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Long-term Durability of Steel Soil Nails in Hong Kong

The long-term performance of soil-nailed slopes requires that the soil nails should be able to withstand corrosive attack from their local environment. Various types of corrosion protection methods for steel soil nails have been examined. Protection approaches used in Japan, France, UK, Nordic countries, USA and Germany are reviewed and compared with that currently being used in Hong Kong. Two case examples of corrosion of steel soil nails are described. They provide useful information for establishing the corrosion rates of hot-dip galvanising and steel soil nails. A survey of the corrosion potential of soils in Hong Kong has been conducted and this included the determination of the relevant physical and electrochemical properties of the soils. The survey results are presented and analysed. They show that a significant portion of the soils that had been taken from potentially aggressive sites could have a relatively high corrosion potential. Use of heat-shrinkable sleeves for protecting steel couplers and use of carbon fibre reinforced polymer reinforcement is also described and discussed.

Keywords: *Durability, Corrosion Protection, Soil Nails, Soil Corrosivity, Carbon Fibre Reinforced Polymer, Heat-shrinkable Sleeve*

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Introduction

Durability is an important aspect of soil nailing because the long-term performance of soil nails depends on their ability to withstand corrosive attack from the surrounding soils. To enhance understanding of the subject, a review of the current state of practice of corrosion protection for steel soil nails in Hong Kong and abroad has been carried out. The review includes exhumation and examination of soil nails of different ages. It also includes a survey of relevant properties of the Hong Kong soils and an assessment of the corrosion potential of these soils. The results indicate that a portion of local soils could have relatively high corrosion potential. This paper presents and discusses the results of the review and the survey, and describes two case examples on corrosion of steel soil nails in Hong Kong. The international practices of corrosion protection are compared with the one currently being used in Hong Kong. The paper also addresses recent initiatives on the use of heat-shrinkable sleeve for protecting steel couplers and the use of carbon fibre reinforced polymer reinforcement in soil-nail applications.

Soil nails in Hong Kong are normally in the form of steel bars that are installed using the drill-and-grout method without prestressing. This paper covers this type of soil nails only.

Factors Affecting Corrosion

Corrosion of steel is primarily an electrochemical process. For this process to occur there must be an electrical potential difference between two points that are electrically connected in the presence of an electrolyte. In the case of steel soil nails in the ground, the electrolyte is the soil pore water which contains both oxygen and dissolved salts.

The corrosivity (or aggressivity) of soils can vary over a wide range because of the variety of soil compositions and properties. In general, the corrosion rate of steel soil nails in a soil depends on the soil's physical and electrochemical characteristics. The physical characteristics are those that control the permeability of the soil to air and water. They include grain size, permeability and moisture content of the soil. Fine-grained soils (silts and clays) are potentially more corrosive than coarse-grained soils (sands and gravels) in which there is greater circulation of air and less water-retention capacity. The electrochemical characteristics are those that determine the ability of the soil pore water to act as an electrolyte for the development of local corrosion cells. Examples are pH value, concentrations of oxygen and dissolved salts, and organic matter and bacteria content. Stray current, where present, can also influence the corrosion rate.

Corrosion Protection Methods

There are a number of options for providing corrosion protection to steel soil nails. They include the provision of (a) cement grout; (b) sacrificial thickness to the steel; (c) sacrificial metallic coating on the steel (eg hot dip galvanising, stainless steel cladding); (d) non-metallic coating on the steel (eg fusion bonded epoxy); and (e) corrugated plastic sheath (single sheath or two concentric sheaths). Depending on the situation and the corrosivity of the soils, one or a combination of the above options is adopted. Their protection mechanisms are discussed below.

Cement grout is a good protection barrier against corrosion for metal if the grout is intact. It can prevent corrosion by forming a physical as well as a chemical barrier. The grout physically separates the steel from the surrounding soil. The chemical protection from cement grout is given by its alkalinity characteristic, which leads to the formation of a thin oxide film on the steel surface. This chemical process is called 'passivation'. The oxide film formed on the steel surface inhibits corrosion. The cement grout, however, tends to crack when subjected to tensile stresses. The cracks can break the physical and chemical barriers by allowing water, oxygen and other corrosion promoting agents to come into contact with the steel. In addition, field investigations have shown that defects such as voids formed in the grout and soil trapped between steel bar and centralisers (Plate 1) can happen. As this kind of installation problem cannot be ruled out, the corrosion protection system could not rely solely on the integrity of grout.

Provision of sacrificial steel thickness is a simple and widely used method of corrosion protection. It allows for corrosion of the steel by over-sizing the cross-section of the steel bar. Products of corrosion that appear over time form a protective coating between the steel and its surrounding. Whilst this coating offers no physical protection to the steel bar, it can slow down the rate of corrosion by changing the kinetics of the chemical reactions.

Zinc is a common type of metal used to provide corrosion protection to steel soil nails. A zinc coating is often applied by the hot dip galvanising

Plate 1 – An Exhumed Soil Nail Showing Soil Trapped between Steel Bar and Centraliser

process. The galvanised zinc coating offers two different types of protection to steel, namely barrier protection and cathodic protection (Hadley & Yeomans, 1990). For the barrier protection, the metallic zinc forms a coating around the steel bar to isolate the steel from the environment. For cathodic protection, the zinc, being anodic to steel, actively protects the steel cathodically by sacrificial dissolution. This delays the onset of the corrosion of steel. The performance of galvanised steel elements is best in alkaline and oxidising soils. Within the range between pH 6 and 12.5, the corrosion rate of zinc is relatively low because a stable protective film is formed on the zinc surface. Outside this range, the corrosion rates of galvanised zinc coatings can be very high.

Non-metallic coatings in the form of fusion-bonded epoxy may be used to protect steel bars from corrosion. The epoxy coatings do not conduct electricity and they isolate the steel bars from the surrounding environment. To be effective, the coatings have to be impermeable to gases and moisture and free of gaps at the interface between the steel and the coating. Care is necessary to ensure a complete continuity of the coating.

When a high level of corrosion protection is needed, corrugated plastic sheaths are used in conjunction with cement grout. The steel bar is grouted inside the corrugated plastic sheath. The annulus between the sheath and the drillhole wall is also grouted with cement. The inclusion of the sheath prevents ingress of water or corrosion promoting agents if cracking of the grout occurs.

Corrosion Rates

The use of sacrificial steel thickness and metallic coating needs to take account of the corrosion rates. Since the natural ground can be highly variable in terms of physical and electrochemical properties both spatially and temporally, these lead to major uncertainties in assessment of corrosion rates. A comprehensive source of information on underground corrosion is the results of the extensive field exhumation and testing on metal pipes and steel sheets carried out by the US National Bureau of Standards in a series of programmes lasting over 20 years (Romanoff, 1957). Results of the studies indicate that the corrosion rates of both steel and zinc buried in the ground can vary greatly among different soil types and they generally decreases with time. There is a rapid loss in the first two years after the burial for both bare and galvanised steels followed by a progressive decrease in the rate of corrosion.

The test data also show that the maximum pitting rates for galvanised steel and bare steel can be up to 5 times and 13 times of those of the surface average corrosion rates, respectively. Similar observations were made by Darbin *et al.* (1988) from tests conducted in France and also by Brady *et al.* (1999) from tests conducted in the UK.

Surveys by Brady & McMahon (1993) on 46 corrugated steel structures buried in the ground for periods between 16 and 34 years showed that corrosion tended to be localised. According to King (1977), test data from the UK could infer maximum pit depth of steel of 5.8 mm in 20 years.

Corrosion Protection Methods Used in Hong Kong

Pre-2002 Practice

Before the year 2002, corrosion protection for temporary soil nails in Hong Kong was provided solely by cement grout. For permanent applications (design life longer than 2 years), the common practice was to increase the degree of protection by providing a zinc coating (in the form of hot dip galvanising) to steel bars in conjunction with a 2 mm sacrificial steel thickness. There were no requirements for assessing the corrosion potential of soils. For the Government's Landslip Preventive Measures (LPM) works, the required weight of zinc coating on steel bars was 610 g/m^2 (approximately 85 μm thick).

Cases of Corrosion of Soil Nails in Hong Kong

There are little field data reported on corrosion of steel soil nails in Hong Kong. Such data are valuable for understanding more about the corrosion behaviour of soil nails. Two cases of corrosion of soil nails in Hong Kong are presented below.

Case 1

At a soil cut slope with masonry facing in Tai Po, two sacrificial soil nails were installed together with other working soil nails in 1988. The sacrificial soil nails were constructed by the drill-and-grout method where high yield steel bars were installed in predrilled holes of 50 mm diameter. Bare steel bars of 19 mm in diameter and 6 m in length were used. The sacrificial soil nails were exhumed in 1997, nine years after installation. The geology of the slope mainly comprises a thin mantle of fill/residual soil overlying completely to highly decomposed granodiorite.

An exhumed section of one of the steel bars showed considerable section loss and deterioration. Pitting corrosion was found on the surface of the steel bar. The maximum pitting depth was about 3 mm (Plate 2), representing an average pitting corrosion rate of about 0.3 mm/year. The corroded area occupied about 10% of the cross-sectional area of the steel bar. Laboratory tests performed on the soil specimens from the site indicate that the corrosion potential of the soil is classified as 'aggressive'. The classification system is given in the later part of this paper. This case shows that cement grout cannot be relied upon to provide an adequate corrosion protection in aggressive ground.

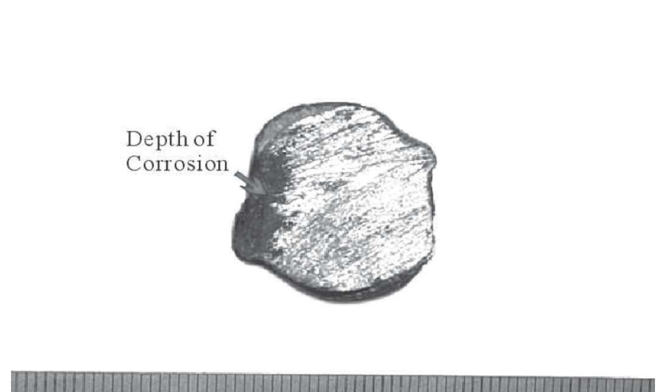

Plate 2 – Pitting Corrosion of Steel Soil Nail

Case 2

At a soil cut slope in Ho Man Tin, a number of soil nails were installed in 1992 for improving the stability of the slope. The soil nails were 9 m long. Each soil nail comprised a 32 mm diameter steel bar grouted in a 100 mm diameter predrilled hole. The bars were protected by a zinc coating of 610 g/m^2 (about 85 µm thick). In 2002 (ten years after installation), the soil nails were exposed for visual inspection during the redevelopment works. From results of corrosivity assessment, the soil, which was completely decomposed granite, was classified as 'aggressive'. Many of the exhumed soil-nail bars exhibited signs of corrosion, especially at locations where the bars were connected by couplers. Voids of various sizes were found in the grout cover. On some occasions, soil was entrapped in the grout at the locations of centralisers (Plate 1). At locations where voids were found, the zinc coating on the steel bar had been corroded away and there was rust on surface of the steel (Plate 3). The corrosion was localised. As the soil nails were installed in the ground for 10 years, the average localised corrosion rate of the zinc galvanising was higher than 8.5 µm per year.

All the exposed couplers and the parts of the steel bars connected by the couplers showed signs of corrosion. This might have been due to the reason that the couplers had induced cracks in the cement grout because of the smaller grout cover at those locations; and the cracks subsequently initiated the corrosion process. The zinc coating could not prevent the steel bar from corrosion under the 'aggressive' soil environment.

Plate 3 – Rusting of Zinc Coating and Steel Reinforcement

Property	Measured Value	Mark	Test Method
Soil Composition	Fraction passing 63 µm sieve ≤ 10%, and PI of fraction passing 425 µm sieve < 2, and Organic content < 1.0%	2	Geospec 3 Test Methods 6.1, 8.1, 8.2, 8.5, 8.6, and 9.1 (GEO, 2001)
	10% < Fraction passing 63 µm sieve ≤ 75%, and Fraction 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 < 10,000 but ≥ 3,000 < 3,000 but ≥ 1,000 < 1,000 but ≥ 100 < 100	0 -1 -2 -3 -4	BS 1377: Part 3: 1990, Test 10.4 (BSI, 1990)
Moisture Content	≤ 20% > 20%	0 -1	Geospec 3 Test Method 5.2
Groundwater 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 5 ≤ pH ≤ 6 4 ≤ pH < 5 or 10 ≥ pH > 9 pH < 4 or pH >10	0 -1 -2 (See Note 1)	Geospec 3 Test Method 9.5
Soluble Sulphate (ppm) (See Note 2)	≤ 200 > 200 but ≤ 500 > 500 but ≤ 1,000 > 1,000	0 -1 -2 -3	Geospec 3 Test Method 9.3
Made Ground (See Note 3)	None Exist	0 -4	–
Chloride Ion (ppm)	≤ 100 > 100 but ≤ 300 > 300 but ≤ 500 > 500	0 -1 -2 -4	Geospec 3 Test Method 9.4

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) Water soluble sulphate as SO_3.
(3) 'Made ground' refers to man-made ground associated with high corrosion rate such as non-engineering fill with rubbish and organic matters.

Table 1 – Soil Corrosivity Assessment

Post-2002 Practice

Corrosion is a potential weak link in the soil-nailed system. As a continuous effort to enhance the performance of soil nails, a new improved approach of corrosion protection was introduced in 2002. The new approach aims to remove the potential weak link and give room for rationalising design of soil nails. The improved approach was used in LPM works on a trial basis till end 2004. It has been fully implemented since early 2005, with some minor modifications made in 2007 (GEO, 2007).

In the new approach, several levels of corrosion protection to soil nails are provided on the basis of the corrosivity of soil, the design life and load carrying characteristics of the soil nails. According to GEO (2007), the ground is classified into one of the following four categories of condition: (a) non-aggressive; (b) mildly aggressive; (c) aggressive; and (d) highly aggressive. The classification is largely based on the method of soil corrosivity assessment developed by Eyre & Lewis (1987). This is a comprehensive assessment method which takes into consideration of most of the factors that affect underground corrosion. These factors include soil composition, groundwater level, resistivity, pH values, and amount of soluble salts (eg sulphates, sulphides, carbonates and chlorides). Ranking marks are used in the classification (Table 1). The overall classification is determined from the sum of pertinent contributing factors (Table 2).

The corrosion protection measures for permanent soil nails depend on the load-carrying characteristics of the soil nails and the corrosion potential of the ground. For soil nails carrying transient design loads, the corrosion protection requirements are summarised in Table 3.

Classification of Soil Corrosivity	Sum of Marks from Table 1
Non-aggressive	≥ 0
Mildly Aggressive	-1 to -4
Aggressive	-5 to -10
Highly Aggressive	≤ -11

Table 2 – Marking Scheme of Soil Corrosivity Assessment

Soil Condition	Corrosion Protection Measures
Non-aggressive or Mildly Aggressive	Hot-dip galvanisation and a 2 mm sacrificial thickness on bar radius
Aggressive or Highly Aggressive	Corrugated plastic sheath together with hot-dip galvanisation

Table 3 – Corrosion Protection Measures for Permanent Soil Nails Carrying Transient Loads

Soil Condition	Corrosion Protection Measures
Non-aggressive	Hot-dip galvanisation and a 2 mm sacrificial thickness on bar radius
Mildly Aggressive, Aggressive or Highly Aggressive	Corrugated plastic sheath together with hot-dip galvanising

Table 4 – Corrosion Protection for Permanent Soil Nails Carrying Sustained Loads

For permanent soil nails carrying sustained design loads (eg soil nails used to support excavations), the corrosion protection requirements are summarised in Table 4. For temporary soil nails with a design life of not more than 2 years, corrosivity assessment of the ground and the provision of sacrificial steel thickness are not necessary, but hot dip galvanising is still required.

Corrosion Protection Methods Used in other Countries

There is some considerable diversity in the approach of providing corrosion protection to soil nails in different parts of the world. In some places, the design allows for corrosion whereas in other places, provisions are made to prevent or minimise corrosion. For comparison with the new practice in Hong Kong, the corrosion protection approaches used in Japan, France, UK, Nordic countries, USA and Germany are described below.

Japan

In Japan, the required corrosion protection measures depend on the corrosivity of the soil and the design life of the soil nails. According to JHPC (1998), the corrosivity of soil should be assessed and the factors to be considered are basically the same as those listed in Table 1. For example, a soil is classified as severe corrosive if it has a pH value of less than 6.5 or a resistivity of less then 700 ohm-cm, or if organic or amino acid is present. For temporary soil nails (design life less than 2 years), there is no requirement for corrosion protection to soil nails. For permanent soil nails in non-corrosive to non-severe corrosive environments, the protection measures include a provision of zinc galvanisation and a sacrificial steel thickness of 1 mm. In addition, a minimum cement grout cover of 10 mm is required even though it is pointed out that the provision of grout cover for corrosion protection is unreliable. If the soil is severe corrosive, the use of steel soil nails is not encouraged and the use of high corrosion-resistant reinforcement, such as fibre-reinforced plastics, is recommended.

France

In France, corrosion protection measures vary according to the corrosivity of the soil, design life of the soil nails and the significance of the soil-nailed structure. According to Clouterre (1991), soils are classified into four categories of corrosivity: (a) highly corrosive; (b) corrosive; (c) average corrosiveness; and (d) slightly corrosive. The corrosivity assessment of ground involves the determination of a 'corrosiveness index' which is based on weightings ascribed to four factors, viz type of soil, resistivity, moisture content and pH value. The sum of the weightings of the four factors gives the overall corrosivity index. The higher the index, the higher the corrosion potential of the soil. The design life of soil nails is divided into three categories: short-term (less than 1.5 years), medium-term (1.5 years to 30 years) and long-term (30 to 100 years). The required corrosion protection measures are given in Table 5 and they mainly involve the provision of sacrificial steel thickness or plastic sheath.

Overall Corrosivity Index, I	Sacrificial Steel Thickness		
	Short-term (< 18 months)	Medium-term (1.5 to 30 years)	Long-term (30 to 100 years)
≤ 4	0	2 mm	4 mm
5 to 8	0	4 mm	8 mm
9 to 12	2 mm	8 mm	Plastic sheath
≥ 13	Protective plastic sheath must be provided		

Table 5 - Provision of Corrosion Protection Measures for Different Overall Corrosivity Index (Clouterre, 1991)

United Kingdom

In UK, an approach for dealing with corrosion of soil nails is given by Murray (1993) of the Transport Research Laboratory. In this approach, corrosion allowances for a soil-nailed structure depend upon the aggressivity of the soil and the design life of the structure. The ground is first classified into one of the following four categories of condition: (a) unlikely to be aggressive; (b) mildly aggressive; (c) aggressive; and (d) highly aggressive. Similar to Tables 1 and 2, the classification is based on the method of soil corrosivity assessment developed by Eyre & Lewis (1987) and the overall classification is determined from the sum of pertinent contributing factors. The rates of loss of galvanising for soils of different aggressivity are given in Table 6.

A plot of the required sacrificial thickness of steel against service life for 'non-aggressive', 'mildly aggressive' and 'aggressive' soils is shown in Fig 1. These corrosion allowances generally correspond to the uniform corrosion rates on the steel surface given by Romanoff (1957). No corrosion allowances are given for 'highly aggressive' soils because construction of permanent soil-nailed structures in this soil type is not recommended. Apart from providing galvanising coating and sacrificial steel thickness, Murray (1993) has also suggested that further protection may be obtained by the addition of a corrugated plastic sheath. However, no guidance has been given as under what situations should the corrugated plastic sheath be provided.

Soil Condition (Based on Eyre and Lewis, 1987)	Rate of Corrosion of Galvanising (μm per year)	Estimated Service Life of Galvanising Coating of 610 g/m^2, 85.4 μm (year)
Unlikely to be Aggressive	4	21
Mildly Aggressive	8	11
Aggressive	14	6

Table 6 – Corrosion Rate of Galvanising Steel under Different Soil Conditions (Murray, 1993)

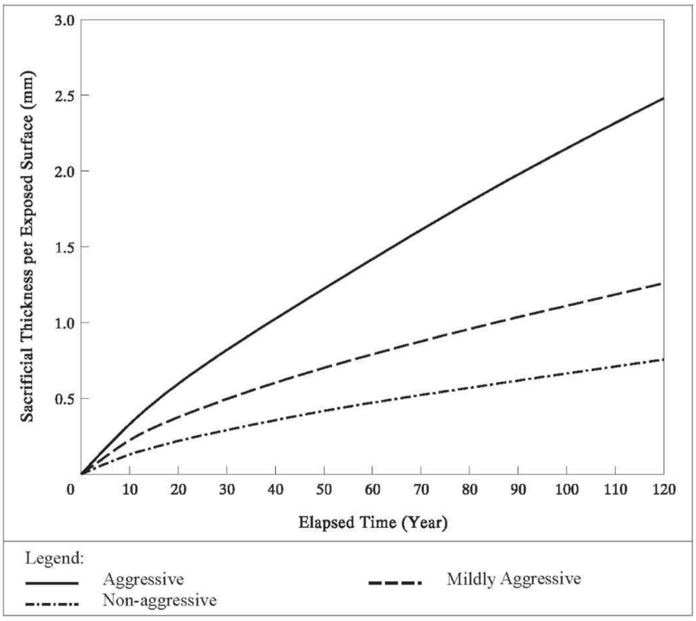

Figure 1 – Sacrificial Thickness of Buried Steel under Different Ground Conditions (Murray, 1993)

Recently, a risk-based approach has been developed and adopted by CIRIA (2005). It involves assessing the 'degradation risk' of the ground using the method generally similar to the soil corrosivity assessment currently used in Hong Kong. The factors to be considered in the assessment include soil type, resistivity, groundwater level, pH of soil and groundwater, water soluble sulphate, oxidisable sulphides and chloride ion. The degradation assessment of the soil is made by summing individual scores for the factors considered and ranking the soil into three categories of ground aggressivity: 'non-aggressive', 'aggressive' and 'highly aggressive'. Table 7 summarises the recommended use of corrosion protection methods in relation to different ground aggressivity categories and soil risk categories.

Type of Soil Nail	Low-risk Category			Medium-risk Category			High-risk Category		
	T or P in ME	T in AE	P in AE	T or P in ME	T in AE	P in AE	T or P in ME	T in AE	P in AE
Steel Surrounded by Cement Grout	✓	✓	✓	✓	✓	✗	✓	✗	✗
Coated Steel Surrounded by Cement Grout	✓	✓	✓	✓	✓	✗	✓	✗	✗
Steel Surrounded by Grouted Impermeable Ducting	✓	✓	✓	✓	✓	✓	✓	✓	✓
Coated Steel Surrounded by Grouted Impermeable Ducting*	✓	✓	✓	✓	✓	✓	✓	✓	✓
Steel Surrounded by Pre-grouted Double Impermeable Ducting*	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes
T Temporary (2 years or less)
P Permanent (more than 2 years)
ME Non-aggressive
AE Aggressive or highly aggressive
✓ Likely to be suitable
✗ Inappropriate
* System particularly suitable for heavy or long nails for permanent works where one of the two protective layers may become damaged during handling or installation.

Table 7 – Corrosion Protection Guidelines for Different Soil Nailing Systems in Relation to Different Risk Categories (CIRIA, 2005)

Nordic Countries

In the Nordic countries, guidelines for corrosion protection of soil nails are given in Rogbeck *et al.* (2003). The requirements on corrosion protection depend on the aggressivity of soil (environment) and design life of the soil nails. Similar to the current method used in Hong Kong, a scoring system is used to assess and classify the level of corrosion potential of soil. Factors to be considered in the assessment include soil type, resistivity, moisture content, salt content, pH values, layering of soil and other factors (eg industrial waste, construction waste, water with salt from road).

Depending on the level of corrosion potential, the ground is classified into three different environmental classes:

• Environmental Class I – low potential for corrosion

• Environmental Class II – normal potential for corrosion

• Environmental Class III – high potential for corrosion

Corroison protection requirements for different environmental classes are outlined in Table 8. In addition to the environmental class, the consequences of failure of the nailed structure should be considered. If the consequences of failure are high, a high degree of corrosion protection may be needed for soil of Environmental Class I.

USA

In USA, ground corrosion potential is assessed based on four factors, viz soil resistivity, pH value, concentration of sulphate and concentration of chloride (Lazarete *et al.,* 2003). Critical values are assigned to these factors, see the second column of Table 9. If the ground property values fall below or above any one of these critical values, the soil is classified as 'aggressive'. The ground is also considered to be 'aggressive' if stray current is present. If the ground conditions satisfy those listed in the third column of Table 9, the ground is classified as 'non-aggressive'. Classification of aggressivity of the ground should consider the possibility of changes during the service life of soil-nailed structure.

The corrosion protection requirements depend on the design life and significance of the soil-nailed structures, and the ground corrosion potential. For temporary (service life $<$18 months) or permanent soil nails in 'non-aggressive ground' and with no serious failure consequence, the steel bar should be protected by cement grout only. For permanent soil nails with serious failure consequence or to be installed in 'aggressive' ground, grout and PVC sheathing encapsulation should be used. Alternatively, grout and epoxy-coated bar may be adopted.

Germany

The German practice represents a more conservative approach. It is designed to prevent corrosion as opposed to designing for a sacrificial thickness of the steel bar. Corrosion protection to permanent soil nails consists of encapsulating the steel bar in a corrugated plastic sheath and cement grout annulus (Glässer, 1990). Permanent soil nails are prepared under factory conditions and are typically delivered to the site in steel channels for protection against bending and cracking during transport. For temporary soil nails with a life of less than 2 years, corrosion protection generally consists of a cement grout annulus only with a minimum cover of 15 to 20 mm. In areas noted for

Environmental Class	Design Life			
	Temporary	2 - 40 years	40 - 80 years	> 80 years
I	No	Low	Normal	Extremely High
II	No	Normal	High	Special Investigation
III	Low	High	Extremely High	Special Investigation

Notes:

No	No corrosion protection is necessary
Low	Low degree of corrosion protection, eg 2 mm sacrificial thickness on steel
Normal	Normal degree of corrosion protection, eg 4 mm sacrificial thickness on steel or grout at least 20 mm thick together with plastic barrier
High	High degree of corrosion protection, eg 8 mm sacrifice thickness on steel or grout at least 40 mm thick together with plastic barrier
Extremely High	Plastic barrier is necessary

Table 8 – Corrosion Protection Requirements for Different Environmental Classes and Design Lives (Rogbeck et al., 2003)

Test	Aggressive	Non-aggressive
pH	< 4.5 > 10	5.5 < pH < 10
Resistivity	< 2,000 ohm-cm	> 5,000 ohm-cm
Sulphates	> 200 ppm	< 200 ppm
Chlorides	> 100 ppm	< 100 ppm

Table 9 – Criteria for Assessing Ground Corrosion Potential (Lazarete et al., 2003)

aggressive ground conditions, corrugated plastic sheath in conjunction with grout cover is used for temporary soil nails as well.

Discussion

The new improved corrosion protection approach used in Hong Kong since 2002 provides different levels of protection to soil nails under different ground corrosivity conditions. It is in general comparable with the approaches being used in some overseas countries where the soil nailing technique is well developed.

Corrosion reduces the cross-sectional area and hence the tensile capacity of the steel bar. It is worth mentioning that the minimum required partial safety factor for tensile failure of soil nails has been reduced from 2.0 to 1.5 since 2006 (GEO, 2007). One of the factors considered for this reduction is the adoption of the improved corrosion protection practice. Soil nails that have been installed with the pre-2002 corrosion protection method are not expected to give significant problems even in aggressive ground. It is because they were designed using a higher partial safety factor against tensile failure.

Corrosivity Assessment of Hong Kong Soils

Shiu & Cheung (2003) reported results of assessment of corrosion potential of soils in Hong Kong. The assessment was based on limited soil test data obtained from projects mostly not related to soil nailing works. With the introduction of the improved corrosion protection approach in 2002, soil corrosivity assessments have been performed on a number of slopes under the LPM Programme. The assessments involve the determination of the composition and the electrochemical properties of the soils, as those listed in Table 1.

Up to mid 2005, results of corrosivity assessments on 281 soil specimens taken from 87 LPM slopes are available. These slopes scatter over different parts of Hong Kong. The test data cover four different types of soils including completely decomposed granite (CDG), completely decomposed volcanics (CDV), colluvium (COLL) and fill (FILL). The numbers of soil specimens tested for the four types of soils are: CDG (117), CDV (76), COLL (47) and FILL (41). Results of the tests are presented and discussed below, along with comments on the relevance and limitations of the test data.

Silt & Clay Content and Plasticity Index

The particle size distribution of a soil, particularly the silt and clay content, is an important factor controlling the water-holding capacity of the soil. Silt and clay are defined as the soil particles passing the 63 µm BS sieve size. The histograms presented in Fig 2 indicate the distribution of silt and clay contents for 90 CDG, 32 CDV, 46 COLL and 48 FILL specimens. The average silt and clay contents of CDG, CDV, COLL and FILL are 38%, 47%, 54% and 36%, respectively. The relatively higher contents of silt and clay in CDV and colluvium indicate that they generally have a higher water-holding capacity than CDG and fill.

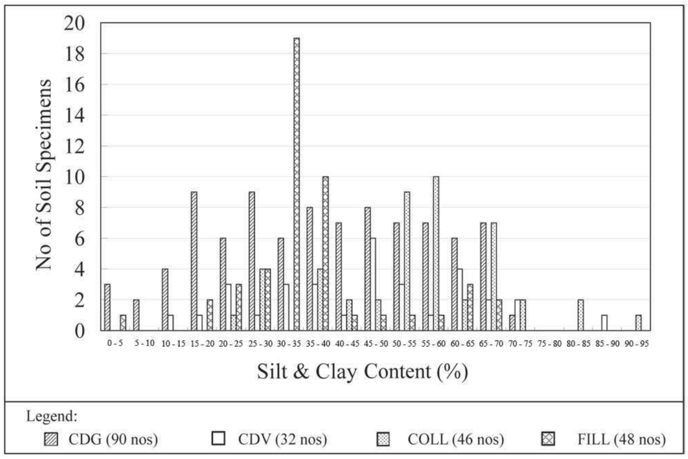

Figure 2 – Distribution of Silt and Clay Content of Soil Specimens

The Atterberg limits of the soil specimens were determined using soils passing the 425 µm BS sieve. The distribution of plasticity indices for 72 CDG, 21 CDV, 44 COLL and 43 FILL specimens is shown in Fig 3. The average plasticity index is 21.6 for CDG, 17 for CDV, 27 for COLL, and 21.4 for FILL. Plasticity indicates the ability of the soils to hold moisture.

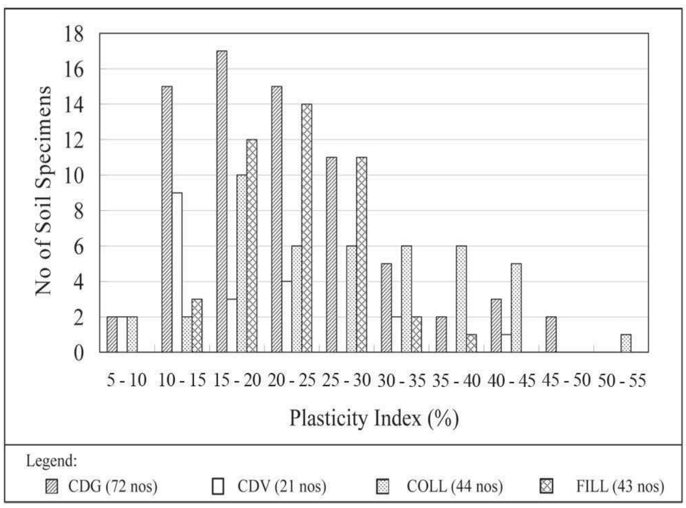

Figure 3 – Distribution of Plasticity Index of Soil Specimens

Moisture Content

Fig 4 presents the distribution of in-situ moisture content of 99 CDG, 35 CDV, 46 COLL and 53 FILL soil specimens. The average moisture

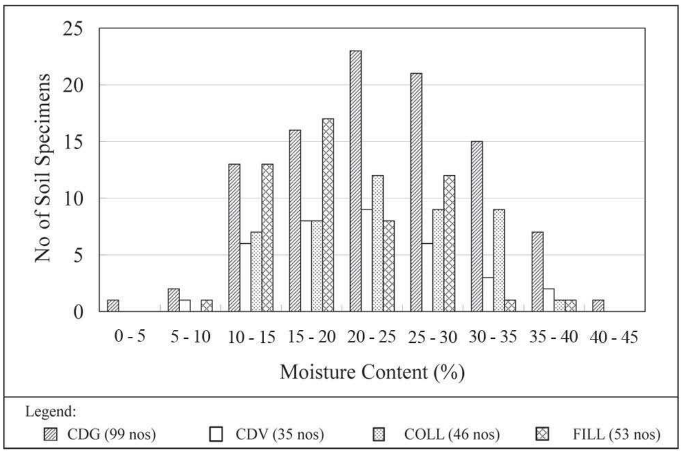

Figure 4 – Distribution of Moisture Content of Soil Specimens

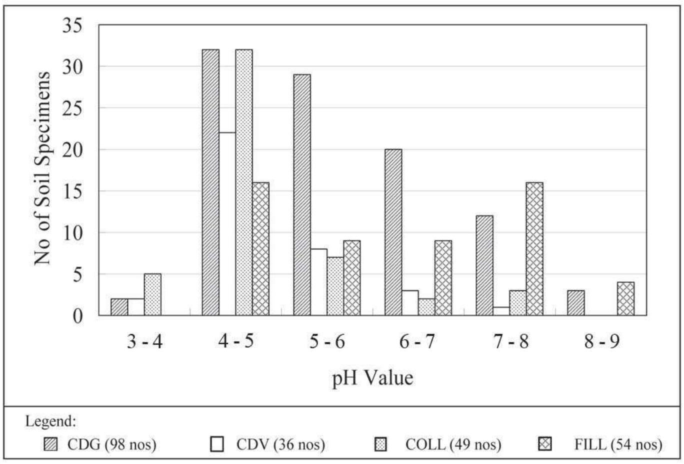

Figure 5 – Distribution of pH Value of Soil Specimen

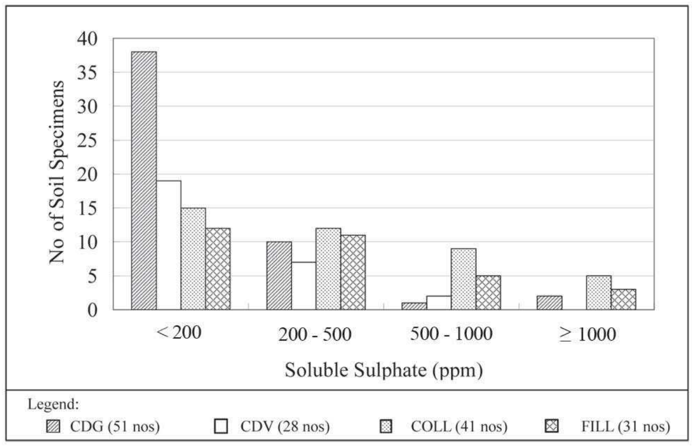

Figure 6 – Distribution of Soluble Sulphate of Soil Specimens

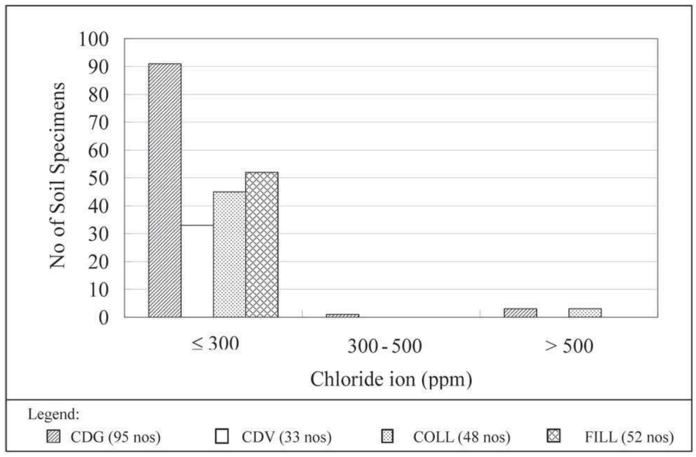

Figure 7 – Distribution of Chloride Ion of Soil Specimens

content is 23% for CDG, 22% for CDV, 23% for COLL and 19% for FILL. The percentage of soil specimens with moisture content greater than 20% is 68% for CDG, 57% for CDV, 67% for COLL and 42% for FILL. The corrosion rate of metals is affected by the oxygen concentration and the relationship between oxygen permeation and moisture content is complex.

pH Value

Fig 5 shows the distribution of pH values of 98 CDG, 36 CDV, 49 COLL and 54 FILL specimens. The pH value for the CDG specimens lies between 3 and 9, with an average of 5.6. The pH value for CDV falls within 3 and 8, with an average of 5. The range of pH values for colluvium is between 4 and 9 and the average value is 4.8. The pH value for FILL specimens is between 4 and 9, with an average of 6.2. The pH value depends very much on the specific site conditions (eg presence of organic acid due to decomposition of vegetation).

Soluble Sulphates

Sulphate reducing bacteria, which cause the most common form of bacterial corrosion, cannot flourish without the presence of sulphate. Sulphate can exist in different forms in soil. For corrosivity assessment purposes, only the water-soluble sulphates need to be considered. Fig 6 shows the distribution of soluble sulphate of 51 CDG, 28 CDV, 41 COLL and 31 FILL specimens. Among these test results, 56% of the soils have a water-soluble sulphate content equal to or less than 200 ppm. The remaining 44% tests have a range of results from 200 ppm to larger than 1,000 ppm. The concentration of sulphates depends on specific site conditions (eg leaking sewers).

Soluble Chloride Ion

Fig 7 shows the distribution of chloride ion for 95 CDG, 33 CDV, 48 COLL and 52 FILL specimens. About 97% of the specimens tested have chloride ion content less than 300 ppm. Similar to that for soluble sulphates, the chloride ion content also depends much on the specific site conditions (eg leaking water mains).

Carbonates and Sulphides

Salts of carbonates and sulphides are reducing agents and are usually analysed qualitatively. Test results on these substances are limited. Most of the test results show that carbonate is either absent or only present in trace amount. The same applies to sulphides.

Soil Resistivity

Resistivity is an important parameter for assessing the corrosivity of a soil. Fig 8 shows the distribution of measured resistivity of 80 CDG, 33 CDV, 42 COLL and 52 FILL soil specimens. Over 92% of the soils tested have resistivity values above 10,000 ohm-cm.

Discussion

Based on the composition and electrochemical properties of the soils determined from the tests, the soil specimens are classified into the following four categories in accordance with Tables 1 and 2: 'highly aggressive', 'aggressive', 'mildly aggressive' and 'non-aggressive'. The distribution of the soil specimens in the four categories is summarised in Table 10.

As indicated in Table 10, the corrosivity of colluvium and fill is generally higher than that of CDG and CDV. One possible reason could be ease

Soil Type	No of Soil Specimens				
	Highly Aggressive	Aggressive	Mildly Aggressive	Non-aggressive	Total
CDG	2 (2%)	31 (26%)	59 (50%)	25 (22%)	117 (100%)
CDV	0 (0%)	12 (16%)	52 (68%)	12 (16%)	76 (100%)
COLL	2 (4%)	31 (66%)	9 (19%)	5 (11%)	47 (100%)
FILL	1 (2%)	13 (32%)	17 (41%)	10 (25%)	41 (100%)
All Soil Types	5 (2%)	87 (31%)	137 (48%)	52 (19%)	281 (100%)

Table 10 – Corrosivity Assessment Results of Soils

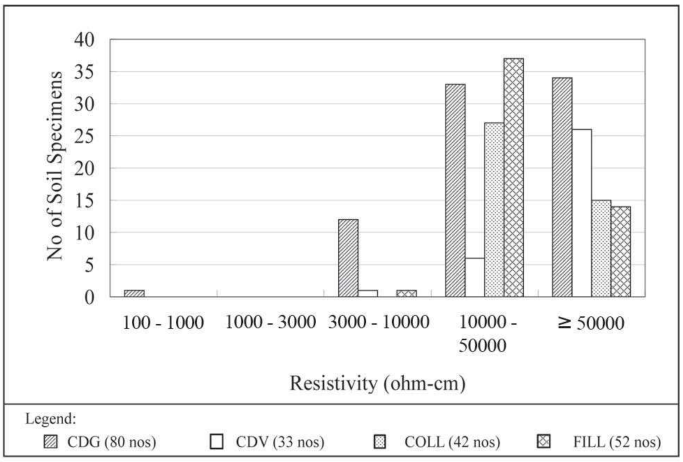

Figure 8 – Distribution of Resistivity of Soil Specimens

of contamination by human activities (eg leakage from sewer) since colluvium and fill layers are usually situated close to ground surface. If all soil types are considered together, about 33% of the soil specimens are classified as aggressive or highly aggressive, indicating that quite a significant portion of the soils tested could have a relatively high corrosion potential. Nevertheless, this only indicates the results of the 87 LPM sites where corrosivity assessment were carried out during the period from 2002 to mid-2005. In the same period, there were a large number of other LPM sites where corrosivity assessments were not conducted because they were considered to be 'non-aggressive' on the basis of their environmental settings. Hence the actual proportion of sites with aggressive ground could be much less than 33%.

Corrosion Protection to Reinforcement Couplers

A coupler is commonly used to connect two steel bars in situations where space is limited and short bars are required, or where the length of soil nails is longer than 12 m. This requires forming threads at the bar ends and as a result removing the zinc coating along the threaded lengths.

The couplers should have sufficient tensile strength. Besides, the elongation between the coupler and the parent bars should be small under tensile force. This is to ensure that the design tensile force can be properly transferred through the couplers and that no unacceptable crack widths are developed in the cement grout. Yet, on some occasions the use of hot dip galvanising as a corrosion protection measure to couplers has difficulties in complying with the requirements in respect of zinc coating thickness and permanent elongation. Thus, zinc rich paint is usually applied directly to the threaded portions of the steel bar. The level of corrosion protection provided by the paint could be less than that of hot dip galvanising. This would render the parts of the threaded steel bars at the locations of couplers more vulnerable to corrosion. This is supported by observations made of exhumed soil nails (Plate 4). To provide a better corrosion protection, the feasibility of using heat-shrinkable sleeve has been explored.

Heat-shrinkable sleeve, which is a tubular sleeve that shrinks upon heating, has been used as corrosion protection measures in overseas countries and in some projects in Hong Kong. It comes in a range of sizes to suit different couplers. The sleeve comprises two layers of material, viz an outer layer of polyethylene and an inner layer of mastic sealant material. The function of the outer polyethylene layer is to render the sleeve to shrink upon heating thereby resulting in having the reinforcement connector tightly encased in the inner mastic material. The mastic material is a viscous sealant which acts as a corrosion inhibitor.

A laboratory investigation involving the application of heat-shrinkable sleeves to a number of samples and testing their performance has been carried out (Plate 5). Each sample consisted of two short steel bars connected by a coupler; the coupler and portions of the bars were encased in a heat-shrinkable sleeve. The samples were submerged in a water tank for different durations ranging between 7 days and 28 days. Subsequently, a series of tests comprising waterproofing tests, tensile strength tests, permanent elongation tests and continuity test (BSI, 1999) were conducted on the samples. The waterproofing test was designed specifically for detecting whether water had entered into the couplers. Results of the test indicated that all the samples were watertight. The tensile strength tests and elongation tests showed that all the samples conformed to the tensile strength and permanent elongation requirements. Also no holidays (pinholes) were found on the surface of the sleeves from the continuity test.

In addition to the laboratory tests, field trials of using heat-shrinkable sleeves were undertaken at an LPM site. The trial has confirmed that the installation of sleeves was easy and quick. Generally, it takes several minutes to install a sleeve of about 300 mm long to each coupler. The use of heat-shrinkable sleeves at couplers is now a standard corrosion protection in LPM works.

Non-metallic Soil Nails

To overcome the problem of corrosion of metallic reinforcement, non-metallic soil nails may be used. Laboratory and field trials have indicated

Plate 4 – Corrosion of Coupler

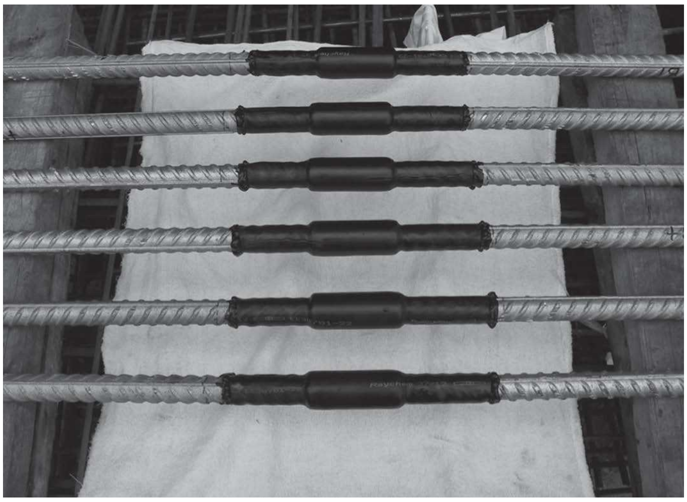

Plate 5 – Samples of Couplers/Bars with Heat-shrinkable Sleeves

that carbon fibre reinforced polymer reinforcement (CFRP) can be an alternative to steel bar in soil nailing works. Details of the trials can be found in Cheung & Lo (2005). The CFRP is highly corrosion resistant. It also has the merits of high tensile strength and being lightweight. However, care should be exercised in soil nail applications because of the brittle behaviour of the material.

Conclusions

To ensure satisfactory long-term performance of soil-nailed systems, the soil nails should not be weakened by corrosion to a degree that would unduly affect their performance. Depending on environmental settings and ground conditions, a number of options can be used for providing different degrees of corrosion protection to steel soil nails (viz cement grout, sacrificial steel, sacrificial metallic coating, non-metallic coating and corrugated plastic sheath).

Test data on physical and electrochemical properties of Hong Kong soils indicate that a significant portion of the soils that had been taken from potential aggressive sites could have a relatively high corrosion potential. Localised corrosions are observed in exhumed soil nails, especially at areas where steel couplers are used to splice steel bars.

The new corrosion protection approach introduced since early 2002 represents an improved practice in Hong Kong. The required levels of corrosion protection depend on the corrosion potential of the ground, and the design life and load-carrying characteristics of the soil nails. This is in general consistent with the approaches being used in other countries where the soil nailing technique is well developed.

Use of heat-shrinkable sleeves is a practical way to provide better corrosion protection to couplers and threaded ends of steel bars.

Acknowledgements

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