis of both full-scale experiments and reduced-scale model tests. The comparison shows that the predictions regarding the nail forces match fairly well with the measured values. It also provides a rational approach to predict the progressive pullout failure, which is generally induced by the sliding of the upper nails.

Comparative studies of the available design methods (i.e., French, Davis and kinematical design methods) to analyze soil-nailed retaining structures were made by Juran et al. (1990b). French and Davis methods ensure global stability of the structure whereas the kinematical method examines the local stability, which can be more critical than the global stability. The Davis method yields a more conservative design scheme as compared with the French method. The kinematical and French methods permit an evaluation of the effect of ground water and nail bending stiffness on the stability of structures.

Hayashi et al. (1990) performed a series of model tests for investigating the mechanism of soil reinforcement of cut slopes with steel bars. Based on the results of their model tests and in-situ experiments, a design method of soil reinforcement with steel bars were developed by modifying the Bishop's method of slope stability, considering the tensile and shear resistances mobilized in each reinforcement.

Plumelle et al. (1990), 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 facing were instrumented and pull-out tests were performed to determine the soil-nail lateral friction. Analysis of the same using using both finite element calculations and the TALREN computer program gave rise to the following conclusions: (I) The line of maximum tensile force and maximum bending moment generated in the nails coincides with the actual failure zone observed. (ii) The mobilized tensile force develops progressively during excavation and can increase with time, especially if the safety factor is low. (iii) Under large deformations, the bending resistance of the nails is mobilized, providing a greater resistance to failure. (iv) The failure surface intersects the ground surface at a distance of approximately 0.35 times height from the wall face. (v) The lateral deformations of the wall are approximately equal to the vertical deformations and are of the order of 0.3% of the wall height. (vi) The FEM analysis predicts lower values for the horizontal displacements developed in the soil mass of nailed structure whereas TALREN method predicts the actual behavior of the same.

Long et al. (1990) reported the importance of some variables like the shape of the assumed failure surface, wall height and inclination, soil strength, inclination and length of nails, on global stability of soil nailed walls. Factor of safety computations for many failure surfaces revealed the presence of numerous local minima. Comparison of results obtained with circular, bilinear and 3-part wedge failure surfaces show that the 3-part wedge is the least constrained failure surface. The estimated factors of safety are affected by the method of analysis and so also by the interslice force inclinations; higher interslice force inclinations result in higher factors of safety. For low values of nail capacity, all the three failure surfaces predict similar stability. As the nail capacity factor increases to 1.25, the influence of the soil nails becomes more important and the failure surface becomes more curved. The higher curvature increases the difference between the factors of safety values computed by using circular and non-circular failure surfaces. The number of rows of nails can significantly influence the shape of the failure surface, its location and the factor of safety. They have shown that the factor of safety increases with increase in the number rows of nail.

Jewell and Pedley (1990) have drawn attention to the errors in the analysis for soil nails, which has been incorporated into design manuals (Mitchell and Villet 1987; Elias and Juran 1988). This analysis may overestimate the shear force by as much as a factor of 10. Hence to assist understanding they evolved revised design equations for elastic and plastic analysis to estimate the forces in nails under combined loading. They reported that, though bending stiffness of the nails are beneficial their influence on slope stability appears to be small compared to that due to the axial reinforcement forces. As such, for design purposes they recommend that the bending stiffness be ignored altogether.

Kakurai and Hori (1990) carried out in-situ measurement of ground displacement and axial forces in the nails of a nailed soil slope. The axial forces increase immediately from the start of the excavation and then gradually increase in between the excavation stages. They carried out an elastic-plastic finite element analysis for determining axial forces in the nails and the local shear safety factor. Measured and calculated values of axial forces were found to match well at one section but not at another section. They further developed a method similar to the Fellenius method to determine the factor of safety of nailed soil slopes considering only axial forces in the nails.

Stocker and Riedinger (1990) made the following observations by carrying out long term test (over a period of 10 years) on a 15m high nailed-wall in a cohesive soil.

(a) The top nail does not substantially contribute to the retaining force of the wall system

(b) The nail force increases for a short duration during construction and remains almost constant thereafter.

(c) The main deformation occurs at the top of the wall.

(d) The horizontal displacements of nailed soil wall are larger than that of anchored structures.

Juran (1987), Juran et al. (1988), Juran and Elias (1990) 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.

Leshchinsky (1990) raised the following questions of deficiencies of the "kinematic limit analysis for design of soil nailed structures"proposed by Juran et al. (1990a) where the boundary conditions at the crest are disregarded. He opined that the values of the predicted nail forces are questionable, especially if viewed through local equilibrium (or local stability). Though horizontal and moment equilibrium are explicitly satisfied the vertical equilibrium seems to be ignored and hence the problem becomes statically determinate once it is solved using this scheme. It appears that one equation is in excess of unknowns, possibly resulting with a redundant and inconsistent solution.

Schlosser (1991) agreed that the influence of bending stiffness and shear on the global safety factor is small, less than 15%. However, the local safety factor in the nail may not be adequately represented if only tensile forces are considered. His multicriteria method is more general and can be applied to small diameter nails and to micropiles, which contribute definitely to bending strength.

Jewell and Pedley (1990a, 1990b, 1991) severely questioned the significance of bending stiffness in soil nailing design, and hence the fundamentals of the multicriteria and, generally speaking, the kinematical and the Cardiff methods. They state that nail shear has a negligible effect and should not be taken into account due to the unnecessary additional computational effort.

Kirsten (1992) has developed methods based on limit equilibrium, closed - form elastic and numerical plastic analyses for the design of a 12 m deep excavation reinforced with nails. The factors of safety against shearing failure at the toe and heel were found to exceed unity. Various analyses give similar factors of safety values. The horizontal displacements determined from the elastic analysis correspond closely to actually observed displacement under stable conditions but those determined from the plastic analysis underestimate the observed displacements.

Kirsten and Dell (1992) developed a method (based on limiting equilibrium) for the design of soil nailing to support cut faces of a basement excavation for an apartment building. Stability of the same, both short term and long term, was considered separately. For short-term loading case, the material is marginally overstressed on the front surface at the bottom, which confirm the importance of not excavating the faces extensively without being duly supported. The factors of safety for the long term loading case exceeded unity by acceptable margin.

Juran et al. (1992), in a reply to the question put by Leshchinsky (1990) asserted that for a standard coulomb material the logarithmic spiral slip line is the only kinematically admissible solution compatible with the observed displacement mode. Their analysis illustrates that in reinforced-soil system the vertical force transferred to the foundation soil is relatively small as compared to lateral earth pressure retained by the reinforcement. The close agreement between the kinematical limit analysis and the experimental data on instrumented full-scale structures reported by them appears to strongly justify the engineering assumptions used in their kinematical analysis.

In response to the queries made by Schewbridge and Sitar (1992) on the strain compatibility design methods Juran and Chen (1992) concluded that the difficulties involved in a rational simulation of the complex engineering behavior of reinforced soil structures are still far from being resolved. The strain compatibility design approach is merely an attempt to improve design practice taking more properly into account the effect of material properties on the structure behavior.

Juran et al. (1992) replied to the criticism made by Jewell and Pedley (1990) for neglecting the effect of nail bending stiffness on the structure stability. They suggested that both the kinematical limit analysis and the model test results illustrate that, the mobilization of the bending-stiffness effect is not a source of improvement to the structure stability. On the contrary, it may result in a significant decrease of the structure stability and should therefore be evaluated in the design. The bending-stiffness effect depends upon a variety of parameters including nail stiffness, nail inclination, soil stiffness (reaction modulus), and boundary conditions. Therefore, it is necessary to develop an appropriate analysis procedure to predict the bending stiffness for different design schemes and experimentally verify the same.

Jewell and Pedley (1992) have reported that the ability of soil nails to increase the shear strength of soil by acting under combined loading, namely, shear and tension is one of the more controversial aspects of design. For any structural member there is a relationship between the maximum bending moment and axial force, where the bending moment is in turn a function of the shear force in the member. The magnitude of this force can be found by adopting either elastic or plastic model of soil-nail interaction. They gave design equations both for grouted nails and nails without grouting. The obtained results revealed that the contribution of bending stiffness in comparison to the same due to the axial force in the nail towards the improvement in soil shearing resistance is very small and the improvement is also highly variable. So the design analysis should be simplified by ignoring the effects of bending stiffness, at the expense of only a marginal conservatism.

Asaoka et al. (1994) studied the development of internal force in the reinforcement (nailing) using rigid plastic finite element method modeled by "no length change condition", a kind of constraint imposed upon the plastic flow of soil skeleton at limiting equilibrium state. The analysis shows that, the increase of safety factor in cases of the c-f material is quite higher than Mises material, because in the c-f material, the bar acts like an anchor while in the Mises material the bar does not show such effects.

Huang and Tatsuoka (1994) analyzed by limit equilibrium methods, the results of a series of plane strain model tests of unreinforced and reinforced sand slopes loaded with a 10 cm. wide strip footing. They modified Janbus' method in order to incorporate the reinforcement force acting on the potential failure surface and inter-slice faces in the force equilibrium formulation. By using the mobilized angles of friction along the failure surface estimated at the moment of peak footing load, the Janbus' method and its modified one using a composite failure surface could predict rather accurately the stability of the unreinforced and reinforced model sand slopes. Factors, which affect the mobilized friction angle along the failure - surface are:

(i) Dependency of f on pressure level, (ii) the strength anisotropy, and (iii) the progressive failure of the slope. So, when a constant value of f is assumed in any rigorous analysis based on the limit equilibrium method, an operational strength parameter for which the effects of these three factors are taken into account should be used. Among these factors, the effect of the progressive failure is most significant as advocated by them.

Nanda (1995) presented results of a finite element analysis of a full scale instrumented experimental nailed-wall including nonlinear soil response, soil-nail interaction and staged construction. The predicted horizontal movements compared well with the measured values near the face. Away from the face, the analysis over predicted the movement. The predicted values of traction in nails compare well with the measured values, with the maximum traction a short distance behind the face.

Lee et al. (1995) applied discrete element method (DEM) to evaluate the stability of soil nailed earth structures. A slope is divided in to a number of slices that are connected with elasto-plastic Winkler springs. The condition of compatibility between slices and the condition of force equilibrium are maintained. They obtained differential equations combining the force equilibrium condition in soil-nail system with the frictional behavior. They estimated the tensile force of the nail at the failure surface by solving the differential equations with boundary conditions.

Sabahit et al. (1995) developed a design method for nailed soil slopes in conjunction with modified Janbu's generalized limit equilibrium method of slices. The minimum reinforcement force required to achieve a desired factor of safety is found by treating the orientation of nails and distribution of reinforcement forces as design variables. Considering overall equilibrium only analysis was carried out. Optimum locations of nails were found out by varying its position. The results predicted by their method are in agreement with those observed results reported in literature. They found that the horizontal position of nail give the optimum orientation.

Sokolevsky (1995) reported that the analysis of the equation for contact resistance to shear in non-cohesive soil allows to assess the influence of various combinations of soil parameters, material parameters, geometrical characteristics of nails, and opens up possibilities for optimization of nailed soil as a composite material.

Kim et al. (1995) investigated the effects of surcharge loading on the failure mechanism of nailed soil structures by performing reduced scale-model tests. Two different testing sequences were used to simulate respectively, the application of soil nailing in both new construction and rehabilitation or widening of earth-retaining system under surcharge loading. When applying surcharge loading, the failure of the system occurred through a progressive breakage of the nails initiated at the top of nails. Under low surcharge loading, the state of stress in the upper nails is close to the stress state for the unloaded wall. The locus of nail breakage points under surcharge loading is fairly close to that obtained with flexible nails without surcharge loading regardless of bending stiffness and construction sequence.

Kim et al. (1996) applied discrete element method (DEM) to evaluate the stability of slopes reinforced with nails. Their method is capable of not only estimating tensile and shear stresses in nails but also providing individual safety factors for soil and nails. They assumed that the nailed slope is composed of slices connected together with elastic - plastic Winkler springs. They considered the real sequence of construction to predict the measured tensile forces in nails for properly evaluating both local and overall stability of a reinforced slope. They considered two real field cases. They conducted a small - scale test in addition for more confidence in using the proposed method.

Abramson et al. (1996) reported that several design methods are available for nailed-soil structures. These are namely the Davis method (Shen et al.,1981), the German method (Gassler and Gudehus, 1981; Stocker et al., 1979) and the French method (Schlosser, 1982), limit equilibrium analysis method (Elias and Juran, 1991), the kinematical method by Juran (1987). They have emphasized that none of the above methods solve the soil nailed slope problems without inconsistencies in the input parameters, analytical methods, and comparisons to field behavior. Some of these inconsistencies include,

Lateral earth pressures inconsistent with nail force and facing pressure distribution (all methods). No distribution of nail forces according to construction sequence and observed measurements. Complex treatment and impractical emphasis on nail stiffness (kinematical method).

They further reported that the spacing, size and length of nails should be determined based on global and internal stability considerations. Design of wall facing is dependent on the nail forces assumed. The desired factor of safety used in the design analysis are different from case to case and should be compatible with the use of the wall (whether permanent or temporary) and economic and risk-to-human-life consequences of the slope.

Barley (1996) discussed that the maximum tension at the point of intersection of nail with potential slip surface must equal to grout/ground bond capacity within the active zone plus the bearing plate capacity (if plate contributes). He recommended the following for three soil nail test requirements prior to nail operations: (i) Pull out test on the distal half of the soil nail within passive zone (ii) Push in test on the proximal half of the nail within the active zone. (iii) Direct bearing test on plate.

Sabahit et al. (1996) presented a seismic design of nailed soil slopes based on pseudo-dynamic approach. They incorporated a finite shear wave velocity based on the assumption that the shear modulus is constant and only the phase not the magnitude of acceleration is varying with depth. The obtained results are compared with pseudo-static approach. They observed that the pseudo - static method can be used for coefficient of horizontal acceleration, K_h less than 0.2, however for K_h greater than 0.2, it is preferable to use pseudo-dynamic analysis. The horizontal placement of the reinforcement requires minimum reinforcement force for equilibrium. Hence, it is preferable to place the reinforcement in the horizontal direction.

Bridle and Davies (1997) conducted a series of large shear box (1.5m x 1.5m) tests to observe soil-nail interaction mechanisms in order to predict the local strength of soil reinforcement. The reinforcement pulls out and forms two plastic hinges on either side of the slip surface. It is indicated that at ultimate conditions a soil-nailed system is statically determinate. A computer program, CRESOL was developed to determine the stability of soil-nailed systems using a global analysis technique and for predicting tensile and shear forces in reinforcing elements under working conditions.

Smith and Su (1997) proposed a three-dimensional modeling of a nailed soil wall curved in plan by finite element method for construction, service and ultimate loading conditions. The horizontal deflection of the wall, surface settlement, the distribution of axial forces, bending moments and shear forces in nails are computed. It is seen that the failure mechanism may change for different loading conditions. The role of bending moment and shear resistance in the nails may be different during construction under service loading and at collapse.

Patra (1998) proposed the use of optimization technique in the optimum design of nailed slope. Stability analysis was conducted by considering both internal and overall equilibrium conditions. In the method so developed both vertical and inclined slices was chosen without any a-priori assumption regarding shape of the slip surface. The nail parameters like diameter of nails, their spacing, orientations and length were considered as the design parameters over and above the co-ordinates of the slip surface. The predicted critical slip surface and the corresponding value of the factor of safety were compared with those obtained from the model tests and other theoretical values reported in literature. It has been observed that the upwardly inclined nails result in optimum design; however the inclination being so small that the nails may be placed horizontally from practical point of view.

Liang et al. (1998a) derived analytical solutions based on the linear elastic-perfectly plastic model which provides insights into the interface interaction between the anchor and soil and general guidelines in design of an anchor system. The proposed analytical solutions consider soil movements along and normal to the anchor axis

The maximum interface friction and tensile stress occurs at the anchor end where the pull out loading is applied. They predicted that the induced anchor stress increases proportionally with interface stiffness, interface strength, deformation coefficient and anchor length, but decreases slightly with anchor diameter. The distribution of both interface friction and tensile stress are strongly dependent on the anchor length. The solutions, can be applied to the areas of anchored geosynthetic system, soil nailed structure.

Liang et al. (1998b) developed a displacement-based approach for the stability analysis of anchor reinforced slope based on anchor-soil interaction derived by them earlier. Interaction between the anchor and the soil at their interface is due to relative movement between them. From the results of progressively mobilized anchor forces one can determine the allowable soil movement for the given anchor parameters, and thus predict the expected anchor forces for the specified global factor of safety. The anchor dimension and inclination should be properly designed to achieve the maximum efficiency.

Luo et al. (2000) reported an analytical model for the description of the relationship of normal pressure exerted by the soil on the shaft of a nail embedded in it, and soil dilation on the assumption that the dilative soil is an elastic medium and the nails are rigid. They demonstrated that the difference between the actual normal pressure and overburden pressure on the rupture surface of a soil nail in pull out is caused by the soil dilation in a dilative soil. They derived also an expression for the efficiency factor, which illustrates the fact that the apparent friction coefficient decreases with the increase of the overburden pressure. The theoretical predictions are in good agreement with reported test results. Two phenomena were described. The actual normal pressure on the shaft of a soil nail in a dilative soil is higher than the overburden pressure and the apparent friction coefficient decreases with the increase of the overburden pressure.

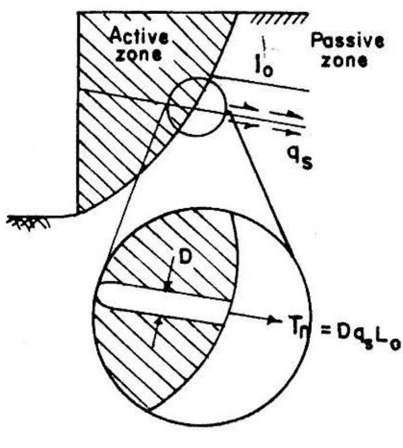

FIGURE 2 : Tension in Nails

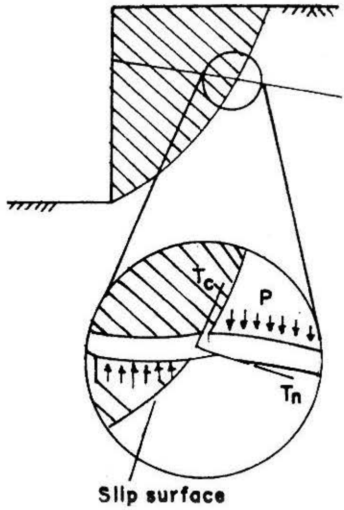

FIGURE 3 : Bending and Shear in Nails at the Slip Surface

Figure 2 and 3 show respectively the cases when the nails are acted upon by tension only and bending and shear only. The difference in load transfer mechanism in tieback wall and soil-nailed wall is shown in Figs.4(a) and 4(b) respectively.

Design Methods

Several methods are available for stability analysis of nailed soil structure, namely, the limit equilibrium method, the limit analysis method and the finite element method. Among these, the limit equilibrium method has attracted the attention of the researchers because of its simplicity, reasonable accuracy and popularity among the practicing engineers. Even

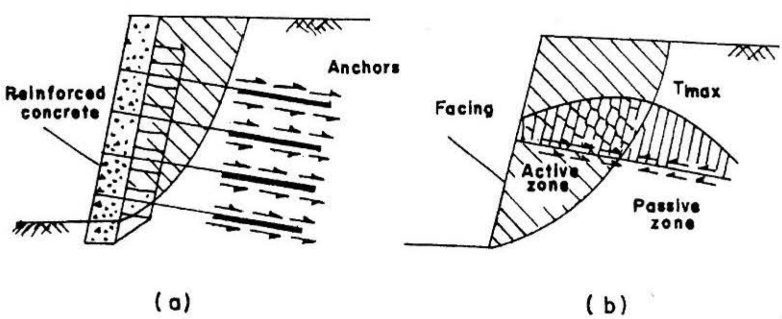

FIGURE 4 : Load Transfer Mechanism (a) Tieback Wall (b) Soil-Nailed Wall

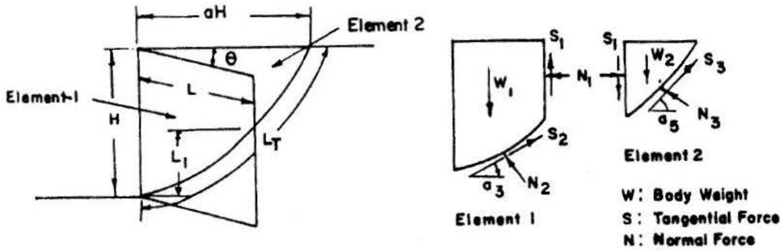

FIGURE 5 : Free Body Diagram of the Failure Surface Extending Beyond Reinforced Mass

though these are not correct from the view of mathematical theory of plasticity for their incorrectly oriented slip surfaces, these have acquitted themselves quite well for their reasonable accuracy and predictions, which are not very much off from the solutions obtained through more rigorous applications. No universally accepted standard method for design of such structures without any controversy could yet be developed. Some of the design methods that are used in various countries are outlined briefly for ready reference.

The Davis Design Method

Shen et al. (1981) developed this limit design procedure assuming the failure surface to be a parabolic curve passing through the toe of the wall. They have used a method similar to the classical method-of-slices of slope stability analysis to evaluate the contribution of the nails for overall stability (Ref. Fig.5). Only tensile forces are to be developed in the nails to compute the factor of safety of the entire mass adopting an iterative procedure considering two conditions, namely a failure surface that extends beyond the reinforced zone and a failure surface, which is entirely within the reinforced zone. The force in each nail (T) is estimated by calculating the frictional resistance of the portion of the member behind the assumed failure surface. The frictional resistance is the skin friction developed between the nail and the surrounding soil. The frictional resistance of each nail cannot exceed the yield strength of the inclusion. The driving force and the resisting force developed along the assumed failure surface must be in equilibrium and the overall factor of safety is obtained when

$$FS_c = FS_\varphi = FS_g$$

where FS_c = factor of safety with respect to cohesion,

FS_φ = factor of safety with respect to friction, and

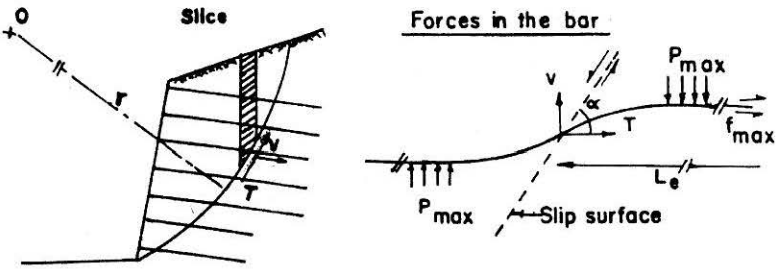

FIGURE 6 : Design of Nailed Soil Walls by Slope Stability Analysis (Schlosser, 1983)

FS_g = factor of safety with respect to pullout resistance parameters.

The French Method

Schlosser (1983) developed this method (Ref. Fig.6). The nailed soil mass is considered as a composite material and the procedure is similar to the Davis method. But, four failure criteria were considered as follows.

(i) shear resistance of the bar $T < R_n$, $V \leq R_c = R_n/2$;

(ii) soil bar friction $T \leq \pi d_n L_e f_{max}$

(iii) normal lateral earth thrust on the bar $p \leq p_l$

(iv) shear resistance of the soil $\tau \leq c + \sigma \tan\varphi$

where T = mobilized tensile force,

L_e = effective length of nail behind failure surface,

F_{max} = limit unit skin friction,

R_n = tensile strength of nail,

R_c = shearing strength of nail,

V = mobilized shear force, and

p_l = limiting passive pressure on the bar

From the principle of maximum work and the Tresca failure criterion, the tensile forces at failure of a nail can be computed as a function of the nail inclination. The driving moment and the resisting moment due to forces developed in the reinforcements and to the mobilized shear resistance of the soil must be in equilibrium. A computer program, TALREN, has been developed by the French company TERASOL based on this method.

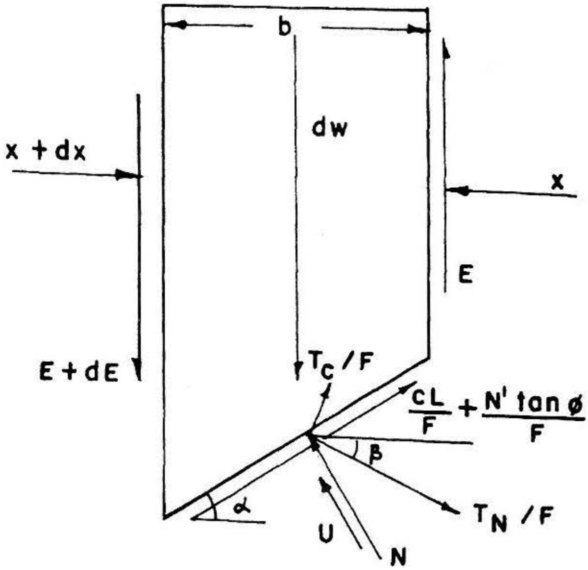

FIGURE 7 : Consideration of Nail Forces as per Tan et al. (1988)

Procedure Developed in Singapore PWD

Tan et al. (1988) reported that, in Singapore PWD, a computer program based on the Bishop's simplified method had been developed for nailed slopes using multi-failure criterion proposed by Blondeau et al. (1984). The contribution from the soil nail is considered as a force acting at the mid-point of the base of the slice. Though the nail intersects other slices, it is assumed that the internal forces acting at the vertical inter slice boundaries are not affected duly by the nails. This assumption though simplistic, is necessary in view of the complexity of the problem. The forces acting on the slice is shown in Fig.7. In deriving the equation for the overall factor of safety of the slope, different partial safety factor can be incorporated for shear and pull out failures of the soil nail. The partial safety factors can be predetermined to control the allowable deformation of the soil nail system. For simplicity, a common factor of safety can be assumed for shear and pull out failure of soil nail and slip surface. The expression for the factor of safety was derived from the vertical and moment equilibrium of the forces acting on the slices.

The values of mobilized pull out and shear resistance are evaluated based on the multi-failure criterion proposed by Blondeau et al. (1984). A simple computer subroutine was written to generate the various failure criteria and to search for the critical failure envelope.

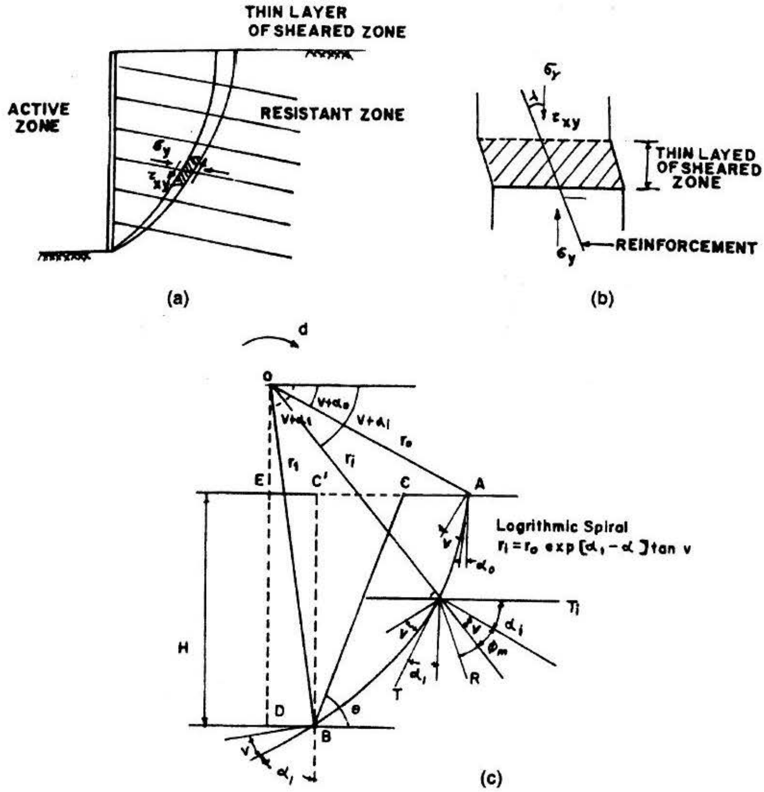

FIGURE 8 : Design by Kinematical Limit Analysis Method (Juran, 1990)

Design by Kinematical Limit Analysis

Juran (1990) reported a kinematical limit analysis design approach (Fig.8a, b, c) that provides a rational estimate of maximum tension and shear force mobilized in each nail. The design was based on the assumptions that: (i) failure occurs by a quasi-rigid body rotation of the active zone that is limited by a log-spiral failure surface, (ii) at failure, the locus of maximum tension and shear force coincides with the failure surface developed in the soil, (iii) the quasi-rigid active and resistant zones are separated by a thin layer of soil at a limit state of rigid plastic flow, (iv) the shearing resistance of the soil, defined by Coulomb's failure criterion, is mobilized all along the failure surface, (v) the horizontal component of the inter-slice forces acting on both sides of a slice comprising a nail are equal.

The design was based on the evaluation of the local stability of each nail with respect to two main failure criteria:

(a) Failure by pull-out of reinforcement

(b) Failure by breakage of reinforcement for flexible nails

For nails with a finite bending stiffness, breakage can occur either by coupled tension/shear or by excessive bending. The maximum tension force in each nail is obtained from the horizontal force equilibrium of the slice comprising the nail. The maximum shear force generated in the nail is obtained from Mohr's circle for the stresses in the nail. The normal soil stress along the failure surface is calculated using Kotter's equation. A computer program was developed for an iterative solution. For homogeneous soils with uniform nail length, design charts were prepared.

Optimum Design by Nonlinear Programming Approach

Sabahit et al. (1995) have applied nonlinear programming techniques in conjunction with modified Janbu's generalized limit equilibrium method of slices (Figs.9a and 9b) to analyze and design soil nailed slopes without any a–priori assumption regarding the shape of the critical slip surface. An expression for the factor of safety of the nailed slope was derived modifying the Janbu's generalized procedure of slices. Both tensile and shear forces in the nails were considered. The system of forces as assumed is shown in Fig.9b. They also suggested an equation to estimate the total reinforcement force required for a desired factor of safety. The distribution of reinforcement tensile forces in each element was expressed as a fraction of total reinforcement force. However, the analysis did not consider the internal equilibrium of the soil-nail interaction. The contribution of nail was considered for the slice in which the nails cut at the base. The minimum reinforcement force required to achieve a desired factor of safety was found by treating the orientation of nails and distribution of reinforcement forces as design variables. The design was carried out in three stages. In stage 1, the critical failure surface of the unreinforced slope was obtained using Janbu's GPS. In stage 2, with the critical surface obtained by unreinforced slope, the total nail force required to raise the factor of safety to a desired value was minimized with respect to the inclination of the reinforcement and the coefficient of distributions of reinforcement forces. In stage 3, the reinforcement force so obtained, the factor of safety of the reinforced slope is computed with respect to the location and shape of the critical surface. The critical slip surface and the corresponding factor of safety value were compared with that obtained in stage 2. The process was terminated when an acceptable convergence criterion was reached. The length of the nail extending beyond the critical surface was decided based on the pull out resistance of the nail per unit length and the available tensile force in each nail.

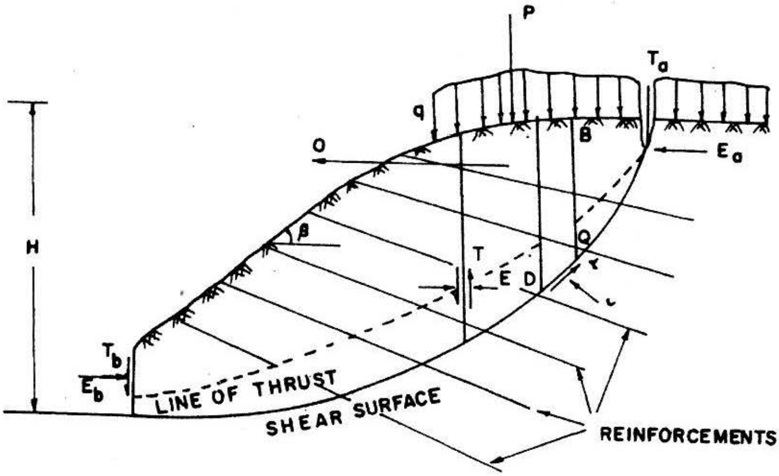

FIGURE 9(a) : A Generalized Nailed Soil Slope with Vertical Slices

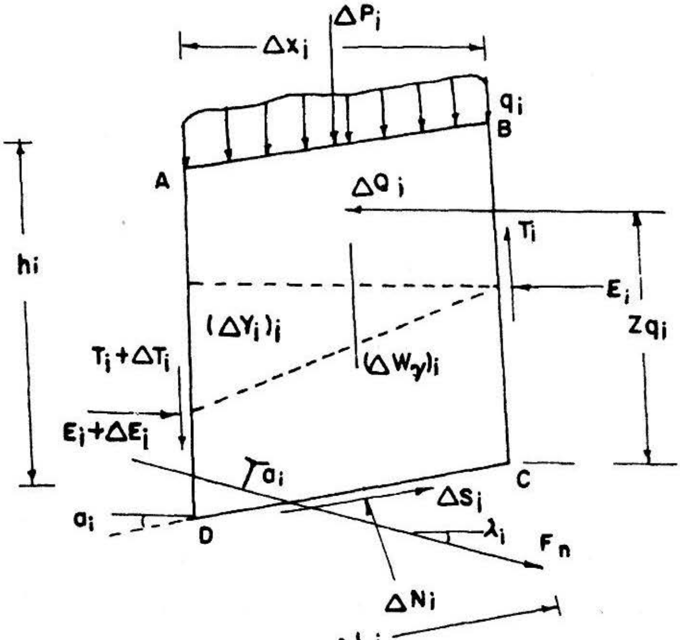

FIGURE 9(b) : System of Forces Assumed by Sabahit et al. (1995)

Patra (1998) used sequential unconstrained minimization technique in the optimal design of nailed soil slopes. In this method both overall and internal equilibrium have been considered. The forces as considered in the analysis are shown in Fig.10a, Fig.10b, Fig.10c. The method is capable of considering both vertical (Fig.10a, Fig.10b) as well as inclined slices (Fig.10c, Fig.10d). Solutions were obtained by formulating the problem as a non-linear programming problem. Sequential unconstrained minimization technique was used in conjunction with Powel's method for multidimensional search and quadratic interpolation technique for unidirectional search to isolate the solution. In this method the nail parameters like diameter of nails, their spacing, orientations and lengths have been considered in addition to the co-ordinates defining the slip surface (as one need not make any a-priori assumption regarding the shape of the slip surface). Such an analysis involves finding the minimum value of the factor of safety corresponding to the most general critical slip surface satisfying both moment and force equilibrium conditions and also the minimum quantity of steel required to achieve a desired factor of safety value. The problem is one of multi-objective and multi-constrained optimization. When initial feasible design vector could not be obtained, extended penalty function method was used.

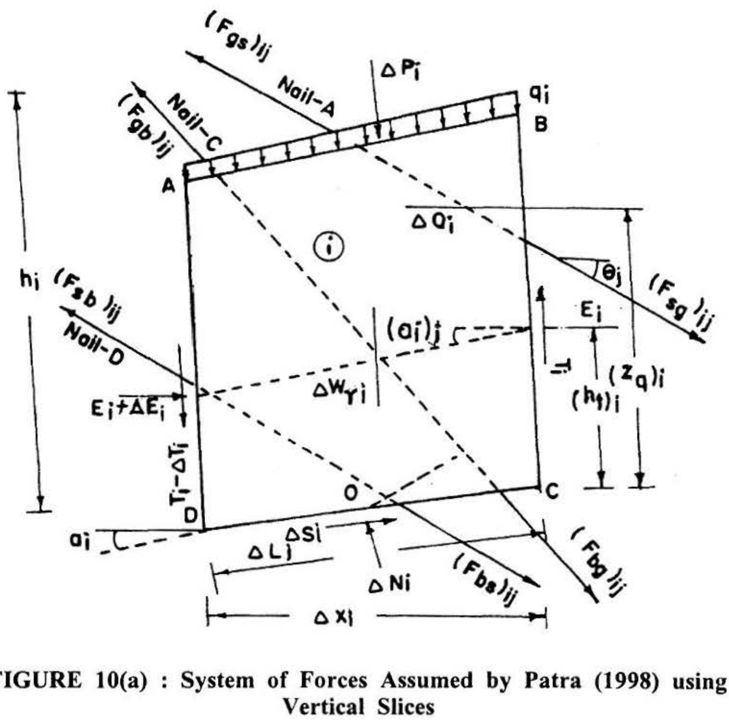

FIGURE 10(a) : System of Forces Assumed by Patra (1998) using Vertical Slices

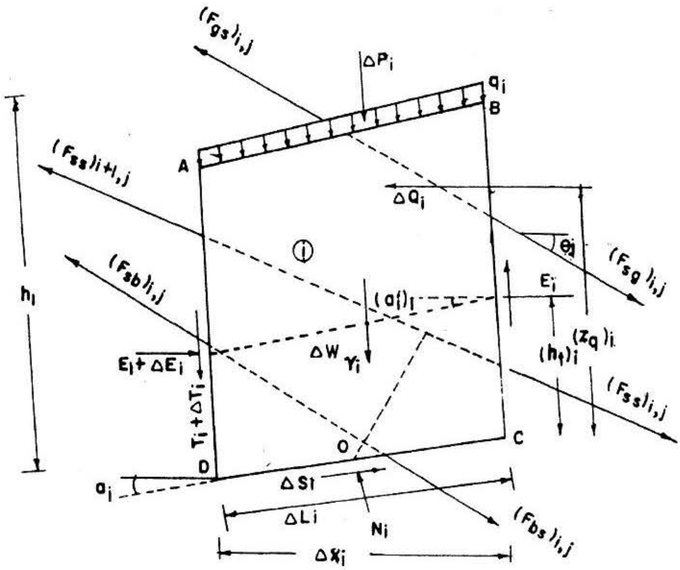

FIGURE 10(b) : System of Forces Assumed by Patra (1998) using Vertical Slices

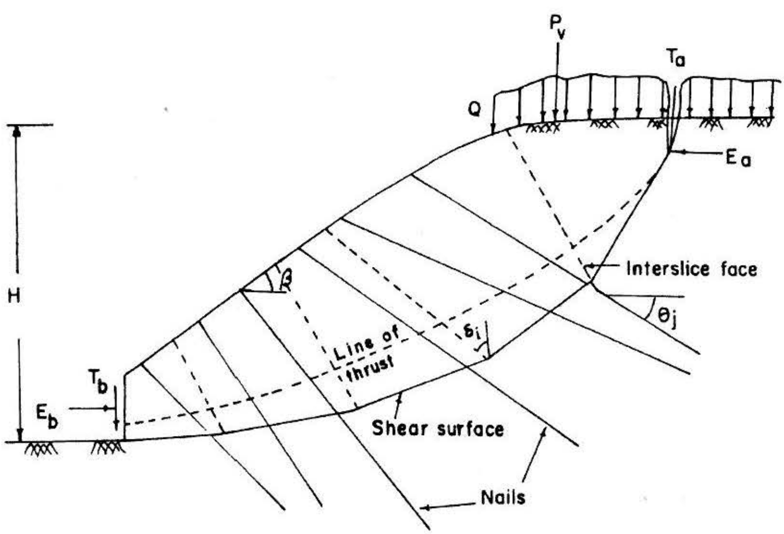

FIGURE 10(c) : A Generalized Nailed Soil Slope with Inclined Slices

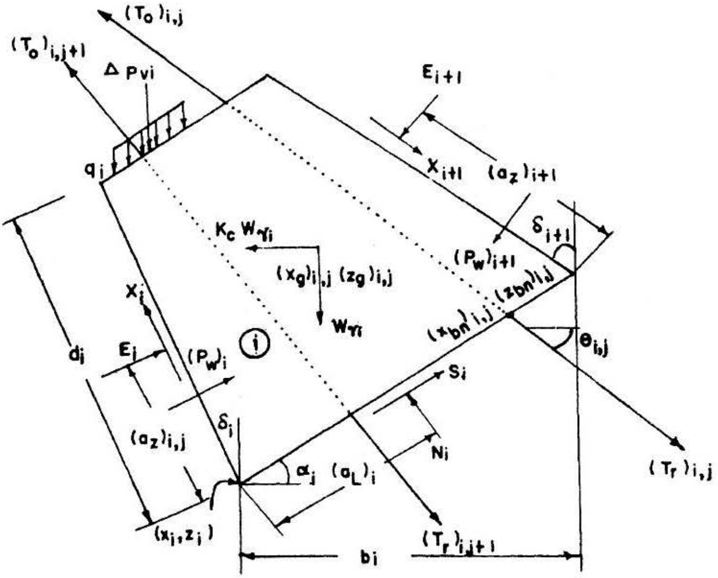

FIGURE 10(d) : System of Forces Assumed by Patra (1998) using Inclined Slices

Comparison of Different Analyses

In Table 2, a comparative study of the several limit equilibrium methods for the analysis of soil-nailed walls has been presented; this Table includes some optimal design procedures, in the original comparison made by Ortigao et al. (1995). In all these methods the soil mass behind the face is divided into an active and passive zone, separated by a slip surface. Analysis is carried out considering the stabilizing effect of nails acting on the slip surface sustaining global stability. But they differ with respect to the shape of the slip surface, the forces assumed to act on a nail and the method of calculation.

The Davies, German and yield methods consider only tension in the nails. Soil nail interaction gives rise to the development of uniform shear stress at the soil-nail interface. In Kinematical, multicriteria, and Cardiff methods, the effect of all the forces due to tension, bending and shear is taken into account. Values of the tension and shear forces at the failure surfaces are calculated treating the nails as beams on an elastic foundation idealized as a series of discrete non-linear springs.

The multicriteria method (French method) is based on the following main assumptions as mentioned in Table 3.

TABLE 2 : Comarison of Methods of Analysis of Soil Nailed Structures

Characteristics	Method							
	Gernam	Davis	Multicriteria	Kinematical	Cardiff	Yield	Nonlinear Programming	
Reference	Stocker et al. 1979	.Shen et al. 1981	Schlosser 1983	Juran et al. 1988	Bridle 1989	Anthoine 1990	Sabahit et al. 1995	Patra 1998
Analysis	Limit equilibrium	Limit equilibrium	Limit equilibrium	Internal stresses	Limit equilibrium	Yield theory	Limit equilibrium	Limit equilibrium
Division of soil mass	2 wedges	2 blocks	Slices	-	Slices	Rigid block	Vertical Slices	Vertical & Inclined Slices
Factor of safety	Global	Global	Global & Local	Local	Global	Global	Global	Global & Local
Failure surface	Bi-linear	Parabolic polygonal	Circular or	Log spiral	Log spiral	Log spiral noncircular	General noncircular	General
Nails resist to :								
Tension	×	×	×	×	×	×	×	×
Shear			×	×	×			
Bending			×	×	×			
Wall geometry	Vertical or inclined	Vertical	Any	Vertical or inclined	Vertical or inclined	Vertical or	Any	Any
No. of soil layers	1	1	Any	1	1	1	1	1
Optimum Design	No	No	No	No	No	No	Yes	Yes

TABLE 3 : Assumptions in Multicriteria

Criterion	Mathematical model
1. Strength of the reinforcement	Tensile strength $T_a \le A_s f_y$
	Shear strength $T_c \le R_c = A_s f_y / 2$
2. Soil-nail friction	$T_{max} \le q_s A_{lat}$
3. Normal stress on the nail	$P \le p_{max}$
4. Soil shear strength	$\tau \le c' + \sigma' \tan \phi'$

where, A_{lat} = peripheral area of nail;
p_{ns} = normal stress exerted by soil on nail;
q_s = constant soil-nail friction;
p = yielding of soil around nail

TABLE 4 : Small Scale Model Tests, Large and Full Scale Field Tests

Literature Reviewed	Type of Tests
Stocker et al. (1979)	model & large scale field tests
Shen et al. (1981a, 1981b)	in-situ earth reinforcement
Gassler and Gudehus (1981)	large scale field tests
Guilloux et al. (1983)	real field situation
Juran et al. (1983)	direct shear tests
Kitamura et al. (1988)	model tests
Nagao et al. (1988)	large scale field tests
Gutierrez and Tatsuoka (1988)	small scale model tests
Tan et al. (1988)	real field situation
Juran and Chen (1989)	model and large scale field tests
Hayashi et al. (1990)	model tests
Plumelle et al. (1990)	full scale tests
Plumelle and Schlosser (1990)	full scale tests
Kakurai and Hori (1990)	real field situation
Stocker and Riedinger (1990)	performance of real nailed-structure
Juran (1987)	field observations
Juran et al. (1988b)	field observations
Juran and Elias (1990)	field observations
Nanda (1995)	full scale experimental wall
Kim et al. (1995)	reduced scale-model tests
Bridle and Davies (1997)	large scale shear box tests
Kim et al. (1996)	real field situation

TABLE 5 : Theoretical Analysis

Literature Reviewed	Method of Analysis
Schlosser (1982)	method of slices, multi-criteria of failure
Gassler and Gudehus (1983)	statistical design approach
Blondeau et al. (1984)	internal & external stability analysis
Sano et al. (1988)	circular or wedge type slip failure
Matsui and San (1988)	finite element formulation
Sawicki et al. (1988)	finite element method
Tan et al. (1988)	modified Bishop's simplified method
Juran and Chen (1989)	strain compatibility approach
Juran et al. (1990a)	kinematical limit analysis
Plumelle et al. (1990)	finite element calculation
Plumelle and Schlosser (1990)	finite element calculation
Long et al. (1990)	circular, bi-linear, three part wedge anlysis
Jewell and Pedley (1990)	bending stiffness of nail be ignored
Kakurai and Hori (1990)	elasto-plastic F.E.M. & like Fellenius method
Kirsten (1992)	limit equilibrium & closed-form elastic and plastic analyses
Kirsten and Dell (1992)	based on limit equilibrium method
Juran et al. (1992)	kinematic limit analysis
Jewell and Pedley (1992)	elastic and plastic analysis
Asaok et al. (1994)	rigid plastic finite element method
Huang and Tatsuoka (1994)	limit equilibrium method
Lee et al. (1995)	discrete element method (DEM)
Nanda (1995)	finite element method
Sabahit et al. (1995)	limit equilibrium method
Sobolevsky (1995)	suggestion for optimization technique
Kim et al. (1996)	discrete element method (DEM)
Briddle and Davies (1997)	global analysis technique
Sabahit et al. (1996)	based on pseudo-dynamic approach
Smith and Su (1997)	3-D finite element method
Patra (1998)	limit equilibrium method
Liang et al. (1998b)	limit equilibrium method
Luo et al. (2000)	pull-out resistance for dilative soils

Discussion and Scope for Future Research

The reviewed literature pertaining to the small-scale model and large scale field tests and analytical approaches for the behavior, mechanism and design of nailed wall is presented in the Tables 4 to 5 respectively. These tables give an overview of experimental (both model and field tests) and theoretical studies made on the subject. It is evident from Table 3 that a good combination of laboratory model tests and field tests have been conducted by various investigators. These investigations have helped in confirming the nature of the failure surface, modeling of nail forces and failure criteria to be adopted in theoretical analysis. It is found that failure mechanism is governed by the location of the loading. Failure modes are translation or rotation of one, two or three rigid bodies. Simple rotation mechanism is more relevant to practical design. Very small displacements are sufficient to generate friction at the soil/nail interfaces mobilizing high tensile forces in nails. But, relatively large displacements are necessary to mobilize the passive lateral earth pressure on the reinforcements and to generate bending moments in the nails. Downward inclined nails are less effective compared to horizontal nails. Bending and shearing resistance do not contribute significantly to the reinforcement effect. These further have been used in validating the various methods developed for analyzing nailed soil slopes. Table 4 shows that Limit Equilibrium Method (LEM) is the most widely used method of analysis of nailed slopes. FEM has also been used for such analysis and it has lot of promise as its use enables one to predict the deformation of both nail and slope. FEM can model the nail-soil interaction and nonhomogenious nature of soils in a better manner than other methods. Some efforts have been made to take into account for the deformation in the nailed soil structures. But, some investigators regarding the correctness of the nail forces estimated by using the kinematic limit analysis approach, expressed serious reservation. As such, there is lot of scope to do further research in this direction and verify the nail forces by performing experiments preferably field tests. Consideration of internal equilibrium also gives a better way of predicting the same than that of considering overall equilibrium. Consideration of only overall equilibrium may lead to unrealistic predictions regarding the nail forces. One area, which has drawn scanty attention in the optimal design of nailed soil slopes. This area needs to be strengthened by further research. Scanty studies that have been made indicate that the optimal inclinations of the nails are so small that it does not matter if the nails are placed horizontally. This aspect needs to be studied in detail and verified through model and field tests.

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