Design Practice and Technical Developments of Soil Nailing in Hong Kong

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Abstract: Soil nailing has been used in Hong Kong since mid 1980s. The technique has gained popularity because it offers effective and economic reinforcing system for a variety of ground conditions. Principles of soil-nailed system including failure modes and nail-ground interactions are highlighted and discussed. Current design approach and method are presented. Considerable experience and knowledge of the mechanisms and behaviour of soil nailed structures have been gained in recent years through systematic research and development studies. The studies include field tests, site trials and monitoring, numerical and physical modeling, and laboratory tests. They lead to the development of many technological advances in the design and construction. Study results are presented along with the advances made.

1 INTRODUCTION

In upgrading sub-standard slopes in early years, options like retaining structures, sub-surface drainage and cutting back to reduce slope angle were preferred. Later, new techniques of strengthening the ground insitu were introduced to minimize the need for excavation and construction of retaining walls. These developments led to the use of soil nails. In Hong Kong, soil nails are generally in the form of steel bars installed by the drill and grout method without prestressing. In early 1990s, some practices for design of soil nails for upgrading existing slopes were summarised by Watkins & Powell (1992), which soon became the norm for soil nail design.

With more existing slopes and retaining walls need to be upgraded each year under the Landslip Preventive Measures (LPM) Programme of the Hong Kong Special Administrative Region, the soil nailing technique has gained popularity since mid 1990s. The technique is now widely applied to stabilize man-made slopes, and sometimes applied to retain deep excavations. Although many soil nails are installed each year and the performance of the soil-nailed slopes is generally satisfactory, an improved understanding of the load transfer mechanism and the mechanical behaviour of soil nails is warranted in order to identify room for rationalisation of the design practice and to ensure the safe application of innovative materials and construction technology. To this end, a number of soil nail related studies have been undertaken systematically since late 1990s. The studies involve field load tests, site trials, numerical and physical modeling, and laboratory tests. They have brought about technological advances in respect of design and construction. New design and construction guidelines have been developed, e.g. GEO Technical Guidance Notes (TGN) numbered 19 and 23 (GEO, 2004a; GEO, 2006). This paper gives an overview of local soil nail design practice and recent technical developments.

2 MERITS AND LIMITATIONS OF SOIL NAILING

The concept of soil nailing involves creating a stable block of composite material by strengthening the insitu ground with soil nails. This requires that the soil nails are installed at close spacing, both horizontally and vertically. The soil nailing technique has a number of merits:

- It is well suited for cramped sites with difficult access because of the use of relatively small and mobile drilling rigs.
- It is a flexible method that can cope with frequent variations in ground conditions during construction.
- It can generally result in time and cost savings compared to conventional techniques of cutting back and retaining wall construction.
- It causes less environmental impact as no earthworks is required and existing trees can be retained.
- It is more robust than the conventional slope stabilization measures of cutting back (Ho et al, 2002).
- It renders ductile failure mechanism of a slope, thus providing warning signs before failure.

Like every other stabilization technique, soil nailing has its limitations:

- The presence of utilities and structures can limit the extent of soil nails.
- Unless agreement is obtained from owner of adjacent land, soil nails cannot extend beyond the lot boundary. This places restriction on the layout of soil nails.
- Special corrosion protection measures such as corrugated plastic sheathing are needed in aggressive ground and they could be costly.
- The presence of high groundwater table can lead to construction problem.
- Nailed excavations may result in relatively large horizontal displacements and cause damages to

nearby structures or utilities.
- Soil nailing in soft clay can have problems of creep and very low nail capacity.
- Sites with highly fractured rocks and open joints or voids may limit its application due to potential grouting problem.

3 PRINCIPLES OF SOIL-NAILED SYSTEM

3.1 *General*

Soil nailing is an in-situ reinforcement technique used for enhancing the stability of slopes, retaining walls and excavations. The nails interact with the ground to support the stresses and strains that would otherwise cause the unreinforced ground to fail. The internal stability of a soil-nailed structure is usually considered in terms of two zones (i.e. active and passive zones) separated by a potential failure surface (see Figure 1). The region in front of the potential failure surface tends to detach from the slope and is defined as the active zone. The region behind the potential failure surface, that remains more or less intact, is the passive zone. The two-zone concept is only a convenient idealism for limit equilibrium model. In reality there is a complex shearing zone subject to shear distortion (CIRIA, 2005). The following description of nail-ground interaction is based on the idealized two-zone system.

The ground has the potential either to move a small amount as a coherent mass, or to flow past the proximal end of the nail if it is not adequately restrained by the nail head, and the soil-nail friction within the active zone.

The shear stress exerted on the surface of soil nails within the active zone is directed outwards and has a tendency of pulling out the nails. The shear stress exerted on the surface of soil nails in the passive zone is directed inward and prevents the pulling out of the nails.

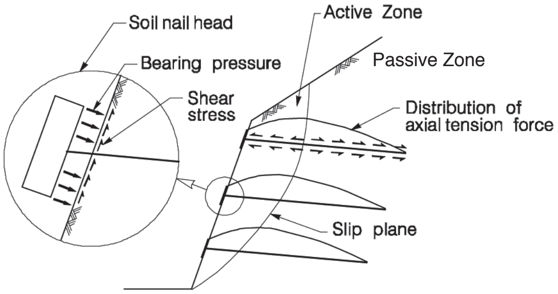


Figure 1. Load transfer mechanism of soil nailed structure

3.2 *Modes of Failure*

The failure mechanisms of nailed structures can broadly be classified as external failure and internal failure.

The external failure modes refer to the development of potential failure surfaces passing beyond the soil nails. The soil-nailed ground mass essentially remains as an integral body. The failure can be in the form of sliding, rotation, bearing failure (for nailed excavation), or other form of loss of overall instability (see Figure 2a).

Internal failure modes refer to failures within the soil-nail ground mass. In the active zone, these could be:

- failure of the bulk of the ground mass
  - ground disintegrates and ‘flows’ around nails
  - bearing failure behind nail head
- failure of ground between nail heads
  - washout or erosion
  - local sliding failure between nail heads
- structural failure of nail element
  - tensile failure of the nails
  - shear and bending failures of the nails
- structural failure of facing/head
  - bending/punching shear
  - nail-head/facing connection

In the passive zone, the failure mode is mainly:

- pullout failure
  - pullout failure of nail along soil-grout interface
  - pullout failure nail along bar-grout interface

The various internal failure modes are illustrated in Figure 2b.

3.3 *Nail-ground Interaction in the Active Zone*

Soil nail acts as a structural element which provides load-transfer into the ground. Forces are developed in a nail through the interaction among the ground, the nail element and nail head (Figure 1). The reinforcing action of the nail element is achieved through two fundamental mechanisms of nail-ground interaction. They are: (i) the nail-ground friction that leads to axial tension or compression in the nail (see Figure 1); and (ii) the bearing pressure exerted by the ground on the nail element that leads to the development of shear stresses and bending moments in the nails (see Figure 3). In these two mechanisms, the interactions between the ground and the nails are complex and the forces developed in the nails are influenced by many factors such as the size of the nail head, the bearing capacity of the ground to resist reaction force from the nail element, relative stiffness of the nail element and ground, and the tensile strength, inclination, shear strength and bending capacity of the nail element.

The development of stresses and strains in the active zone is resisted by the soil shear strength and the strength of the nail element under combined loadings of tension, bending and shear. When there is a small ground movement in the active zone, in particular at the shearing zone where the active zone moves downwards relative to the passive zone, the nail element will experience both axial and lateral strains. The axial strain will mobilize tensile forces, and the lateral strain will mobilize shear force and bending moment in the nail element. If the nail element is aligned with the direction of the tensile strain of the soil, the predominant action of the nail element is in tension and the shear force and bending moment induced in the nail are small. The tensile force improves the shearing strength of the soil by: (i) reducing the driving force on the soil; and (ii) increasing the normal stresses on the failure plane of the soil and consequently increasing the frictional resistance of the soil (Jewell & Wroth, 1987).

If the nail element is placed normal to the potential shear surface of the soil, bending moment and shear forces will be the dominant actions in the nail. In this case, the soil nail becomes a dowel element. The nail-ground lateral interaction will be as follows (Tan et al, 2000):

Elastic soil - elastic nail

When there is small ground movement initially in the active zone, in particular at the shearing zone, both the soil and the nail element will be stressed in the range of elastic state. The elastic state will be maintained if equilibrium is reached.

Plastic soil - elastic nail / Elastic soil - plastic nail

If equilibrium cannot be reached in the stage of elastic-soil-elastic-nail, the ground movement in the active zone will continue until either the soil or the nail element, or both of them reaches plastic state. The state to be reached depends on the relative stiffness of the soil and the nail element. If the nail element is much stiffer and stronger than the soil, the soil will yield first when its bearing capacity is reached (Figure 4(a)). If the soil is much stiffer and stronger than the nail element, the nail element will yield (formation of a plastic hinge) or rupture (brittle failure) when the yielding or rupture point with respect to the combined action of tension, bending, and shear of the nail is reached (Figure 4(b)). A plastic hinge will be formed in the nail element only if it is ductile, otherwise it will rupture.

Plastic soil - plastic nail

If equilibrium for the lateral ground-nail interaction still cannot be reached, ground movement in the active zone will further increase until both the soil and the nail element reach plastic state. In this case, the soil reaches its bearing capacity and yields; and the nail element either yields with a formation of plastic hinge or ruptures, depending on whether the nail element is ductile or not (Figure 4(c)).

It has been demonstrated by means of laboratory tests (e.g. Pedley (1990), Jewell & Pedley (1992), Bridle & Davies (199&)), numerical analyses (e.g. Shiu & Chang (2006), Smith & Su (1997)) and monitoring of in-service and test nailed structures (e.g. Plumelle et al (1990), Gässler (1997)) that under the working conditions, the mobilized shear and bending resistances of soil nails are small. Further discussion is given in Section 6.3 below.

3.4 *Interaction between Nail Head and Ground*

The ground movement in the active zone is resisted by nail elements as well as nail heads. The resistance that can be provided by a nail head depends on the stiffness of the head and the soil underneath, and the shear strength of the soil.

The head-ground interaction is affected by the direction of the resultant compressive and shear strains developed beneath the nail head in response to the ground movement in the active zone. If the resultant strain is close to a direction perpendicular to the base of nail head, the head-ground interaction will mainly be in the form of bearing mechanism. The mean effective stress in the soil behind the nail head will increase due to the confinement effect of the nail head. The shear strength of the soil will increase correspondingly. This is illustrated by the results of numerical analysis shown in Figure 5. The earth pressure acting on the nail head will mobilize tension in the nail element. If the resultant strain is in a direction that significantly deviates from the normal of the base of the nail head, the head-ground interaction will be a combination of bearing and sliding mechanisms.

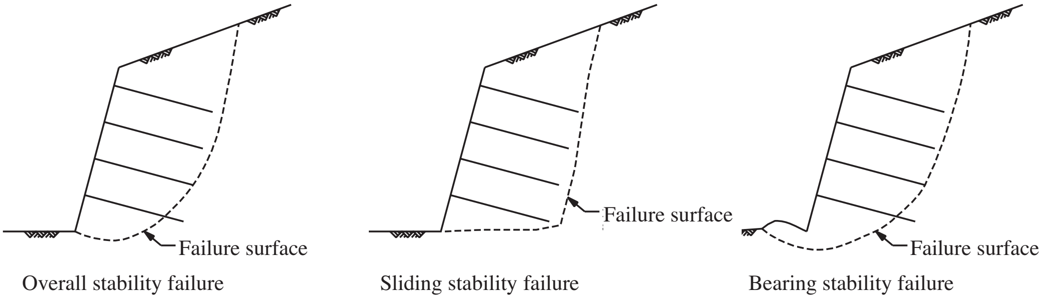
The mobilization of frictional force along nail element in the passive zone depends on many factors. Nevertheless, the basic principles are contact stress and interface friction. Immediately upon the formation of a drillhole in the ground for nail construction, the radial stress at the drillhole face drops to zero, irrespective of the overburden pressure. The hole remains stable by soil arching. Subsequent grouting will restore a certain level of the radial stress in the soil around the hole. The contact stress at the ground/grout interface depends on the pressure exerted by the grout. As it is common practice to grout up the drillhole under gravity, the contact pressure at the drillhole face is small compared to the overburden pressure. This seems to imply small bond strength at the ground/grout interface. In reality, the drillhole face, which is formed by percussive drilling, is fairly irregular and rough. Upon pulling of the soil nail, shearing will occur within the ground mass in a finite zone surrounding the nail element. If the soil is dilative, the effect of restrained dilatancy will come into place. The effect of this can be significant and can lead to high soil-nail friction.

4 DESIGN APPROACH AND METHOD

4.1 *Analytical Design Approach*

The current soil nail design approach is essentially a combination of global safety factor approach (permissible stress design) and partial safety factor approach. The common design sequence is to determine the most critical potential failure surface for the unreinforced slope, determine the stabilization force required to provide the required global factor

(a) External failure modes



(b) Internal failure modes

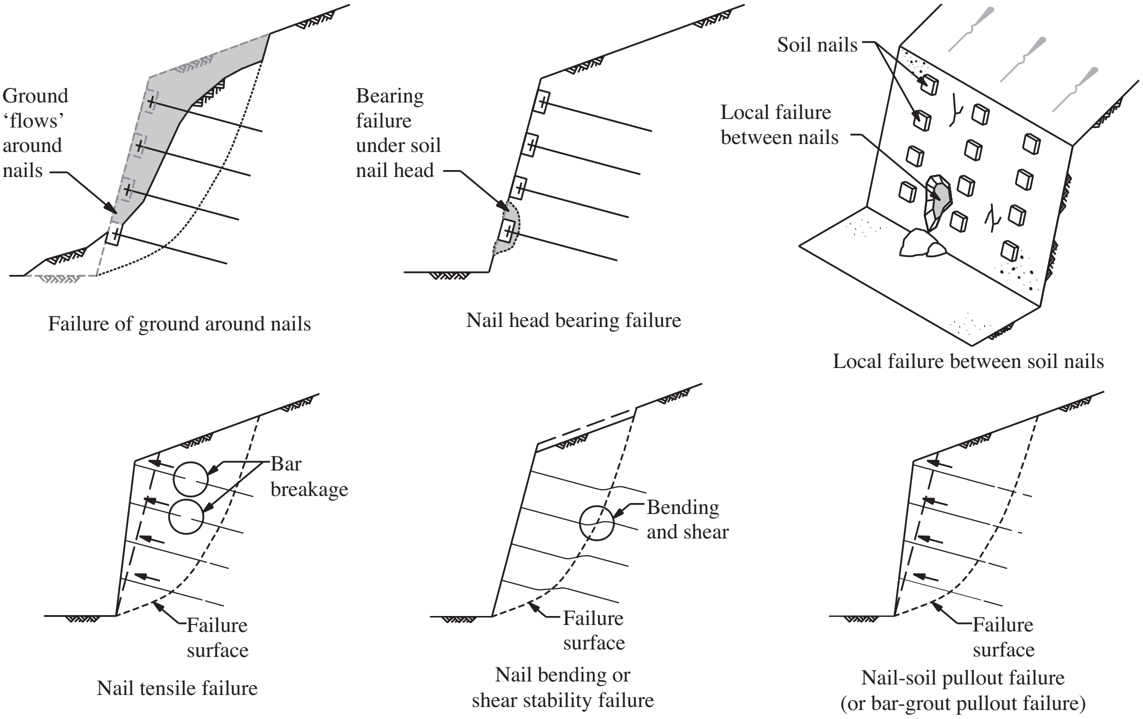


Figure 2. Principal modes of failure

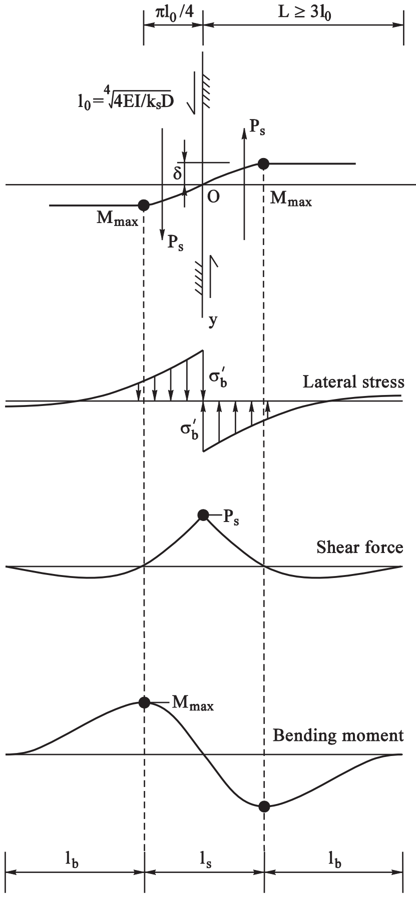
of safety to the slope, then provide this force by the action of soil nails. The diameter, length and spacing of the nails are determined to provide adequate partial safety factors against different internal failure modes.

The global safety factor to be used for a nailed slope is the same as that for the design of unreinforced slope as recommended in the Geotechnical Manual for Slopes (GCO, 1984). Although not explicitly stated, the global safety factor deems to cover uncertainties related to ground model, shear strength of soils, design groundwater level etc, which exist in the design of unreinforced slopes.

For the design of stabilization works to existing retaining walls using soil nails, the minimum required global factors of safety against sliding, overturning and bearing of the retaining walls as recommended in the first edition of Geoguide 1 (GCO, 1982) are to be followed. This usually results in a few rows of widely spaced and long soil nails even for tall retaining walls. Strictly speaking, the walls designed in this way behaves more like a tieback wall and it does not fully satisfy the soil nailing concept of reinforcing the insitu ground (using closely spaced soil nails) to form a stable block of composite material.

Three partial safety factors are applied to cover uncertainties related to the design of soil nail elements. They are summarized in Table 1.

The requirements for the soil nail design are given in GEO Technical Guidance Note No. 23 (GEO, 2006).



Legend:

k_s	Coefficient of subgrade reaction	l_o	Transfer length of nail
δ	Lateral displacement of nail	E	Modulus of Elasticity of nail
I	Nail moment of inertia	D	Nail diameter
M_{max}	Maximum bending moment in nail	P_s	Shear force in nail
δ_b'	Maximum bending moment in nail		

Figure 3. Nails subjected to bending moment and shear force (after Schlosser, 1982)

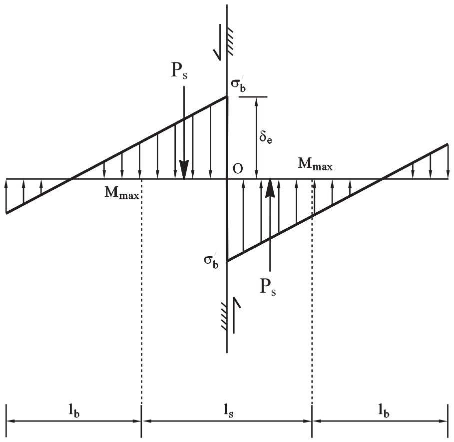
The sizes of nail heads are to be determined by one of the following three methods:

- design table derived from numerical analysis (see Section 6.1 below);
- the lower-bound nail head design method adopted from the one given by UK Department of Transport (1994);
- prescriptive design approach (see Section 4.2 below).

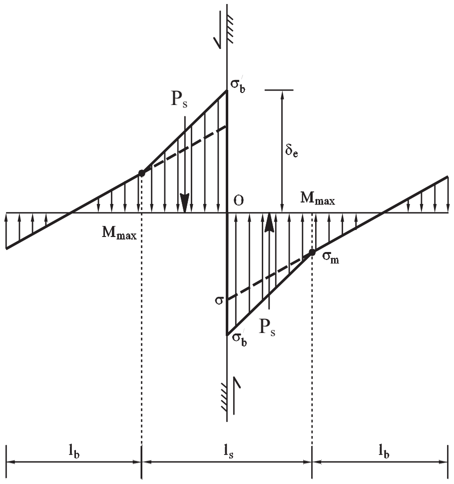
Table 1. Partial factors of safety

Modes of failure	Partial factors of safety
Bond failure at grout-soil interface	1.5 on weathered granite and volcanic rocks; and 2.0 on others
Bond failure at grout-bar interface	2.0
Tensile failure of steel bar	1.5 on yield strength of bar

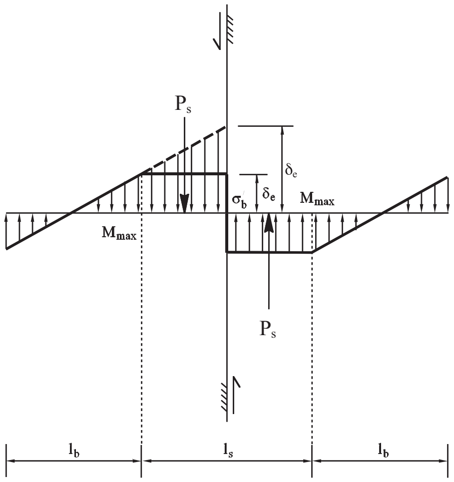
Note: The partial factors of safety are applied to soil nail with reinforcement in the form of high yield steel bar.



(a) plastic soil - elastic nail

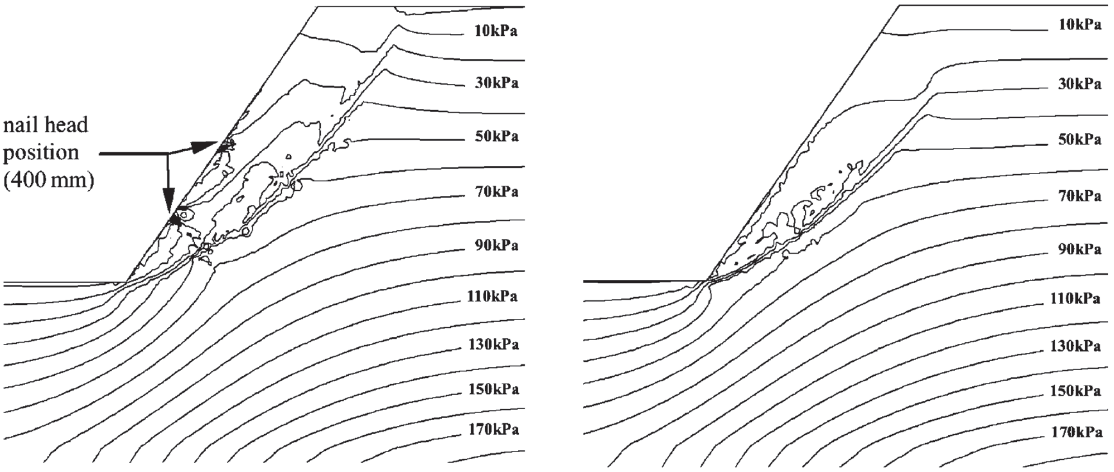


(b) elastic soil - plastic nail



(c) plastic soil - plastic nail

Figure 4. Progressive development of stress in lateral nail-ground interaction (after Tan et al, 2000)



(a) Contours of mean effective stress in soil nailed slope

(b) Contours of mean effective stress in unreinforced slope

Figure 5. Contours of mean effective stress in (a) soil nailed slope, and (b) unreinforced slope

The structural design of nail heads follows recommendations stipulated in relevant structural design codes. Details for the design of soil nail heads are given in GEO (2004b).

The concept of limit state also applies to the current design approach. A limit state is typically defined as: "any limiting condition beyond which the structure ceases to fulfill its intended function" (Day, 1997). Soil nail design for slopes is mainly carried out for the ultimate limit state, i.e. design against possible failure modes. As soil nails are passive reinforcing elements, certain ground movements in the active zone are inevitable in order to mobilize axial tensile force, shear stress and bending moment in the nails. Designs for serviceability limit state are performed in cases where there is concern on ground movement (e.g. nail excavation in close proximity of structures/utilities).

The design against possible failure modes can be carried out using the analytical method. Limit equilibrium methods (LEM) of slices are routinely used. Shiu et al (2007) have reviewed the use of limit equilibrium methods for soil nail design. They cautioned that the behaviour of soil nailed structure is a strain compatibility problem and the effect of nail inclination cannot be accounted for in LEM. Furthermore, it is possible to define a wide variety of nail length patterns that satisfy stability requirements but that may not satisfy serviceability requirements (Shiu & Chang, 2005). Users of LEM computer programs should recognize the potentially erroneous results and interpret the results carefully. It is important that only methods that consider both moment and force equilibrium, such as the Morgenstern and Price method, are used in soil nail design. Although LEM involves assumptions and has certain weaknesses, the method does provide a useful and practical technique for the analysis of slopes (both unreinforced and reinforced).

4.2 *Prescriptive Design*

Apart from the analytical approach, soil nails can be designed prescriptively for stabilization of existing cut slopes and retaining walls. Prescriptive measures are pre-determined, experienced based and suitably conservative modules of works prescribed to a slope feature to improve its stability without detailed ground investigation and design analyses. Use of soil nails as prescriptive measures for upgrading soil cut slopes have been successfully applied since the publication of GEO Report No. 56 (Wong et al, 1999). The scope of application of prescriptive measures has now been extended to include improving stability of substandard concrete or masonry retaining walls (Lui & Shiu, 2004). Prescriptive design of soil nail heads is given in GEO (2004b).

4.3 *Use of Soil Nails in Loose Fill*

Guidelines on the design of soil nails for the stabilization of loose fill slopes are given in the publication "Soil Nails in Loose Fills Slopes - A Preliminary Study" by the HKIE Geotechnical Division (HKIE, 2003). The main design recommendations are as follow:

- Steady state shear strength should be adopted for loose fill in the design.
- Global stability should be provided for by bonding soil nails into a competent stratum.
- Local (near surface) stability should be provided for by a concrete grid structure covering not less than 50% of the slope surface and connecting soil nail heads. Soil nail spacing should not be more than 1.5 m horizontally and vertically.
- The grid structure should be designed to withstand bending moments and shear forces generated by the loose fill it is retaining. It should be adequately founded on a competent stratum.

- The potential of leakage from water-carrying services should be duly considered.

5 AESTHETIC CONSIDERATIONS

In addition to safety, designers should pay due regard to slope appearance in their designs. In the past, vegetation covers were provided only to gentle slopes and hard covers such as chunam and shotcrete were used on steep slopes. As cut slopes stabilized by soil nails are usually steep, most soil-nailed slopes constructed in the early 1990s had a hard cover. Improvement in detailing of surface covers, involving the use of an erosion control mat in conjunction with a steel wire mesh, has allowed the provision of vegetation covers to slopes with a gradient up to 55° and sometimes 60° (Figure 6). Many soil-nailed slopes in Hong Kong have been successfully vegetated using this technique (Figure 7).

Where the provision of vegetated surface cover on a slope is practically not feasible, hard landscape treatment is generally provided to improve its appearance. Engineers are now more knowledgeable in landscape design concept than before. The commonly used methods are masonry block facing, ribbed or other patterned concrete finishes, toe planters, colouring and planter holes, coupled with suitable retention of existing vegetation (Chan, 2005).

Comprehensive technical guidelines on landscape treatment and bio-engineering for man-made slopes and retaining walls are given in GEO Publication No 1/2000 (GEO, 2000).

6 RECENT TECHNICAL DEVELOPMENT

6.1 *Effect of Soil Nail Head*

Soil nail heads used in slope stabilization works in Hong Kong are usually in the form of isolated reinforced concrete pads. To investigate the effect of soil nail heads on stability of nailed slopes, numerical simulations have been carried out using the two dimensional finite element code, Fast Lagrangian Analysis Continua (FLAC). Figure 8 shows the slope model used. Strength reduction technique (Dawson et al, 1999) is employed to compute the factors of safety (FoS). In the simulations, nail heads of different sizes are modeled in plain strain. The slope without any soil nails (i.e. unreinforced) has a minimum FoS close to 1 (Shiu & Chang, 2004). Based on the FLAC analysis, Figure 9 shows the relationship between the calculated FoS of the model slope and nail head sizes. The FoS increases from 1 for the unreinforced slope to 1.2 for the nailed slope with no nail heads. Substantial increases in the FoS are obtained with nail head sizes from 400 mm wide to about 800 mm wide. The trend of increase levels off for nail head sizes larger than 800 mm wide. It shows that nail head can have significant effect on the stability of a nailed slope.

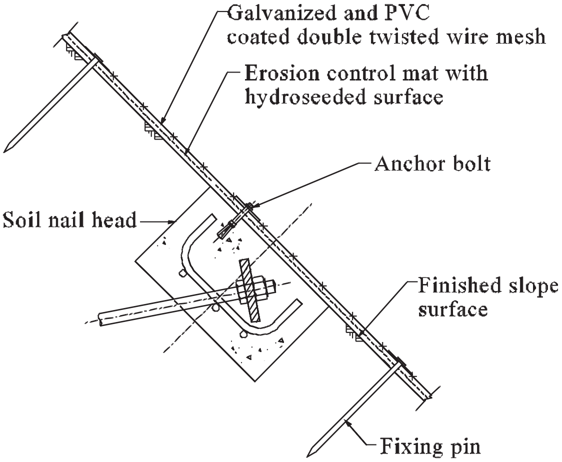


Figure 6. Fixing details of steel wire mesh and erosion control mat on slope face with soil nail heads

Figure 10 compares the axial tensile forces developed in soil nails without nail heads with those in nails with heads of 800 mm wide. It shows that for the nails with no nail heads, no tensile force is developed at the front end of the nail (Figure 10(a)); but for the soil nails with nail heads, large tensile forces are mobilised in the nails at the connections to the nail heads (Figure 10(b)). The large mobilised tensile forces in the latter case indicate significant interaction between nail heads and the ground, which greatly increase the stability of the slope.

A series of centrifuge tests has been conducted in the Geotechnical Centrifuge Facility of the Hong Kong University of Science and Technology to investigate the reinforcing effect of soil nails and nail heads (Zhou et al, 2006). Figure 11 shows an instrumented model used in one of the nailed slope centrifuge tests. The test results support the results of the numerical

Figure 7. Details of the use of steel wire meshes in conjunction with non-degradable erosion control mats

Nail Parameters
Grout hole diameter = 100mm
Bar diameter = 40mm
Soil nail length = 20m
Vertical spacing = 2500mm
Horizontal spacing = 1500mm
f_y = 460 N/mm^2

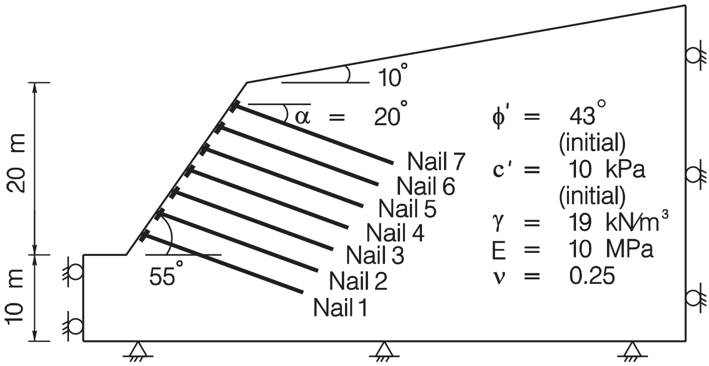


Figure 8. Geometry and material parameters of model slope

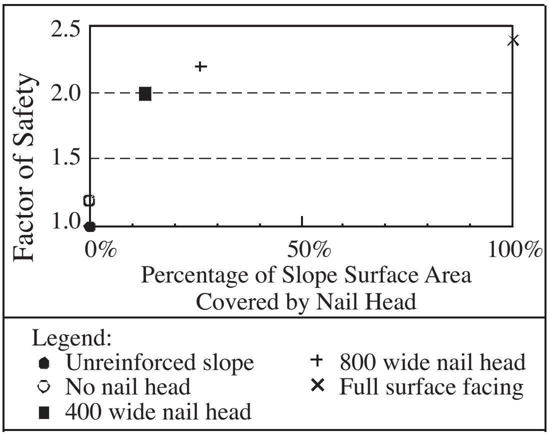


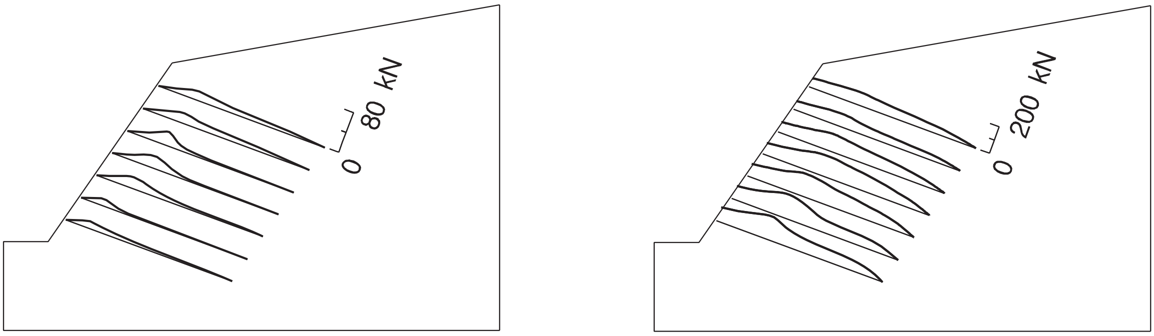
Figure 9. Relationship between factor of safety and nail head size

simulations that nail head can substantially improve the stability of nailed slopes.

Numerical analysis has also been performed to examine the bearing capacity failure of square soil nail heads. A small slope model of 5 m in height was used and various slope angles were considered. In the analysis, the nail head was pushed into the ground by a nail force to simulate the situation of soil moving out from a slope and pressing against the soil nail head. The nail forces used are determined from the allowable tensile strength of steel bars. Figure 12 and 13 show respectively the shear strains and the displacement vectors at the point of bearing failure for a 600 mm x 600 mm nail head on a 45° slope. Typical results of the analyses in terms of c'-ϕ' envelope for limit equilibrium (i.e. when bearing failure occurs) are plotted in Figure 14. In this plot, the nail head loads are expressed as diameters of steel bars. Details of the study are given in Shiu & Chang (2004). A number of the plots have been developed for different slope angles and nail head sizes. Knowing the shear strength parameters of the soil, the steel bar diameter and the slope angle, a designer can determine the size of nail head from these plots. A design table has been derived from the plots and it forms the basis of the design method derived from numerical analysis as mentioned in Section 4.1 above.

6.2 *Effect of Nail Inclination*

Unlike the reinforcement in reinforced fill structures, which are placed in horizontal direction, soil nails



(a) No Soil Nail Head

(b) 800 mm Wide Soil Nail Head

Figure 10. Variation of axial nail forces for (a) no nail head and (b) 800 mm soil nail head

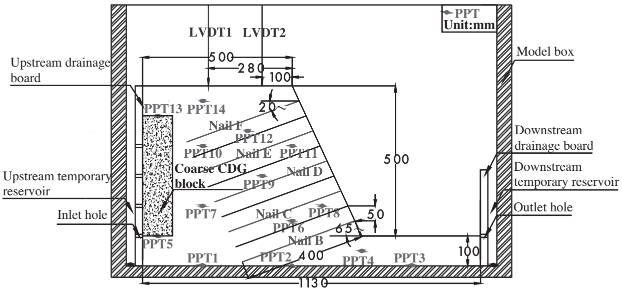


Figure 11a. Set-up of a nailed-slope model in centrifuge test

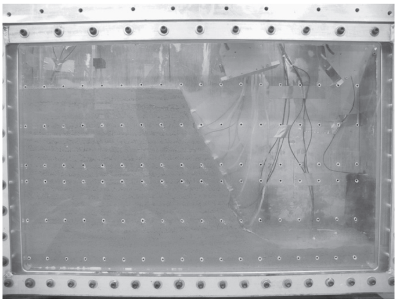


Figure 11b. Side view of the slope model in centrifuge test

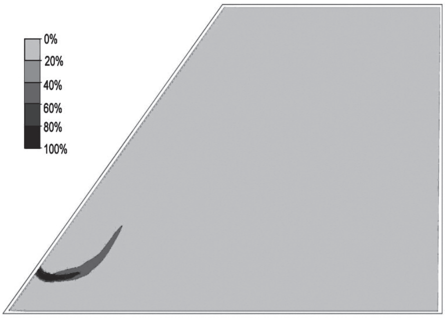


Figure 12. Typical shear strain plot

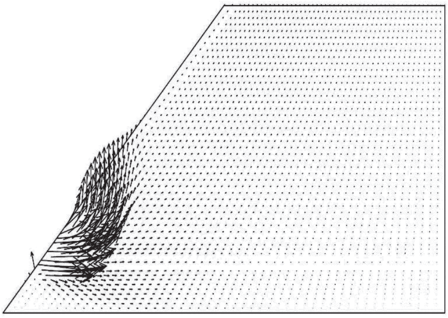


Figure 13. Typical displacement vector plot

can be installed in the ground at various inclinations. In congested sites, soil nails are sometimes steeply inclined. Different nail inclinations can produce different effects on the behaviour of nailed structures. Studies of these effects have been conducted by means of numerical simulations (Shiu & Chang, 2005) in which the two-dimensional FLAC with strength reduction technique was employed.

Tensile or compressive axial forces can be developed in soil nails and this depends on the nail inclination, α, which is the angle of the soil nail below the horizontal. Figure 15(a) shows that for soil nails with a small inclination of 20°, tensile forces are developed in all the nails. On the other hand, Figure 15(b) indicates that when the nails are inclined steeply at an inclination of 55°, compressive forces are developed in the top four nails whereas tensile forces are mobilized only in the bottom three nails. Tensile nail forces can improve stability whereas compressive forces can have opposite effect. Increases in FoS (ΔFoS) due to the soil nails were calculated for different nail inclinations. Figure 16 shows the relationship between the calculated ΔFoS and nail inclinations (α) for the model slope. The ΔFoS is close to 1 with little variations for the range of α between 0° and 20°. The ΔFoS decreases quickly as α increases beyond 20°, reflecting that the reinforcing effects of the nails reduce rapidly with increasing nail inclinations. At α = 55°, the value of ΔFoS is almost zero.

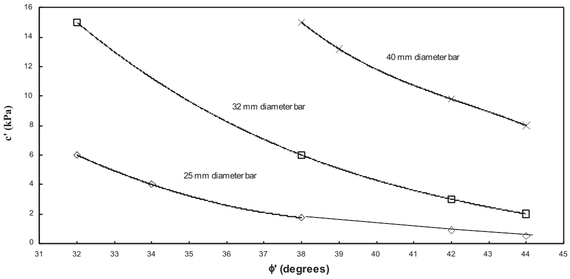
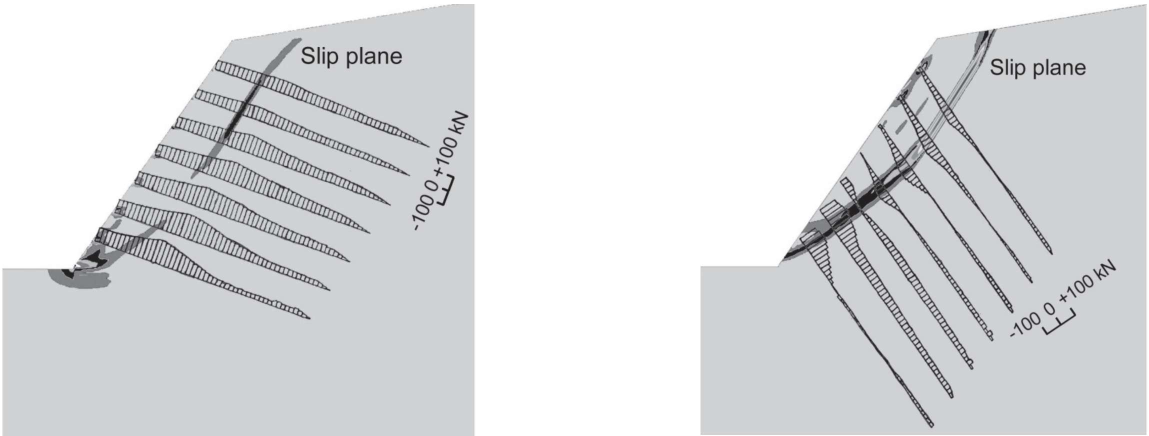


Figure 14. Shear strength required for 600 mm x 600 mm nail heads on a 45° slope to mobilise allowable tensile strength of nails of specified diameters

Behaviour of nailed structures is a strain compatibility problem. A nail force develops through the interaction among the deforming soil, the soil nail and nail head. An important point here is that depending on the nail inclination, compressive forces rather than tension forces can be mobilized in soil nails. This contradicts the common design assumption used in limit equilibrium methods that only tensile forces are developed in soil nails. The limit equilibrium methods do not consider strains and displacements, and as a result, they may give rise to invalid results in calculating nail forces and factors of safety of nailed slopes with steeply inclined nails. The development of compressive force in soil nails should be considered in such cases. The use of limit equilibrium methods for soil nail design is discussed in the paper by Shiu et al (2007).



(a) α = 20° (b) α = 55°

Figure 15. Axial force distribution in nails for (a) α = 20° and (b) α = 55°

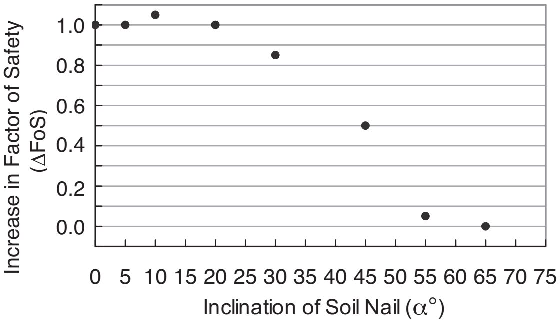


Figure 16. Variation of increase in factor of safety against inclination of soil nails

6.3 *Effect of Bending Stiffness of Soil Nail*

Steel soil nails can sustain shear forces which may also enhance the shear strength of soil. The development of shear forces in nails involves a mechanism which is dependent on the bending strength of the nail, the soil bearing strength, and the orientation and shear deformation of reinforcement. To study the effect of bending stiffness of the nails on nail forces and displacements, numerical simulations have been conducted using the slope model shown in Figure 8 (Shiu & Chang, 2005). Nails with different inclinations have been investigated. For each nail inclination, the FoS of the nailed slope, the tensile forces, shear stresses and bending moments developed in the nails are computed.

The maximum axial force developed in a nail is T_{max}. Figure 17 shows the total of the maximum tensile forces mobilised in all the soil nails (ΣT_{max}) at limit equilibrium condition of the slope model. The maximum shear force in a nail at the location where the shear plane intersects the nail is Ps_{max}. The total of the maximum shear forces (ΣPs_{max}) mobilized in the soil nails at limit equilibrium condition of the model are also plotted in Figure 17. The value of ΣPs_{max} rises steadily with increasing nail inclination (α). The rise is small, from 31 kN/m at α = 10°, to 76 kN/m at α = 55°. In contrast, the value of ΣT_{max} decreases rapidly with increasing nail inclination. For small nail inclinations, ΣT_{max} is much larger than ΣPs_{max}. Comparing between Figure 16 and 17, it can be noted that both ΔFoS and ΣT_{max} generally decrease with increasing nail inclinations. This similarity illustrates that ΔFoS is strongly influenced by the nail axial force. The ΔFoS is not sensitive to the mobilized shear resistances in the nails. The modeling results show that small shear forces are mobilized in soil nails and they have little effect on the factor of safety of the slope, except at very steep nail inclination where dowel action starts to play a role. The contribution from bending and shear to the calculated factor of safety of a slope is therefore generally ignored.

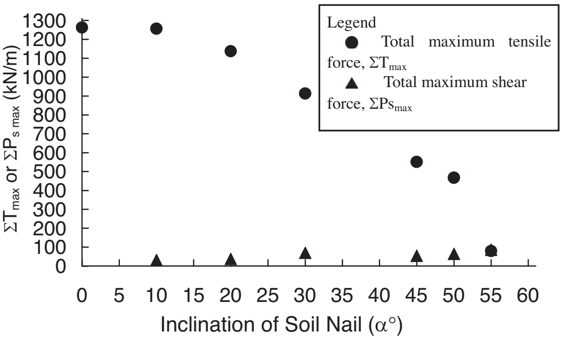


Figure 17. Variation of total maximum tensile force (T_{max}) and total maximum shear force (Ps_{max}) with nail inclination (α)

Soil nails are not effective in providing dowel action. For that purpose, other types of structural element should be considered, e.g. large diameter piles. Nevertheless, steel soil nails have large shear ductility. As a result of the mobilization of shear and bending ductility at large deformations, a nailed structure tends to exhibit ductile failure rather than sudden failure.

6.4 *Pullout Resistance of Soil Nails*

Pull-out capacity is a key parameter for the design of soil nails. At present, methods for estimating pullout capacity are not unified as reflected by the many approaches used in different technical standards and codes of practice, such as effective stress method (GEO (2006), CIRIA (2005)), empirical correlation with SPT N values (JH, 1998), correlation with pressuremeter tests (Clouterre, 1991), and correlation with soil types (FHWA, 2003). The merits and limitations of the various methods are summarized in Table 2. The effective stress method is adopted in Hong Kong.

Table 2. Merits and limitations of the methods for determining ultimate pull-out resistance

Method	Merits	Limitations
Empirical Correlation	Related to field performance data; can better account for influencing factors.	Need a large number of field data and take a long time to establish a reasonable correlation; a general correlation may not be applicable to all sites.
Pull-out Test	Related to site-specific performance data.	Need to carry out a considerable number of field pull-out tests during the design stage; not feasible for small-scale project; time consuming.
Undrained Shear Strength	Based on soil mechanics principles; easy to apply.	Generally not suitable for Hong Kong; many factors that affect the pull-out resistance are not accounted for.
Effective Stress	Based on soil mechanics principles; easy to apply.	Many factors that affect the pull-out resistance are not accounted for.
Pressuremeter	Related to field performance data; can better account for influencing factors.	Need a large number of field data to establish a reasonable correlation; a general correlation may not be applicable to all sites; pressuremeter test is not common in Hong Kong.

Field pull-out test data have been collected from LPM contracts since 2004. Improved test set-up and procedures, which include minimising friction loss along a test nail, imposing better control on the length of the grouted portion and increasing the test load by using large bar size, were adopted in these tests. A total of 914 test results were collected. About 84% of the tests were conducted in granite or volcanic saprolite. The rest were conducted in other types of material such as fill, colluvium and moderately decomposed rock.

Most (423 nos.) of the pull-out tests were only tested to 90% of the yield strength of steel (T_p), i.e. not reaching the ultimate pull-out resistance (T_{ult}). Figure 18 shows the plot of the ratio of the field to the estimated pull-out resistance against the overburden pressure of those tests which have reached the ultimate pull-out resistance. Figure 19 presents the same plot with all the test data (542 nos., i.e. those reaching either T_{ult} or T_p). The field pull-out resistances are generally several times higher than those estimated using the effective stress method, but the safety margin (i.e. $T_{ult\ (field)}/\ T_{ult\ (estimate)}$) gradually decreases when overburden pressure increases. Some of the field pull-out tests (26 nos.) were carried out under saturated condition, and the results do not show particularly low pull-out resistance when compared with other pull-out tests carried out under dry condition of the same overburden pressure and similar soil shear strength.

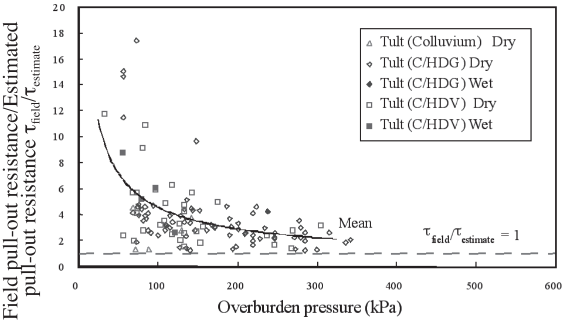


Figure 18. Plot of field (T_{ult}) to estimate pull-out resistance against overburden pressure

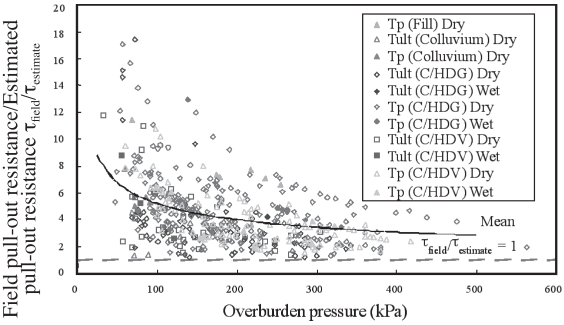


Figure 19. Plot of field ($T_p + T_{ult}$) to estimate pull-out resistance against overburden pressure

Many factors that affect the pullout resistance of a soil nail are difficult to be quantified in a design. The current effective stress method does not account for factors including soil arching, restrained soil dilatancy, soil suction, roughness of drillhole surface, over-break, etc. All these factors except soil arching tend to result in higher pullout resistance than the design value. Field pullout test data support this hypothesis in that the actual pullout resistance is generally higher than that estimated using the effective stress method.

Laboratory pullout tests have been carried out in recent years by a number of researchers to investigate the development of soil/nail interface shear, such as Lee et al (2001), Pradhan et al (2003), Junaideen et al (2004), Chu and Yin (2004). They provided useful information on the behaviour of soil nails in pullout in different types of compacted and loose fill. Most recently, Yin & Su (2006) studied the effects of hole drilling process, overburden pressure, degree of saturation of the soil, and grouting pressure on pullout resistance. Compacted fill of completely decomposed granite was used in the tests. The following observations were made from the study: (a) the drilling process during soil nail installation led to stress reduction in the soil around the drillhole and the pullout resistances of the nails were not dependent on the amount of vertical surcharge applied if gravity grouting was adopted; (b) the peak pullout strength of soil nail in fully saturated soil was lower than that in partly saturated soil; and (c) pullout resistances of the nails increased with an increase of grouting pressure.

6.5 *Potential Effect of Blockage of Subsurface Drainage by Soil Nailing Works*

Soil nails installed in the ground may impede groundwater flow and as a result dam up the water level. To study the significance of this effect, a number of numerical models were set up in both 2-D and 3-D for various geological settings, subjected to infiltration (Halcrow, 2005). Typical nail spacings of 1 m to 2 m were adopted in the models. Figure 20 illustrates an example of computed flow nets and water table distributions for a slope under three conditions: (a) without soil nails; (b) soil nails with excessive grout loss, and (c) soil nails with no grout loss.

Results of the numerical modeling show that under typical conditions where there is little grout loss during the grouting operation, there should be no significant blockage of the drainage paths. It is also found that the influence of soil nails on groundwater flow can be significant if excessive grout escapes laterally to affect large volumes of the country rock. Therefore, measures should be taken to avoid excessive grout loss. Where excessive grout loss occurs during installation of soil nails, the cause should be investigated and, if necessary, measures taken to monitor rises in hydraulic head and to take action to drain the ground upstream of the nails.

6.6 *Long-term Durability of Soil Nails*

Durability is an important aspect of soil nailing system. The long-term performance of soil nails depends on their ability to withstand corrosion attack from the surrounding ground. To enhance understanding of the subject, a review of the current state of practice of corrosion protection in different parts of the world has been carried out (Shiu & Cheung, 2003). The review also included a survey of the chemical properties of common Hong Kong soils and an assessment of their corrosion potential. In addition, soil nails of different ages were exhumed from the ground and they revealed that localized corrosion could occur even if hot dip

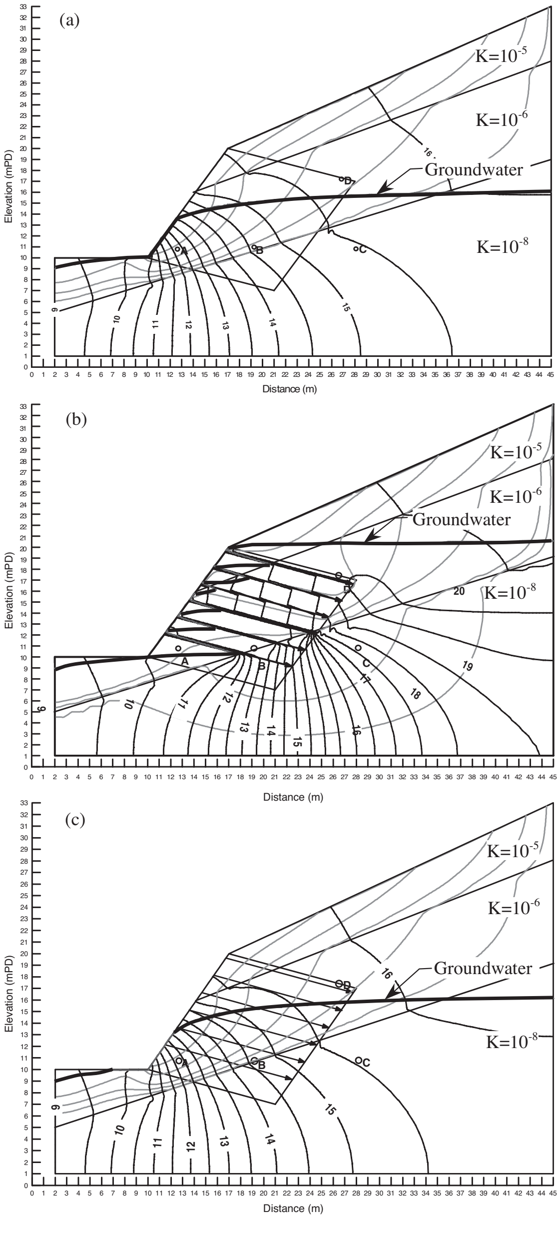


Figure 20. Flow patterns in a slope (a) without soil nails, (b) soil nails with excessive grout loss, (c) soil nails with no grout loss (after Halcrow, 2005)

Table 3. Soil corrosivity assessment scheme

Property	Measured Value	Mark
Soil Composition	Fraction passing 63 µm sieve ≤ 10 %, and PI of fraction passing 425 µm sieve < 2, and organic content < 1.0 %	2
	10 % < Fraction passing 63 µm sieve ≤ 75 %, and fraction passing 2µm sieve ≤ 10 %, and PI of fraction passing 425 µm sieve < 6, and organic content < 1.0 %	0
	Any grading, and PI of fraction passing 425 µm sieve < 15, and organic content < 1.0 %	-2
	Any grading, and PI of fraction passing 425 µm sieve ≥ 15 and organic content < 1.0 %	-4
	Any grading, and organic content ≥ 1.0 %	-4
Resistivity (ohm-cm)	≥ 10,000	0
	< 10,000 but ≥ 3,000	-1
	< 3,000 but ≥ 1,000	-2
	< 1,000 but ≥ 100	-3
	< 100	-4
Moisture Content	≤ 20%	0
	> 20%	-1
Ground-water level	Above groundwater level and no periodic flow or seepage	1
	Local zones with periodic flow or seepage	-1
	At groundwater level or in zones with constant flow or seepage	-4
pH	6 ≤ pH ≤ 9	0
	5 ≤ pH < 6	-1
	4 ≤ pH < 5 or 10 ≥ pH > 9	-2
	pH < 4 or pH >10	See Note 1
Soluble Sulphate (ppm)	≤ 200	0
	> 200 but ≤ 500	-1
	> 500 but ≤ 1,000	-2
	> 1,000	-3
	(Water soluble sulphate as SO_3)	
Made Ground	None	0
	Exist	-4
Chloride Ion (ppm)	≤ 100	0
	> 100 but ≤ 300	-1
	> 300 but ≤ 500	-2
	> 500	-4

Note 1: If pH value is less than 4 or greater than 10, the ground should be classified as aggressive regardless of the results of other test items.

Note 2: "Made ground" refers to man-made ground associated with high corrosion rate such as non-engineering fill with rubbish, organic matters, etc.

galvanization was provided, particularly in areas where voids existed in the cement grout (Figure 21). The review has resulted in the development of an improved corrosion protection system.

It is now a design requirement that different levels of corrosion protection are to be employed in accordance with the design life and aggressivity of the ground (GEO, 2005). A scoring system is used to categorize the ground into four different levels of aggressiveness: "non-aggressive", "mildly aggressive", "aggressive" and "highly aggressive". The scoring system is based on the physical properties and chemical characteristics of the soils, see Tables 3 and 4. For soil nails to be installed in soils classified as "non-aggressive" or "mildly aggressive", the protection includes the provision of hot-dip galvanizing and a 2 mm sacrificial thickness on the radius of the steel bar. For "aggressive" or "highly aggressive" soil, corrugated plastic sheath in addition to hot dip galvanization should be provided (GEO, 2006).

To overcome the problem of corrosion of metallic reinforcement, the feasibility of using non-metallic soil nails has also been examined. Field installation trials have demonstrated that carbon fibre reinforced polymer reinforcement (CFRP) can be an alternative to steel bar in soil nailing works (Figure 22). The CFRP is highly corrosion resistant. The fibres in CFRP composites are carbon in nature, and the matrix is a resin. The CFRP reinforcement is lightweight and as such it greatly eases the installation works, especially at cramped slopes behind buildings.

The CFRP reinforcement has high tensile strength. Figure 23 compares the typical stress-strain behaviour of a CFRP reinforcement with that of a high yield steel reinforcement. The brittle behaviour and low bending capacity of CFRP are concerns that need to be carefully considered. As such, CFRP is not yet ready for wide and general application. Despite this, a set of interim design and construction guidelines has been developed in order to facilitate trial use and gain more insight and experience (Cheung & Lo, 2005). Further laboratory tests and investigations are being carried out on this innovative use of the material in soil nailing.

Table 4. Classification of corrosivity of soil

Classification of soil corrosivity	Total mark from the soil corrosivity assessment scheme
Non-aggressive	≥ 0
Mildly aggressive	-1 to -4
Aggressive	-5 to -10
Highly aggressive	≤ -11

Figure 21. Localized corrosion in exhumed soil nail

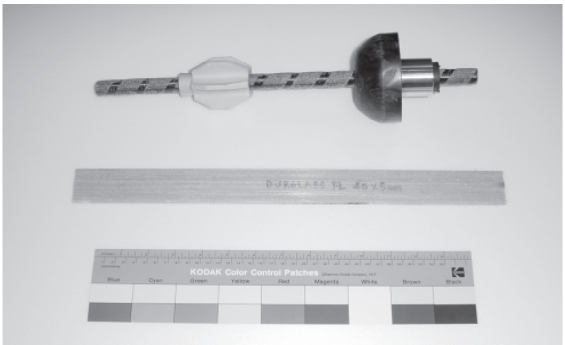


Figure 22. Typical circular section and rectangular section of CFRP

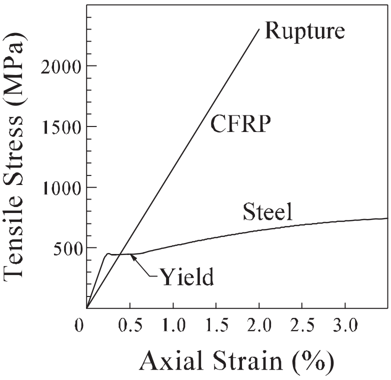


Figure 23. Stress/strain curves of typical high yield steel bar and CFRP bar

7 PERFORMANCE OF SOIL-NAILED SLOPES

7.1 *Post-construction Monitoring*

Field monitoring of nailed slopes and excavations provides information on the behaviour of the feature for verifying design assumptions and parameters and for enhancing understanding on the load transfer mechanism of soil nails. The majority of soil nailing applications in Hong Kong are for stabilizing marginally stable slopes, and field monitoring is usually not undertaken. There are cases involving use of soil nails for supporting deep excavations where instrumentation was installed for monitoring the performance of the nailed excavations during and after construction (e.g. Shiu et al 1997; Yim & Yuen, 1998).

Shiu et al (1997) reported the results of field monitoring in a 13.5 m high cutting to angles up to 80°. The instrumentation systems included an inclinometer casing for monitoring lateral deformations of the nailed excavation during and after construction. Nine soil nails in the most critical section of the slope were instrumented with vibrating wire strain gauges to measure the distribution and changes of nail forces during different stages of excavation. Figure 24 shows the nailed excavation and locations of strain gauges.

Figure 25 illustrates the lateral displacements recorded during different stages of excavation. The lateral displacement increased as the excavation depth increased. The maximum displacement at the top of the nailed slope at the end of construction was 13 mm which is equal to about 0.1% of the height of excavation.

Figure 26 shows the strain measurements (expressed as forces) from the nail on row 7 over the monitoring period. The responses of the strain gauges to the subsequent lifts of excavation are indicated clearly as rapid increases in forces. Following the completion of construction, there was a slow increase in force for a short period of time and no further noticeable changes thereafter.

The distribution of nail forces along the nails on rows 3 and 7 and their responses to excavation lifts are shown in Figure 27. The effect of advancing excavation was significant on row 7 but much less noticeable on row 3. The stress distribution in row 3 was rather uniform and did not increase appreciably with depth of excavation. Similar observations can be made on other nails at the upper part of the slope, indicating that the upper nails (rows 1 to 4) did not have substantial contribution to the retaining force of

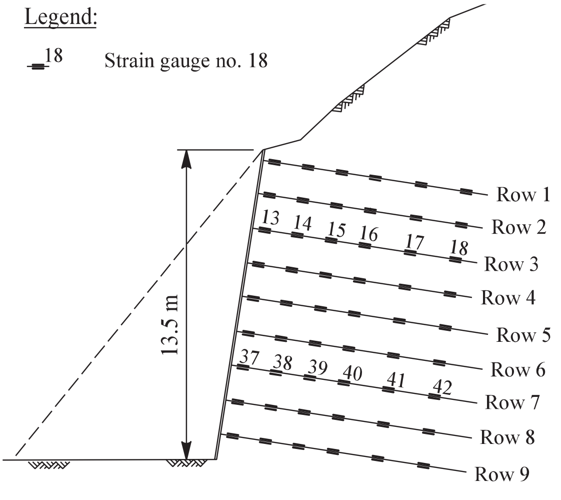


Figure 24. Critical section of the soil nailed slope

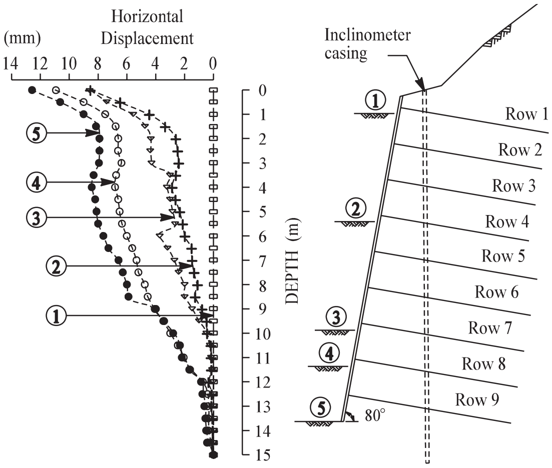


Figure 25. Lateral displacements of the nailed excavation

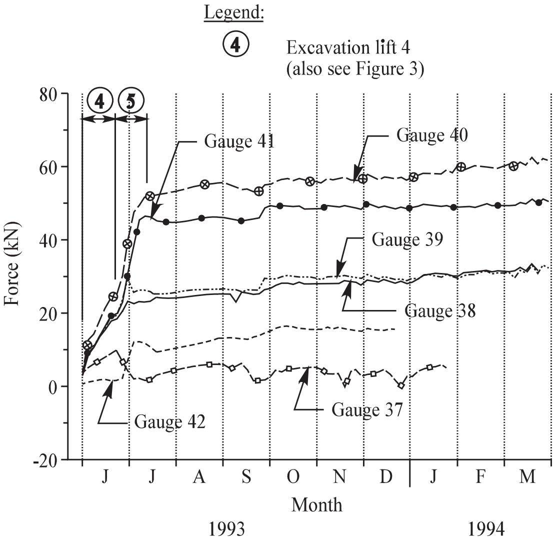


Figure 26. Nail forces against time for row 7

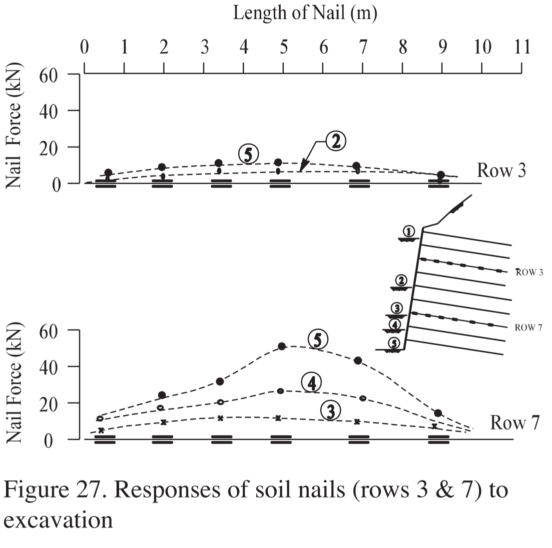


Figure 27. Responses of soil nails (rows 3 & 7) to excavation

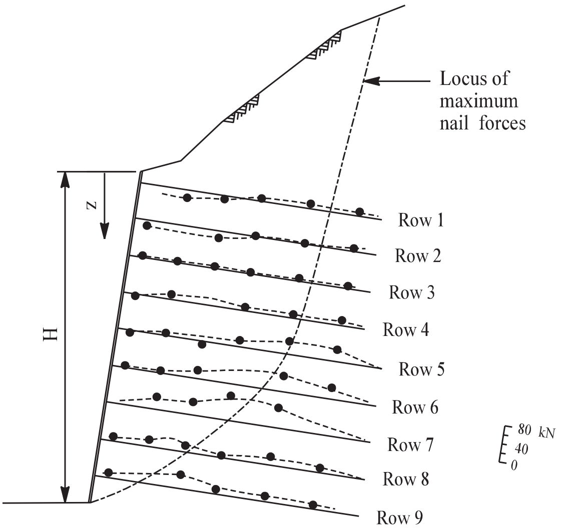


Figure 28. Distribution of nail forces at the end of construction

the nailed slope. Unlike the upper nails, row 7 carried a distinct peak force. The forces mobilized in this nail were small initially but they increased substantially with subsequent lifts of excavation. Other nails in the lower part of the slope also showed the same pattern of changes in forces. This illustrates that they contributed significantly to the stability of the nailed slope. Figure 28 presents the distribution of axial forces along each soil nail at the end of construction.

7.2 *Landslides at Soil-nailed Slopes*

Whilst soil nailing is considered as a robust solution for enhancing slope stability, landslides do occur in soil-nailed slopes. Since 1993, a total of 31 such landslide incidents have been reported to the Geotechnical Engineering Office of the Civil Engineering Development Department. Of these, 24 incidents occurred at completed slopes and 7 occurred in temporary slopes. Those on completed slopes were all minor landslides (minor landslide being defined as one with failure volume less than 50 m^3; major landslide being one with failure volume of 50 m^3 or more), with sizes ranging from less than 1 m^3 to 35 m^3.

The landslides on completed slopes all involved shallow failures or surface erosions in the active zone (Figure 29). The common factors contributing to the landslides were inadequate slope protection, inadequate drainage provisions or presence of adverse geological or hydrogeological conditions. There was no report of external failure or passive zone failure. There were no failures at soil-nailed slopes with a hard cover neither.

The sizes of landslides on temporary soil-nailed slopes were much larger (Figure 30). There were three major landslides on temporary slopes, with failure volume ranging from about 50 m^3 to 1,700 m^3. A

Figure 29. Shallow failure at a completed soil-nailed slope

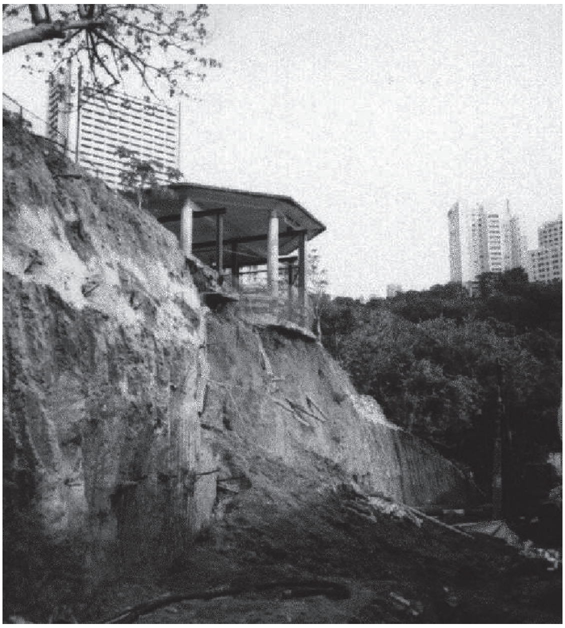


Figure 30. Major failure at a temporary soil-nailed slope without nail head

common factor in these major landslides was that soil nail heads had not yet been constructed at the time of failure.

8 CONCLUSIONS

Systematic research and development studies have brought advances in soil nailing technique. Development and advancement in the technology will continue. This can open up more opportunity for its applications and enable constant improvement in understanding the behaviour of soil nail structures, allowing use of new materials and cost-effective designs with fewer contingencies. The technological advances enable safe and durable nailed structures to be designed and constructed.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, Government of the Hong Kong Special Administrative Region.

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