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Geoguide 7 – Guide to soil nail design and construction

Geoguide 7 - Guide de conception et de construction d'ongle de sol

W.K. Pun, W.M. Cheung & K.W. Shum
Geotechnical Engineering Office, Civil Engineering and Development Department
The Government of the Hong Kong Special Administrative Region

ABSTRACT
The soil nailing technique has gained its popularity on slope stabilisation in Hong Kong since the early 1990s. Experience gained over the years of application has led to the development of the technique in respect of design method, construction, quality control and new technology. In recent years, the Geotechnical Engineering Office (GEO) of the Civil Engineering and Developement Department in Hong Kong has carried out a series of soil-nail-related studies and summarised the experience gained with an ultimate goal of preparing improved guidelines on the design and construction of soil nails. The Guide to Soil Nail Design and Construction (Geoguide 7) was published in 2008. The Geoguide 7 presents a recommended standard of good practice for the design, construction, monitoring and maintenance of soil-nailed systems. This paper highlights the salient points of the content of the Geoguide.

RÉSUMÉ
Le sol clouant la technique a gagné sa popularité sur la stabilisation de pente à Hong Kong depuis le début des années 90. Une expérience acquise au cours des années de l'application a mené au développement de la technique en ce qui concerne la méthode de conception, la construction, le contrôle de qualité et la nouvelle technologie. Ces dernières années, l'Office géotechnique de technologie (GEO) à Hong Kong a effectué une série d'études sol-ongle-connexes et a récapitulé l'expérience acquise avec un but final de préparer les directives améliorées sur la conception et la construction des ongles de sol. Le guide de la conception d'ongle de sol et de la construction (Geoguide 7) a été édité en 2008. Le Geoguide 7 présente un niveau recommandé de la bonne pratique pour la conception, la construction, la surveillance et l'entretien des systèmes sol-cloués. Cet article accentue les points saillants de la teneur du Geoguide. Les études qui ont mené aux conseils recommandés sont également discutées.

Keywords :

1 INTRODUCTION

The soil nailing technique was introduced to Hong Kong in the 1980s. Soil nailing was first used in Hong Kong as a prescriptive method to provide support to deeply weathered zones in otherwise sound material. This was followed by a few cases where passive anchors or tie-back systems were used. In the mid-1980s a small number of soil-nailed supports to temporary cuts were made. In the early 1990s, the experience of design and construction of soil nails was summarised by Watkins & Powell (1992), which soon became the standard practice in Hong Kong.

Along with the increasing number of existing slopes and retaining walls upgraded by the Government and private owners, the soil nailing technique has gained popularity since the mid-1990s. Nowadays, soil nailing is the most common slope stabilising method in Hong Kong. In 2008, the GEO published the Geoguide 7 – Guide to Soil Nail Design and Construction (GEO, 2008) to promulgate the recommended standard of good practice for the design, construction, monitoring and maintenance of soil-nailed systems.

The Geoguide summarised the experience gained from the use of the soil nailing technique in Hong Kong and the findings of a series of soil nail related studies, including literature reviews, field tests, laboratory investigations and numerical modelling. The guidance primarily covers the use of high yield deformed steel bars installed by the drill-and-grout method for reinforcing slopes, retaining walls and excavations.

This paper highlights the salient points of the content of the Geoguide. The studies that have led to the recommended guidance are also discussed.

2 DESIGN CONSIDERATIONS

A soil-nailed system is required to fulfil fundamental requirements of stability, serviceability and durability during construction and throughout its design life. Other issues such as cost and environmental impact are also important design considerations. The design of the soil-nailed system should ensure that there is an adequate safety margin against all the perceived potential modes of failure. The deformation of the system should not result in excessive ground settlement and affect the efficient use of nearby structures, facilities or services. Appropriate corrosion protection measures should also be provided to the steel reinforcement to ensure that the soil-nailed system is sufficiently durable.

2.1 *Design for stability*

The design for stability of a soil-nailed system generally entails the setting up of ground and design models, consideration of potential failure mechanisms, stability analyses, determination of soil-nail design capacity, soil-nail head and facing design, and detailing.

2.1.1 *Failure mechanisms*

The failure mechanisms of soil-nailed systems can broadly be classified as external failure and internal failure. External failure refers to the development of potential failure surfaces essentially outside the soil-nailed ground mass. The failure can be in the form of sliding, rotation, bearing, or other forms of loss of overall stability (see Fig. 1a). Internal failure refers to failures within the soil-nailed ground mass. Internal failures can occur in the active zone, passive zone, or in both of the two zones of a soil-nailed system (see Fig. 1b).

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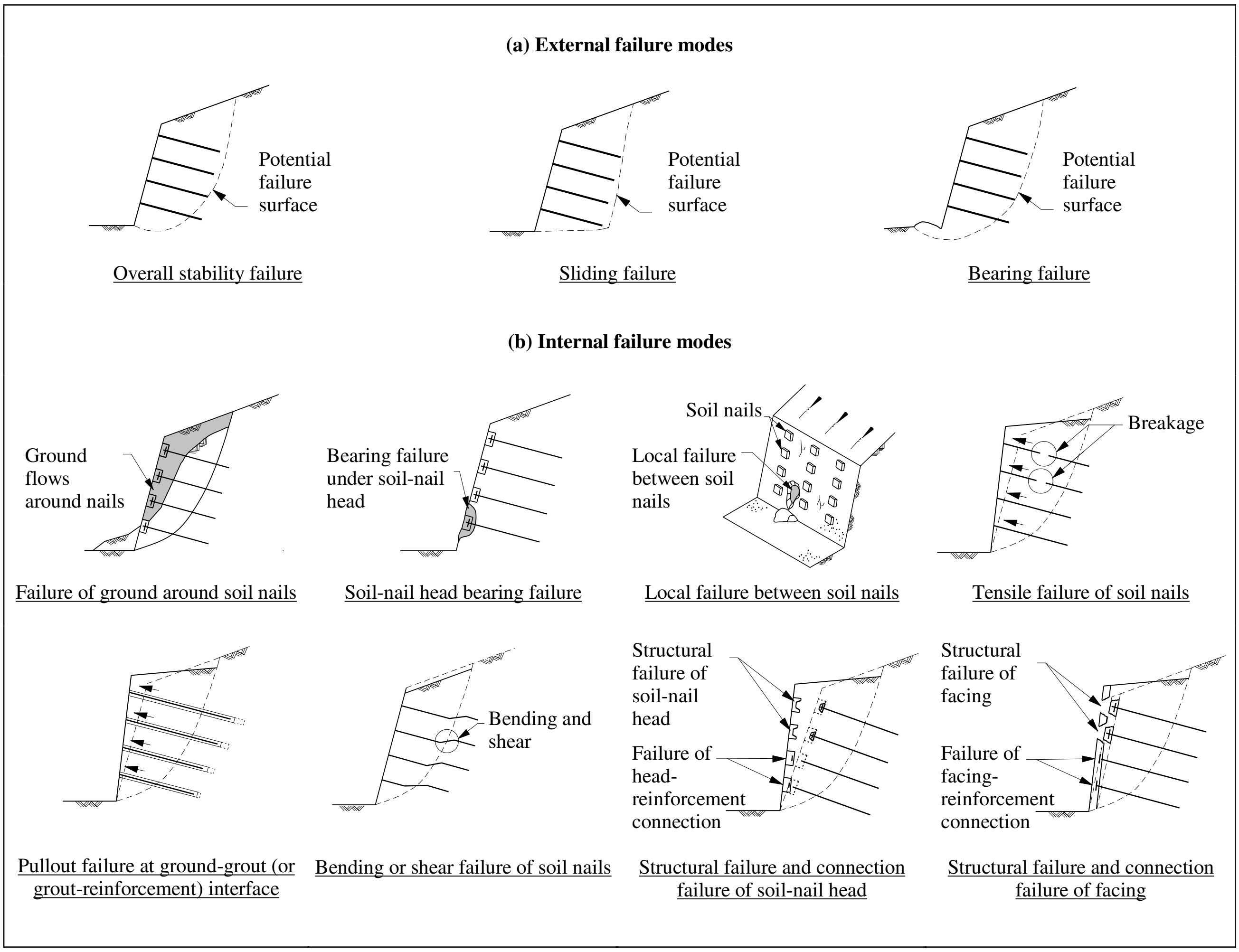

Figure 1. Potential failure modes of a soil-nailed system

2.1.2 *Design approach*

In Hong Kong, the soil nail design approach is essentially a combination of global safety factor approach (permissible stress design) and partial safety factor approach. In this approach, a global safety factor is used to determine the required soil nail forces. The global safety factor takes account of the consequence of failure and covers all uncertainties related to ground stability, such as design ground model, shear strength of soil, and design groundwater level. Three other safety factors are applied to guard against the internal failure modes of (i) tensile failure of soil-nail reinforcement, (ii) pullout failure between the cement grout and soil, and (iii) pullout failure between the soil-nail reinforcement and cement grout. The minimum safety factors recommended in Geoguide 7 for a new soil-nailed cut slope for a 10-year return period rainfall are summarised in Table 1.

Table 1. Recommended minimum safety factors

Global instability	1.0 to 1.4 [Note 1]
Tensile failure of soil-nail reinforcement	1.5
Pullout failure at soil-grout interface	1.5 [Note 2] 2.0 [Note 3]
Pullout failure at grout-reinforcement interface	2.0

Notes: (1) Corresponding to different consequence of failure.
(2) For soil nails carrying transient loads and boned in weathered granite or volcanic rocks.
(3) For soil nails carrying sustained loads or for soil nails carrying transient loads and bonded in soils other than weathered granite or volcanic rocks.

2.1.3 *Method of stability analysis*

Analytical methods involving trial wedges (single-wedge or double-wedge) and limit equilibrium methods (LEM) of slices on circular, spiral, or other non-circular slip surfaces are commonly used. It is essential to have a good understanding of the principles behind the calculation methods so that the appropriate method is used and the results are interpreted correctly. For instance, the factor of safety of a soil-nailed slope computed using the simplified Janbu method is insensitive to the location of the applied soil nail force. This is an inherent limitation of the method, and it may give rise to an over- or under-estimation of the true safety margin. In light of this, Geoguide 7 recommends only stability analysis methods that satisfies both moment and force equilibrium be used in soil nail design. Details of the review on limit equilibrium methods for soil nail design conducted by GEO is given in GEO Report No. 208 (Shiu et al., 2007).

While these methods are good enough for design purpose, none of them can account for the actual behaviour of a soil-nailed system, which is a strain compatibility problem. It is possible to define a wide variety of nail length patterns that satisfy stability requirements but that may not satisfy serviceability requirements. Hence, under special circumstances, a stress-strain analysis may be required for assessing the design capacity of soil nails or for ground deformation assessment (see Section 2.2).

2.1.3 *Pullout Resistance*

Pullout 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 (CIRIA, 2005), empirical correlation with SPT N values (JHPC 1998), empirical correlation with pressuremeter test results (Clouterre 1991), and empirical correlation with soil types (FHWA 2003).

The effective stress method is adopted in Geoguide 7. The allowable pullout resistance provided by the soil-grout bond strength in the passive zone, T_P, is given by (Schlosser & Guilloux 1981):

$$T_P = \frac{c' P_c L_c + 2D\sigma_v' \mu^* L_c}{F_P} \quad (1)$$

where c' is effective cohesion of the soil, P_c is outer perimeter of the cement grout sleeve, L_c is bond length of the cement grout sleeve in the passive zone, D is outer diameter of the cement grout sleeve, σ'_v is vertical effective stress in the soil, μ^* is coefficient of apparent friction of soil (μ^* may be taken to be equal to tan ϕ', where ϕ' is the effective angle of shearing resistance of the soil), F_P is factor of safety against pullout failure at soil-grout interface, which is given in Table 1.

For design purpose, the vertical effective stress in the soil is calculated from the overburden pressure, which implies that the contact pressure at the soil-grout interface is governed by the overburden pressure. This assumption is not necessarily true because the normal stress at the face of the drillhole is reduced to zero after drilling due to arching effect and the grouting pressure is generally so low that only a small contact pressure can be restored. The contact pressure is likely much less than the overburden pressure.

The effects of hole drilling process, overburden pressure and grouting pressure on pullout resistance was investigated by means of laboratory pullout tests by Yin & Su (2006) initiated by GEO. Compacted fill of completely decomposed granite was used in the tests. The study showed that (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; and (b) pullout resistances of the soil nails increased with an increase of grouting pressure.

Pullout tests are routinely carried out in sacrificial test nails in Hong Kong for the verification of design assumptions. In order to examine the significance of the potential stress reduction due to the arching effect, the results of about 900 pullout tests were reviewed. The pullout resistance measured in the field was compared with the theoretical values estimated by the effective stress method. 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.

Many of the test nails were not loaded to bond failure because the ultimate pullout resistance (T_{ult}) of the bonded section was higher than the yield strength of steel. The pullout tests were stopped when the test load reached 90% of the yield strength of steel (T_P) to avoid tensile failure of the steel reinforcement. Figure 2 shows the plot of the ratio of the field pullout resistance to that estimated using the effective stress method against the overburden pressure. The field pullout resistances were generally several times higher than those estimated, but the safety margin (i.e., $T_{ult(field)}/T_{ult(estimate)}$) gradually decreases when overburden pressure increases.

The difference between the measured and the estimate pullout resistance is due to many factors including soil arching, restrained soil dilatancy, soil suction, roughness of drillhole surface, and over-break, which are hard to quantify in design. All these factors except soil arching tend to result in higher pullout resistance than the design value. The finding of the review gives assurance on the adequacy of the effective stress method. Nevertheless, as a precaution against the possibility that the positive contribution to the pullout resistance from soil dilatancy, drillhole irregularities, etc. being less than the negative effect due to soil arching in the case of high overburden pressure, Geoguide 7 recommends to limit the maximum overburden pressure to 300 kPa in the estimation of pullout resistance. Although effective stress method has it own limitations, experience has shown that the method together with the recommended factor of safety give an adequately safe design solution for the ground conditions commonly encountered in Hong Kong.

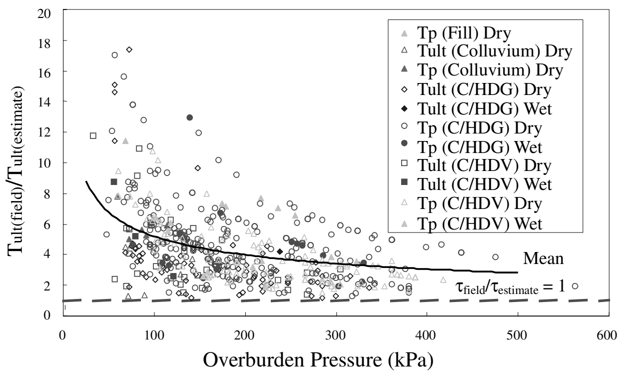

Figure 2. Potential failure modes of a soil-nailed system

2.2 *Design for serviceability*

The performance of a soil-nailed system should satisfy the serviceability requirements in respect of deformation, otherwise it may result in excessive ground settlement, facing deterioration, or damage to the surface or subsurface drainage system. The deformation of a soil-nailed system is governed by various factors, which include the ground profile, soil stiffness, groundwater conditions, layout of soil nails, slope facing and construction workmanship. The soil nailing technique is commonly applied to enhance the stability of soil cut slopes in Hong Kong. The deformation of such soil-nailed systems is generally small if they are designed and constructed in accordance with Geoguide 7, and a deformation analysis is generally not required.

When excessive deformation of a soil-nailed system is a cause for concern, a deformation analysis should be carried out. For example, for those slopes and retaining walls that are reinforced by steeply inclined soil nails, or where the soil nails are required to carry sustained loads, a deformation analysis may be warranted. The analysis should demonstrate that the anticipated deformations of the soil-nailed system are within acceptable limits with due consideration given to the serviceability requirements of the affected structures, facilities and services. Numerical modelling using stress-strain finite element or finite difference computer programs may be used.

2.3 *Design for durability*

Soil-nailed system should be sufficiently durable, so that they are capable of withstanding attack from the existing and envisaged corrosive environment without unduly affecting their stability and serviceability. Appropriate corrosion protection measures should be provided to the steel reinforcement. Geoguide 7 recommends three classes of corrosion protection measures:

- Class 1 – Hot-dip galvanising with a minimum zinc coating of 610 g/m^2 plus corrugated plastic sheathing,
- Class 2 – Hot-dip galvanising with a minimum zinc coating of 610g/m^2 plus a 2 mm sacrificial thickness on the radius of the steel reinforcement, and
- Class 3 – Hot-dip galvanising with a minimum zinc coating of 610 g/m^2.

The provision of corrosion protection measures to steel reinforcement should be based on soil aggressivity. Soil aggressivity assessment can be carried out based on a marking system developed by Eyre & Lewis (1987) with modifications to suit Hong Kong's conditions. The soil aggressivity assessment scheme recommended in Geoguide 7 is given in Table 2.

For soil nails carrying transient loads with design life up to 120 years, Class 1 corrosion protection measures should be provided in sites with 'highly aggressive' or 'aggressive' soil, whereas Class 2 corrosion protection measures should be provided in sites with 'mildly aggressive' or 'non-aggressive' soil. For temporary soil nails, Class 3 corrosion protection measures is considered sufficient.

Table 2. Soil aggressivity 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 %, andFraction passing 2 μm 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	Note 1
Soluble Sulphate SO_3 (ppm)	≤ 200	0
	> 200 but ≤ 500	-1
	> 500 but ≤ 1,000	-2
	> 1,000	-3
Made Ground (Note 2)	None	0
	Exist	-4
Chloride Ion (ppm)	≤ 100	0
	> 100 but ≤ 300	-1
	> 300 but ≤ 500	-2
	> 500	-4

Classification of soil aggressivity	Total Mark
Non-aggressive	≥ 0
Mildly aggressive	-1 to –4
Aggressive	-5 to -10
Highly aggressive	≤ -11

Notes: (1) If pH value is less than 4 or greater than 10, the soil should be classified as aggressive regardless of the results of other test items.
(2) "Made ground" refers to man-made ground associated with high corrosion rate such as non-engineering fill with rubbish and organic matters.

3 CONSTRUCTION

In designing soil nails, due consideration should be given to the buildability of the soil nails to ensure that the design is practical and buildable. Also, it is of paramount importance that the quality of materials and workmanship of the works meet the design requirements.

The experience in Hong Kong shows that soil nails can generally be constructed by means of the drill-and-grout method without many difficulties. However, under some unfavourable ground conditions, construction problems may be encountered. For example, the following geological conditions are susceptible to excessive grout leak during soil nail installation:

- fill, containing a significant proportion of coarse materials, i.e., boulders, cobbles, gravel, and sand;
- colluvium and fluvial deposits with a high proportion of coarser material;
- erosion pipes which may be partly infilled by porous and permeable material;
- material boundaries within colluvium, and between colluvium and in-situ material, and within corestone-bearing saprolite, especially at the margins of corestones, open joints, faults and shear zones, and other discontinuities (e.g., zones of hydrothermal alternation, etc.) that are weathered and eroded, and so are open;
- landslide scars, tension cracks, and other features related to slope deformation, as these may include voids within transported and in-situ materials; and
- drainage lines intersecting slopes, within which colluvium may be present, erosion pipes may be developed, and preferred groundwater through-flow indicated by seepage locations/horizons may also occur.

4 CONCLUSIONS

The Geoguide 7 : Guide to Soil Nail Design and Construction was published in 2008. It summaries the experience that has been gained over the years of applying soil nailing technique in Hong Kong. The Geoguide presents a recommended standard of good practice for the design, construction, monitoring and maintenance of soil-nailed systems.

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