

ON THE NAILED SOIL SLOPES RESEARCH DEVELOPMENT

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ABSTRACT: The slope stability was researched over the past decades, understandings the behavior of nailed soil slopes, with their properties and characteristics, have guided to development of enhanced recognizing of the variation in nailed soil slopes parameters. Failures can arise over time, hence the identification of the necessities and the restrictions of laboratory and in situ testing for evaluating nailing parameter have to be deeply understood. Many researcher have enriched and refined the knowledges of the principles of soil nailing mechanics that associate soil behavior to slope stability and factor of safety. This paper is aimed to explore some of important state of the art development of nailed soil slope and analytical techniques extended by extensive investigation of the mechanics of slope stability analyses. The most significant effective parameter that play important role in slope safety factor in almost of many works are length, nailing angle, and distance between center to center of nails. Slope angle, connection of nailed head, the distance with toe and nail diameter were also the points that cannot be neglected in their study. Choosing the proper cable or pile element in the finite element modeling and the mobilized both axial and shear forces are also reviewed in this paper.

Keywords: *Soil Nailing, Soil Slope, Nailing Angle, Slope Angle, Factor of Safety*

1. INTRODUCTION

The stability analysis of slopes plays a very important role in civil engineering. Stability analysis is used in the construction of transportation facilities such as highways, railroads, airports, and canals; the development of natural resources such as surface mining, refuse disposal, and earth dams; as well as many other human activities involving building construction and excavation. Failures of slopes in these applications may be caused by movements within the human created cut or fill, in the natural slope, or a combination of both. Slopes failures involve such a variety of processes and causative factors that they afford unlimited possibilities of classification. For instance, they can be divided according to the form of failures, the type of materials moved, the age, the stage of development, or the cause of movements [1].

The incidence of soil slope instability is, and has been, a natural hazard of major proportions and is ongoing to this day. While stabilization can be afforded by excavation and reconstruction, oftentimes structures and utilities are involved requiring in situ stabilization methods. It is important to recognize that rather than being a purely empirical method, in situ slope stabilization has a formalized and well accepted theoretical background [2].

2. LITERATURE REVIEW

2.1 Slope Stability

2.1.1 Modes of Failures

Bromhead [3] subdivide the whole of mass movement into three major classes: slides, falls and flows. The major differences between these three are in the way in which movement takes place. In a slide, the moving material remains largely in contact with the parent or underlying rocks during the movement, which takes place along a discrete boundary shear surface. The term flow is used when the material becomes disaggregated and can move without the concentration of displacement at the boundary shear. Although a flow can remain in contact with the surface of the ground it travels over, this is by no means always the case. Lastly, falls normally take place from steep faces in soil or rock, and involve immediate separation of the falling material from the parent rock or soil mass, with movement involving only infrequent or intermittent contact thereafter, until the debris comes finally to rest.

Small mass movements tend to be of one type alone: either a slide, a fall or a flow. Larger movements may often change from one to another as they progress. For instance, a large rockfill may develop into a flow and finish up as a slide [3].

Abramson [4] illustrates the typical slides that can be expected to occur in soil slopes. These usually take the form of either: (1) translational, (2) plane or wedge surface, (3) circular, or (4) non circular or a combination of these types, such as described in Fig. 1.

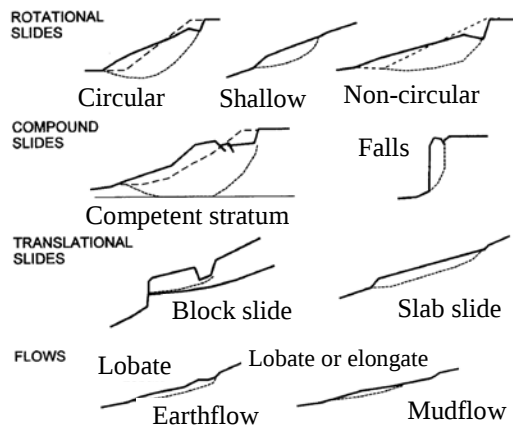


Fig 1. Types of mass movement in clay slopes
Source: Abramson [4]

Reference [5] enhanced slope stability or increased landslide resistance with vegetation and they note that vegetation roots had a stabilising effect on the slope, limited to the rooting depth.

2.12 Ordinary Methods of Slices

Reference [6] describe the equation for the Ordinary Method of Slices with shear strength expressed in terms of effective stresses, the preferred equation for factor of safety is Eq. (1):

$$F = \frac{\sum [c' \Delta l + (W \cos \alpha - u \Delta l \cos^2 \alpha) \tan \phi']}{\sum W \sin \alpha} \quad (1)$$

2.2 Soil nailing

2.2.1 Concept

Soil reinforcements include mechanically stabilized earth (MSE) walls, reinforced soil slopes (RSS), and soil nailing walls. Soil nailing is an in situ soil reinforcement technique that has been used during the past four decades. The main components of a soil nailed retaining system are the in situ ground, the tension-resistant nails, and the facing element. The nails are usually corrosion-resistant steel bars or other metallic elements that can resist tensile stresses, shear stresses, and bending moments. They generally are placed in drilled boreholes and grouted along their total length or driven into the ground. The facing is not a major structural load-carrying element, but, rather, ensures local stability of the soil between the nails and protects the ground from surface erosion and weathering effects. It generally consists of a thin layer of shotcrete about 4 to 6 in. (100–150 mm) thick with wire or steel mesh between the nails. Prefabricated or cast-in-place concrete panels have increasingly been used in the construction of permanent structures to satisfy specific needs and accommodate adequate

drainage. Successive incremental excavations with a height of 3 to 6 ft (0.9–1.8 m) are first made on the ground, the nails are then installed, and the shotcrete is applied. The next process is repeated until completion. Fig. 2 shows a typical section of this soil nailed retaining system [1].

Reference [7] stated that as with mechanically stabilized earth (MSE) walls, the reinforcements are passive and develop their reinforcing action through nail-ground interactions as the ground deforms during and following construction. Nails work predominantly in tension but are considered by some to work also in bending/shear in certain circumstances. Consideration of shear/bending contributions is not included in the recommended design methods presented later in this manual. The effect of the nail reinforcement is to improve stability by (a) increasing the normal force and hence the soil shear resistance along potential slip surfaces in frictional soils; and (b) reducing the driving force along potential slip surfaces in both frictional and cohesive soils. A construction facing is also usually required and is typically shotcrete reinforced by welded wire mesh.

There are three main categories of in-situ reinforcement techniques used to stabilize soil slopes and support excavations. These are nailing, inserted micro-piling, and doweling. In soil nailing (Fig 2), the reinforcement is installed horizontally or sub-horizontally (approximately parallel to the direction of major tensile straining in the soil) so it contributes to the support of the soil partially by directly resisting the destabilizing forces and partially by increasing the normal loads (and hence the shear strength) on potential sliding surfaces [7].

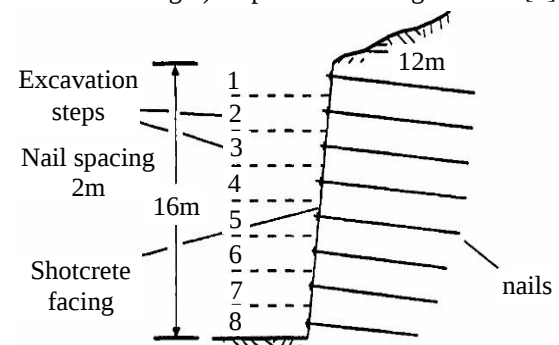


Fig 2. Insitu reinforcement techniques
Source: Byrne [7]

This paper is concerned only with soil nailing. Furthermore, the method of analysis presented herein addresses tension only as the resisting element for excavation support systems and slope stabilization. The reinforced soil body becomes the primary structural element. The reinforced zone (Fig 3) performs as a homogenous and resistant unit to support the unreinforced soil behind it in a manner similar to a gravity wall [7].

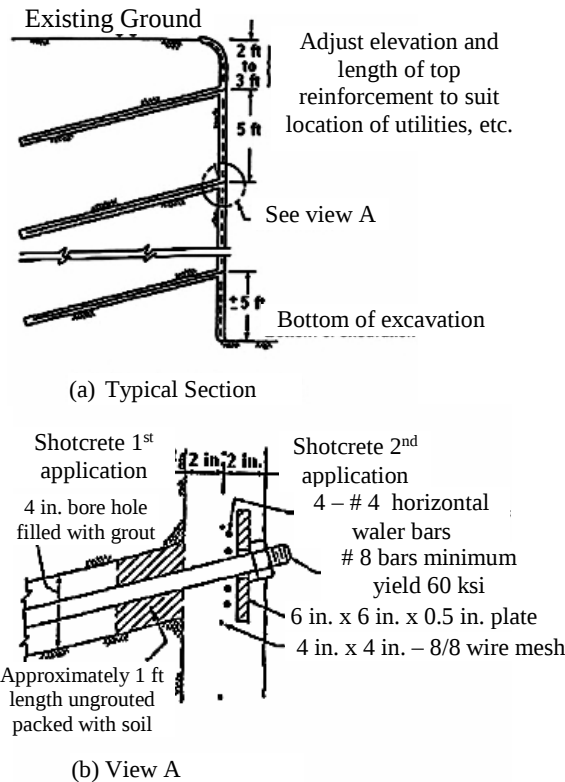


Fig 3. Construction details of soil nailing system
Source: Huang [1]

2.2.2 Advantages of Soil Nailing

Reference [7] also explained that soil nailing (SN) exhibits many of advantages as a method of ground support/reinforcement, together with additional benefits that are unique to nailing. The top down construction technique of soil nailing offers the following more benefits:

Soil nailing improved economy, material saving and lessened environmental impact compared to conventional retaining walls, through the elimination of the need for a cut excavation and backfilling, through the incorporation of the temporary excavation support system into the permanent support system and through reduction in the right-of-way (ROW) requirements as the nails are typically shorter than the tieback anchors. Soil nailing also improved safety by eliminating cramped excavations cluttered with bracing.

SN also make higher system redundancy as the soil nails are installed at a far higher density than the prestressed tieback anchors, and the consequences of a unit failure are therefore correspondingly less severe. It should be noted that this does not necessarily imply higher system reliability for soil nail walls, since each tieback is tested during installation, whereas only a small percentage of nails are tested.

The SN system is relatively robust and flexible and can accommodate significant total and

differential settlements. SN retaining walls have been documented to perform well under seismic loading conditions. Then the field monitoring of SN has indicated that overall movements required mobilizing the reinforcement forces are relatively small and correspond generally to the movements that would be expected for well braced systems (Category I) in Peck's classification.

Utilization of SN also eliminate of the need for a high capacity structural facing (i.e., soldier piles and thick CIP) since the maximum earth pressure support loads are not transferred to the excavation face. SN also improved construction flexibility:

- in heterogeneous soils with cobbles, boulders or other hard inclusions, as these obstructions offer fewer problems for the relatively small diameter nail drill holes than they do for the large diameter soldier pile installations.
- where overhead access is limited (e.g., road widening under an existing bridge) through the elimination of the requirement for drilled or driven soldier piles installed through the bridge deck or in hand dug pits.
- can follow difficult excavation shapes using splayed nails and can cope with significant variations in soil conditions encountered during construction. Nail layout modifications during construction can be easily accomplished.
- Ease of construction and reduced construction time - soldier pile installations are not required, soil nails are not prestressed, and construction equipment is relatively small, mobile, and quiet which particularly advantageous on urban sites.
- The vertical components of the nail reaction at the facing are smaller than those for tiebacks and are also distributed more evenly over the entire excavation face. This eliminates the need for significant wall embedment below grade, such as is required for tieback soldier piles.

Other favorable features of SN retaining systems that the method is well-suited to sites with difficult or remote access because of the relatively small size and the mobility of the required construction equipment, also well-suited to urban construction where noise, vibration, and access can pose problems and finally well-suited to specialist applications such as the rehabilitation of distressed retaining structures [7].

2.3 Finite Element Methods

Huang [8] explained that The Bureau of Mines has developed a computer program for pit slope stability analysis by finite-element stress analysis and the limiting equilibrium method. Finite-element stress analysis satisfies static equilibrium and can account for the stress changes due to varied elastic properties, non-homogeneity, and geometric shapes. In addition to the stress analysis,

the program includes finite-element model mesh generation, plotting of the model mesh and stress contours, calculation of a factor of safety along a circular or a plane failure surface, and location of a critical circular failure surface. The stress field in the slope is determined by 2D plane strain analysis using triangular finite elements shown in Fig. 4.

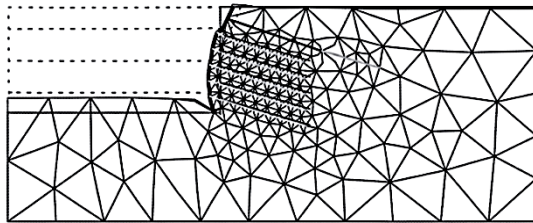


Fig 4. Triangular discretization of soil slope elements with nailed anchors
Source: Ortigao and Sayao [9]

3. STATE OF THE ART OF NAILED SOIL SLOPES RESEARCH

Reference [10] developed a generalized procedure for the optimum design of nailed soil slopes and they focused to examine the effect of distribution of reinforcement forces and the inclination of the reinforcement in optimizing the amount of reinforcement required to improve the stability of a nailed soil slope. They found that the total length of nails required would be less if the nails are placed in the lower part of the slope. In their proposed method, they suggest that the near-horizontal placement of the nails and use of longer nails at the mid-height of the slope leads to an optimum design of nailed soil slopes.

Using discrete element method, reference [11] also analyse the soil nailed earth slope and they proposed a mechanism to simulate characteristics of interactive behavior of nail and surrounding ground, and it was replaced by elastoplastic springs. The main feature of the their method is the ability to consider the real construction sequence and appropriately consider the observed interface behavior between nails and the adjacent ground.

The effect of the nail skew angle of soil nailing wall was investigated by Bang and Chung [12] and they obtain that as the skew angle increases that the lateral deformations increase at an accelerating rate, that the vertical deformations are not affected much, and that the out-of-plane deformations first increase and then decrease at skew angles beyond 40 degrees. They also conclude that the nail length should be longer as the nail skew angle increases.

Asoudeh and Oh [13] study on the strength parameter selection in stability analysis of residual soil nailed walls and they found that residual soil slopes with cohesion parameter of less than 10kPa (no matter how much is the friction angle) and with acceptable amount of reinforcement have the

high probability of collapse and these types of slopes are sensitive to value of cohesion.

While reference [14] performed numerical experiments of soil nails in loose fill slopes subjected to rainfall infiltration effects and their numerical results indicate that shallow failure can develop in a loose fill slope when the pore water pressure in the top 3 m of filling material increases. Their numerical analyses showed that when soil nails were installed in a loose fill slope without nail heads or a facing structure, global sliding failure occurred. They pointed out that although the development of global failure was delayed by the presence of soil nails, the low frictional resistance of the nails at shallow depths failed to arrest the development of a flow slide. They suggest that the deformation of the loose fill slope was found to be greatly reduced if the soil nails were connected to a facing structure at the slope surface. They proposed the entire nail-facing structure acted as an earth-retaining structure.

Stability analysis of steep nailed slopes also investigated by reference [15] by conducting shaking table tests to analyze its seismic resistance. They captured that a slope is dramatically deformed when the peak amplitude of acceleration exceeds the critical amplitude of acceleration. They noted that nailed slopes did not collapse immediately, however, even when subjected to strong acceleration, revealing the ductile character of the resistance of the nailed structure. The nail angle only weakly affects the seismic resistance of a nailed slope, but increasing the length of nails increased the seismic resistance of the slope. Their experimental results show that a nailed slope subjected to an excitation with a smaller frequency amplification factor exhibits a greater horizontal displacement and lower seismic resistance.

An optimum design of nailed soil slopes also proposed by Patra and Basudhar [16] and they underlined that consideration of internal equilibrium in addition to overall equilibrium significantly alters the position of the critical slip surface and thus affects the nail volume required to achieve a desired factor of safety. They also pointed out that upwardly oriented nails with longer nails in the upper part of the slope generally lead to an optimal design. However, the value of the upward inclination of the nails is generally small and ranges from nearly zero to a maximum of 6°. They also proposed that unequal spacing of the nails with decreasing values of their lengths from top to bottom of the slope results in the optimal design. But, they found that other nail parameters (outside (inclination, diameter, spacing and length) remaining the same, by providing extra nail length in the resistive zone over and above a certain length of individual nails the stability of a given slope cannot be increased further.

A numerical study on the optimum layout of soil-nailed slopes was performed by Fan and Luo [17] and they said that the optimal nail's orientation, in relation to the horizontal, decreases with an increase in the slope angle, and it increases with an increase in the backslope angle. They also concluded that the role of nail length at any given elevation in the factor of safety of soil-nailed slopes and soil-nailed walls decreases as the backslope angle increases.

Giri and Sengupta [18] investigate the dynamic behaviour of small scale nailed soil slopes and they summarized that the failure surfaces appeared to be shallow, likely to be circular and confined to the zone near the slope surfaces. They observed that the number of cracks appeared to be less as the slope angle increases, hence with the increase in slope angle, the slope becomes more unstable and fails with less number of loading cycles. The mass movement and size of possible failure wedge decrease with loading cycles decreased and they supposed that these the reason for the development of less number of failure cracks in steep slopes.

Pullout is also the problem of nailed soil slopes, and hence reference [19] extend the evaluations of pullout resistance of grouted soil nails and they said that the pullout shear strength for laboratory tests and field observations increased with the increase of normal stress and generally presented a tendency that appears to follow the Mohr-Coulomb failure criterion. They also observed that the apparent cohesion observed in laboratory was substantially lower than that derived from the field due to the effect of soil dilatation. However, the values of the angle of interface friction were found to be similar for both tests.

Another numerical modeling of soil nails in loose fill slope under surcharge loading was done by reference [20] and their numerical predictions obtained from different modeling approaches illustrate that the overall response of the nailed slope is more sensitive to the soil-nail interface characteristics, but less to the end conditions of the nails. They concluded that this is due to the fact that the maximum nail force is always mobilized at the middle portion of the nail, with very little relative movement and, hence nail forces, being mobilized at the two ends.

Wei and Cheng [21] researched about soil nailed slope by strength reduction and limit equilibrium methods and they established that the Poisson ratio and the stiffness or arrangement of the nail heads have little influence on the factor of safety and the failure mechanism of a slope. They found that the factor of safety from the strength reduction method and the limit equilibrium method are similar under most cases, and that all of the safety factor from the strength reduction method are slightly greater than those from the limit

equilibrium method. But, in the case when there is an external pressure on top of a slope and the bond stress is assumed to be dependent on the overburden or confining stress, there are great differences between both two methods.

For reinforced nailed steel wire mesh application, Da Costa and Sagaseta [22] proposed an analysis of shallow instabilities in soil slopes and they commented that when the ratio of the thickness of the shallow unstable layer to the height of the slope is lower enough (about 3%), the analysis as an infinite slope can be adequate. Further, they also stated that the solution for any case with cohesion and friction can be obtained for a purely friction soil by means of a reduction of the slope height, this reduction depends on the soil cohesion and friction, slope geometry and water condition. Once the effect of the cohesion is considered with this reduction of height, the slope can be calculated with zero cohesion. In all the analyses they carried out, the results show the shallow stabilization effect of a mesh applying a pressure on the slope surface, showing a higher possible reduction on the cohesion when the pressure acting on the slope surface is increased.

In the reference [23] studied the influence of slope geometry and nail parameters on the stability of soil-nailed slopes and they obtain that mobilization of axial forces in nails significantly depends on its inclination with respect to the slip surface. They said that nails inserted at the bottom portion of the slope primarily develop tensile forces whereas the nails inserted at the upper portion of the slope develop compressive forces. They also deduce that the presence of water or phreatic surface reduces the soil nail interface strength and also increases the saturated weight of soil in active zone. Rotte et al. also pointed that this phenomenon may lead to increase in disturbing force and at the same time it reduces the restraining force also. Hence, overall factor of safety of a soil-nailed slope reduces.

Seismic stability analysis of soil nail reinforced slope was examined by reference [24] using kinematic approach of limit analysis and they underlined that the critical seismic yield acceleration coefficient increases with increasing soil frictional angle and soil cohesion cut slope ratio, while it decreases as the height of slope increases. They pointed out that the critical seismic yield acceleration coefficient increases with increasing length and bond strength of soil nail as well as decreasing space distance of soil nail while the effects of the incline angle of soil nail on the critical seismic yield acceleration coefficient is insignificant for different height slope.

Pull-out tests and slope stability analyses of nailing systems were research by Jeon [25] comprising single and multi rebars with grouted

cement and he noted that the numerical results using the cable element showed that the axial forces of nail increased as the nail diameter increased. His numerical results using the pile element showed that the increment in the resisting axial force and shear force on the nail grout surface in axial direction was relatively small, but the increment in the resisting shear force mobilized on the cross-section of the nail, bending moment of the nail and the normal force mobilized on the nail grout surface in axial direction increased. Jeon also underlined that as the nail diameter increased, a large portion of the driving forces was resisted by bending. His results suggested that bending played a key role in the stabilizing mechanism.

While the effect of nail characteristics on slope stability based on limit equilibrium and numerical methods was examined by Maleki and Mahyar [26] and they pointed that length, nailing angle, and distance between center to center of nails are the most important effective parameters in slope safety factor of the excavation trench. They summarized that the highest safety factor will result whenever the optimum angle of nails in the slope is in the 20–40 degrees range.

Reference [14] carry out about the influence of soil nail orientations on stabilizing mechanisms of loose fill slopes and they concluded that the orientation of the soil nails has a direct influence on the stabilizing mechanisms. Their analysis results suggested that installing the nails to an inclination of nearly perpendicular to the slope face could lead to significant slope movement especially when sliding failure prevails, for instance, due to interface liquefaction. They also supposed that slope movement could be reduced by the provision of an embedded toe wall which increases the structural rigidity of the overall soil-nail-facing system along the potential sliding axis.

Using strength reduction method, reference [27] described the stability of soil nailed slope and they inferred that the factor of safety increases almost linearly with nail length until it reaches the effective reinforcement length, at which the length of the factor of safety reaches its maximum value. They stated many important matter, i.e. the nail reinforcement loads are asymmetrical; they are larger at the center and smaller at both ends. They also obtain an optimum nail orientation θ_{op} that leads to the optimal performance in the overall stability of the slope and θ_{op} decreases with increasing nail length. The factor of safety of the slope initially increases with the increase in nail orientation until reaching θ_{op} and then decreases linearly. Reference [27] also found the optimal location of the nail is found out to be approximately half the way of the slope.

In the reference [28], Li have researched on overloading design method for the slope of deep

foundation pit with layered soil braced by soil nail. Li inferred that the energy safety factor $K_{min} = 2$ correspondence appears plastic on the edge of vertical slope. Li also underline that her concept is clarity, method is easy, and construction design is convenient. Li also pointed out that the three and upper three layered soil deep foundation pit design calculation by energy safety factor, can imitate the tow layered soil calculation in her work.

Yang and Drumm [29] report the numerical analysis of the load transfer and deformation in a soil nailed slope and they noted that most of the long term deformations occurred in the upper slope which was supported by the short (about 3 m) nails suggesting that these nails were not effective. They also mentioned that The nail tensile forces were very small under the service loading, but under the surcharge loading the locations of the maximum tensile forces corresponded to the point where the potential failure surface intersected the nails.

Reference [30] studied the effect of pressure-grouted soil nails on the stability of weathered soil slopes and they underlined that the pressure-grouted soil nails exhibits obvious reinforcing effects for the slope stability with increasing the safety factor by around fifty and eleven percent compared with safety factors for natural slope and gravity-grouted reinforced slope, respectively. They also found that the slope reinforced with pressure-grouted soil nails exhibits expanded failure surface from the slope surface compared with that for the gravity-grouted reinforced slope. They explained that the expanded failure surface occurs by the increased stiffness of the reinforced slope system due to grouting pressure.

The influence of c and ϕ values on soil nailing reinforced wall slope in thick miscellaneous fill site was researched by reference [31] and they stated that soil cohesion and internal friction angle of the soil have great influence on the stability of the soil nailing wall, so their values must be reasonably selected according to the geological conditions and experience. They inferred that when $\phi < 18^\circ$, the influence of soil cohesion on the economy is much larger. The influence of internal friction angle on the economy is also much larger.

Three-dimensional modeling of spatial reinforcement of soil nails was analysed by reference [32] and they focuses on the behavior of the nailed slope under surcharge loading when different treatments of surface grillage structure connecting nail heads are adopted. They explore that the stabilizing forces mainly come from the upper row of soil nails along which the effective confining pressure is significantly increased due to the surcharge loading. They also implied that larger slope deformation can occurs when an overburden surcharge is increased near to its capacity, and the multiple point constraint

simulating the surface grid structure would impose additional restraint effects on the potential relative displacements at the connected nail heads.

A work done by reference [33] was stability analysis of soil nailing supporting structure based on system failure probability method. They stated that The system failure probability method considers principal failure modes of the soil nailing supporting structure and random factors of the system. Their method can reflect real conditions of project than the traditional stability analysis method based on safety coefficient. They also said that according to empiric and engineering experience, global sliding, partly sliding inside the supporting area and pullout of soil nails are defined as principal failure modes of the supporting system.

Effectiveness of hybrid anchor soil nails in stabilizing slopes and stability assessment based on mechanics were researched by reference [34] and they stated that the application of a hybrid anchor at the free end is an effective way to eliminate creep in active soil nails, as well as giving extra pullout capacity. They also implied that the application of the structural surface cover tied down using the hybrid anchor would be an effective way of stabilizing slopes against shallow rainfall-induced failure.

Stability of a high loess slope reinforced by the combination system of soil nails and stabilization piles was analyzed by reference [35] and they summarized that by using only one support measure of the soil nails and stabilization piles cannot meet the requirements of the overall stability of the slope. When the depth of excavation is relatively shallow, the contribution to the overall stability of soil nails is larger than piles; and with the increment of the excavation depth, the effect of stabilization piles began to dominate.

While reference [36] investigate the failure behavior and mechanism of slopes reinforced using soil nail wall under various loading conditions. They explained that soil nailing significantly increased the stability level and restricted the tension cracks of the slopes and underlined that increasing the nail length improved the stability of reinforced slopes with deeper slip surfaces. They also pointed that the reinforced slope exhibited a significant failure process during loading. The slippage failure of the slope and fracture of the cement layer developed in turn with a coupling effect until final landslide occurred.

The deformation behavior was proposed by reference [37] in the case of excavated high loess slope reinforced with soil nails and pre-reinforced-stabilizing piles. They revealed that the axial nail load presented an obvious increase during excavation, which indicates that the layout of soil nails played an effective role for the stabilization

of excavated slope. They also inferred that the potential sliding surface of slope soil above pre-reinforced-stabilizing piles displays in an arc-shape with its toe of slip surface located at the top of pile. Instead, the potential sliding surface of soil between piles is present in an polyline type.

Koerner [2] focused on relatively small and localized soil slopes which can be remediated in a low-cost manner and discussed about in-situ stabilization of soil slopes using nailed or anchored geosynthetics. He implies that other than increasing surface effects on the encapsulated soil mass's shear strength parameters, there are positive effects afforded by soil nails and to a related extent by cabled soil anchors.

Reference [38] studied the seismic design method for slope supporting structure of soil nailing and the results showed that the ductility of soil nail slope anchor structure has a good seismic performance, given the calculation model and seismic design method is simple, effective and feasible, and provide a theoretical basis for seismic design of soil nailing slope supporting structures.

Reference [39] performed a stability analysis of steep nailed slopes under seismic condition using 3-D finite element method such as MIDAS/GTS. Sahoo et al. found that the effect of nail length and the frequency amplification factor on the seismic resistance of nailed soil slopes is very little though there is a substantial variation in the nature and magnitude of facing displacement because of variation in the earthquake loading. But, agree with others, they inferred that inclined nails resist the deformation of steep slopes in a better way than the horizontally placed nails under seismic conditions. The effect of slope angle on the seismic resistance of nailed soil slopes is quite significant, hence the magnitude of facing displacement is greater in case of a slope having slope angle of 90° than the slope angle of 80°.

In the soil nailing wall slope protection design manner, Wu [40] give a good design method illustration in the Northern Shaanxi project. He summarized that soil nailing wall supporting is long contact with the surrounding soils along the soil nailing passed form a complex, under the condition of deformation occurs, through soil nail and soil cohesive force and friction force on the contact interface, make the passive soil nailing tension, and through the tension with constraints on working face of soil reinforcement, improve the overall stability and bearing capacity, the ductility of the reinforced soil mass deformation.

Integrated application of micro steel pipe piles and soil nailing frame beam for loose deposit slopes was explained by [41]. Using MIDAS/GTS, they stated that on the basis of the numerical analysis of the stability of the slope with or without the integrated treatment technology, their

results showed that the stability coefficient increased from 0.9375 to 1.3125, the stability state changed from an unstable state to a stable state successfully.

While reference [42] study the laboratorium model of screw-in soil nail for slope reinforcement against slip failure and they summarized that the novel screw-in soil nail could be potentially used to stabilize natural and man-made slopes, though full-scale simulations are recommended to formulate the installation procedure and to validate the effectiveness.

4. RESULTS ANALYSIS

In the example, author give a case study of landslide phenomenon occurred in Parit Raya River, Trenggalek, East Java, Indonesia. Hence, the additional reinforcement with soil nailing need to overcome the landslide damage. The existing data such described in Fig. 5 and Fig. 6, the length of retaining wall was 375 m, the height was between 8 m to 8,5 m suffered damage in the structure along side 90 m due to landslides in the area. Slope geometry was 1:1 (45°) of slope.



Fig 5. Field observation of existing retaining wall
Source: Parit Raya Project

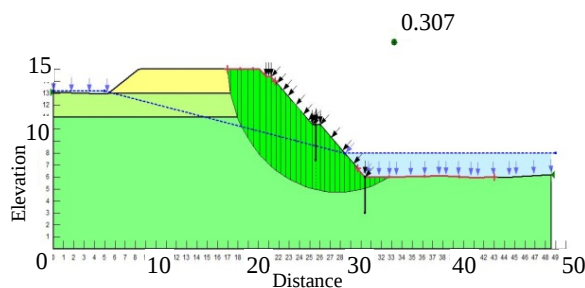


Fig 6. Contours of existing slope before soil nailing reinforcement
Source: Parit Raya Project

On the improvement of soil-nailing, the nail was consist of steel rebar of diameter 32 mm, and diameter of cement injection 0,3 m, with the distance spacing of 1 m and 2 m horizontally, the vertical nail length was 8 m. The rebar used 3 D32 from 10 m the top of the slopes and 5 D32 was used for 12 m from the bottom of the slopes such depicted in Fig. 7.

Soil Parameters

The physical properties of the soil used is T4 because the nearest point to the P18 point with depth of each layer is 2 m, the following summary data is ground at the point T4:

Layer-1

$\gamma = 18.71 \text{ kg/cm}^3$; $c = 24 \text{ kg/cm}^2$; $\phi = 15.508^\circ$

Layer-2

$\gamma = 18.01 \text{ kg/cm}^3$; $c = 3,30 \text{ kg/cm}^2$; $\phi = 13.927^\circ$

Layer-3

$\gamma = 17,07 \text{ kg/cm}^3$; $c = 1,40 \text{ kg/cm}^2$; $\phi = 10,628^\circ$

Weight Facing of Stone

Density of facing stone is 220 kN/m^2 , for 0,5 m thick, the density was 110 kN/m^2 .

Bond Skin Friction

The soils condition are silty clay, hence the value of the bond skin friction used was 100 kPa adopted from [43].

From the analysis also found that the sliding line height is high enough so the depth of the pile is not suitable to hold the sliding line surface that occurs. Before the contruction has been reinforced, factor of safety that obtained from landslide analysis using SLOPE/W was only 0,307 while by Bishop method [44] analysis,. Hence, the results shows that the slope is not safe and also the damage occurs visually there.

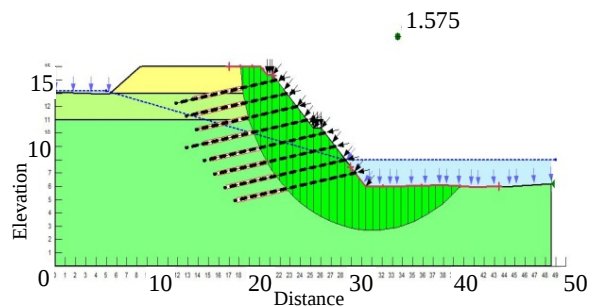


Fig 7. Contours of reinforced slope using soil nailing improvement
Source: Parit Raya Project

Table 2 Factor of safety of slope stability after soil nailing reinforcement

Slices	Factor of Safety			
	Ordinary	Bishop [44]	Janbu [45]	Morgenstren & Price [46]
P18	1,724	1,575	1,666	1,563

From Fig. 7, the analysis of slope stability at P18 that have been reinforced by soil nailing, the value of the factor of safety increase become as 1,575 that shown in Table 2, that shown the slope has been stabilized and safely reinforced.

5. CONCLUSION

This review explores the state of the art of slope stability research development in stabilizing the slope especially behavior of nailed soil slopes. It can be inferred that the use of soil nailing will fulfill the factor of safety to assist slope stability improvement. This paper basically guided to development of enhanced recognizing of the variation in nailed soil slopes parameters. The identification of the necessities of laboratory and in situ testing for evaluating nailing parameter have to be deeply explained. This paper also surveys some of important procedures extended by extensive investigation of the mechanics of slope stability. The most significant effective parameter that can be inferred in slope safety factor in almost proposed research are nail length, nailing angle, and distance between center to center of nails. Slope angle, connection of nailed head, the distance with toe and nail diameter were the points that cannot be neglected in analysis and design.

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