Interim Review on Long-term Monitoring of Corrosion of Soil Nails

GEO Report No. 334

F.W.Y. Ko

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

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Preface

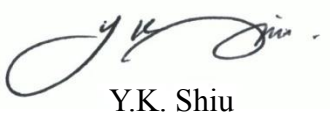
In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

W.K. Pun
Head, Geotechnical Engineering Office
March 2018

Foreword

This report presents an interim review on long-term monitoring of corrosion of soil nails. It summaries the findings of the soil nail exhumation exercises between 2010 and 2013, which are part of the study on long-term monitoring of corrosion of soil nails.

The interim review was carried out by Ms Florence W.Y. Ko under my supervision. Mr Andrew H.K. Wu (previously at Architectural Services Department), Mr C.F. Yam and Mr Frankie L.C. Lo were responsible for managing the soil nail exhumation exercises in 2010, 2011 and 2013 respectively. The Drafting Unit of the Standards and Testing Division assisted in formatting this report. All contributions are gratefully acknowledged.



Y.K. Shiu
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Abstract

In 1999, the Geotechnical Engineering Office (GEO) initiated a study of long-term durability of soil nails, with a view to developing an improved approach for designing and specifying corrosion protection for soil nails. In order to collect long-term data on the corrosion rates of soil nails, the GEO commenced in 2004 a long-term monitoring of the corrosion of sacrificial soil nails with different types of corrosion protection provisions. Soil nails, in the form of 1.5 m long, 32 mm diameter high-yield deformed steel bar, with different types of corrosion protection provisions were installed in the last quarter of 2004 at four different sites under the Landslip Preventive Measures Programme. The GEO has also collaborated with the Architectural Services Department to monitor the sacrificial soil nails installed at Slope No. 11SW-D/C2089 at the Hong Kong Stadium.

Exhumation of soil nails at the five monitoring sites was carried out between 2010 and 2013. In general, no significant corrosion was observed on all the exhumed soil nails with different corrosion protection provisions. Monitoring of corrosion of the sacrificial soil nails installed at the five sites will be continued according to the monitoring schedule.

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1 Introduction

In 1999, the Geotechnical Engineering Office (GEO) initiated a study of long-term durability of soil nails, with a view to develop an improved approach for designing and specifying corrosion protection for soil nails. The study was one of the recommendations made by the Slope Safety Technical Review Board in their November 1998 meeting. The study comprised a review of relevant literature on corrosion of steel in soils and technical guidance documents from France, the UK and the USA on effectiveness and reliability of the various corrosion protection provisions. As part of the study, five different types of corrosion protection provisions used for steel soil nails (viz. cement grout, sacrificial steel, sacrificial metallic coating, non-metallic coating and corrugated plastic sheath) were examined. Two case studies on corrosion of steel soil nails (one in Japan and the other in Hong Kong) were also reviewed. It was concluded that there was not enough information to determine accurately the corrosion rates of steel and zinc coating in soils of different aggressivities. Detailed findings and recommendations of the study are documented in Shiu & Cheung (2003).

In order to collect long-term data on the corrosion rates of soil nails, the GEO commenced in 2004 a long-term monitoring of the corrosion of sacrificial soil nails with different types of corrosion protection provisions (i.e. cement grout, sacrificial steel, hot-dip galvanizing and epoxy coating). Soil nails, in the form of 1.5 m long, 32 mm diameter high-yield deformed steel bar, with different types of corrosion protection provisions were installed in the last quarter of 2004 at four different sites under the Landslip Preventive Measures (LPM) Programme, namely Slope No. 12NW-C/C82 at Hang Hau Road, Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street, Slope No. 11NE-D/C520 at Po Lam Road, Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road. The GEO has also collaborated with the Architectural Services Department (ArchSD) to monitor the sacrificial soil nails installed at Slope No. 11SW-D/C2089 at the Hong Kong Stadium. Sacrificial soil nails, in the form of 1.5 m long, 32 mm diameter high-yield deformed steel bar, were installed at the slope at an elevation of about 1.5 m above the slope toe as part of the re-development of the Hong Kong Stadium in 1994.

2 The Sites

2.1 Slope No. 11SW-D/C2089 at the Hong Kong Stadium

Slope No. 11SW-D/C2089 is a 13 m (max.) high, 80° inclined soil cut slope located straightly behind the Hong Kong Stadium (Figure 2.1). It affects road/footpath with moderate traffic density at its crest and the back of the Hong Kong Stadium at its toe. The slope is not openly accessible and access to its toe for maintenance is gained through the grand-stand structures of the Stadium (ArchSD, 2010). It has been assigned to be Consequence-to-life Category 1. The slope is entirely covered by hard surfacing. It is currently maintained by Leisure and Cultural Services Department with ArchSD as its works agent. The slope was formed by cutting into the existing ground and installing soil nails during the re-development of the Hong Kong Stadium in the early 1990s. As the slope was formed prior to the requirement of the soil aggressivity assessment in Geoguide 7 (GEO, 2008), the initial classification of the slope in terms of soil aggressivity is not known.

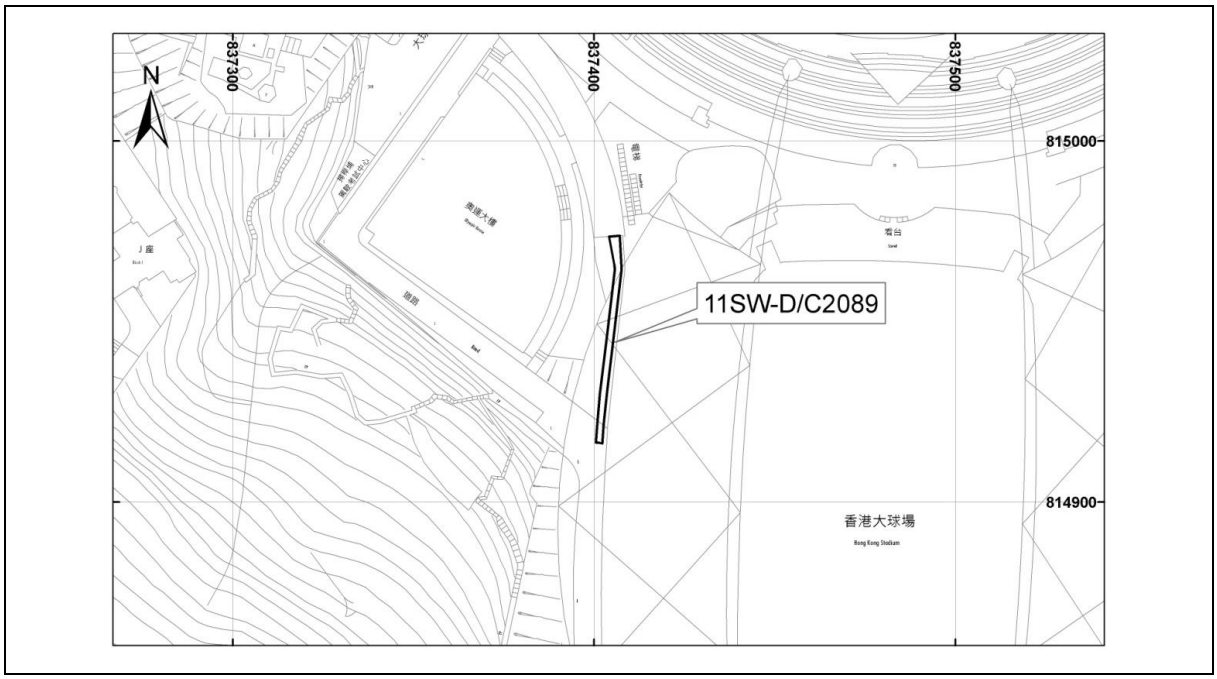


Figure 2.1 Location Plan of Slope No. 11SW-D/C2089 at the Hong Kong Stadium

2.2 Slope No. 12NW-C/C82 at Hang Hau Road

Slope No. 12NW-C/C82 is a 24 m (max.) high, 35° inclined soil cut slope overlooking a substation at Hang Hau Road, Tseung Kwan O (Figure 2.2). It affects undeveloped green belt at its crest and the substation at its toe, and has been assigned to be Consequence-to-life Category 2. The slope is covered by vegetation. It is currently maintained by Highways Department (HyD). The desk study revealed that the Stage 3 Study for the slope under the LPM Programme was completed in 2002. The recommended slope upgrading works comprising mainly soil nail installation with double corrosion protection were completed in June 2004 under Contract No. GE/2002/01. The slope was initially classified as "mildly aggressive" in accordance with Table 4.1 of Geoguide 7 (GEO, 2008).

2.3 Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street

Slope No. 11SW-A/CR595 (sub-division 1) is a 35 m (max.) high, 40° inclined soil cut slope with a 2 m (max.) high retaining wall at its toe. It is located near Belcher's Street and behind 16-30 Li Po Lung Path, Kennedy Town (Figure 2.3). It affects Ricci Hall of the University of Hong Kong at its crest and a number of residential buildings at its toe, and has been assigned to be Consequence-to-life Category 1. Majority of the slope is covered by vegetation. It is of mixed responsibilities with sub-division 1 currently maintained by Lands Department. The desk study revealed that the Stage 3 Study for sub-division 1 of the slope under the LPM Programme was completed in 2002. The recommended slope upgrading works comprising mainly soil nail installation and skin wall construction were completed in May 2006 under Contract No. GE/2002/01. The slope was initially classified as "mildly aggressive" in accordance with Table 4.1 of Geoguide 7 (GEO, 2008).

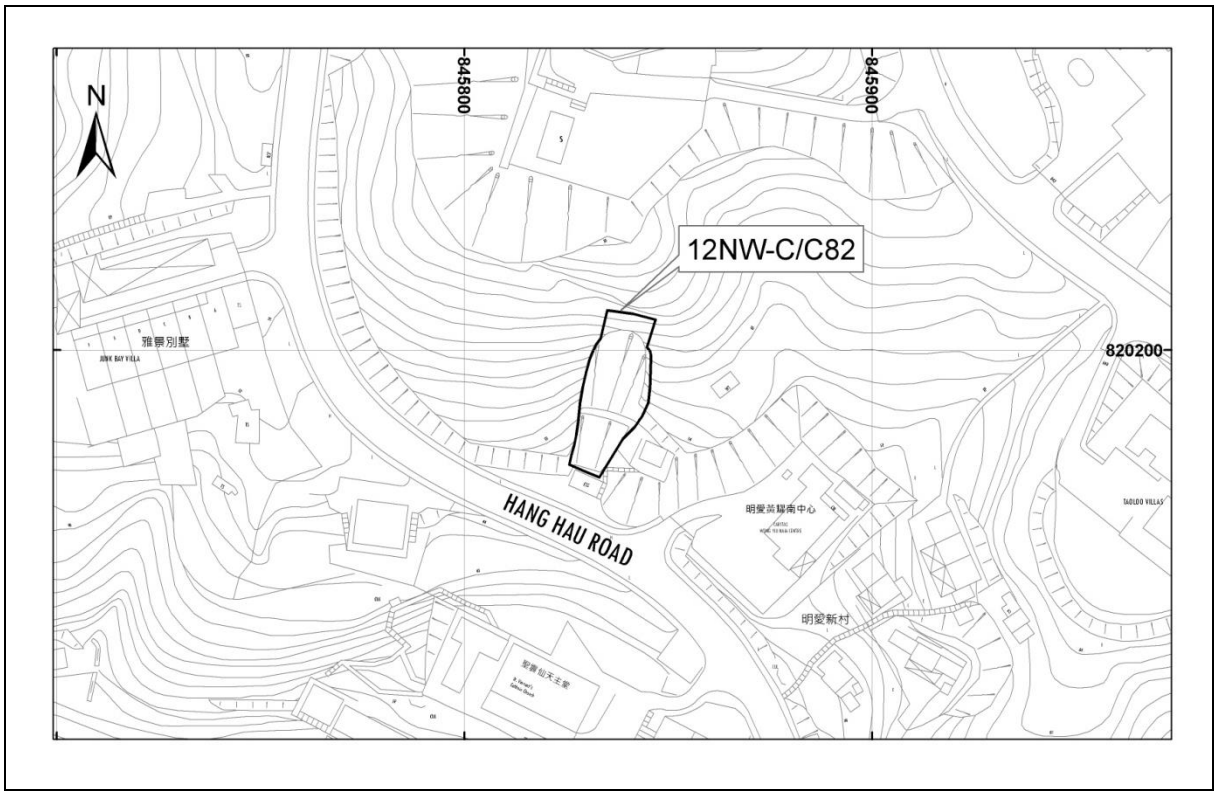


Figure 2.2 Location Plan of Slope No. 12NW-C/C82 at Hang Hau Road

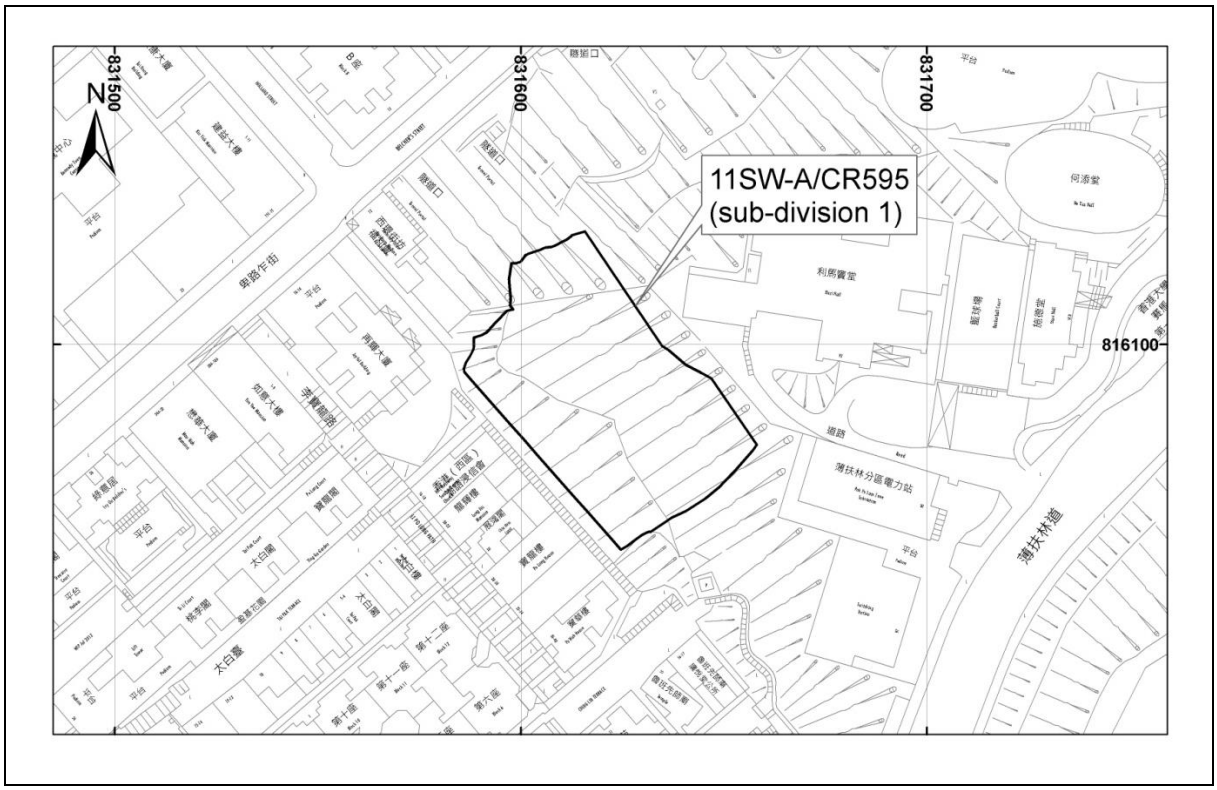


Figure 2.3 Location Plan of Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street

2.4 Slope No. 11NE-D/C520 at Po Lam Road

Slope No. 11NE-D/C520 is a 60 m (max.) high, 35° inclined soil cut slope located above Po Lam Road and opposite to King Lam Estate, Tseung Kwan O (Figure 2.4). It affects a minor footpath at its crest and Po Lam Road at its toe and has been assigned to be Consequence-to-life Category 2. Majority of the slope is covered by vegetation. It is currently maintained by HyD. The desk study revealed that the Stage 3 Study for the slope under the LPM Programme was completed in 2002. The recommended slope upgrading works comprising mainly soil nail installation were completed in October 2005 under Contract No. GE/2002/01. The slope was initially classified as "aggressive" in accordance with Table 4.1 of Geoguide 7 (GEO, 2008).

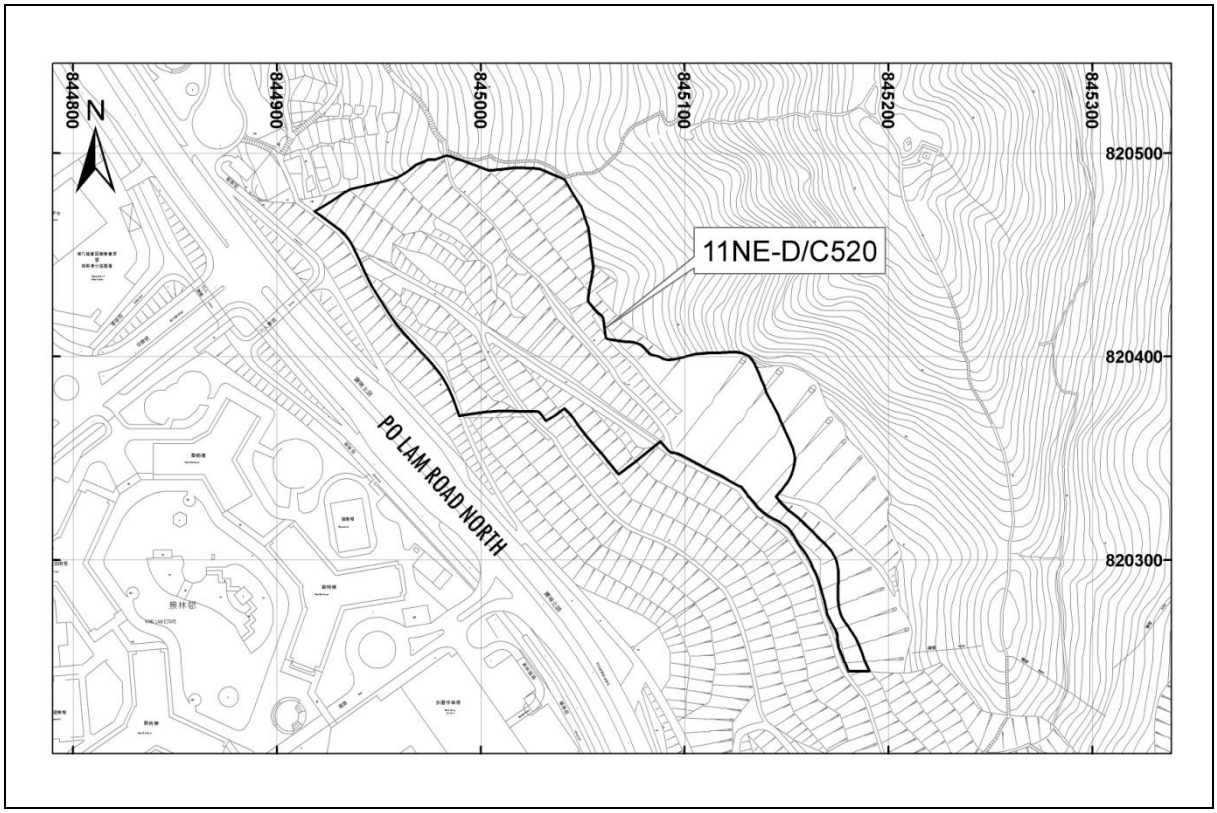


Figure 2.4 Location Plan of Slope No. 11NE-D/C520 at Po Lam Road

2.5 Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road

Slope No. 11SW-C/FR83 (sub-division 3) is a 9 m (max.) high fill slope with a 2 m (max.) high concrete retaining wall at its toe, affecting Findlay Road at its crest and Baker Road Peak Tram Station at its toe (Figure 2.5). It has been assigned to be Consequence-to-life Category 1. The slope is entirely covered by vegetation. It is of mixed responsibilities with sub-division 3 currently maintained by Lands Department.

Slope No. 11SW-C/C839 is a 16 m (max.) high, 50° inclined soil cut slope adjoining Slope No. 11SW-C/FR83 (sub-division 3) to the west (Figure 2.5). It affects natural hillside at its crest and Plantation Road at its toe, and has been assigned to be Consequence-to-life Category 3. The slope is entirely covered by hard surfacing. It is currently under the maintenance responsibility of HyD.

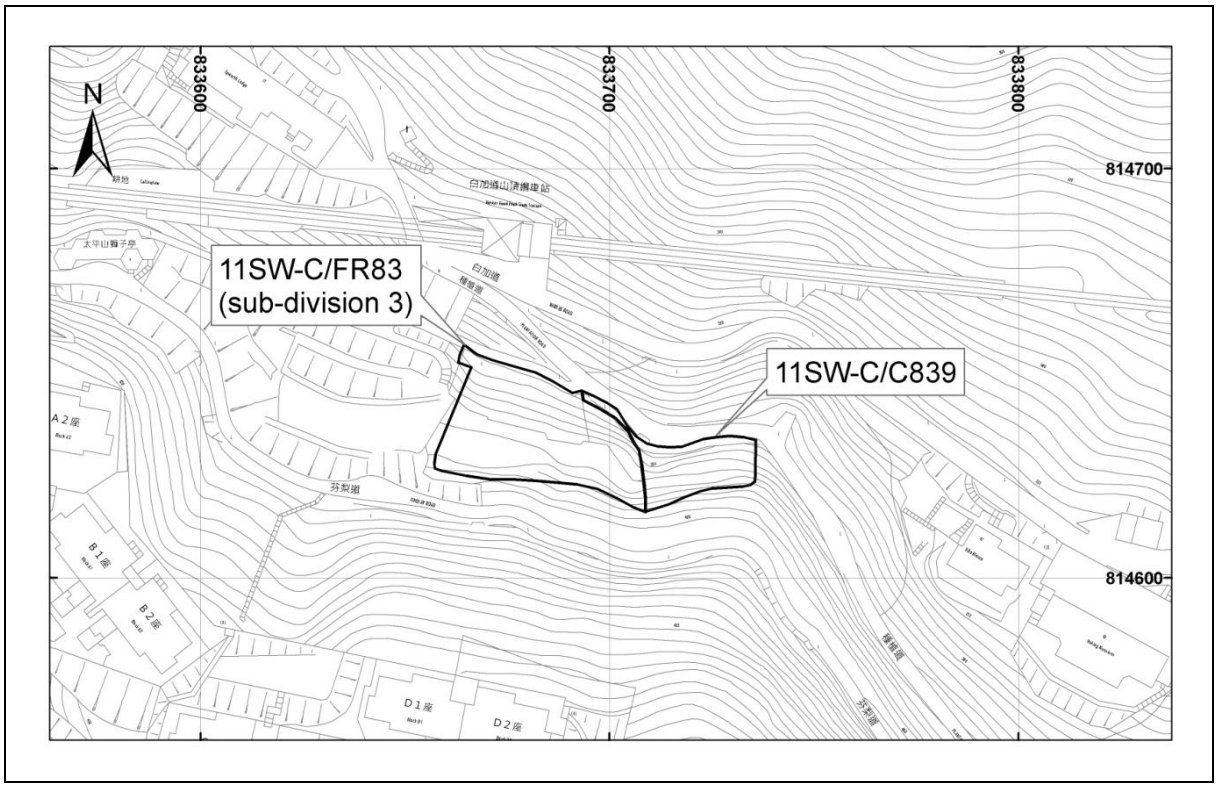


Figure 2.5 Location Plan of Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road

Both slopes were initially classified as "mildly aggressive" in accordance with Table 4.1 of Geoguide 7 (GEO, 2008).

The desk study revealed that the Stage 3 Study for both slopes under the LPM Programme was completed in 2002. The recommended slope upgrading works comprising mainly soil nail installation and skin wall construction were completed in March 2005 under Contract No. GE/2002/01.

3 Monitoring Schedule and Requirements

Table 3.1 summarizes the original schedule of the sacrificial soil nails at the five sites. Their approximate locations on sites are shown in Figures 3.1 to 3.5. The monitoring schedule of these sacrificial soil nails is given in Table 3.2. It was planned in such a way to monitor the corrosion of the sacrificial soil nails with different types of corrosion protection provisions.

Table 3.1 Original Schedule of Sacrificial Soil Nails

Site	Soil Aggressivity	Soil Nail ID	Nail Number	Diameter / Length	Coupler	Corrosion Protection	Grout Sleeve
Slope No. 11SW-D/C2089 at the Hong Kong Stadium	Non-aggressive	T1-T12	12	32 mm / 1.5 m	No	Plain steel	No, direct contact with ground
Slope No. 12NW-C/C82 at Hang Hau Road	Mildly aggressive	SB1-SB6	6	32 mm / 1.5 m	No	Plain steel	No, direct contact with ground
		SB7-SB12	6	32 mm / 1.5 m	No	Hot-dip galvanized	No, direct contact with ground
		SB13-SB18	6	32 mm / 1.5 m	No	Epoxy coated	No, direct contact with ground
		SB19-SB24	6	32 mm / 1.5 m	No	Stainless steel solid/clad	No, direct contact with ground
		SN1-SN6	6	32 mm / 1.5 m	No	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN7-SN8	2	32 mm / 1.5 m	Yes	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN9-SN10	2	32 mm / 1.5 m	No	Epoxy coated	Yes, 100 mm grout sleeve
		SN11	1	32 mm / 1.5 m	Yes	Epoxy coated	Yes, 100 mm grout sleeve
Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street	Mildly aggressive	SN1-SN6	6	32 mm / 1.5 m	No	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN7-SN8	2	32 mm / 1.5 m	No	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN9-SN10	2	32 mm / 1.5 m	No	Epoxy coated	Yes, 100 mm grout sleeve
		SN11	1	32 mm / 1.5 m	Yes	Epoxy coated	Yes, 100 mm grout sleeve
Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road	Mildly aggressive(1)	SN1-SN6	6	32 mm / 1.5 m	No	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN7-SN8	2	32 mm / 1.5 m	Yes	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN9-SN10	2	32 mm / 1.5 m	No	Epoxy coated	Yes, 100 mm grout sleeve
		SN11	1	32 mm / 1.5 m	Yes	Epoxy coated	Yes, 100 mm grout sleeve
Slope No. 11NE-D/C520 at Po Lam Road	Aggressive	SB1-SB6	6	32 mm / 1.5 m	No	Plain steel	No, direct contact with ground
		SB7-SB12	6	32 mm / 1.5 m	No	Hot-dip galvanized	No, direct contact with ground
		SB13-SB18	6	32 mm / 1.5 m	No	Epoxy coated	No, direct contact with ground
		SN1-SN6	6	32 mm / 1.5 m	No	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN7-SN8	2	32 mm / 1.5 m	Yes	Hot-dip galvanized	Yes, 100 mm grout sleeve
		SN9-SN10	2	32 mm / 1.5 m	No	Epoxy coated	Yes, 100 mm grout sleeve
		SN11	1	32 mm / 1.5 m	Yes	Epoxy coated	Yes, 100 mm grout sleeve

Note: (1) Please refer to the key findings discussion in Section 4.4 (a) on Page 30.

Table 3.2 Monitoring Schedule of Sacrificial Soil Nails (Sheet 1 of 2)

(A) Monitoring Schedule of Sacrificial Soil Nails at Slope No. 11SW-D/C2089 at the Hong Kong Stadium

Type	Corrosion Protection	Grout Sleeve	Coupler	Soil Aggressivity	Site	Nail Number	2002	2010	2019	2029	2039	2049
							8 years[1]	16 years	25 years	35 years	45 years	55 years
1	Plain steel	No, direct contact with ground	No	Non-aggressive	11SW-D/C2089	12	2 (T10, T12)[2]	2 (T4, T8)	2	2	2	2

Notes: (1) The sacrificial soil nails were installed in 1994.
(2) The report that contains the findings of the exhumation exercise in 2002 could not be located.

(B) Monitoring Schedule of Sacrificial Soil Nails at the Other Four Slopes

Type	Corrosion Protection	Grout Sleeve	Coupler	Soil Aggressivity	Site	Nail Number	2011	2013	2019	2029	2039	2049
							7 years[1]	9 years	15 years	25 years	35 years	45 years
1	Plain steel	No, direct contact with ground	No	Mildly aggressive	12NW-C/C82	6	2 (SB1, SB4)	-	1	1	1	1
				Aggressive	11NE-D/C520	6	-	2 (SB1, SB5)	1	1	1	1
2	Hot-dip galvanized	No, direct contact with ground	No	Mildly aggressive	12NW-C/C82	6	2 (SB7, SB10)	-	1	1	1	1
				Aggressive	11NE-D/C520	6	-	2 (SB9, SB11)	1	1	1	1
3	Epoxy coated	No, direct contact with ground	No	Mildly aggressive	12NW-C/C82	6	2 (SB13, SB16[2])	-	1	1	1	1
				Aggressive	11NE-D/C520	6	-	2 (SB13, SB16)	1	1	1	1
4	Stainless steel	No, direct contact with ground	No	Mildly aggressive	12NW-C/C82	6	2 (SB19, SB22)	-	1	1	1	1

Table 3.2 Monitoring Schedule of Sacrificial Soil Nails (Sheet 2 of 2)

(B) Monitoring Schedule of Sacrificial Soil Nails at the Other Four Slopes (cont'd)

Type	Corrosion Protection	Grout Sleeve	Coupler	Soil Aggressivity	Site	Nail Number	2011	2013	2019	2029	2039	2049
							7 years[1]	9 years	15 years	25 years	35 years	45 years
5	Hot-dip galvanized	Yes, 100 mm grout sleeve	No	Mildly aggressive	12NW-C/C82	6	2 (SN1, SN4)	-	2	-	2	-
					11SW-A/CR595	6	2 (SN2, SN4)	-	1	1	1	1
					11SW-C/FR83, C839	6	-	2 (SN1, SN6)	-	2	-	2
				Aggressive	11NE-D/C520	6	-	2 (SN1, SN4)	1	1	1	1
6	Hot-dip galvanized	Yes, 100 mm grout sleeve	Yes	Mildly aggressive	12NW-C/C82	2	1 (SN7)	-	-	1	-	-
					11SW-A/CR595	2	1 (SN7[3])	-	-	-	1	-
					11SW-C/FR83, C839	2	-	-	1	-	-	1
				Aggressive	11NE-D/C520	2	-	1 (SN7)	-	-	-	1
7	Epoxy coated	Yes, 100 mm grout sleeve	No	Mildly aggressive	12NW-C/C82	2	-[4]	-	-	1	-	1
					11SW-A/CR595	2	1 (SN9[5])	-	-	1	-	-
					11SW-C/FR83, C839	2	-	-	1	-	1	-
				Aggressive	11NE-D/C520	2	-	1 (SN9)	-	-	-	1
8	Epoxy coated	Yes, 100 mm grout sleeve	Yes	Mildly aggressive	12NW-C/C82	1	-	-	-	-	-	1
					11SW-A/CR595	1	-	-	-	1	-	-
					11SW-C/FR83, C839	1	-	1 (SN11)	-	-	-	-
				Aggressive	11NE-D/C520	1	-	-	-	-	-	1

Notes:
(1) The sacrificial soil nails were installed in 2004.
(2) SB16 is hot-dip galvanized instead of epoxy-coated as in the original schedule (see Table 3.1).
(3) No coupler at SN7 was found.
(4) SN9 was not exhumed in 2011 in the end due to obstruction by existing tree roots.
(5) SN9 is hot-dip galvanized instead of epoxy-coated as in the original schedule (see Table 3.1) and a coupler is found at mid-length of the nail.

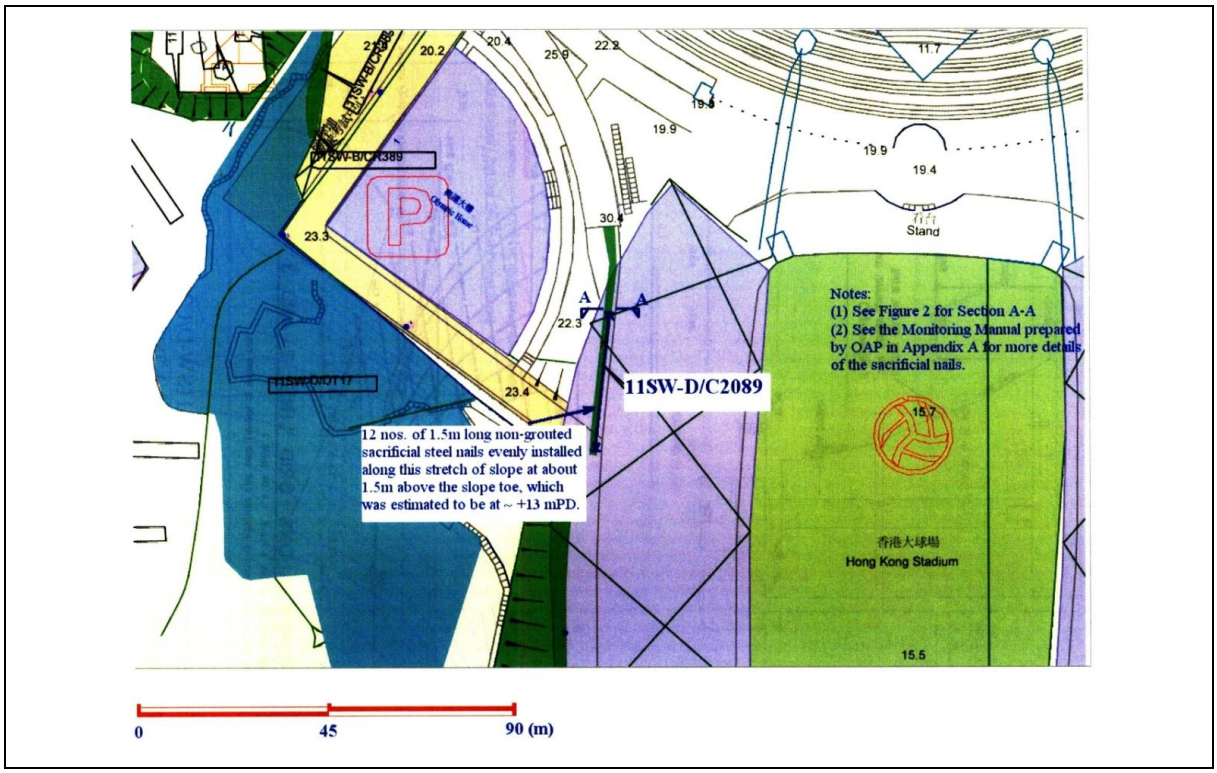


Figure 3.1 Approximate Locations of Sacrificial Soil Nails at Slope No. 11SW-D/C2089 at the Hong Kong Stadium

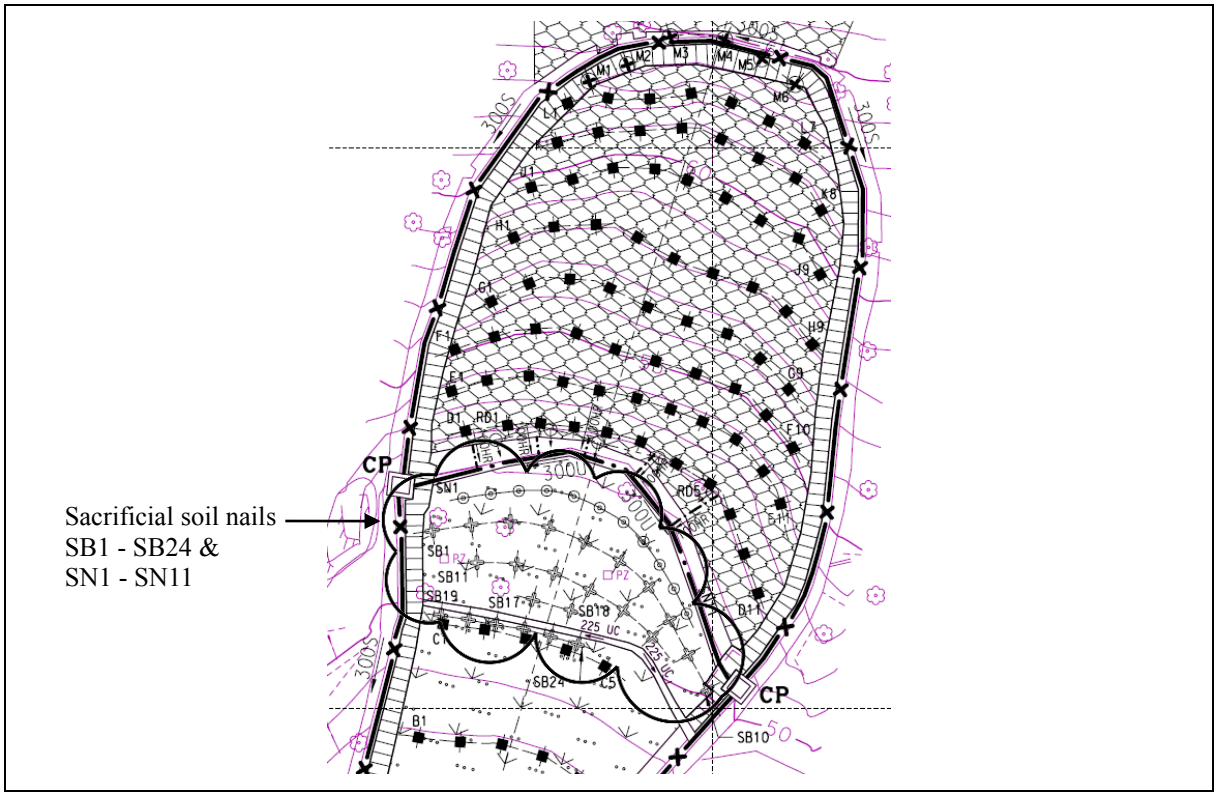


Figure 3.2 Approximate Locations of Sacrificial Soil Nails at Slope No. 12NW-C/C82 at Hang Hau Road

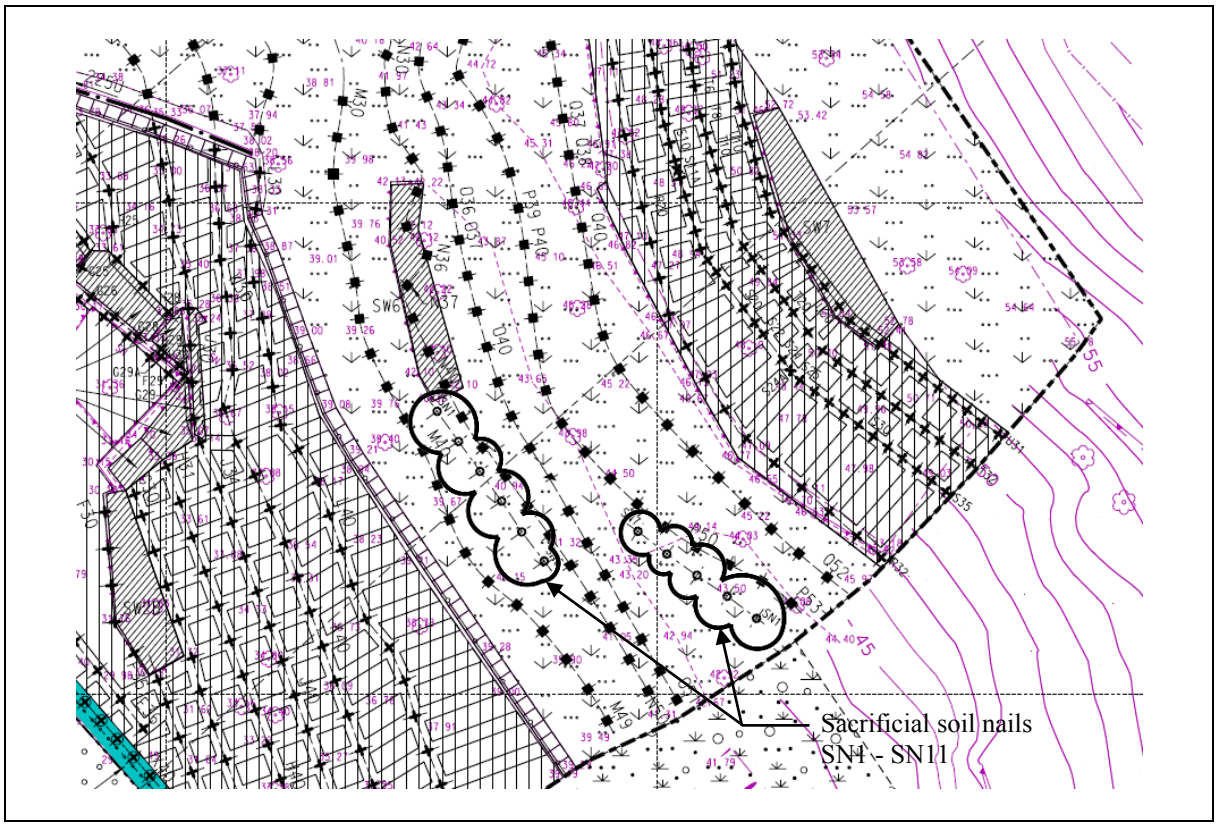


Figure 3.3 Approximate Locations of Sacrificial Soil Nails at Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street

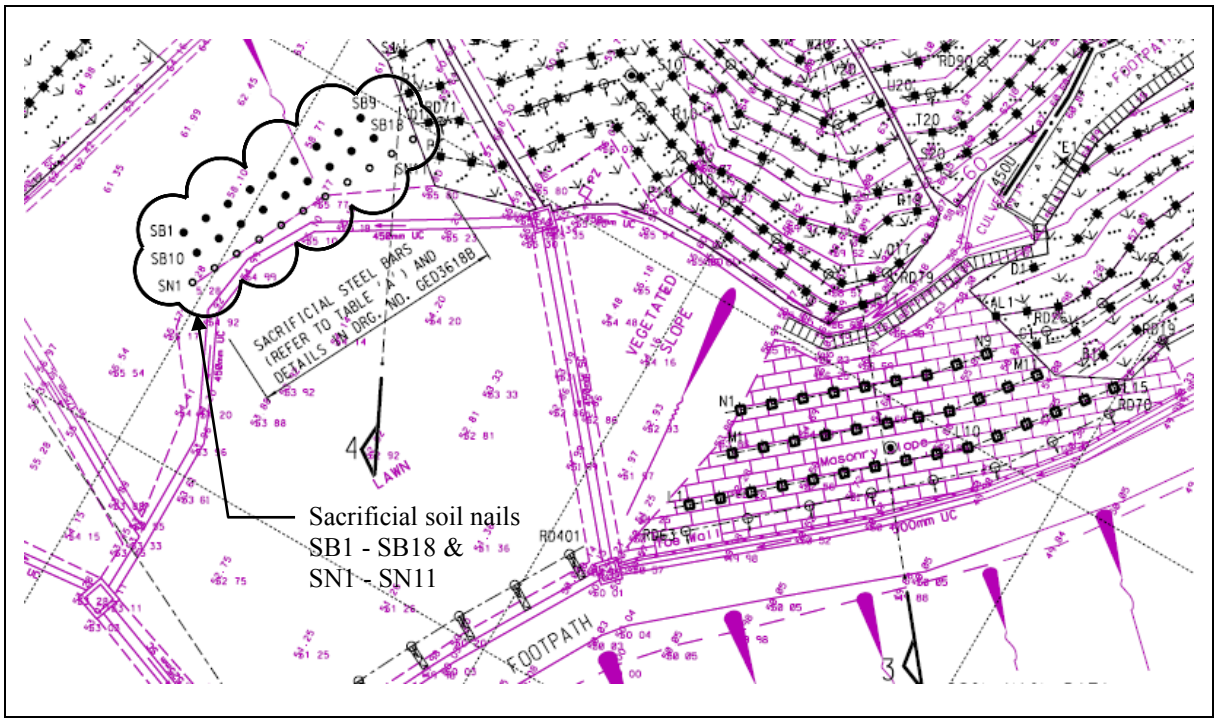


Figure 3.4 Approximate Locations of Sacrificial Soil Nails at Slope No. 11NE-D/C520 at Po Lam Road

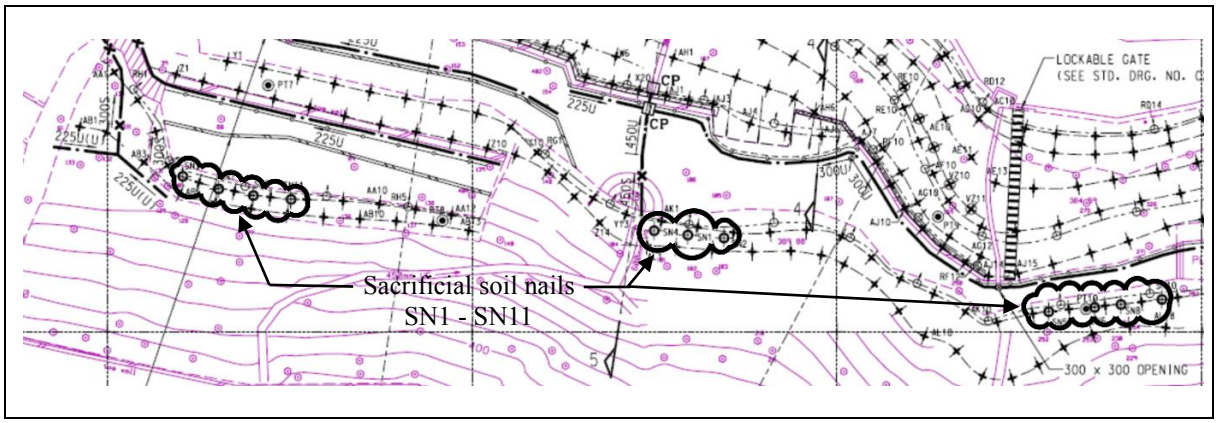


Figure 3.5 Approximate Locations of Sacrificial Soil Nails at Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road

4 Exhumation Exercises between 2010 and 2013

4.1 General

Exhumation of two soil nails was carried out at Slope No. 11SW-D/C2089 (at the Hong Kong Stadium) in 2010, 15 soil nails at Slope No. 11SW-A/CR595 (sub-division 1) (at Belcher's Street) and Slope No. 12NW-C/C82 (at Hang Hau Road) in 2011, and 13 soil nails at Slope No. 11NE-D/C520 (at Po Lam Road), Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 (at Plantation Road) in 2013. For these previous exhumation exercises, both visual inspection of the surface conditions of the exhumed soil nails and laboratory testing of the exhumed soil nails and the soils around them were carried out for assessing the corrosion and strength of the steel bars, and soil aggressivity. Table 4.1 summarizes the visual inspection and laboratory testing schedule for the sacrificial soil nails in the previous exhumation exercises.

4.2 Exhumation Exercise in 2010

Exhumation of two sacrificial soil nails (No. T4 and T8) was carried out for Slope No. 11SW-D/C2089 at the Hong Kong Stadium in 2010. They were selected at random on site.

The Slope Safety Group, Property Services Branch of the ArchSD was responsible for undertaking the exhumation exercise. The tasks under the exercise included:

(a) fieldworks on soil nail exhumation;

(b) laboratory tests on soil including classification tests, chemical tests and resistivity/redox potential tests for assessment of soil aggressivity;

(c) laboratory tests on exhumed nails including measurement of nail weight after removal of rust and tensile test;

Table 4.1 Visual Inspection and Laboratory Testing Schedule of Sacrificial Soil Nails

Site <Year of Exhumation>	Soil Nail ID	Corrosion Protection[1]	Visual Inspection		Laboratory Tests[2]		
			Phase 1 (for grout sleeve)	Phase 2 (for soil nails)	Carbonation	Zinc Coating Thickness	Tensile
Slope No. 11SW-D/C2089 at the Hong Kong Stadium <2010>	T4	Nil	-	√	-	-	√
	T8	Nil	-	√	-	-	√
Slope No. 12NW-C/C82 at Hang Hau Road <2011>	SB1	Nil	-	√[4]	-	-	-
	SB4	Nil	-	√[4]	-	-	-
	SB7	Z	-	√[4]	-	-	-
	SB10	Z	-	√[4]	-	-	-
	SB13	E	-	√[4]	-	-	-
	SB16	Z	-	√[4]	-	-	-
	SB19	S	-	√[4]	-	-	-
	SB22	S	-	√[4]	-	-	-
	SN1	Z, G	√	√	√	√	√
	SN4	Z, G	-[3]	-	-	-	-
	SN7	Z, G	√	√	√	√	√
Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street <2011>	SN2	Z, G	√	√	√	√	√
	SN4	Z, G	√	√	√	√	√
	SN7	Z, G	√	√	√	√	√
	SN9	Z, G	√	√	√	√	√
Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road <2013>	SN1	Z, G	√	√	√	√	√
	SN6	Z, G	√	√	√	√	√
	SN11	E, G	√	√	√	-	√
Slope No. 11NE-D/C520 at Po Lam Road <2013>	SB1	Nil	-	√	-	-	√
	SB5	Nil	-	√	-	-	√
	SB9	Z	-	√	-	√	√
	SB11	Z	-	√	-	√	√
	SB13	E	-	√	-	-	√
	SB16	E	-	√	-	-	√
	SN1	Z, G	-[3]	√	√	√	√
	SN4	Z, G	√	√	√	√	√
	SN7	Z, G	√	√	√	√	√
	SN9	E, G	√	√	√	-	√

Notes:

(1) The following abbreviations are used to denote the corrosion protection provisions of the sacrificial soil nails:
Nil: Plain steel without any corrosion protection provision and grout sleeve,
Z: Hot-dip galvanized soil nails without any grout sleeve,
E: Epoxy coated soil nails without any grout sleeve,
G: 100 mm diameter grout sleeve,
S: Stainless steel soil nails without any grout sleeve.

(2) The following standards were adopted for carrying out the corresponding laboratory tests:
(a) Carbonation test by Castco Testing Centre Ltd. in 2011 - HKHA, MTS (2008/2010) Package D Specification, Part D Clause 4.3.1 Method 1,
(b) Carbonation test by PWCL in 2013 - A.M. Neville 3rd Ed. 1995 (PWLTM CHM 5.6),
(c) Measurement of zinc coating thickness - BS EN ISO 2178:1995, and
(d) Tensile test - CS2:1995.

(3) The grout cover was crushed completely during the coring, therefore no Phase 1 inspection was carried out.

(4) The surface conditions of the soil nails were only briefly inspected straight after their exhumation on site. No detailed examination of their surface conditions was carried out at the laboratory.

(d) visual inspection/examination of nails;

(e) review of laboratory test results and findings from examination; and

(f) preparation of the review report.

ArchSD (2010) gives the details of the fieldworks and laboratory testing, such as the methodology of exhumation, laboratory tests undertaken, details of visual inspection, testing results and observations. Key findings are summarized below:

(a) According to the laboratory test results on soil aggressivity, the site was classified as "non-aggressive" in accordance with Table 4.1 of Geoguide 7 (GEO, 2008).

(b) The two exhumed sacrificial soil nails were plain steel bars installed in direct contact with the ground. Extensive surface corrosion was observed on the nail bars while no pitting corrosion was spotted (Figure 4.1).

(c) The results of the tensile tests showed that the yield stress of the two rusty plain steel bars was about 10% greater than its characteristic strength of 460 MPa. The allowable tensile strength of the rusty steel bars was considered not affected by their corrosion condition.

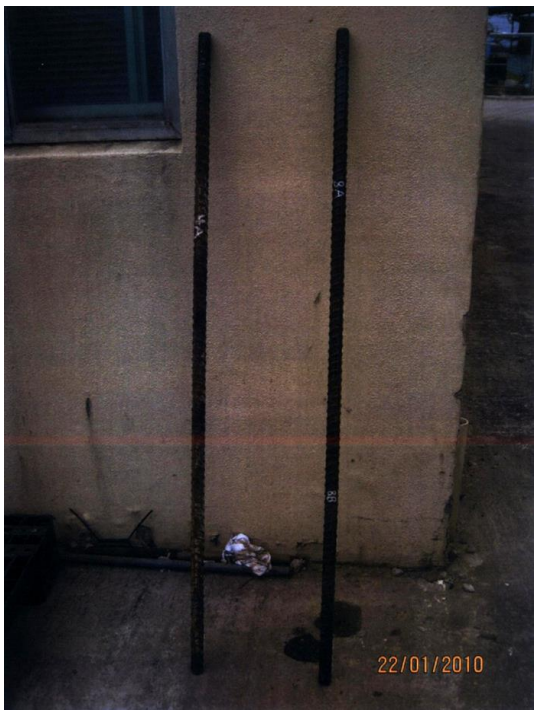


Figure 4.1 Example of Sacrificial Soil Nails with Extensive Surface Corrosion at Slope No. 11SW-D/C2089 at the Hong Kong Stadium

4.3 Exhumation Exercise in 2011

Exhumation of 15 soil nails was carried out for Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street and Slope No. 12NW-C/C82 at Hang Hau Road in February and May 2011 respectively after 7 years of completion of their installations (see Table 3.2 for their soil nail IDs). Laboratory tests were carried out for six soil nails with grout sleeve (i.e. SN2, SN4, SN7 and SN9 at the Belcher's Street site; SN1 and SN7 at the Hang Hau Road site).

AECOM Asia Company Limited (AECOM), the Landslide Investigation Consultant under Agreement No. CE 9/2009 (GE), was responsible for undertaking the exhumation exercise. The tasks under the exercise included:

(a) fieldworks on soil nail exhumation;

(b) laboratory tests on soil including classification tests, chemical tests and resistivity/redox potential tests for assessment of soil aggressivity;

(c) laboratory tests on exhumed nails including carbonation test, zinc coating measurement and tensile test;

(d) visual inspection/examination of nails;

(e) review of laboratory test results and findings from examination; and

(f) preparation of the review report.

AECOM (2012) gives the details of the fieldworks and laboratory testing, such as the methodology of exhumation, fieldwork records, laboratory testing schedule, key aspects for visual inspection, testing results and observations. Key findings are summarized below:

(a) According to the laboratory test results on soil aggressivity, both sites were classified as "mildly aggressive" in accordance with Table 4.1 of Geoguide 7 (GEO, 2008). This is the same as the previous classification.

(b) For the two plain steel bars installed in direct contact with the ground (i.e. SB1 and SB4 at the Hang Hau Road site), extensive sign of corrosion was observed on the surface (Figure 4.2). No pitting corrosion was observed by means of visual inspection. They were not examined further at the laboratory, e.g. cutting into short lengths for inspection of the cross sections.

(c) The seven exhumed soil nails with grout sleeve (i.e. SN2, SN4, SN7 and SN9 at the Belcher's Street site; SN1, SN4 and SN7 at the Hang Hau Road site) were all protected with hot-dip galvanization. Out of the seven soil nails, six (i.e. SN2, SN4, SN7 and SN9 at the Belcher's Street site; SN1 and SN7

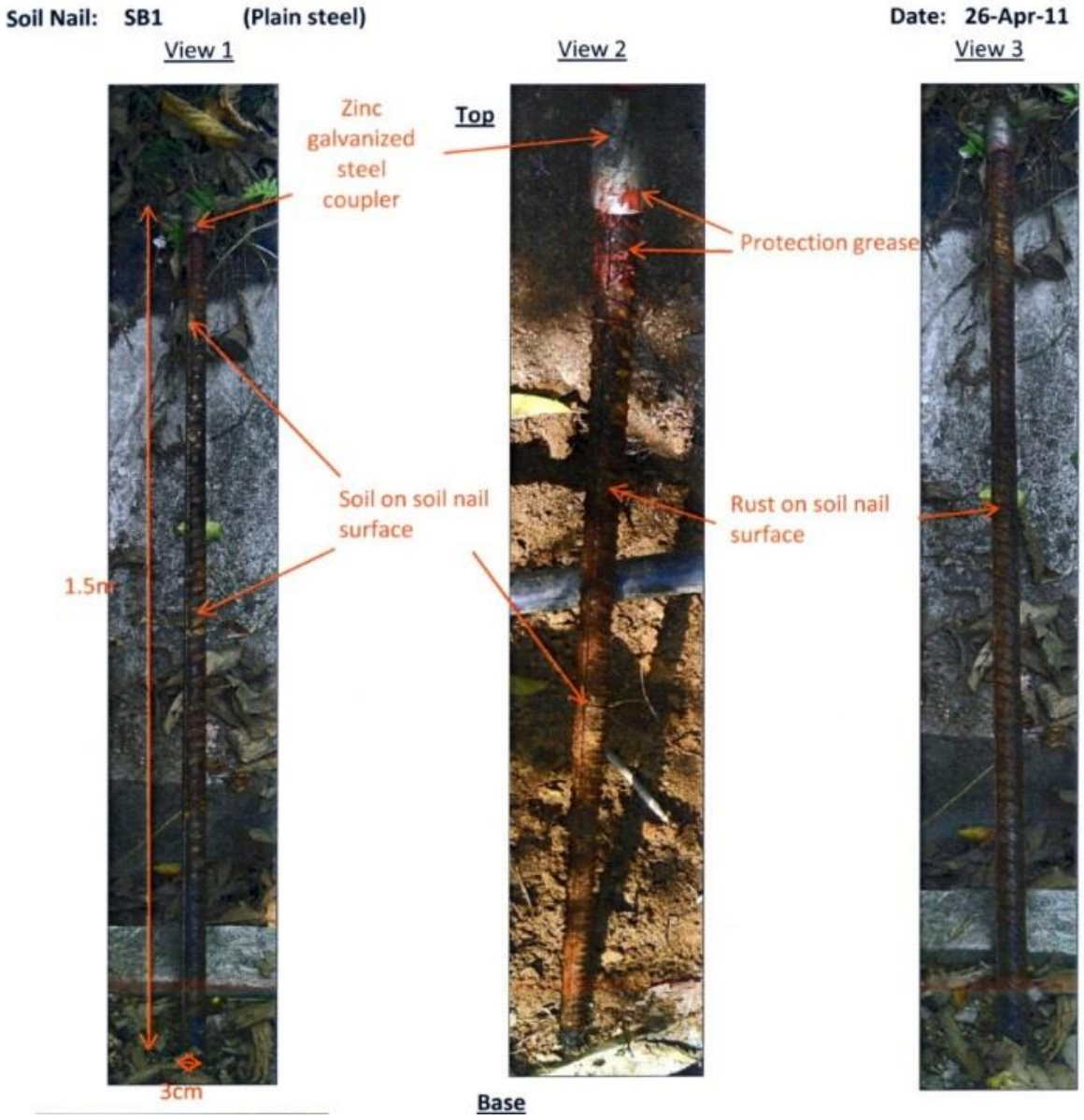
at the Hang Hau Road site) were exhumed with the grout sleeves fully or partially preserved. Different extent of defects, in terms of voiding and cracking of the grout sleeves, were identified on the grout covers of these six nails (Figure 4.3), possibly due to poor workmanship during grouting. The grout cover of the soil nail SN4 at Hang Hau Road site was completely crushed during coring (Figure 4.4).

(d) Six out of the seven exhumed soil nails with grout sleeve (i.e. SN2, SN4, SN7 and SN9 at the Belcher's Street site; SN1 and SN7 at the Hang Hau Road site) were further tested at the laboratories. Two samples of grout sleeve were collated from each soil nail for carbonation tests (i.e. altogether 12 samples). According to the laboratory results, two samples (SN2 and SN7 at the Belcher's Street site) showed minor sign of carbonation. The zinc coating thicknesses of the six hot-dip galvanized steel bars were greater than 85 μm for a minimum zinc coating weight of 610 g/m^2 (HKSARG, 2006). All six soil nails showed no significant signs of corrosion (Figure 4.5).

(e) For the two nails with provisions of couplers (both were zinc-galvanised and grout-protected) (i.e. SN9 at the Belcher's Street site and SN7 at the Hang Hau Road site), mild surface corrosion was observed on the exposed threaded sections of the nail bars, while no major sign of corrosion was noted on the zinc-galvanised nail bars or couplers (Figure 4.6).

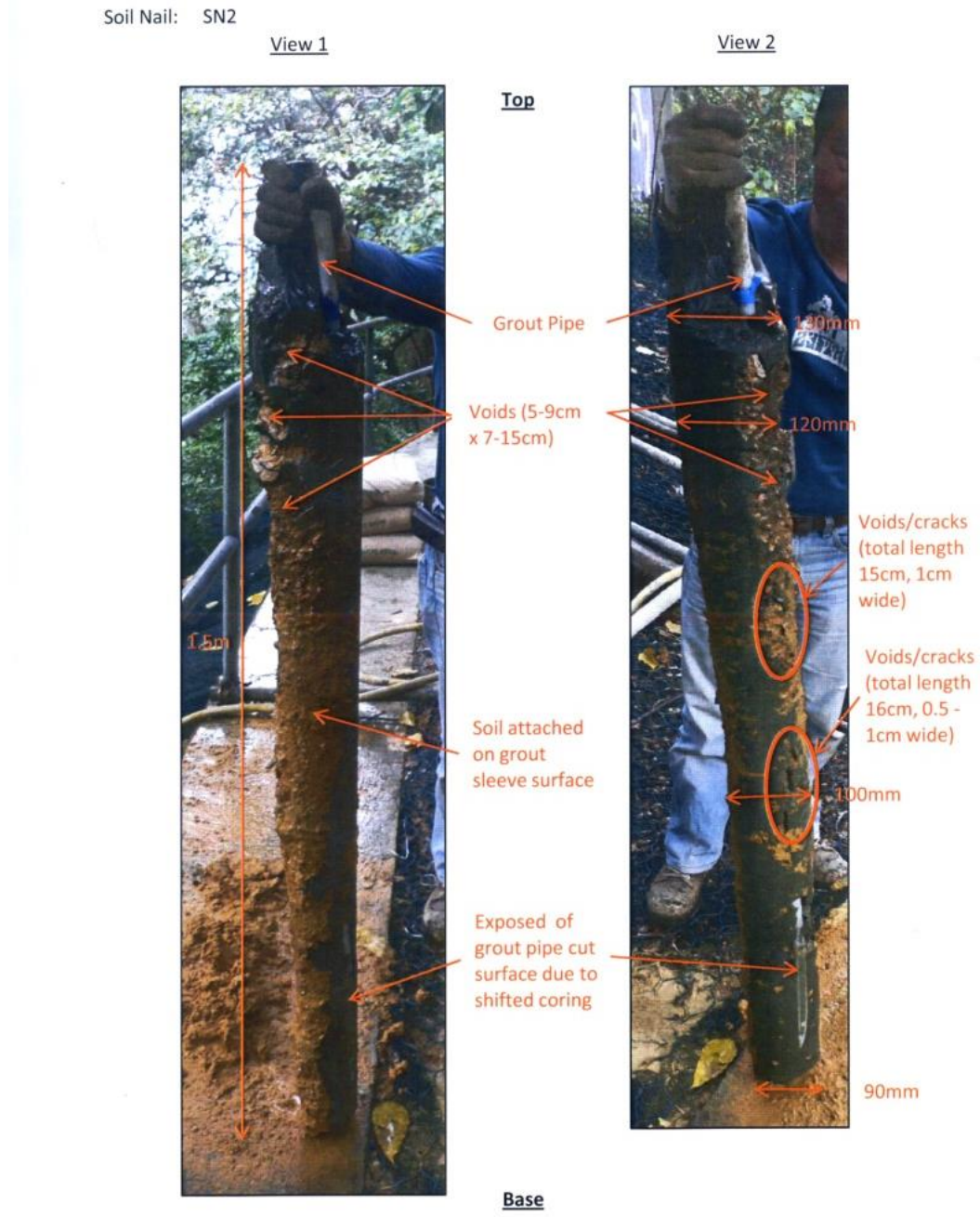
(f) The results of the tensile tests showed that the yield stress of the six exhumed soil nails with grout sleeve was about 15% greater than their characteristic strength of 460 MPa. The allowable tensile strength of the steel bars was considered not affected by their corrosion condition.

More photos showing the conditions of the grout sleeves and surface corrosion of soil nails are documented in AECOM (2012).



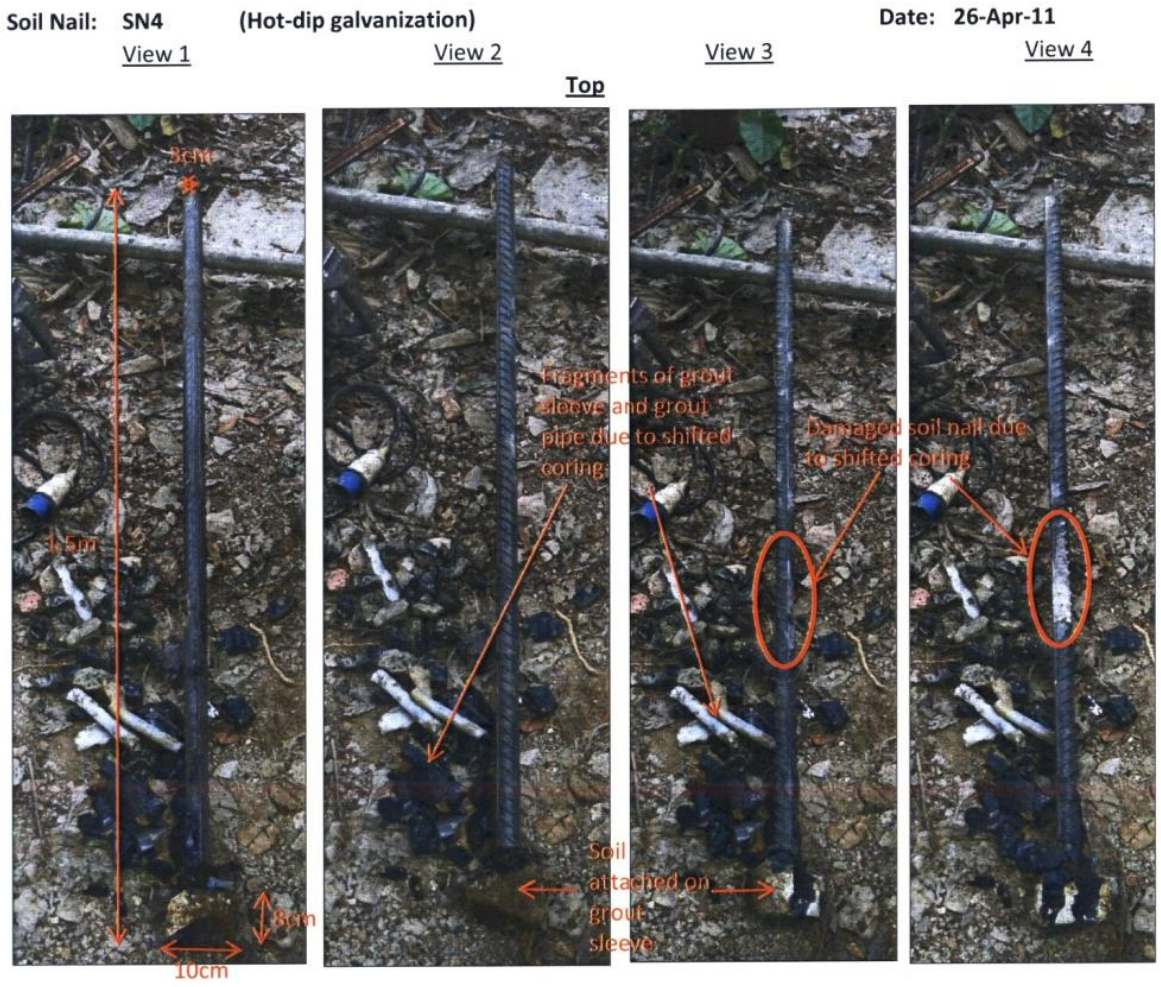
Sacrificial soil nail SB1 from the Hang Hau Road site

Figure 4.2 Example of Sacrificial Soil Nails with Extensive Surface Corrosion in Exhumation Exercise in 2011



Sacrificial soil nail SN2 from the Belcher's Street site

Figure 4.3 Example of Voids and Cracks on Grout Sleeves in Exhumation Exercise in 2011



Sacrificial soil nail SN4 from the Hang Hau Road site

Figure 4.4 Example of Completely Crushed Grout Sleeves in Exhumation Exercise in 2011

Sacrificial soil nail SN2 from the Belcher's Street site

Plate No.2

Plate No.3

Plate No.4

Plate No.5

Figure 4.5 Example of Surface Conditions of Hot-dip Galvanized Soil Nails with Grout Sleeves in Exhumation Exercise in 2011

Plate No.2

Plate No.3

Sacrificial soil nail SN9 from the Belcher's Street site

Plate No.4

Figure 4.6 Example of Surface Conditions of Couplers in Exhumation Exercise in 2011

4.4 Exhumation Exercise in 2013

Exhumation of a total of 13 sacrificial soil nails was carried out for Slope No. 11NE-D/C520 at Po Lam Road, Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road in August/September 2013 after 9 years of completion of their installations (see Table 3.2 for soil nail IDs).

Six of the 13 exhumed soil nails were installed without grout sleeve and all were at the Po Lam Road site (i.e. SB1, SB5, SB9, SB11, SB13 and SB16). The remaining seven exhumed soil nails were installed with grout sleeve (i.e. SN1, SN4, SN7 and SN9 at the Po Lam Road site; SN1, SN6 and SN11 at the Plantation Road site). Two soil nails (SN7 at the Po Lam Road site and SN11 at the Plantation Road site) were installed with couplers.

Fugro Scott Wilson Joint Venture (FSWJV), the Landslide Investigation Consultant under Agreement No. CE 12/2011 (GE), was responsible for undertaking the exhumation exercise. The tasks under the exercise included:

(a) fieldworks on soil nail exhumation;

(b) laboratory tests on soil including classification tests, chemical tests and resistivity/redox potential tests for assessment of soil aggressivity;

(c) laboratory tests on exhumed nails including carbonation test, zinc coating measurement and tensile test;

(d) visual inspection/examination of nails;

(e) review of laboratory test results and findings from examination; and

(f) preparation of the review report.

FSWJV (2014) gives the details of the fieldworks and laboratory testing, such as the methodology of exhumation, fieldwork sequence, laboratory testing schedule, key aspects for visual inspection, testing results and observations. Key findings are summarized below:

(a) According to the laboratory test results on soil aggressivity, both sites were classified as “aggressive” in accordance with Table 4.1 of Geoguide 7 (GEO, 2008). For the Po Lam Road site, the classification remained unchange. For the Plantation Road site, results of the latest aggressivity assessment indicated that the overall mark of soil was -5, which is slightly higher than the initial mark of -4 determined in 2004. The classification was shifted from “mildly aggressive” to “aggressive”. Given that there is only slightly difference in the overall mark and that further aggressivity assessments would be carried out in future exhumation exercises, the original classification “mildly aggressive” has been adopted in this interim review.

(b) Out of the six exhumed soil nails that were in direct contact with the ground (i.e. SB1, SB5, SB9, SB11, SB13 and SB16 at the Po Lam Road site), four were protected with either hot-dip galvanization (i.e. SB9 and SB11) or epoxy coating (i.e. SB13 and SB16). The soil nails with hot-dip galvanization showed no significant signs of corrosion (Figure 4.7). For the two soil nails protected with epoxy coating, no signs of damage of the protective coating were observed (Figure 4.8). The remaining two plain steel samples (i.e. SB1 and SB5) displayed extensive surface corrosion. Pitting corrosion was spotted at one single location (measured 2 mm in depth) on one of the two plain steel bars (Figure 4.9). The estimated rate of pitting corrosion of the soil nail at the "aggressive" site is about 0.25 mm/year (i.e. 2 mm depth of possible pitting corrosion after 8 years of the nail installation), which is in order of the similar assessment for Hong Kong conditions (Shiu & Cheung, 2003).

(c) The seven exhumed soil nails with grout sleeve (i.e. SN1, SN4, SN7 and SN9 at the Po Lam Road site; SN1, SN6 and SN11 at the Plantation Road site) were all protected with either hot-dip galvanization (SN1, SN4, SN7 at the Po Lam Road site and SN1, SN6 at the Plantation Road site) or epoxy coating (SN9 at the Po Lam Road site and SN11 at the Plantation Road site). Out of the seven soil nails, six were exhumed with the grout sleeves fully or partially preserved (i.e. SN4, SN7 and SN9 at the Po Lam Road site; SN1, SN6 and SN11 at the Plantation Road site). Different extent of defects, in terms of voiding and cracking of the grout sleeves, were identified on the grout covers of these six nails (Figure 4.10), possibly due to poor workmanship during grouting. The grout cover of one soil nail (i.e. SN1 at Po Lam Road site) was completely crushed during coring (Figure 4.11).

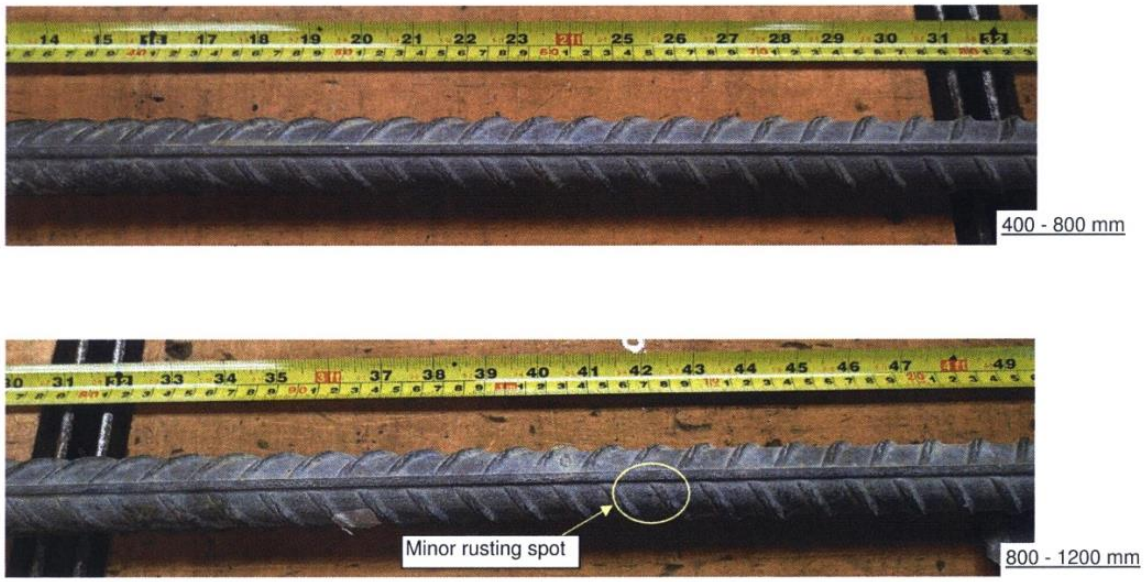
(d) One sample of grout sleeve was collated from each of the six exhumed soil nails with the grout sleeves preserved for carbonation tests. According to the laboratory results, none of the six samples showed sign of carbonation. The zinc coating thickness of the five hot-dip galvanized steel bars with grout sleeve were also greater than 85 μm for a minimum zinc coating weight of 610 g/m^2 (HKSARG, 2006). All the seven soil nails with grout protection showed no significant signs of corrosion (Figure 4.12).

(e) For the two nails with provisions of couplers (i.e. SN7 (zinc-galvanized, grout-protected) at the Po Lam Road site and SN11 (epoxy-coated, grout-protected) at the Plantation Road site), mild surface corrosion was observed on the exposed threaded sections of the nail bars, while no major sign of corrosion were noted on the zinc-galvanised nail bars or

couplers (Figure 4.13).

(f) For each of the 11 exhumed soil nails without couplers, the results of the tensile tests showed that the yield stress was about 12% greater than its characteristic strength of 460 MPa. The yield stress of the two rusty plain steel bars was comparable to that of the other steel bars with either hot-dip galvanization or epoxy coating. The allowable tensile strength of the steel bars was considered not affected by their corrosion condition.

More photos showing the conditions of the grout sleeves and surface corrosion of soil nails are documented in FSWJV (2014).

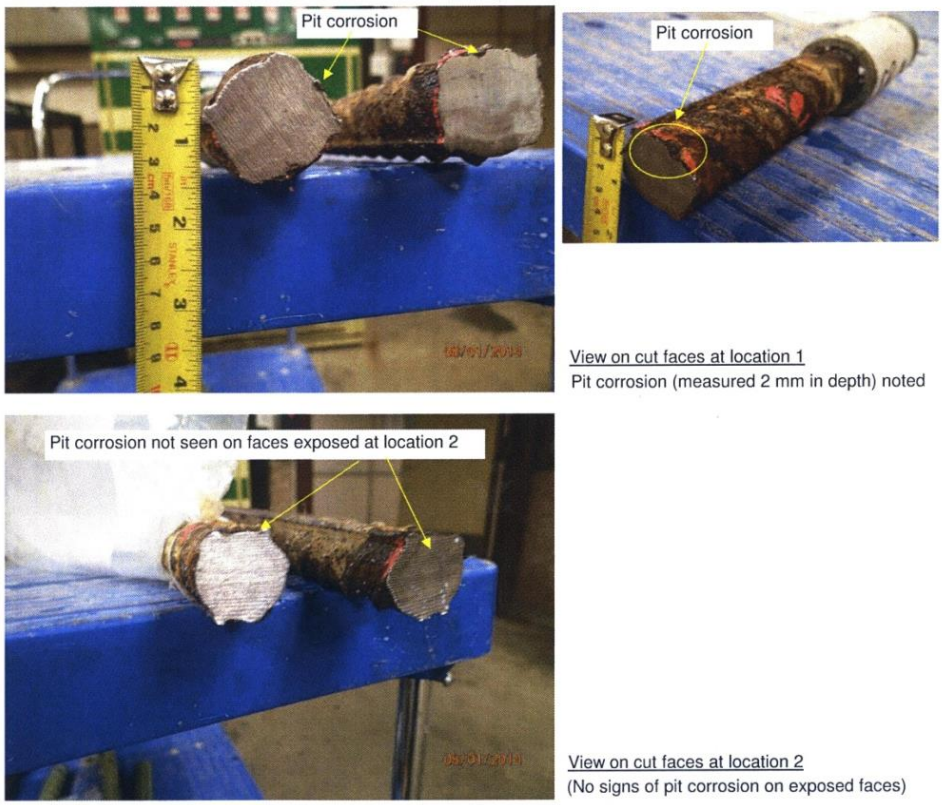


Sacrifical soil nail SB9 from the Po Lam Road site

Figure 4.7 Example of Sacrificial Hop-dip Galvanized Soil Nails with No Significant Signs of Surface Corrosion in Exhumation Exercise in 2013

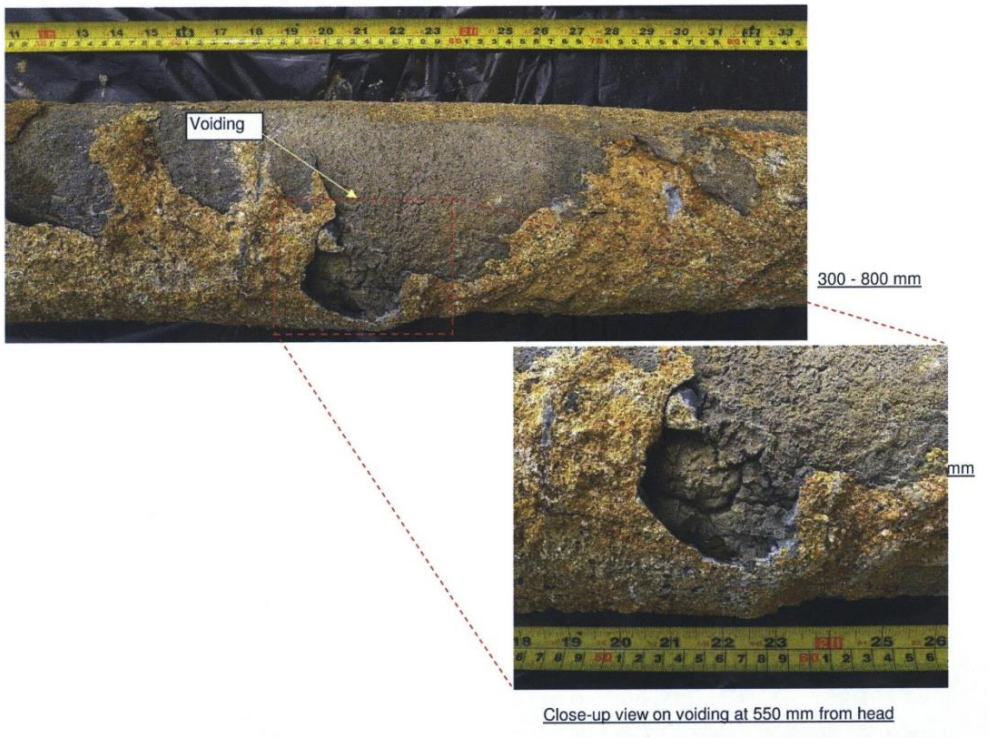
Sacrificial soil nail SB16 from the Po Lam Road site

Figure 4.8 Example of Sacrificial Epoxy Coated Soil Nails with No Signs of Damage of Protective Coating in Exhumation Exercise in 2013



Sacrificial soil nail SB1 from the Po Lam Road site

Figure 4.9 Example of Pitting Corrosion on Soil Nails in Exhumation Exercise in 2013



Sacrificial soil nail SN11 from the Plantation Road site

Figure 4.10 Example of Voids and Cracks on Grout Sleeve in Exhumation Exercise in 2013

Sacrificial soil nail SN1 from the Po Lam Road site

Figure 4.11 Example of Completely Crushed Grout Sleeve in Exhumation Exercise in 2013

Sacrificial soil nail SN6 from the Plantation Road site

Figure 4.12 Example of Surface Conditions of Hot-dip Galvanized Soil Nails with Grout Sleeve in Exhumation Exercise in 2013

Sacrificial soil nail SN7 from the Po Lam Road site

Figure 4.13 Example of Surface Conditions of Couplers in Exhumation Exercise in 2013

5 Discussions and Recommendations

5.1 Corrugated Sheathing

Five different types of corrosion protection provisions used for steel soil nails (viz. cement grout, sacrificial steel, sacrificial metallic coating, non-metallic coating and corrugated plastic sheath) were examined in the study by Shiu & Cheung (2003). With the use of corrugated sheathing, "triple" corrosion protection is provided to steel bar (i.e. hot-dip galvanizing, cement grout and corrugated sheathing). Such high protection level should be adequate for soil nails with a design life of 120 years even in highly aggressive soil condition. It is therefore not included in the long-term monitoring programme. For the other protection methods, the effectiveness of protection will deteriorate with time (e.g. hot-dip galvanizing, cement grout and other metallic coatings), or the protection system will break down completely if the non-metallic protection layer (e.g. epoxy grout) is slightly damaged. One of the main objectives of the monitoring programme is to collect long-term data on the performance of these time-dependent protection methods.

5.2 Fieldwork Operations

Coring was employed for the exhumation of the soil nails. Some difficulties were encountered during the course of the exhumation works which affected those nails with grout sleeve. As a result, the grout sleeve of some soil nails were completely/partially damaged. The difficulties were diagnosed to have primarily related to hard ground materials encountered, coupled with inefficient equipments and/or insecure support of the drilling rig during coring. To overcome such difficulties, it is essential to verify the ground materials in which the nails are embedded and to ensure a stable and efficient coring. It is recommended that a trial core should be carried out before the exhumation of soil nails at each of the nail exhumation sites, or adjacent to any nail location in which the nature of the ground materials is in doubt, to test the suitability of the coring equipment deployed and the adequacy of support for the coring rig at such ground conditions.

5.3 Measurement of Thickness of Zinc Coating

The weight and length of the 16 hot-dip galvanized soil nails before and after coating were measured prior to their installation on site in 2004. A summary of the measurement is presented in Table 5.1. The initial coating thickness of each hot-dip galvanized soil nail may be derived based on its weight per unit length before and after coating, cross-sectional area and nominal density of the coating. The nominal density of the zinc coating is 7.2 g/cm^3 in accordance with BS EN ISO 1461 (BSI, 2009). The calculated initial coating thickness of the soil nails is given in Table 5.1. Their corresponding zinc coating thickness after exhumation in 2011 and 2013 respectively was measured using the magnetic method in accordance with BS EN ISO 2178 (BSI, 1995a) in the laboratory and their values are also presented in Table 5.1.

It is noted that based on the results of the measurements using the magnetic method, there is in general an increase in the coating thickness, which is impossible. The discrepancy may be due to the use of different methods in making the measurements. The calculated and

measured thicknesses in Table 5.1 should not be compared directly.

The magnetic method in accordance with BS EN ISO 2178 (BSI, 1995a) has its own limitations. It is highlighted that the magnetic method is "most appropriate within works and for routine quality control. Because the area on which each measurement is made in the method is very small, individual figures may be lower than the values for the local or mean coating thickness. If a sufficient number of measurements is made within a reference area, effectively the same local thickness will be determined by magnetic as well as gravimetric methods".

The gravimetric method is given in BS EN ISO 1460 (BSI, 1995b). It is considered more robust and scientific, and is therefore recommended for use in future exhumation exercises to measure the zinc coating thickness of the exhumed soil nails, together with the magnetic method.

Table 5.1 Measurement of Zinc Coating

Site	Soil Nail ID	Corrosion Protection(1)	Before Coating		After Coating		Calculated Thickness(2) (μm)	Mean Measured Thickness(3) (μm)
			Weight (kg)	Length (m)	Weight (kg)	Length (m)		
Slope No. 12NW-C/C82 at Hang Hau Road	SN1	Z, G	9.572	1.498	9.698	1.500	116	236
	SN7	Z, G	10.096	1.501	10.222	1.501	115	288
Slope No. 11SW-A/CR595 (sub-division 1) at Belcher's Street	SN2	Z, G	9.557	1.502	9.673	1.503	106	257
	SN4	Z, G	9.532	1.497	9.644	1.498	103	262
	SN7	Z, G	10.030	1.491	10.162	1.494	122	224
Slope No. 11SW-C/FR83 (sub-division 3) and Slope No. 11SW-C/C839 at Plantation Road	SN1	Z, G	9.660	1.501	9.783	1.501	112	189
	SN6	Z, G	9.573	1.502	9.696	1.502	112	186
Slope No. 11NE-D/C520 at Po Lam Road	SB9	Z	9.504	1.502	9.634	1.503	119	183
	SB11	Z	9.416	1.496	9.509	1.500	86	183
	SN1	Z, G	9.480	1.491	9.589	1.493	101	171
	SN4	Z, G	9.518	1.490	9.647	1.490	119	183
	SN7	Z, G	10.185	1.504	10.306	1.505	111	180

Notes:
(1) Z denotes hot-dip galvanized soil nails and G denotes 100 mm diameter grout sleeve.
(2) This is the thickness calculated based on its weight per unit length before and after coating, cross-sectional area and nominal density of the coating.
(3) This is the mean thickness measured using the magnetic method in accordance with BS EN ISO 2178 (BSI, 1995a) in the laboratory.

6 Conclusions

In general, no significant corrosion was observed in all the exhumed soil nails with different corrosion protection provisions. Monitoring of corrosion of the sacrificial soil nails installed at the five sites will be continued according to the monitoring schedule.

7 References

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