Soil nail design with respect to Hong Kong conditions

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ABSTRACT: Soil nailing has been used in Hong Kong as one of the engineering solutions to stabilize temporary and permanent cut slopes since early nineteen eighties. Most of the applications are related to upgrading existing slopes that can be self-standing. In these cases, the technique has been used to enhance the factor of safety against landslip in order to meet current design standard. This paper briefly reviews a number of soil nailing design methodologies used in other continents, and presents the soil nailing design method used in Hong Kong for comparison. Design of a prototype soil nailed structure using these methods is demonstrated for illustration, and evaluation is attempted to assess the economy of the designs.

1 INTRODUCTION

In historical Hong Kong, as limited by geological and topographical constraints, many cut slopes have been formed to acquire more lands for development. In early nineteen eighties, the Hong Kong Government commissioned a Landslip Preventive Measures (LPM) programme (Watkins & Powell 1992) aims at identifying existing slope structures that pose high risk to the public, and recommending and carrying out engineering works to improve the stability of these slope structures. The engineering works comprises construction of retaining walls, cutting back the slopes to less steeper gradient, and soil nailing. Taking into account the advantages of the application of soil nailing to slope structures, to include:

(1) Reduced construction time;
(2) Less working space;
(3) Light construction equipment;
(4) High mobility of construction equipment;
(5) Applicability to difficult slope structure geometry; and
(6) Less environmental nuisance to the public.

Soil nailing to existing slope and man-made cut slopes having less than the required factor of safety against landslip has now become the most commonly employed engineering solution in Hong Kong for stabilization of slope structures. Design of the soil nailed slopes is generally based on limit equilibrium method using assumed critical failure surface. The early LPM programme has proven to be so successful that an accelerated LPM work targets at screening critical slopes for upgrading has been subsequently commissioned, and is now extended to the next ten years.

To further improve the effectiveness of the LPM work, the use of prescriptive measure based on past local experience was also studied. This has resulted the Geotechnical Engineering Office of Civil Engineering Department of the Hong Kong Government to publish a report titled "Application of Prescriptive Measures to Soil Cut Slopes" (GEO Report No.56) in 1996. The report serves to present a recommended standard of good practice for applying prescriptive measures using soil nails to upgrading existing soil structures (the report has been extended to cover masonry walls in 1999) without detailed ground investigation and design analyses.

2 BEHAVIOUR AND FAILURE MECHANISM OF SOIL NAILED STRUCTURES

The general behaviour of soil nailed structure assumes that the nail reinforcements embedded beyond the critical failure surface of reinforced soil mass should provide sufficient anchorage resistance to tie back. In case that the slope structure cannot be self-stand, movement along the critical failure surface is anticipated. Tensile force, together with shear force and bending stiffness, are therefore developed in the nail reinforcements at the interface of the critical failure surface. For enhancement of factor of safety of marginally stable slopes that can be self-standing, tensile force provided by nail reinforcement may not develop without movement of active zone of the reinforced soil mass.

Failure mechanism of soil nailed structures can generally be considered for the following aspects:

(1) Internal stability (where the failure surface entirely passing through the reinforced soil mass);

(2) External/Overall stability (where the failure surface may partially cut or entirely pass beyond the reinforced soil mass).

For the internal stability, the following failure modes of the nail reinforcement are generally considered:

(a) Pull-out failure of nail reinforcements (in passive zone of the reinforced soil mass);

(b) Tensile failure of nail reinforcements;

(c) Bearing failure of nail head/facing of the nail reinforcements.

To achieve the internal stability of the soil nailed structures, it is necessary to design the total tensile force provided by nail reinforcements to be greater than the maximum force required to provide stability of the critical failure surface of the structure at a stated factor of safety. In addition, it is necessary to check that the embedded length of the nail reinforcement embedded beyond the critical failure surface provides sufficient anchorage force (or pull-out strength) to the design tensile strength of the nail reinforcement. Also, it is necessary to ensure that the bearing capacity of the nail head is adequate to provide the designed tensile force of the nail reinforcement.

For the external stability of the soil nailed structures, the following failure modes are generally considered for the reinforced soil mass to ensure adequate factor of safety for:

- Overturning
- Sliding
- Bearing
- Overall stability of slope structure

The overall stability of slope structure is generally the controlling mode of external failure.

3 SOIL NAILING DESIGN METHODS

Most of the current soil nailing design methods used in Hong Kong and other Continents are derived from classical slope stability analysis methods modified to incorporate the additional resisting forces provided by nail reinforcements. These methods of analysis evaluate (global or partial) factor of safety along assumed failure surfaces. The methodologies include German Method, French Method, Modified Davis Method, FHWA Design Method, UK Method as well as design method used in Hong Kong, (as shown in Figure 1).

3.1 *German method (Stocker et al. 1979, Gassler & Gudehus 1981, Gassler 1997)*

The German Method assumes the following:

(1) bi-linear failure surface passing the toe of slopes/cuttings;

(2) soil mass is divided into two soil wedges;

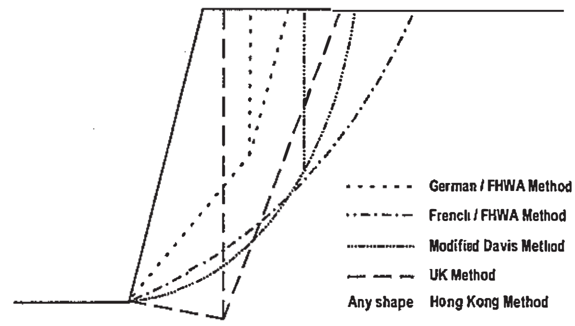


Figure 1. Assumed failure surfaces of different design methods.

(3) soil wedge at slope/cutting face reinforced with soil nails;

(4) soil wedge at back has no reinforcement and considered as a wedge exerting active earth pressure force on reinforced soil wedge in front;

(5) only tensile resistance provided by nail reinforcements embedded in passive zone is considered; and

(6) constant ultimate pull-out capacity with depth of nail reinforcement embedded.

3.2 *French method (recommendations CLOUTERRE 1991)*

The French Method assumes the following:

(1) circular failure surface passing the toe of slopes/cuttings;

(2) tensile and shear resisting forces provided by nail reinforcements are considered;

(3) development of nail shear/bending resistance forces arising from relative displacement between active and passive zones along failure surface is considered;

(4) failure modes of nail reinforcements (multi-criteria rule) including tensile failure, pull-out failure; grout-reinforcement failure; and bending/shear failure of each nail reinforcement is checked in limit equilibrium analysis; and

(5) constant ultimate pull-out capacity with depth of nail reinforcement embedded.

The design method involves complex numerical solution. A computer software "TALREN" was developed based on method of slices with the incorporation the multi-criteria rule of nail failure, relative displacement of active zone along failure surface and bending stiffness of nail reinforcements in the internal stability analysis.

3.3 *Modified Davis method (FHWA-RD-89-193)*

The Modified Davis Method (Bang & Erickson 1989, Elias & Juran 1991) assumes the following:

(1) a parabolic failure surface passing through the toe of slopes/cuttings;

(2) soil mass is divided into two soil wedges;

(3) soil wedge at slope/cutting face reinforced with soil nails;
(4) only tensile resistance of nail reinforcement embedded in passive zone is considered; and
(5) constant ultimate pull-out capacity with depth of nail reinforcement embedded.

3.4 *FHWA design method (FHWA-SA-96-096R)*

In 1992, FHWA initiated a Demonstration Project (DP103). Based on the experimental results gained from DP103 (Singla 1999), it is concluded that the Modified Davis Method overestimates the nail force of lower nail reinforcement and underestimates of upper nail reinforcement. A new design manual for "Design & Construction Monitoring of Soil Nail Walls" (Byrne et al. 1998), which summarizes the experience gained in the demonstration project and presented a soil nail design method, was published. The design method is based on limit equilibrium approach and assumes the following:
(1) both bi-linear and circular failure surfaces passing through the toe of slopes/cuttings;
(2) soil mass is divided into two soil wedges;
(3) each nail reinforcement extends beyond the critical failure surface;
(4) only tensile resistance provided by nail reinforcements is considered;
(5) nail tensile force acting at inter-wedge boundary is considered; and
(6) constant ultimate pull-out capacity with depth of nail reinforcement embedded.

The design method considers pull-out resistance of the nail reinforcements on both active and passive zone of the soil mass and allows the structural face capacity of the wall facing to be incorporated into the stability analysis. The design method also recommends a unique length pattern of nail reinforcements.

3.5 *UK design method (Advice Note HA68/94 1994)*

The design method is based on the limit equilibrium of a two-part wedge failure mechanism, and recommends adopting pre-defined vertical nail spacing pattern. The method assumes the following:
(1) bi-linear failure surface passing through the toe of slopes/cuttings;
(2) inter-wedge friction is neglected;
(3) the reinforced soil mass slides on the plane of nail reinforcements;
(4) only tensile resistance provided by nail reinforcements is considered;
(5) evenly distribution of tensile force; and
(6) ultimate pull-out capacity increase with depth of nail reinforcement embedded.

A review has been undertaken to produce a revised Advice Note taking into account of the experience gained in using HA68/94, advances in the methods used to reinforced slopes/cuttings, and the requirements given in BS8006 and EuroCode7.

3.6 *Design method used in Hong Kong*

The design method used in Hong Kong is based on limit equilibrium approach based on global factor of safety (Powell & Watkins 1991). Method of slices such as Janbu Rigorous Method (i.e. method of slices) is used to calculate the maximum horizontal force required to increase the factor of safety of the slope structures to meet the current design standard. The design method assumes the following:
(1) failure surface of any shape passing through the toe of slopes/cuttings;
(2) only tensile resistance of nail reinforcement embedded in passive zone is considered;
(3) internal forces at the vertical slice boundaries are not affected by the nail reinforcements; and
(4) ultimate pull-out capacity increase with depth of nail reinforcement embedded.

The internal failure modes including pull-out failure of nail reinforcements from passive zone, tensile failure of nail reinforcements, bearing failure of nail head/facing, and grout-reinforcement failure need to be considered. Three aspects are then considered:

(a) *Pull-out capacity of nail reinforcement*
In Hong Kong, in-situ soils usually comprise completely decomposed granite (CDG), completely decomposed tuff (CDT) and colluvium. These soils are granular materials and exhibit soil dilatant behaviour. The coefficient of apparent friction (μ^*) of the surrounding soil is taken as tan φ' where φ' is the effective friction angle of in-situ soil. The determination of "pull-out" capacity of nail reinforcements are re-formulated as below:

$$T_p = \Sigma L\,(\pi\, d_{hole}\, c' + 2\, d_{hole}\, \sigma'_v \tan \varphi')/F_p\,,$$

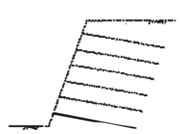
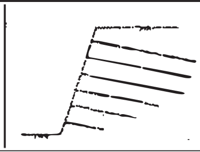
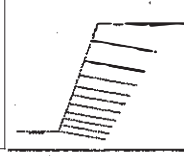
where:
T_p pull-out resistance per unit length of nail reinforcement.
F_p factor of safety of pull-out resistance.
L length of nail reinforcement embedded in passive zone.
c' effective cohesion strength of surrounding soil.
d_{hole} diameter of drill hole of nail reinforcement.
σ'_v effective vertical stress of overburden pressure acting on the nail reinforcements.
(Note that equivalent width of nail instead of nail perimeter is considered for σ'_v term)

(b) *Tensile resistance of nail reinforcement*

$$T_t = \sigma_y A_s / F_t,$$

where:
T_t design tensile strength of nail reinforcement.
F_t factor of safety of tensile strength of nail reinforcement.
σ_y ultimate tensile strength of nail reinforcement.
A_s is the effective cross-sectional area of nail reinforcement.

Table 1 Illustration/comparison using various (limit state) design methods.

	German Method	Modified Davis Method	FHWA Design Method	UK Design Method	Hong Kong Design Method
Soil Properties					
In-situ soil type : Granular soil (eg, colluvium)					
Density of in-situ soil : 20 kN/m³					
Friction angle of in-situ : 35 deg.					
Soil skin friction (kN/m²)	120	120	120	¼ (3 + Ka) γ h	γ h tan φ'
Nail Properties					
Inclination to horizontal : 10 deg.					
Ultimate tensile strength : 420 N/mm²					
Nail diameter : 32 mm					
Drill hole diameter : 100 mm					
Vertical spacing (m)	1.5	1.5	1.5	Not applicable	1.5
FOS of tensile strength	1.7	1.8	1.8	CIRIA RP396	1.8
Max. allowable nail tensile force (kN)	(Use US's factor of safety to determine allowable tensile strength of nail reinforcement)				
Partial / (Global) Factor Of Safety					
Soil frictional angle	1.1	1.2	1.35	1.3	(1.2)
Pull-out resistance	1.3	2	2	1.3	(2)
Design Output					
Maximum Tensile Force (kN)	163	281	327	289	201
Number of nail per vertical panel	6	6	6	9	6
Horizontal spacing (m)	1.5			0.5 at top layer 0.75 at 2nd layer 1 at 3rd & 4th layer 1.5 for the rest	1.5
Maximum length of nail (m)	5.4	7.9	10.9	6.2	9.5
Total length of nail per vertical panel [per metre run] (m)	22 [14.7]	47.4 [31.6]	52 [34.7]	70.5 [47]	57 [38]
Layout of soil nails					
Partial / Global Factor Of Safety					
Soil frictional angle	1				
Pull-out resistance	1				
Design Output					
Maximum Tensile Force (kN)	139.8	216	215	182	150
Number of nail per vertical panel	6	6	6	6	6
Horizontal spacing (m)	1.5			0.75 at top layer 1 at 2nd layer 1.5 for other layer	1.5
Maximum length of nail (m)	4.5	5	7.1	5	5.5
Total Length of nail per vertical panel [per metre run] (m)	16.3 [10.9]	30 [20]	33.9 [22.6]	33.7 [22.5]	33 [22]

For corrosion protection of steel nail reinforcements, a sacrificial layer of 2mm thickness on the radius of nail reinforcement and a minimum thickness of 10mm cement grout cover are to be provided. The steel nail reinforcements are usually hot-dip galvanized.

(c) *Bearing capacity of nail head/facing*
The local practice is to adopt a 400x400 mm^2 concrete facing. Alternatively, bearing capacity formula taking into account of the design tensile strength of the nail reinforcements and the inclination angle of nail reinforcements to the slope/cutting face can be used to calculate the allowable bearing capacity of nail head/facing.

4 ILLUSTRATION/COMPARISON USING VARIOUS (LIMIT STATE) DESIGN METHODS

For illustration purpose, a typical cut slope of 10 m high, with slope angle of 70° to horizontal is used as a prototype for design using these design methods. The output obtained using different design methods is presented in Table 1. It is noted that the French design method is not covered in the illustration. It is due to the fact that the method involves complicated formulation of indeterminant equations using multi-criteria rule for nail failure consideration (that can normally be calculated using "TALREN" design package), and cannot be easily verified.

It is interesting to note from the results of the following:

(1) These design methods assumed partial factors of safety ranges from 1.1 to 2.
(2) The maximum tensile force required ranges from 163 to 327 kN/m width of slope.
(3) The number of soil- nail layers ranges from 6 to 9.
(4) The maximum length of nail reinforcements ranges from 5.4 to 10.9 m.
(5) The layout of the nail reinforcements is quite different.
(6) Total length of soil nail required per m width of slope ranges from 22 to 70 m.

It is also interesting to note that the HA68/94 advise note used for Transport Department of United Kingdom yielded the highest and the German method yielded the lowest soil nail length/m width of slope. The reason that the HA68/94 gives the highest soil nail length/m width slope may be due to the fact that the method assumes each nail reinforcement layer to provide the same tensile force. However, it is also assumed that the frictional resistance of the nail reinforcement depends on the effective overburden pressure experienced by the nail. As a result, the top layers of reinforcement nail which are subject to a lesser overburden pressure requires to be much closer and longer than the lower layers, in order to provide the same anchorage force.

For comparison purpose, the partial factor of safety for the soil materials is set to 1 for further evaluation. The output of the designs is also presented in the Table. It is interesting to note that the methods used in the US, UK and HK all yielded similar soil nail length/m width slope of around 33/m width of slope, except that the Davis method and the German method give a value of 10% and 50% lower respectively.

5 DISCUSSION

The amount of nail reinforcements obtained using Hong Kong Method is generally consistent with the output obtained using other methods though these methods adopt partial factor of safety approach.

The Hong Kong method assumes evenly distributed nail reinforcement forces, but allow checking of overall anchorage tension forces rather than by layer.

In Hong Kong, soil nail application is used to enhance the factor of safety of existing slopes or slope cuttings against landslip failure of factor of safety greater than 1.

Soil nail in Hong Kong can be used as a prescriptive measures to improve slope stability.

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