LONG-TERM DURABILITY OF STEEL SOIL NAILS

GEO REPORT No. 135

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THE GOVERNMENT OF THE HONG KONG

SPECIAL ADMINISTRATIVE REGION

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PREFACE

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R.K.S. Chan
Head, Geotechnical Engineering Office
June 2003

FOREWORD

This Report presents the results of a study on the long-term durability of steel soil nails. It supersedes Special Project Report No. SPR 4/2001.

In this study, a review of relevant literature on corrosion protection for steel soil nails has been carried out. A survey of the relevant properties of the Hong Kong soils tested and an assessment of the corrosion potential of these soils have been conducted. The corrosivity assessment is based on the methods given in guidance documents from France, the UK and the USA.

This study was carried out by Mr Y.K. Shiu and Mr W.M. Cheung of the Special Projects Division, with much of the data collection performed by the technical officer Mr K.C. Chan and the HKUST summer student Miss P.Y. Tai. A number of colleagues have provided useful comments on a draft version of this Report. All contributions are gratefully acknowledged.

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ABSTRACT

Steel soil nails are used extensively for slope improvement works in Hong Kong. A study has been carried out to review the effectiveness and reliability of the current corrosion protection provisions with regard to the long-term durability of steel soil nails.

The study comprises a review of relevant literature on corrosion of steel in soils and technical guidance documents from France, the UK and the USA. Based on this review and a survey of properties which reflect the corrosion potential of soils, it is found that a significant portion of the local soils tested could have a relatively high corrosion potential. However, the data available are fairly limited and only provide a general indication of the potential corrosivity of the soils tested. The corrosivity of a site depends highly on the site-specific conditions. 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) have been examined. Two case studies on corrosion of steel soil nails (one in Japan and the other in Hong Kong) have also been reviewed.

It is concluded that at present there is not enough information to determine accurately the corrosion rates of steel and zinc coating in soils of different aggressivities.

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1. INTRODUCTION

Corrosion protection is a very important aspect of soil nailing because the long-term performance of the soil nails depends on their ability to withstand corrosion attack from the surrounding soils.

The objective of this study is to review the effectiveness and reliability of the current corrosion protection provisions with regard to the long-term durability of steel soil nails. The study includes a review of relevant literature on corrosion protection provisions for steel soil nails and a survey of the properties which reflect the corrosion potential of the soils in Hong Kong in which steel nails are commonly embedded.

2. PRINCIPLES OF CORROSION

2.1 General

Corrosion of steel is primarily an electrochemical process. For it to occur there must be a 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.

Corrosion occurs at the reactive anode areas and the non-reactive cathode areas on the steel surface. The processes involved are illustrated by the following equations and in Figure 1.

At anode $$Fe \rightarrow Fe^{++} + 2e$$
$$Fe^{++} \rightarrow Fe^{+++} + e$$
At cathode $$O_2 + 2H_2O + 4e \rightarrow 4OH^-$$
Combined reaction $$4\,Fe + 3O_2 + 2\,H_2O \rightarrow 2Fe_2O_3 \cdot H_2O \text{ (Rust)}$$

In other words, oxygen and water have to be present simultaneously in order for steel to corrode. Corrosion can also occur due to attack by deleterious substances present in the soils. For example, steel is corroded rapidly by hydrochloric acid:

$$Fe + 2HCl \rightarrow FeCl_2 + H_2$$

2.2 Factors Affecting Corrosion Rate

The corrosivity 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 chemical 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 chemical characteristics are those that determine the ability of the soil to act as an electrolyte for the development of local corrosion cells. They include alkalinity, acidity, concentrations of oxygen and dissolved salts, and organic matter and bacteria content. These factors affect electrical resistance, which is accepted as an important parameter for measuring corrosivity of a soil (Eyre & Lewis, 1987; Fontana, 1987; King, 1977). Stray current, where present, can also influence the corrosion rate.

The factors affecting the corrosivity of soils are further discussed in Appendix A.

3. SOIL CORROSIVITY CLASSIFICATION SCHEMES

3.1 General

Different schemes are used in different parts of the world for classifying the corrosivity of soils. Each scheme emphasizes a slightly different combination of the factors discussed in Section 2.2 above and critical values are assigned to the factors. The soils are classified to be “aggressive” or “non-aggressive” according to the actual values being above or below these critical values.

In Hong Kong, a scheme is used to determine the suitability of fill materials for use in reinforced fill structures (GEO, 1989). There is no classification system for *insitu* soils for soil nailing works. The classification schemes in common use in France, the United Kingdom and the United States are outlined below.

3.2 Classification Scheme Used in the United Kingdom

In the context of soil nailing, Murray (1993) classifies soils into the following four categories of condition:

(a) unlikely to be 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 most of the factors that affect corrosion rate. Ranking marks are used in the classification. The overall classification is determined from the sum of pertinent contributing factors, viz. soil composition, soil resistivity, moisture content, pH value, soluble salt content, etc. Details of the soil corrosivity assessment are given in Section B.1 of Appendix B.

3.3 Classification Scheme Used in France

Recommendations Clouterre of the French National Research Project (1991) classifies soils into four categories of corrosivity:

(a) highly corrosive;

(b) corrosive;

(c) average corrosiveness; and

(d) slightly corrosive.

The corrosivity assessment 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. Details of the assessment are given in Section B.2 of Appendix B.

3.4 Classification Scheme Used in the United States of America (USA)

As recommended in Byrne et al (1998), critical values are assigned to four factors, viz. soil resistivity, pH value, concentration of sulphate and concentration of chloride. If the actual soil property values fall below or above any one of these critical values, the soil is classified as “aggressive”. Otherwise, the soil is regarded as “non-aggressive”. Details of the assessment are contained in Section B.3 of Appendix B.

4. CORROSION RATES

A comprehensive source of information on underground corrosion is the results of the extensive field exhumation and testing on metal pipes and sheet steel carried out by the US National Bureau of Standards (NBS), in study programmes originating as early as 1910 (Romanoff, 1957). Results of the studies are widely reported in literature relating to corrosion of metals in soil (Elias & Juran, 1991; Elias, 1997; Fontana, 1987; King, 1977; McKittrick, 1978; Zhang, 1996). The NBS started a 10-year programme in 1924, in which specimens were buried in 47 types of soil with resistivity ranging from 60 ohm-cm to 45,100 ohm-cm and pH values from 3.1 to 9.5. The specimens were exposed ten years after burial. The average corrosion rates of hot dip galvanized (zinc) coatings in most soils were found to be below 10 μm per year. The test results also indicated that in most soils, zinc coatings of 85 μm or less were completely destroyed, whereas for 130 μm zinc coatings, some of the coating remained on the steel for at least half of the specimens examined. Table 1 shows the results obtained in the NBS investigation.

In 1937, the NBS conducted another test programme, using 38 mm steel pipe specimens which were either bare or galvanized with a nominal 130 μm zinc coating. The specimens were buried in 15 soils of different characteristics. The specimens were subsequently exposed at time periods ranging from 4 to 11.2 years after the burial. The results of the weight loss and maximum pit depths for the specimens tested are shown in Table 2. The maximum pitting rates for galvanized steel and bare steel can be up to 5 times and 13 times of those of the surface average corrosion rates respectively. The test programmes concluded that the life of galvanized steel buried in soil would be greatly dependent on the nature of the soil. A nominal 85 μm zinc coating would provide protection for at least 10 years in inorganic oxidizing soils. A 130 μm coating appeared to be adequate (for 10-13 years) in most inorganic reducing soils but would not afford sufficient protection in highly reducing organic or inorganic soils.

The NBS test data indicate that the rate of corrosion of both steel and zinc decreases with time. There is a rather rapid loss in the first two years for both bare and galvanized steels followed by a progressive decrease in the rate of corrosion. 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 United Kingdom. From the NBS test data, the average loss of thickness for steel as a function of time can be predicted by the following equation (Romanoff, 1957).

$$X = Kt^{n} \quad \text{.......................................} (1)$$

where t is time in years, X is the depth of general corrosion or pit depth in μm at time t and K and n are constants that depend on the soil and site characteristics (n is always less than 1.0).

For low carbon steels in a number of soil burial conditions, NBS established a “n” constant varying from 0.5 to 0.6 and “K” constants between 150 and 180 μm (Elias, 1997). For galvanised steels, “K” constants in the range between 5 and 70 μm can be inferred but “n” constants were not evaluated.

Results of container tests and electrochemical tests reported by Darbin et al (1988) indicate that for the range of soil fill utilised in reinforced soil structures in France, the constant “n” may be taken as 0.6 for galvanised steel while the zinc coating is still present, and from 0.65 to 1 for carbon steel once significant corrosion occurs. The constant K calculated at the end of the first year for galvanised steel was found to vary between 3 and 50, with the higher values consistent with more aggressive soils characterized by lower resistivities and higher concentrations of chlorides and sulphates. Figures 2 and 3 show the log-log plots of the test data of metal loss versus time for these tests.

From the NBS corrosion test results, Elias (1997) suggested the following equations for determining corrosion loss of galvanized steel using the uniform model concept:

$$X = 25t^{0.65} \quad \text{(Average) ....} (2)$$

$$X = 50t^{0.65} \quad \text{(Maximum) ....} (3)$$

and the following equations for corrosion loss of carbon steel:

$$X = 40t^{0.80} \quad \text{(Average) ....} (4)$$

$$X = 80t^{0.80} \quad \text{(Maximum) ....} (5)$$

For reinforced fill structures with selected backfills that meet the stringent electrochemical requirements, Elias (1997) has proposed that the maximum loss per side due to corrosion may be computed by assuming the following loss rates:

Zinc corrosion rate for the first two years	15 μm/yr
Zinc corrosion to depletion	4 μm/yr

Carbon steel loss rate 12 μm/yr

In the UK, the corrosion allowances for corrugated steel buried structures are specified in Department of Transport (1988). The assumed corrosion rates for buried structures are given in Table 3. They are smaller than those rates given in equations (2) to (5). It is worth noting that the assumed rates were established for uniform corrosion conditions with no allowances for pitting. Corrosion does not normally occur in a uniform manner. Loss of cross-sectional area will be greater where significant pitting or greater localised corrosion occurs than a loss computed by distributing corrosion losses uniformly over an element (Elias, 1997). 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. Brady et al (1999) pointed out that it would be misleading to express the rate of corrosion in terms of the mean reduction in thickness when pitting is prevalent. The NBS data also suggest that pitting depths could be significantly deeper than depths due to uniform loss. According to King (1977), test data from the UK could infer maximum pit depth of steel of 5.8 mm in 20 years.

A study by the Swedish Corrosion Institute (Camitz & Vinka, 1989) included field test on carbon steel and steel coated with zinc and an alluminium-zinc alloy. Specimens were placed in different types of soils in Sweden, above and below the groundwater table, for up to four years. The results of the study are reproduced in Figure 4. The results suggest that corrosion rate for both the carbon steel and the zinc-coated steel is in general higher in soils of low pH values. Also, the corrosion of carbon steel and zinc coatings is lower in sands and higher in clays. The corrosion rate on carbon steel specimens is higher above the groundwater table than below, whereas for zinc coatings the groundwater table has no distinct effect on corrosion rate. In addition, the corrosion rate was lower on specimens embedded in a homogeneous sand fill than specimens buried directly in the *insitu* soils.

The corrosion rate of buried galvanized steel varies greatly among different types of soil. According to ZALAS (1989), the performance of galvanized steel elements is best in alkaline and oxidising soils, where a 600 g/m^2 zinc coating will, in general, give an additional life of about 10 years to pipes. Highly reducing soil is the most aggressive and may consume a zinc coating at more than 13 μm per year. Unprotected galvanized coatings should not be used in environment with a pH of less than 6 or greater than 12.5 (ZALAS, 1989). Within the range of pH 6 to 12.5, the corrosion rate of zinc is relatively low since a stable protective film is formed on the zinc surface. Figure 5 shows the relationship between corrosion rate and acidity of soil.

5. CORROSION PROTECTION METHODS

5.1 Corrosion Protection Options

5.1.1 General

There are a number of options for providing different degrees and modes of corrosion protection to steel bars used in soil nails. They include the provision of:

(a) cement grout;

(b) sacrificial thickness to the steel;

(c) sacrificial metallic coating on the steel (e.g. hot dip galvanising);

(d) non-metallic coating on the steel (e.g. epoxy); and

(e) corrugated plastic sheath.

Depending on the situation, one or a combination of the above options are adopted.

5.1.2 Corrosion Protection by Provision of Cement Grout

Cement grout can prevent corrosion by forming a physical barrier and a chemical barrier. The physical barrier separates the steel from the surrounding soil. The chemical protection function of the grout is its alkalinity and the property of steel to form a tight oxide film on its surface in an alkaline environment. However, as the cement grout is subject to tensile stresses when the steel bar is under load, micro-cracks will occur. Also, shrinkage cracks may form during the setting of the cement grout. The cracks can break the physical and chemical barriers provided by the cement grout by allowing water, oxygen and other corrosion promoting agents to come into contact with the steel. There is no rational basis for predicting the rate of corrosion under such conditions. Furthermore, it is very difficult to check the quality of the grout in the ground: drillhole collapses (e.g. in loose ground or in areas with groundwater flow) before the grout sets can cause problems. The excavation works at a re-development site on the Hong Kong Island revealed that the grout cover could be as low as 5 mm (see Plate 1) even though the drillhole was greater than 100 mm in diameter. It is widely accepted although a rather conservative approach that for permanent soil nails, the grout is assumed to offer no protection and the corrosion rate is the same as that for the steel installed directly in the ground (French National Research Project, 1991; Mitchell & Villet, 1987).

5.1.3 Corrosion Protection by Provision of Sacrificial Steel Thickness

This 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, it may slow down the rate of corrosion by changing the kinetics of the chemical reactions.

5.1.4 Corrosion Protection by Provision of Metallic Coating

Zinc is the most common type of metal used to provide corrosion protection to steel soil nails. The zinc coating is often applied by the hot dip galvanizing process.

The galvanized zinc coating is strongly resistant to most corrosive environments. The rate of corrosion of zinc lies between 1/17 (in rural atmospheres) and 1/80 (in marine atmospheres) to that of steel (Hadley & Yeomans, 1990; ZALAS, 1985).

Hot dip galvanizing offers the following two types of protection to steel:

Barrier protection - the metallic zinc forms a corrosion resistant coating around the steel reinforcement to isolate the steel from the environment.

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. Where there is damage or minor discontinuity in the zinc coating, protection of the steel can still be maintained by the cathodic action of the surrounding galvanized coating.

The protective life of a zinc coating is roughly proportional to the mass of zinc per unit of surface area. As discussed in Section 4, depending on the aggressivity of the soil, a nominal 85 µm (610 g/m^2) coating would provide protection for 6 and 21 years in "aggressive" and "non-aggressive" soils respectively (Murray, 1993).

5.1.5 Corrosion Protection by Provision of Non-metallic Coating

Non-metallic coatings in the form of fusion-bonded epoxy have been used in the USA to protect the 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 also necessary to ensure a complete continuity of the coating. Problems have been encountered in epoxy-coated steel where severe corrosion of the steel bars has occurred due to ingress of water and oxygen through cracks in the epoxy.

5.1.6 Corrosion Protection by Provision of Corrugated Plastic Sheath

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 steel bar can be grouted in the plastic sheath in the drillhole on site or it can be factory grouted into the sheath which is then grouted on site into the drillhole.

The inclusion of the sheath prevents ingress of water or corrosive substances if cracking of the grout occurs.

Recently, a corrosion protection method employing double-corrugated sheaths has been developed. In this method, the steel bar is encased in two concentric corrugated plastic sheaths with the core and the annulus space fully grouted with cement (Barley, 1992).

Both the single-sheath and the double-sheath systems correspond with the corrosion protection systems for permanent prestressed ground anchors specified in the EN 1537:1999.

5.2 Corrosion Protection Methods Used in Hong Kong, UK, France and USA

5.2.1 General

In the following Sections, the corrosion protection approaches used in Hong Kong, UK, France and USA are described. Except that in Hong Kong, each of these approaches considers the corrosivity of the ground and the design life of the nailed structure, and uses one or a combination of the above protection options.

5.2.2 Corrosion Protection Method Used in Hong Kong

There are no specified standards for corrosion protection of soil nails in Hong Kong. For temporary soil nails, corrosion protection is usually provided solely by the cement grout. For permanent applications, the common practice is to increase the degree of protection by providing a zinc coating (in the form of hot dip galvanizing) to the steel bars with a provision of a 2 mm sacrificial thickness on the radius of the steel bar. For the Landslip Preventive Measures (LPM) works, the required weight of zinc coating on the steel bars is 610 g/m^2 (approximately 85 μm thick). On some occasions, a higher degree of protection has been provided in that the steel bar is surrounded by cement grout which in turn is surrounded by a corrugated plastic sheath grouted in the drillhole.

A mechanical coupler is used to couple two steel bars in situations where space is limited and short bars are required to be used. This requires forming threads at the bar ends and as a result removing the zinc coating along the threaded lengths. Zinc-rich paint is usually applied on the threads for corrosion protection purposes.

5.2.3 Corrosion Protection Method Used in the UK

The code of practice for strengthened/reinforced soil and other fills (BS 8006:1995) provides little guidance on corrosion protection for soil nails. It indicates that "Nails protected in accordance with the recommendations for corrosion protection in BS 8081 may require less or no corrosion protection". BS 8081, which deals with the construction of ground anchorages, has now been superseded by EN 1537:1999.

An approach for dealing with corrosion is given by Murray (1993) of the Transport Research Laboratory. In this approach, the corrosion allowances for the nailed structures vary according to the aggressivity of the soil and are a function of design life. The rates of loss of galvanizing for soils of different aggressivity are given in Table 4. The loss rates are based on the standard given in Department of Transport (1988) for buried corrugated culverts.

A plot of the required sacrificial thickness of steel against service life for "non-aggressive", "mildly aggressive" and "aggressive" soils is shown in Figure 6. These corrosion allowances generally correspond to the uniform corrosion rates on the steel surface given by Romanoff (1957). Similar remark has also been made by Johnson & Card (1998) of the Transport Research Laboratory. No corrosion allowances are given for "highly aggressive” soils because construction of permanent nailed structures in this soil type is not recommended.

Apart from providing galvanizing 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.

5.2.4 Corrosion Protection Method Used in France

The recommended corrosion prevention measures are given in French National Research Project (1991). These measures vary according to the corrosivity of the soil and the design life of the nails. They mainly involve the provision of sacrificial steel thickness or plastic sheath. If zinc galvanizing is provided, its corrosion protection effect is ignored. 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 requirements for corrosion protection depend on the overall corrosivity index (I) of the soil/site, and the type and design life of the nailed structure, as shown in Table 5. This overall corrosivity index is the sum of the corrosiveness index ΣA, and the index C, where C depends on the type of soil nailed structures (for example, $C = 0$ for non-critical structures whereas $C \geq 2$ for critical structures, in terms of failure consequence).

5.2.5 Corrosion Protection Method Used in the USA

Guidelines on corrosion protection of soil nails are given by Byrne et al (1998) of the US Department of Transportation. Apart from ground conditions that are not suitable for soil nailing (e.g. loose clean granular soils with field standard penetration test N values lower than about 10, soils with a relative density of less than about 30%, organic soils, etc), the requirements for corrosion protection depend on the design life of the nailed structures and the aggressivity of the soil. Table 6 shows the details of these requirements. Zinc galvanization is not a standard corrosion protection method for soil nails.

6. SOIL DATABASE

6.1 Content of Database

Part of this study is to establish a database on the physical and electrochemical properties of the soils in Hong Kong, and thereby gain a general appreciation of the corrosion potential of the soils. The database set up contains information on the specimen location, soil type, soil composition, Atterberg Limits, moisture content, resistivity, pH value and contents of soluble salts and organic matter. These data are mainly retrieved from the reports of laboratory tests and ground investigations carried out under the GEO’s term contracts during the period 1993 to 1998. They also include some recent laboratory tests done on soils taken from LPM sites. Test data obtained from marine investigations are excluded from the database.

In the database, there are a total of 169 sets of test results on soil specimens taken from

42 sites. The locations of the sites are shown in Figure 7. The test data cover five different types of soils including completely decomposed granite (CDG), completely decomposed volcanics (CDV), completely decomposed dacite (CDD), colluvium of unknown origin (COL) and alluvium (ALL). Among the 169 sets of test results, only 93 sets have adequate information for determining the corrosivity of the soils. They are the test data on CDG (59 sets) and CDV (34 sets). Therefore, the soil corrosivity study has been confined to CDG and CDV. The test data are kept in file GCSP 2/D11/2-2 in the Special Projects Division. The database provides an indication of the general corrosivity of CDG and CDV, which are the most common soil types encountered in soil nailing works in Hong Kong.

A review of the test data has been conducted. Results of the review are presented and discussed below, along with comments on the relevance and limitations of the test data.

6.2 Silt and Clay Content

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 Figure 8 indicate the distribution of silt and clay contents for 48 CDG and 32 CDV specimens. The average silt and clay contents of CDG and CDV are 29% and 42% respectively. These values are comparable with those reported by Lumb (1962; 1965 & 1966). The relatively higher contents of silt and clay in CDV indicate that they generally have a higher water-holding capacity than CDG.

6.3 Plasticity Index

The Atteberg limits of the soil specimens were determined using soils passing the 425 µm BS sieve. The distribution of plasticity indices for 43 CDG and 20 CDV specimens is shown in Figure 9. The average plasticity indices for these CDG and CDV soil specimens are 13% and 8% respectively. These values are comparable with those reported by Lumb (1962; 1965 & 1966).

6.4 Moisture Content

As reliable groundwater information is generally not available from the drillhole logs, moisture contents of the soil specimens are used in the corrosivity assessment. Figure 10 presents the distribution of moisture content of 50 CDG and 27 CDV soil specimens. The average moisture content of the CDG and CDV soil specimens are 22% and 23% respectively. The corrosion rate of metals is affected by the oxygen concentration (Fontana, 1987; Uhlig, 1971) and the relationship between oxygen permeation and moisture content is complex.

6.5 Organic Matter

There are only a few test results on the organic matter content: 10 on CDG and 3 on CDV. The organic matter content of these 13 samples lie between 0.03% and 0.70%. The organic matter content depends very much on specific site conditions (e.g. presence of vegetation at the base of colluvium or leaking sewers).

6.6 Soil Resistivity

The database does not contain any test results on resistivity. In view of the fact that this is an important parameter for assessing the corrosivity of a soil, values of *insitu* soil resisitivity measured at five sites in Hong Kong (Chan & Chen, 1999) are included here for reference. They are summarised in Table 7.

6.7 pH Value

Figure 11 shows the distribution of pH values of 44 CDG and 18 CDV specimens. The pH value for the CDG specimens lies between 3 and 10, with an average of 6.3. The pH value for CDV falls within 4 and 9, with an average of 6.2. Similar to the measurement of organic matter content, the pH value depends very much on the specific site conditions (e.g. presence of organic acid due to decomposition of vegetation).

6.8 Soluble Sulphates

Sulphates can exist in different forms in soil. For corrosivity assessment purposes, only the water-soluble sulphates need to be considered. There are totally 45 test results for CDG and 30 for CDV. Among these 75 (45+30) test results, 57 (76%) tests have a water-soluble sulphate content equal to or less than 200 ppm. The remaining 18 (24%) tests have an erratic range of results from greater than 200 ppm to 1,000 ppm. The concentration of sulphates depends on specific site conditions (e.g. leaking sewers).

6.9 Soluble Chloride Ions

There are 21 test results for CDG and 10 for CDV. Among these 31 (21+10) test results, 26 (84%) tests have a chloride ion content equal to or less than 100 ppm. The remaining 5 (16%) test results have a chloride ion content of greater than 100 ppm to 1,200 ppm. Similar to that for soluble sulphates, the chloride ion content also depends much on the specific site conditions.

6.10 Carbonates and Sulphides

Salts of carbonates and sulphides are reducing agents and are usually analysed qualitatively. Similar to organic matter, test results on these substances are limited. Results of only 9 tests on CDG specimens for carbonates and 8 tests on CDG specimens for sulphides are available. All the test results indicate positively the presence of carbonates or sulphides.

7. CORROSIVITY ASSESSMENT OF HONG KONG SOILS

7.1 General

Corrosivity of the CDG and CDV specimens was assessed according to the three overseas classification schemes (see Section 3 above):

(a) UK Approach

(b) French Approach

(c) US Approach

The results of the assessment, along with the corresponding corrosion protection measures required (see Section 5.2 above), are outlined below. These corrosion protection requirements are compared with the corrosion protection provisions currently used in Hong Kong for permanent soil nails.

7.2 UK Approach

7.2.1 Corrosivity Assessment

Figure 12 shows the distribution of ranking marks of 59 CDG and 34 CDV specimens according to the UK classification scheme for soil corrosivity (Eyre & Lewis, 1987). Table 8 presents the distribution of corrosivity of the soil specimens. Out of the 59 CDG specimens, 8 (14%) are classified as “non-aggressive”. The remaining 30 (51%) and 21 (35%) soil specimens are classified as “mildly aggressive” and “aggressive” respectively. For the 34 CDV specimens, one (3%) is found to be “non-aggressive”. 21 (62%) and 12 (35%) specimens are classified as “mildly aggressive” and “aggressive” respectively.

If considering the CDG and CDV together (93 specimens), 10% of them are classified as “non-aggressive”, 55% “mildly aggressive” and 35% “aggressive” (see Table 8).

7.2.2 Corrosion Protection Requirements

As described in Section 5.2.2, the corrosion allowances for steel and the rates of loss of galvanization for soils of different corrosivity are given in Figure 6 and Table 4 respectively (Murray, 1993). With the current corrosion protection provisions for permanent soil nails in Hong Kong (i.e. 610 g/m^2 (85 μm) hot dip galvanizing and 2 mm sacrificial thickness of steel), the service life of the nails, using the UK approach, would be more than 120 years for “non-aggressive” and “mildly aggressive” soils and about 95 years for “aggressive” soils. However, as mentioned in Section 4, this estimation conforms to the provision for uniform corrosion only.

7.3 French Approach

7.3.1 Corrosivity Assessment

Figure 13 shows the distribution of weightings of the same 59 CDG and 34 CDV specimens according to the French approach. Table 9 presents the distribution of corrosivity of these CDG and CDV specimens. Out of the 59 CDG specimens, 47 specimens (80%) are classified as “slightly corrosive”. The remaining 12 specimens (20%) are classified as of “average corrosiveness”. For the 34 CDV specimens, no specimen is found to be “highly corrosive” or “corrosive”. 31 (91%) and 3 (9%) specimens are classified as “slightly corrosive” and of “average corrosiveness” respectively.

If considering both the CDG and CDV together (93 specimens), 84% of them are “slightly corrosive” and 16% are of “average corrosiveness”.

7.3.2 Corrosion Protection Requirements

Following the French corrosion protection approach, for “long-term” soil nails (design life from 30 to 100 years), the protection measures are 4 mm sacrificial thickness to the steel for “slightly corrosive” soils, and 8 mm for soils of “average corrosiveness” (see Table 5). These requirements are higher than the current corrosion protection provisions used for permanent soil nails in Hong Kong (610g/m^2 hot dip galvanizing plus 2 mm sacrificial steel thickness).

7.4 US Approach

7.4.1 Corrosivity Assessment

Out of 59 CDG specimens, 20 specimens (34%) are classified as “aggressive”; whereas 39 specimens (66%) are “non-aggressive”. For the 34 CDV specimens, 13 (38%) are classified as “aggressive”. The remaining 21 specimens (62%) are “non-aggressive”.

If considering both the CDG and CDV together (93 specimens), 65% of them are “non-aggressive” and 35% are “aggressive”.

7.4.2 Corrosion Protection Requirements

For permanent soil nails (design life of 75 years for permanent structures and 100 years for embankments), the corrosion protection requirements include epoxy resin-bonded coating of a minimum of 0.3 mm to the steel bar and 25 mm grout cover for “non-aggressive” soils, and encapsulation with plastic sheath for “aggressive” soils (see Table 6). It should be noted that the latter requirement is applied to all critical structures regardless of the corrosivity of the soils. These corrosion protection requirements are higher than those being used in Hong Kong for permanent soil nails.

8. CASE STUDIES ON CORROSION OF SOIL NAILS

8.1 General

There are not many field data reported on corrosion of soil nails. Such data are potentially valuable for helping to understand more about the corrosion behaviour of soil nails. As part of this review, two previous case studies on corrosion of soil nails are found and examined.

8.1.1 Case Study 1 - Japan

Between 1993 and 1994, an investigation into the long-term durability of soil nails was conducted in Japan by Tayama et al (1996). In the investigation, the soil nails installed at nine sites for about 10 years were exposed and inspected. Chemical analyses were carried out on the soils and groundwater taken from the sites. The results are reproduced in Table 10. At seven of the nine sites, three soil nails at each site were exhumed by over-coring with a length ranging from 1.2 m to 8 m. No details have been provided on how the soil nails at the other two sites were exposed. The grout covers of the exposed soil nails ranged from 7 mm to 30.6 mm.

Partial uniform corrosion and pitting corrosion were observed in some of the soil nails. For each of the steel bars examined, the corroded area ratio (defined as the ratio of the corroded area to the cross-sectional area of a bar) and the depths of pitting corrosion were measured at 10 cm intervals. The results are given in Table 11. The corroded area ratio was found to vary from 0 to 100%. The distribution of this ratio along the bar lengths is shown in Figure 14. The maximum pit depths were in the range between 1.4 mm and 5.8 mm for the steel bars without galvanizing, whereas a pit depth of 0.84 mm was found in one case of galvanizing. The corrosion condition of the bar heads was found to be related to the types and detailing of the slope facing (see Figure 15). Heavy corrosion was found at locations behind the concrete nail heads.

The causes of the corrosion were probably due to (a) shortage of grout around the reinforcing bars at the crown of the grout column; and (b) inadequate grout cover in deeper areas.

8.1.2 Case Study 2 - Hong Kong

In 1988, soil nails were installed to stabilize a masonry retaining wall No. 7NW-B/R4 in Tai Po (Watkins, 1987). Two sacrificial soil nails were also installed at the same time, at depths of about 1 m. Both the working and the sacrificial soil nails were constructed by grouting high yield steel bars in 50 mm diameter predrilled holes. Bare steel bars of 19 mm diameter were used. The nails were 6 m long. The masonry retaining wall is essentially a cut slope with a thick masonry facing. The geology of the slope mainly comprises a thin mantle of fill/residual soil overlying completely to highly decomposed granodiorite.

In May 1997, inspection pits were excavated to expose the two sacrificial nails. A short segment (about 1 m long) was cut from each of the two soil nails. Based on visual inspection, the grout annulus of the segment of one of the nails was intact and there was no sign of corrosion on the steel bar. For the segment of the other nail, voids were found in the grout annulus, indicating that the grouting work was not properly carried out. Pitting corrosion was found on the surface of the steel bar. The corrosion condition of this steel bar is shown in Plate 2. The maximum pitting depth is about 3 mm (Plate 3), representing an average 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 were performed on eight soil specimens obtained from the inspection pits in order to measure the corrosivity of the soil environment. The laboratory tests included determination of the pH value and the contents of organic matter, soluble sulphate, sulphide, chloride and carbonate. Based on the test results, the corrosion potential of the soil is classified as “aggressive” under the UK classification, “average corrosiveness” under the French classification and “non-aggressive” under the US classification.

From file records, leakage from an underground foul manhole at the crest of the retaining wall was reported in the 1990s, which is also evident by the rich organic matter content of more than 0.7%. The leakage may account for the high corrosion potential of the soil tested.

9. GEOSYNTHETIC SOIL NAILS

To overcome the problem of corrosion of metallic reinforcement, non-metallic soil nails may be considered. The last two decades have seen rapid development in geosynthetics. Many types of geosynethetic materials have been tried or considered in soil nailing work:

(a) polyester,

(b) carbon fibre,

(c) glass fibre reinforced plastic, and

(d) other polymeric materials.

An economic and technical appraisal of geosynthetic soil nails was carried out by Woods & Brady (1995). The study showed that there was a good potential for geosynthetic nails. However, the authors pointed out that a fundamental study of the various material interactions, in particular the bond between the grout and geosynthetic, was needed before full scale trials were to be carried out.

Turner (1999) reported the construction of a trial soil nail wall reinforced with a patented system called PermaNail. Each soil nail consisted of one or more straps of high modulus polyester fibres which were grouted in a drillhole. Carbon fibre soil nails have also been used in the UK to stabilize 6 m high steep slopes (Haywood, 2000).

Because of lack of experience in using geosynthetics in soil nailing, care should be exercised when considering the use of these materials. For soil reinforcement, the durability of the geosynthetics may be affected by (i) degradation due to mechanical damage during site handling (e.g. abrasion and wear, punching, tear, etc); (ii) loss of strength due to creep and hydrolysis; and (iii) deterioration from exposure to ultraviolet radiation and heat of hydration during grouting.

10. DISCUSSION

There is no classification scheme in Hong Kong for assessing the corrosivity of soils. Of the three overseas schemes reviewed, the one developed by Eyre & Lewis (1987) and used in UK is the most comprehensive as it considers most of the factors that affect underground corrosion. The study of the Hong Kong soil properties database indicates that, based on the overseas criteria, a significant portion of the local soils has a high corrosion potential. However this result may be biased on the high side since soil chemical tests are not routine tests and the order of such tests indicates that the engineers have special concern on soil corrosivity. Although the number of sites may not be large enough to be representative of the territory-wide condition, the database provides a general indication of the aggressiveness of CDG and CDV tested.

Hot dip galvanizing is effective in providing corrosion protection to the steel bar. The nominal zinc coating weight of 610 g/m^2 (85 µm) can give a service life of about 6 years in “aggressive” ground and about 21 years in “non-aggressive” ground (see Table 4). Based on equations (4) and (5) given in Section 4, a 2 mm sacrificial steel thickness may have an average service life of about 130 years (based on uniform corrosion) but it would be reduced to 56 years in an aggressive environment.

If ignoring the effect of the cement grout, Hong Kong’s corrosion protection provisions for permanent soil nails are quite similar to those for reinforced fill structures (i.e. 610 g/m^2 hot dip galvanizing and sacrificial steel thickness allowances of 1.25 mm for cohesive frictional fill/0.75 mm for frictional fill). The design life of reinforced fill structures in Hong Kong is 120 years (GEO, 1989). The fill for these structures has to meet stringent physical and electrochemical properties requirements in order to ensure low corrosion potential. On the other hand, the natural ground in which the soil nails are installed can be highly variable in terms of corrosion potential.

In common with the requirements for reinforced fill structures, the design life of permanent soil nailed structures is 120 years. For temporary soil nails, the design life is normally 2 years or less.

Results of the comparative analysis presented in Section 7 above indicate that the French and the American corrosion protection requirements for permanent soil nails are more demanding than those in Hong Kong. During the course of this study, no English literature on the corrosion protection practice in Germany has been located. However, according to Glässer (1990), the standard corrosion protection for permanent soil nails in Germany is the use of a corrugated plastic sheath with a grout annulus of at least 5 mm around the steel bar.

Unlike the American and French approaches, the UK approach (Murray, 1993) permits the service life of the soil nails to be estimated. With the provision of 610 g/m^2 hot dip galvanizing and 2 mm sacrificial steel thickness, a soil nail based on the UK approach may have a service life of more than 120 years in “mildly aggressive” soils and 98 years in "aggressive" soils. It must, however, be noted that the UK approach considers only the uniform corrosion of steel and there is no allowance for localised pitting corrosion. The available field test data (see Sections 4 and 8 above) indicate that pitting of steel is a common phenomenon in underground corrosion. The rates of pitting corrosion can be many times higher than those of uniform corrosion (up to 5 times higher in galvanized steel and 13 times in bare steel). According to the UK approach, the sacrificial thickness of steel in "aggressive" soils for a period of 120 years would need to be about 2.5 mm (see Figure 6). This is very much less than the 3 mm maximum pit depths recorded for the bare steel soil nail in Hong Kong with a burial period of just 9 years (see Section 8.1.2). This raises the question as to whether the UK approach is applicable to Hong Kong soil conditions.

Couplers are commonly used to splice the steel bars, especially at locations with limited working space. The couplers can induce cracks in the cement grout because of the smaller grout cover at those locations. This would initiate the corrosion process, in particular pitting, at the threaded bar lengths within the couplers. Furthermore, paint is usually applied directly to the threaded portions of the steel bar without the use of a primer. This is not in accordance with the proper procedure specified in EN 1461:1999 (previously BS 729:1971). The level of corrosion protection provided by the paint is less than that of hot dip galvanizing. This, coupled with the crack-inducing effect of the couplers, would render the parts of the threaded steel bars at the locations of the couplers more vulnerable to corrosion. This problem can be overcome if a corrugated plastic sheathing is used.

The long-term performance of soil nails requires that the nails should not be weakened by corrosion to a degree as to affect their performance. Review of technical literature, soil test results and two cases of exhumed nails showed that corrosion might pose problem in the combined conditions of unfavourable ground, defective grouting and no zinc coating. About one third of the sites with available soil test results are rated unfavourable. There is little information of defective grout. Nearly all nails in Hong Kong are zinc-coated. The probability of all the unfavourable conditions occurring at the same time may be low.

The many uncertainties in factors affecting corrosion and reaction dynamics make it impossible to accurately determine corrosion rates theoretically. We have to accept imperfection of knowledge. In the end, decisions on what measures to be adopted is a matter of balancing between cost and effectiveness. Where the remaining uncertainties can be further reduced by practicable investment of additional effort, this should proceed. If the risk of the existing corrosion protection system is not excessive and improvement is impracticably costly, the system should stay. The cost and practicability of different improvement measures need to be further explored.

11. CONCLUSIONS AND RECOMMENDATIONS

The long-term performance of soil nails requires that the nails should be able to withstand corrosive attack from their local environment. At present, there is not enough information to determine accurately the corrosion rates of steel and zinc coating in soils of different aggressivities. It is recommended that further studies be carried out to provide data on the aggressivities of soils and the long-term corrosion rates. This would help to determine the service life of steel soil nails with different corrosion protection provisions.

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LIST OF TABLES

Table 1 - Test Results of the National Bureau of Standards Underground Corrosion Programme in 1924 (Romanoff, 1957; Zhang, 1996)

Galvanized Steel Pipe Specimen No. (see Notes 1 & 2)	Soil Type	Resistivity (ohm - cm)	pH	Average Corrosion Rate of Zinc Coating (µm/year)
1	Allis silt loam, Cleveland, Ohio	1215	7.0	11.8
2	Bell clay, Dallas Tex.	684	7.3	1.5
3	Cecil clay loam, Atlanta, Ga.	30000	5.2	1.7
4	Chester loam, Jenkintown, Pa.	6670	5.6	7.9
5	Dublin clay adobe, Oakland, Calif.	1345	7.0	7.7
6	Everett gravelly sandy loam, Seattle, Wash.	45100	5.9	0.5
7	Maddox silt loam, Cincinnati, Ohio	2120	4.4	10.8
8	Fargo clay loam, Fargo, N. Dak.	350	7.6	3.2
9	Genesee silt loam, Sidney, Ohio	2820	6.8	5.0
10	Gloucester sandy loam, Middleboro, Mass.	7460	6.6	5.2
11	Hagerstown loam, Loch Raven, Md.	11000	5.3	3.7
12	Hanford fine sandy loam, Los Angeles, Calif.	3190	7.1	2.2
13	Hanford very fine sandy loam, Bakersfield, Calif.	290	9.5	3.7
14	Hempstead silt loam, St. Paul, Minn.	3520	6.2	1.1
15	Houston black clay, San Antonio, Tex.	489	7.5	1.5
16	Kalmia fine sandy loam, Mobile, Ala.	8290	4.4	4.2
17	Keyport loam, Alexandria, Va.	5980	4.5	14.8 (see Note 3)
19	Lindley silt loam, Des Moines, Iowa	1970	4.6	2.9
20	Mahoning silt loam, Cleveland, Ohio	2870	7.5	4.9
22	Memphis silt loam, Memphis, Tenn.	5150	4.9	5.2
23	Merced silt loam, Buttonwillow, Calif.	278	9.4	40.6 (see Note 3)
24	Merrimac gravelly sandy loam, Norwood, Mass.	11400	4.5	1.1
25	Miami clay loam, Milwaukee, Wis.	1780	7.2	1.45
26	Miami silt loam, springfield, Ohio	2980	7.3	2.9
27	Miller clay, Bunkie, La.	570	6.6	3.9
28	Montezuma clay adobe, San Diego, Calif.	408	6.8	8.8
29	Muck, New Orleans, La.	1270	4.2	25.5 (see Note 3)
30	Muscatine silt loam, Davenport, Iowa	1300	7.0	1.9
31	Norfolk fine sand, Jacksonville, Fla.	20500	4.7	0.67
32	Ontario loam, Rochester, N.Y.	5700	7.3	2.4
33	Peat, Milwaukee, Wis.	800	6.8	7.4
35	Ramona loam, Los Angeles, Calif.	2060	7.3	1.3
36	Ruston sandy loam, Meridian, Miss.	11200	4.5	1.0
37	St. John's fine sand, Jacksonville, Fla.	11200	3.8	8.7
38	Sassafras gravelly sandy loam, Camden, N.Y.	38600	4.5	0.85
40	Sharkey clay, New Orleans, La.	970	6.0	4.0
41	Summit silt loam, Kansas City, Mo.	1320	5.5	2.2
42	Susquehanna clay, Meridian, Miss.	13700	4.7	3.0
43	Tidal marsh, Elizabeth, N.J.	60	3.1	5.5
44	Wabash silt loam, Omaha, Nebr.	1000	5.8	1.9
45	Unidentified alkali soil, Casper, Wyo.	263	7.4	7.5
46	Unidentified sandy loam, Denver, Colo.	1500	7.0	0.7
47	Unidentified silt loam, Salt Lake City, Utah	1770	7.6	4.3

Notes:
(1) Specimen No. refers to the original identification.
(2) Average zinc coating thickness of the 47 specimens is 121 µm.
(3) Zinc coating corroded completely; data included the corrosion of steel.

Table 2 - Test Results of the National Bureau of Standards Underground Corrosion Programme in 1937 (Romanoff, 1957; Zhang, 1996)

Specimen No.	Soil Type	Resistivity (ohm - cm)	pH	Galvanized Steel		Steel	
				Average Corrosion Rate (µm/year)	Maximum Pitting Rate (µm/year)	Average Corrosion Rate (µm/year)	Maximum Pitting Rate (µm/year)
1	Acadia clay	190	6.2	22.9	22.5	83	361
2	Cecil clay loam	17790	4.8	3.8	16.9	16.2	209
3	Hagerstown loam	5210	5.8	3.9	16.9	19.6	260
4	Lake Charles clay	406	7.1	26.3	36.7	132	409
5	Muck	712	4.8	43.0	180.6	82.7	277
6	Carlisle muck	1660	5.6	14.1	22.2	35.8 [a]	56.4
7	Rifle peat	218	2.6	77.4 [a]	234	85.5	164
8	Sharkey clay	943	6.8	7.2 [a]	34	20.1	135
9	Susquehanna clay	6920	4.5	4.3	16.9	25.3	192
10	Tidal marsh	84	6.9	9.6	22.6	51.1	226
11	Docas clay	62	7.5	7.6	28.2	43 [a]	226
12	Chino silt loam	148	8.0	7.6	16.9	33.4	183
13	Mohave fine gravely loam	232	8.0	11.9	16.9	58.8 [a]	409
14	Cinders	455	7.6	58.0	286	151	409
15	Merced silt loam	278	9.4	9.9 [b]	18.5	64	344

Notes:
(1) "a" denotes data averaged over 4 years.
(2) "b" denotes data averaged over 11.2 years.
(3) All data averaged over 9 years.

Table 3 - Rate of Corrosion of Galvanizing Coating and Steel under Different Soil Conditions (Department of Transport, 1988)

Soil Condition	Rate of Corrosion of Galvanizing (µm/yr)	Calculation for Thickness of Sacrificial Steel M (µm)
Non-aggressive	4	$M = 22.5\ t^{0.67}$
Aggressive	14	$M = 40\ t^{0.80}$
Legend: t time in years		

Table 4 - Rate of Corrosion of Galvanizing Steel for Different Categories of Soil Aggressivity (Murray, 1993)

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

Table 5 - Provision of Corrosion Prevention Measures for Different Overall Corrosivity Index, I (French National Research Report, 1991)

Overall Corrosivity Index, I	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 6 - Provision of Corrosion Prevention Measures (Byrne et al, 1998)

Type of Application	Aggressivity	Corrosion Prevention Provisions
Permanent (75 to 100 years) - 75 years for permanent structures - 100 years for abutments	Aggressive	- encapsulated nails should be used (grouting the nail inside a corrugated plastic sheath). - minimum grout cover between the sheath and borehole circumference should be not less than 12 mm and that between plastic sheath and the steel bar should not be less than 5 mm. (See Note).
	Non-aggressive	- nails should be epoxy resin-bonded using an electrostatic process with a minimum coating of 0.3mm. - a minimum grout cover of 25 mm should be provided. - centralizers should be placed at distances not exceeding 2.5 m centre to centre.
Temporary (1.5 to 3 years)	Aggressive	Not specified.
	Non-aggressive	Provision of grout around steel soil nail.
Note: Encapsulation is also applicable to critical structures (e.g. retaining walls adjacent to lifeline and high volume roadways), or where field observations have indicated corrosion of existing structures.		

Table 7 - Soil Resistivity Measured at Five Sites in Hong Kong (Chan & Chen,1999)

Location	Material	Resistivity (ohm-cm)
Siu Sai Wan	CDV	20,000 to 110,000
Shum Wan	CDV	6,000 to 46,000
Tiu Keng Leng	CDG	15,000 to 60,000
Yue On Court	CDV	10,000 to 20,000
Kowloon Bay Calibration Site	CDG	45,000 to 100,000

Table 8 - Marking Based on 59 CDG and 34 CDV Specimens (UK Approach)

Assessed Soil Condition	Marks	No. of CDG Specimens	No. of CDV Specimens	Total No. of Specimens
Non-aggressive	0 or Greater	8 (14%)	1 (3%)	9 (10%)
Mildly aggressive	-1 to - 4	30 (51%)	21 (62%)	51 (55%)
Aggressive	-5 to - 10	21 (35%)	12 (35%)	33 (35%)
Highly aggressive	-11 or Less	0	0	0

Table 9 - Corrosiveness Index Based on 59 CDG and 34 CDV Specimens (French Approach)

Assessed Soil Condition	Corrosiveness Index, A	No. of CDG Specimens	No. of CDV Specimens	Total No. of Specimens
Slightly corrosive	Less than 4	47 (80%)	31 (91%)	78 (84%)
Average corrosiveness	5 to 8	12 (20%)	3 (9%)	15 (16%)
Corrosive	9 to 12	0	0	0
Highly corrosive	Greater than or equal to 13	0	0	0

Table 10 - Results of Chemical Analyses on Soils and Ground Water at Nine Sites in Japan (Tayama et al, 1996)

Investigation Site	Soil Analysis		Water Analysis				
	pH	Specific resistance (ohm-cm)	pH	Specific resistance (ohm-cm)	$C1^-$ (ppm)	SO_4^{2-} (ppm)	NO^{3-} (ppm)
A	8.64	12,300	8.10	3,570	4.06	22.77	N.D.
B	5.70	50,250	7.28	9,840	4.38	5.31	0.78
C	6.12	29,500	6.85	11,380	4.38	6.95	1.73
D	10.90	2,440	8.10	4,440	7.62	8.33	0.80
E	11.41	1,770	8.32	2,793	9.41	30.93	N.D.
F	7.98	7,752	5.76	800	120.02	448.98	N.D.
G	7.30	14,706	7.30	14,706	1.07	4.98	1.70
H	5.95	15,385	7.06	6,667	7.62	12.13	1.52
I	5.58	27,777	7.56	2,817	17.55	21.49	1.61
*Remarks	serious if ≤ 4	serious if < 700	serious if < 4	serious if < 700	serious if several hundreds	serious if several hundreds	

Legend:

* Japan Highway Public Corporation (1992)

Table 11 - Results of Corrosion Investigation in Japan (Tayama et al, 1996)

Investigation Site	Specifications of Earth Reinforcing Work			Corrosion of Reinforcing Bar				Results of Tensile Test		Reference Strengths	
				Above Ground	Below Ground						
	Bar & Bore*1	Covering (mm)	Type of Facing (see Figure 15)	Bar Head	M.C.A.R. (%)*2	L.M.C. (cm)*3	M.D.P.C. (mm)*4	Yield strength (MPa)	Tensile strength (MPa)	Yield strength (MPa)	Tensile strength (MPa)
A	D=25, SD35	7.5	I	Observed	74	0 - 10	5.76	-	559	343 or more	490 or more
	L=1.2							-	539		
	∅=40							-	588		
B	D=19, SD30	13.0	I	Observed	95	0 - 10	1.75	-	549	294 or more	480-617
	L=3.0							363	549		
	∅=46							363	559		
C	D=29, SD30	30.6	II	Nil	0	-	Nil	392	608	294 or more	480-617
	L=8.0							392	608		
	∅=90							392	608		
D	D=22, SD30	22.0	II	Observed	38	10-20	Nil	353	559	294 or more	480-617
	L=2.4							-	559		
	∅=66							353	539		
E	D=25, SD30	8.5	II	Nil	38	0-10	1.40	421	608	294 or more	480-617
	L=2.0							382	669		
	∅=42							441	627		
F	D=32, SD30	7.0	II	Nil	100	140-190	1.87	363	549	294 or more	480-617
	L=2.0							412	608		
	∅=46							412	608		
G	D=25, SD30	7.5	IV	Nil	9	390-400	0.84	392	578	294 or more	480-617
	L=5.0*5							392	578		
	∅=40							392	578		
H	D=25	10.5	III	Nil	-	-	-	-	-	-	-
	L=4.0*5										
	∅=46										
I	D=25	20.6	IV	Observed	-	-	-	-	-	-	-
	L=4.0										
	∅=66										

Legend:

*1 Diameter (D mm), steel grade (SD) and length (L m) of reinforcing bars and diameter (∅ mm) of bore

*2 Maximum corroded area ratio (M.C.A.R.)

*3 Location of maximum corrosion (distance from ground surface) (L.M.C.)

*4 Maximum depth of pitting corrosion (M.D.P.C.)

*5 Galvanization of steel bar

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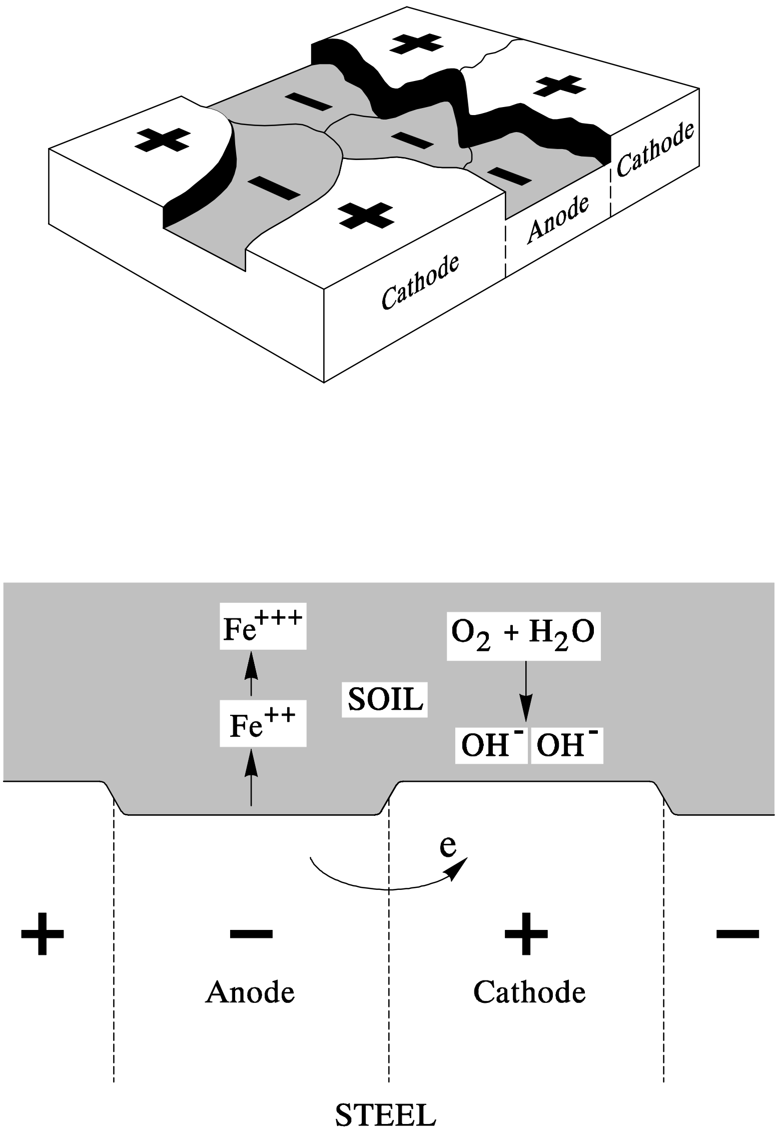
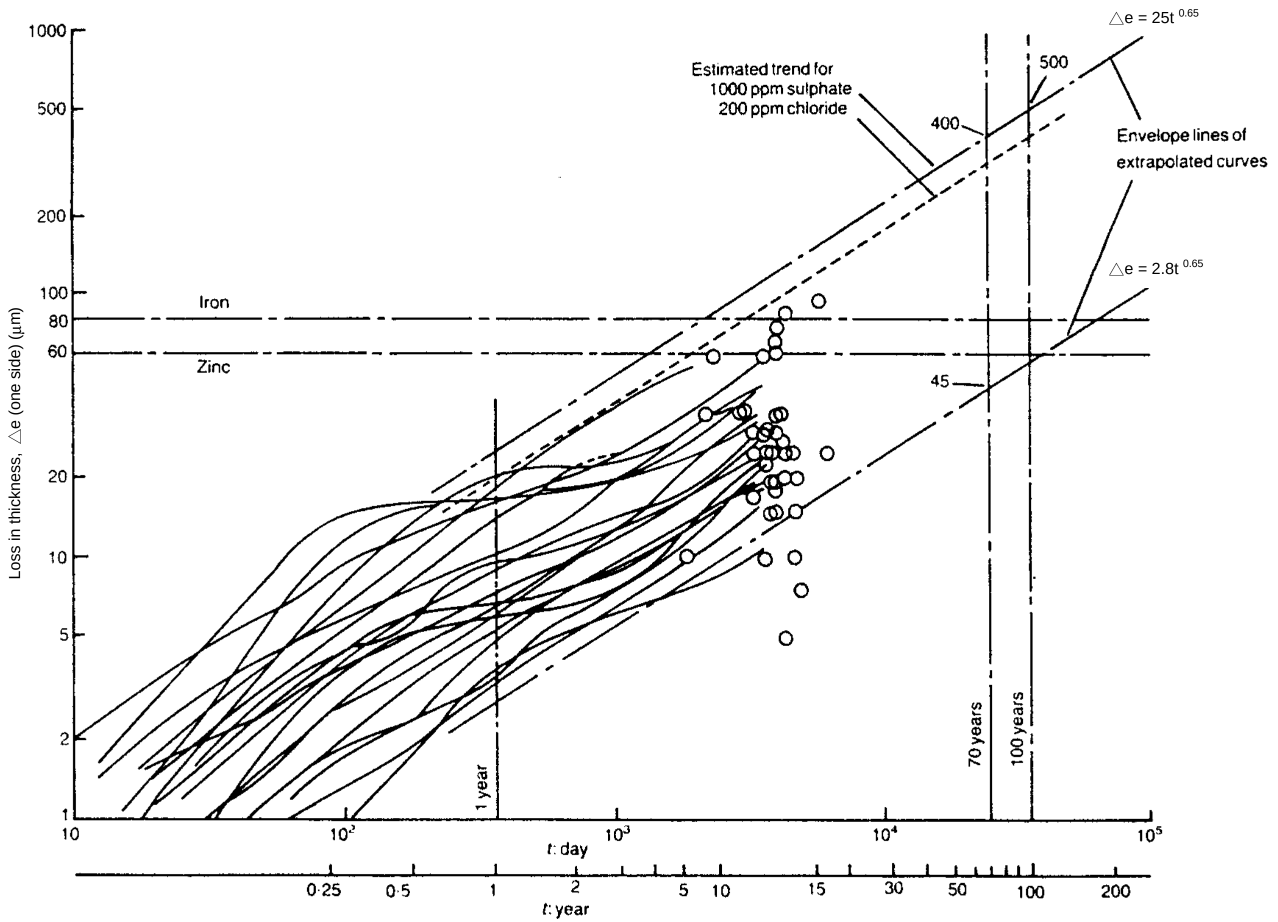


At Anode	$Fe \rightarrow Fe^{++} + 2e$
	$Fe^{++} \rightarrow Fe^{+++} + e$
At Cathode	$O_2 + 2H_2O + 4e \rightarrow 4OH^-$
Combined reaction	$4Fe + 3O_2 + 2H_2O = 2Fe_2O_3H_2O$ (Rust)

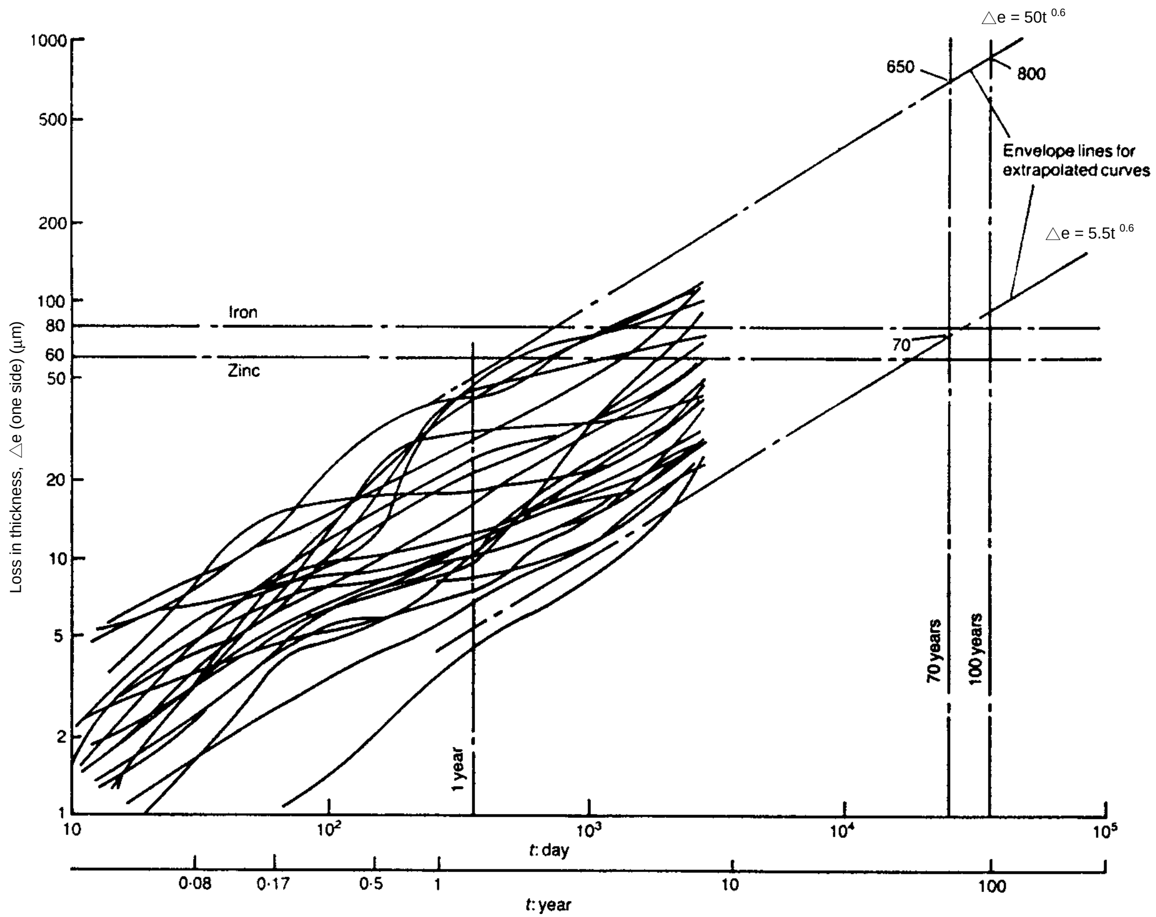
Figure 1 - Schematic Diagram Showing Electrochemical Reactions Involved in the Corrosion of Steel (Modified from British Steel Corporation)



Legend:

○ Assessed from inspection of structure

Figure 2 - Electrochemical Tests for Quarter-saturated Soils Which Comply with Specifications for Dry Structures (Darbin et al, 1988)



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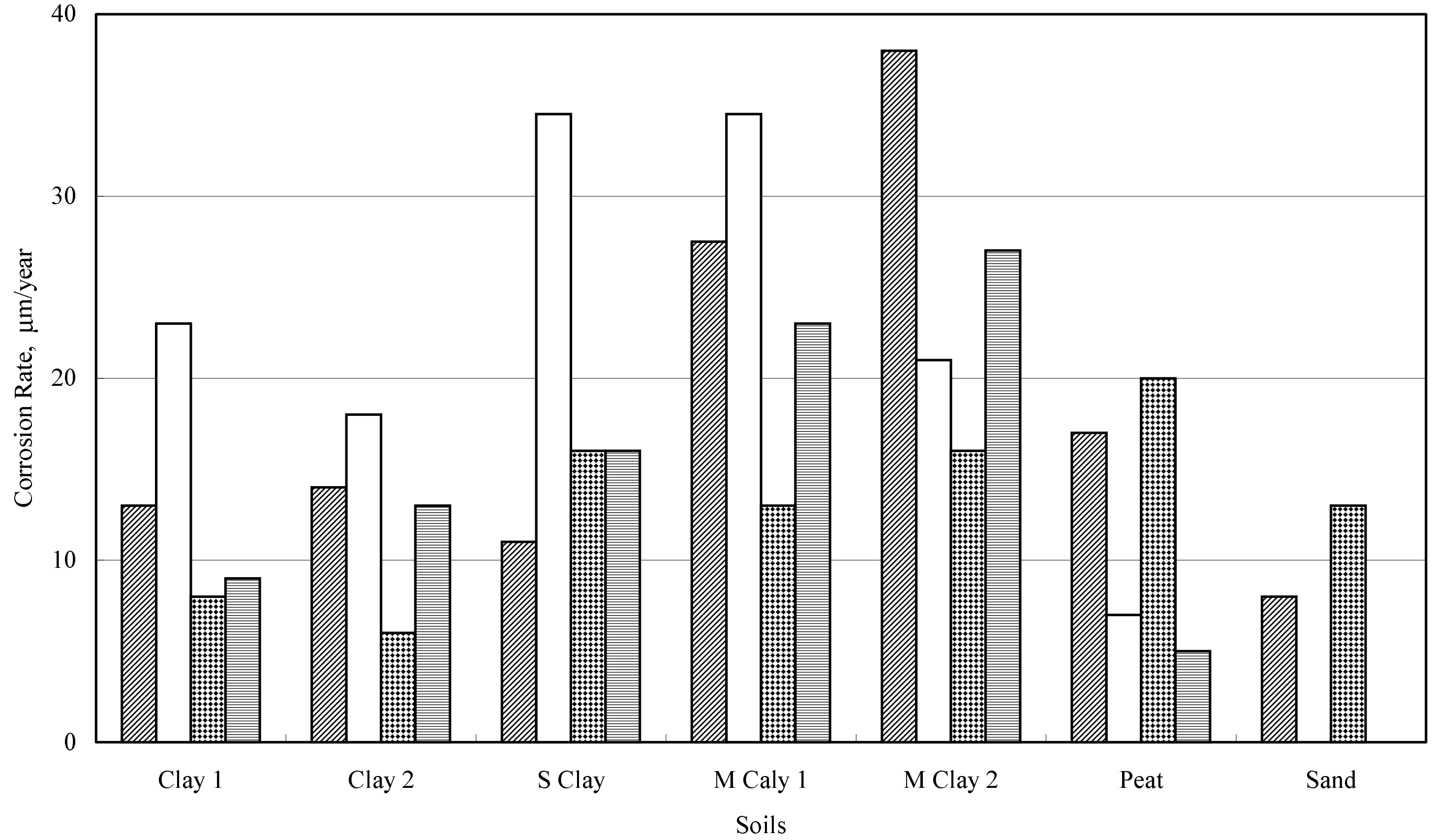
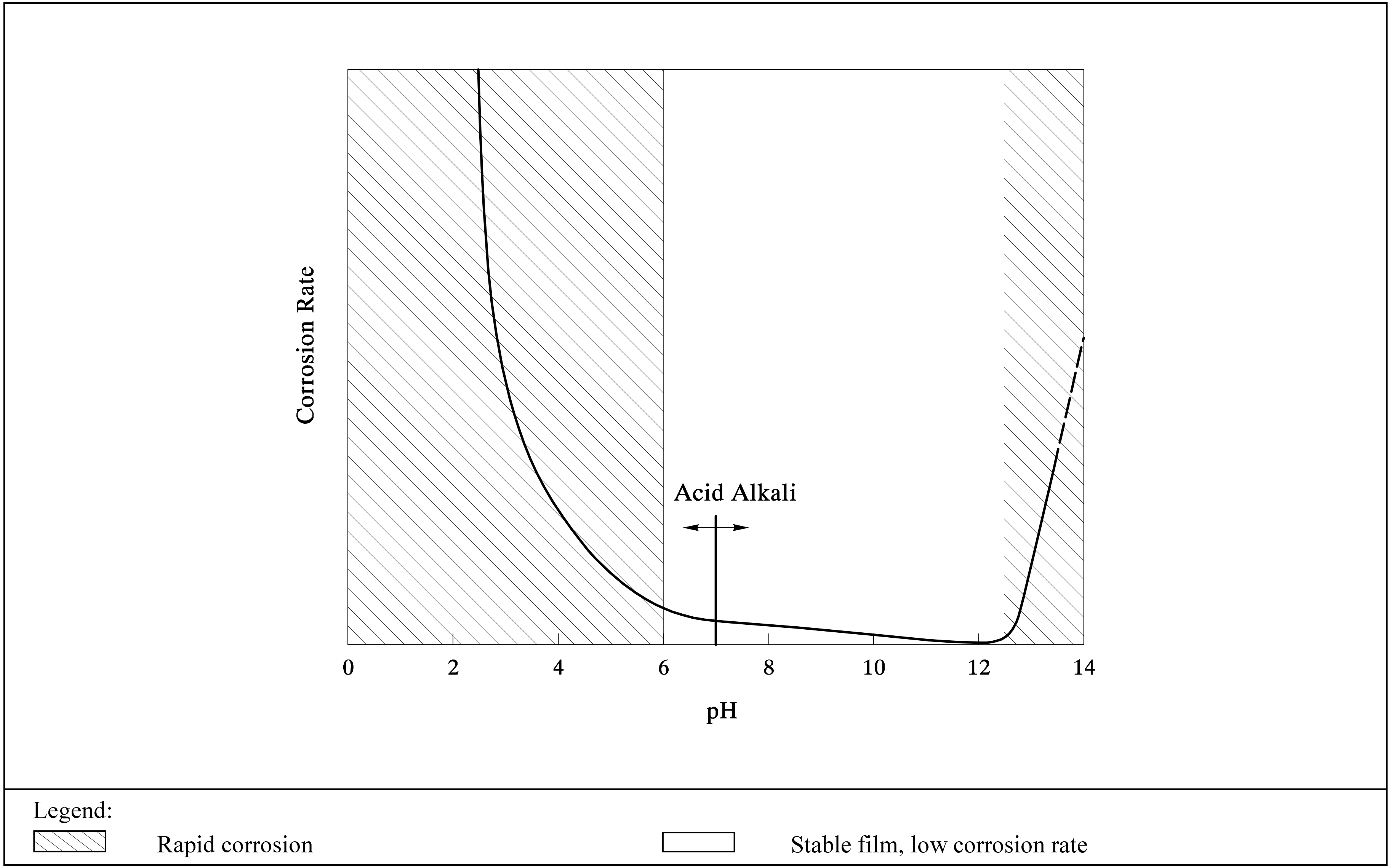


Legend:

Above GW table, specimen placed directly in insitu soil
Below GW table, specimen placed directly in insitu soil
Above GW table, specimen embedded in sand fill
Below GW table, specimen embedded in sand fill

Figure 4 - Corrosion Rates of Galvanized Steel Specimens after Three Years (Camitz & Vinka, 1989)



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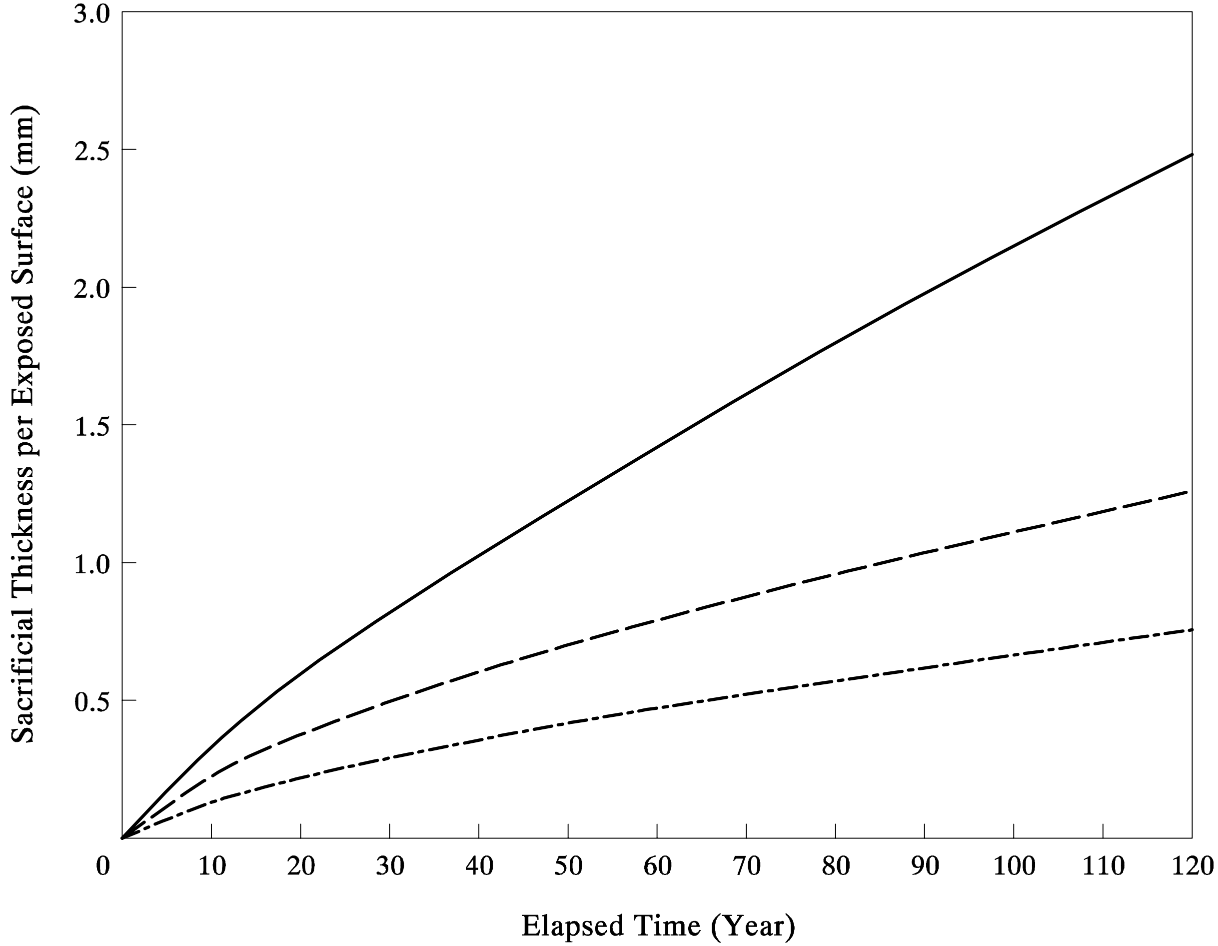


Legend:

——— Aggressive

— — — — Mildly aggressive

—·—·—· Non-aggressive

Figure 6 - Sacrificial Thickness of Buried Steel Surfaces (Murray, 1993)

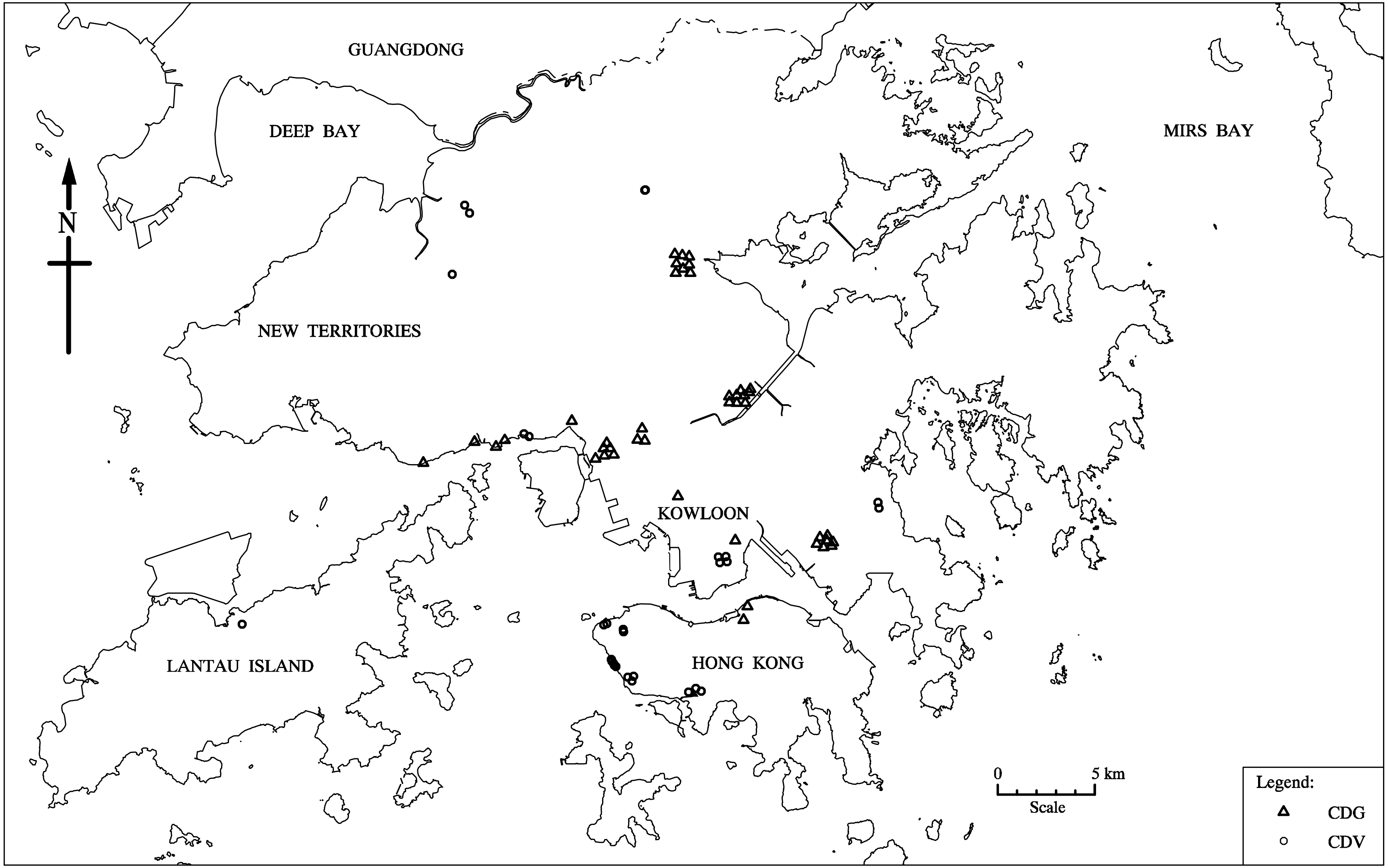


Figure 7 - Locations Where the Soil Specimens were Taken for Corrosivity Assessment

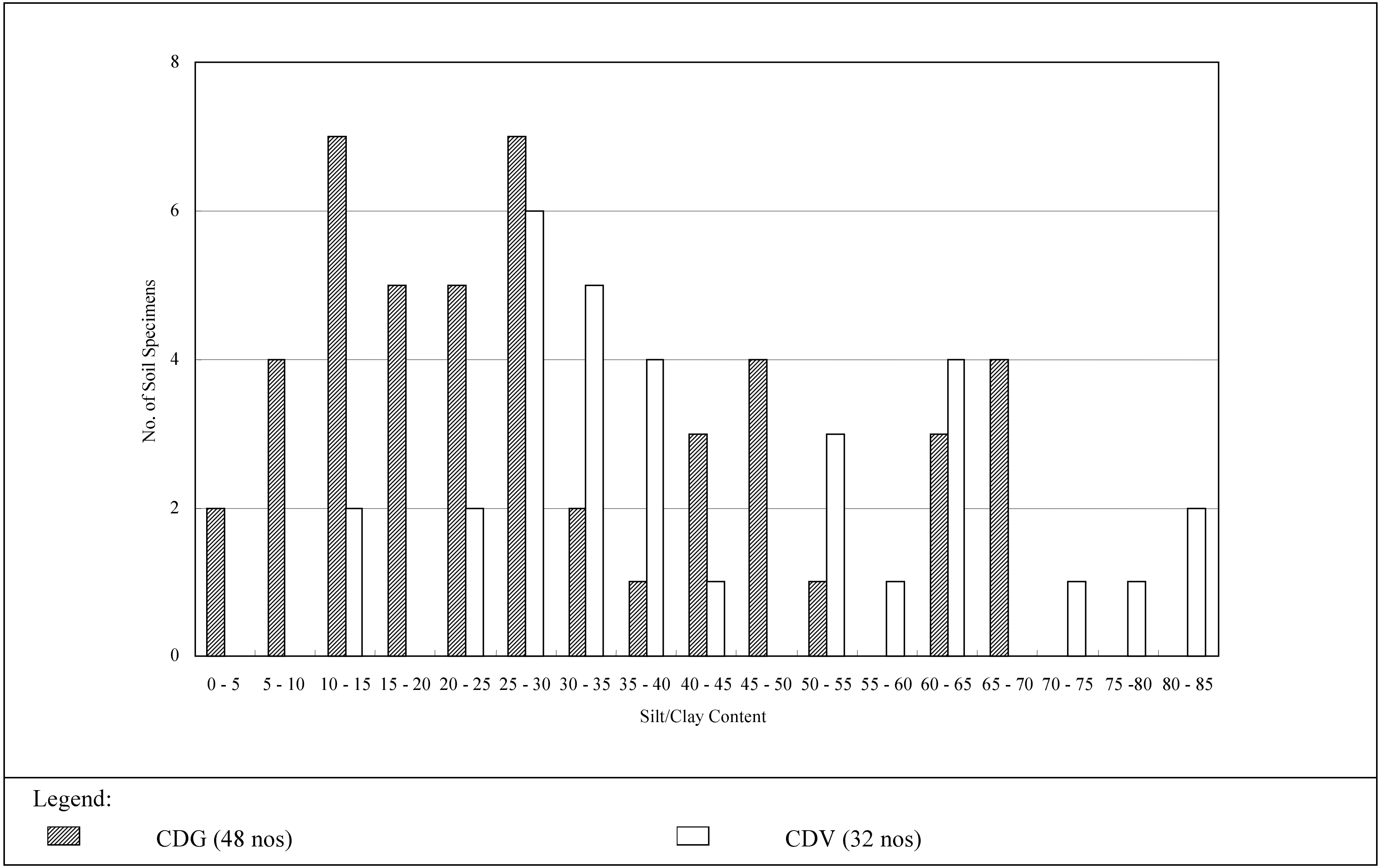


Figure 8 - Distribution of Silt and Clay Content of the Soil Specimens

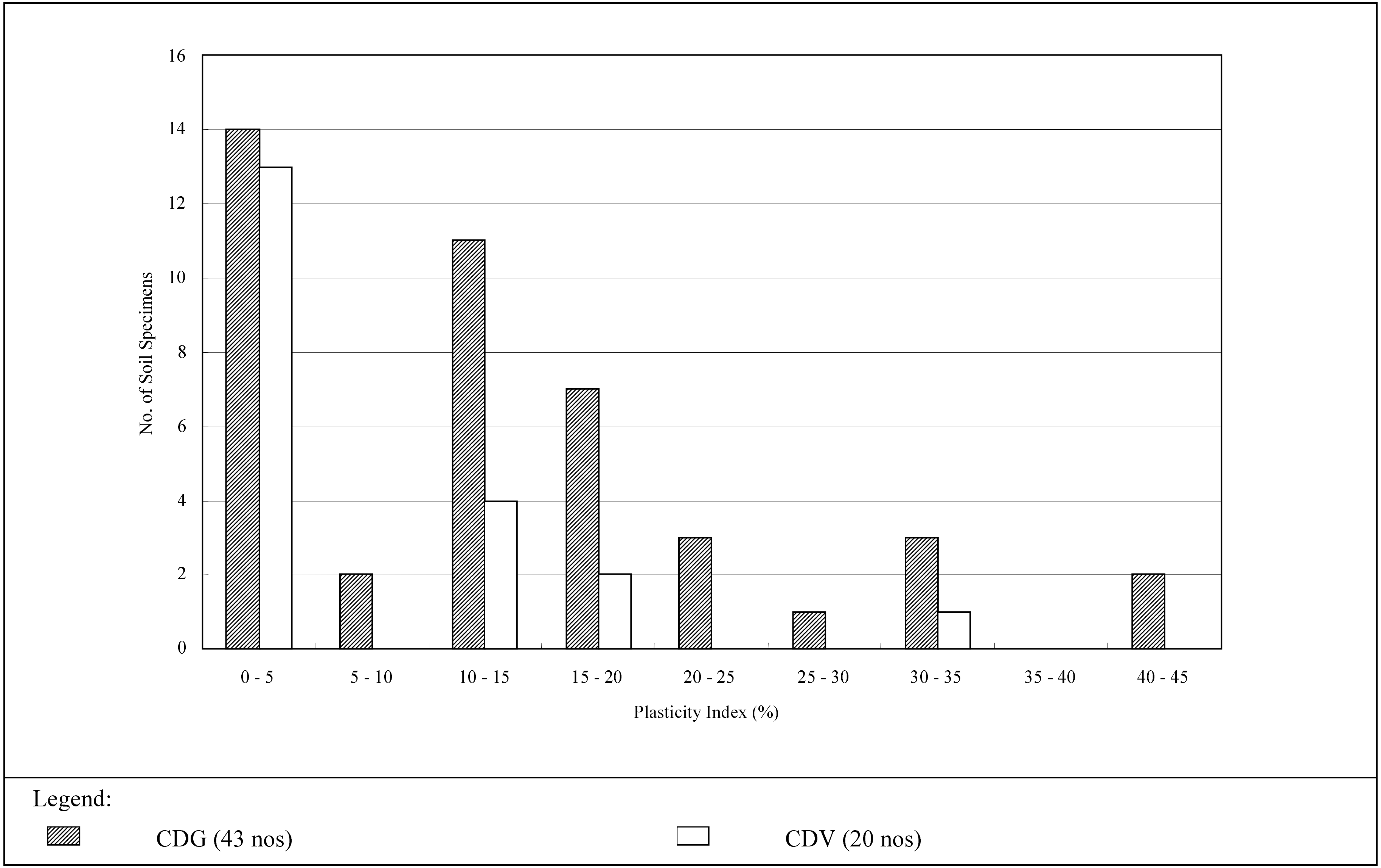
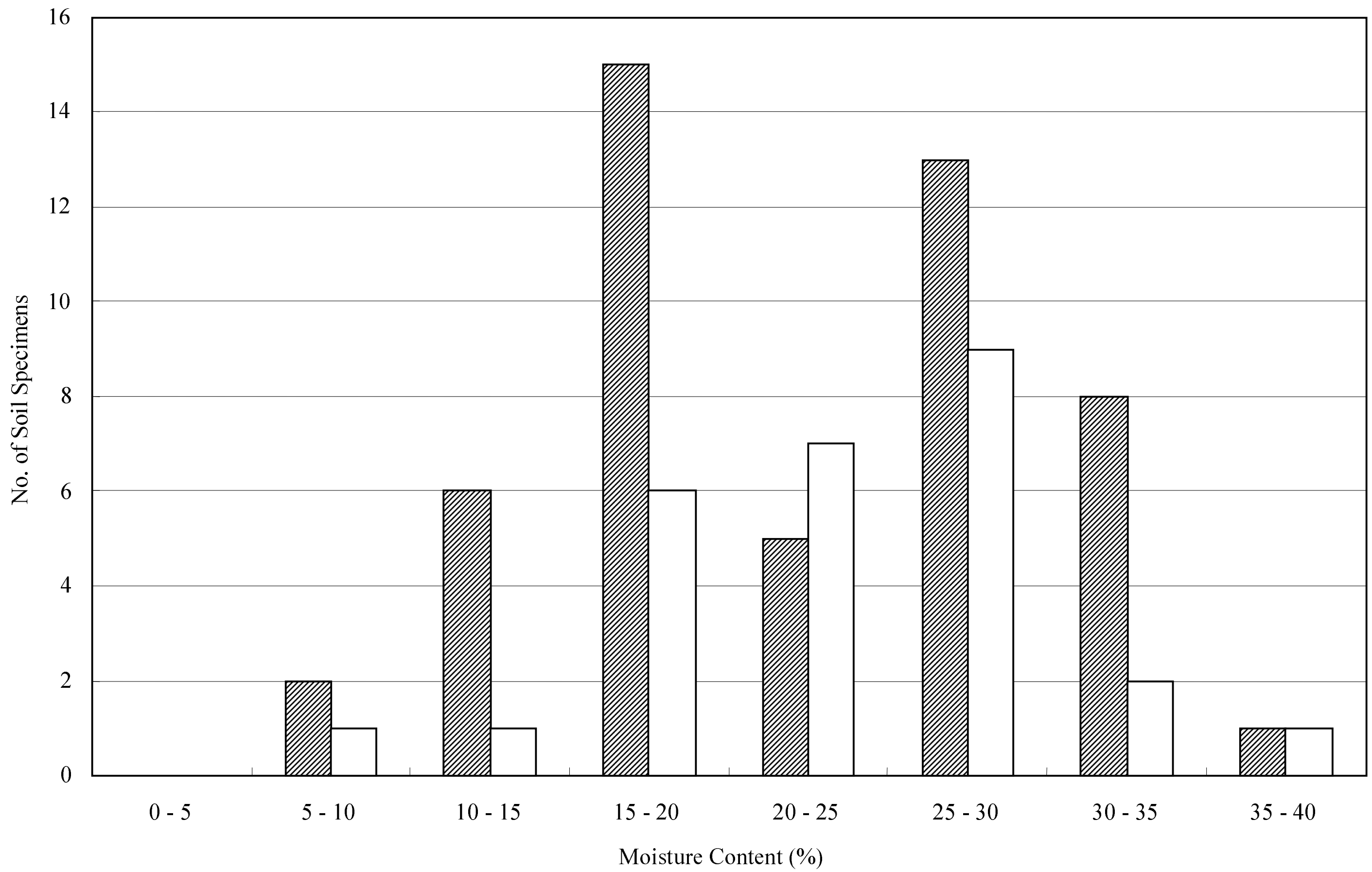


Figure 9 - Distribution of Plasticity Index of the Soil Specimens



Legend:

CDG (50 nos) CDV (27 nos)

Figure 10 - Distribution of Moisture Content of the Soil Specimens

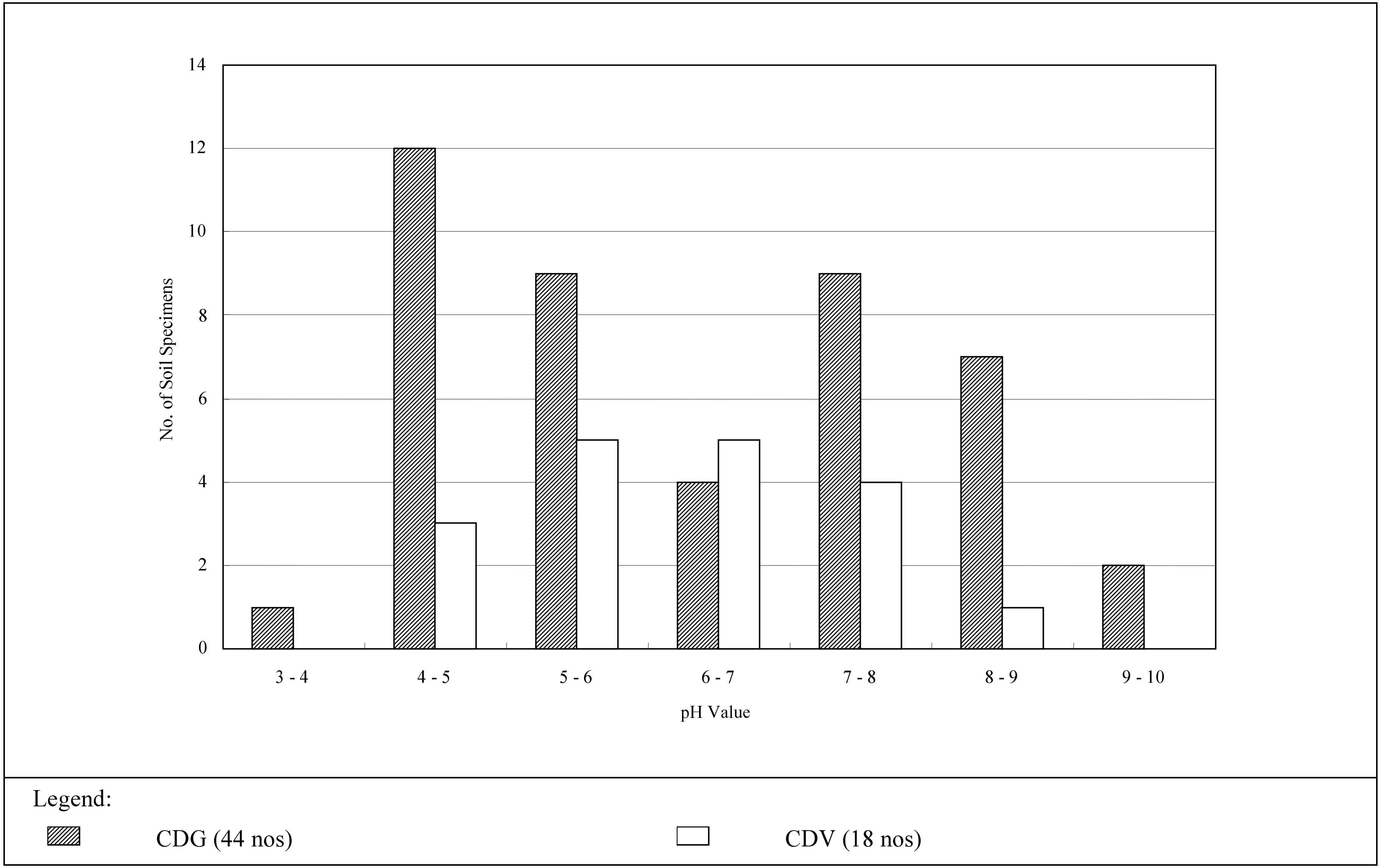
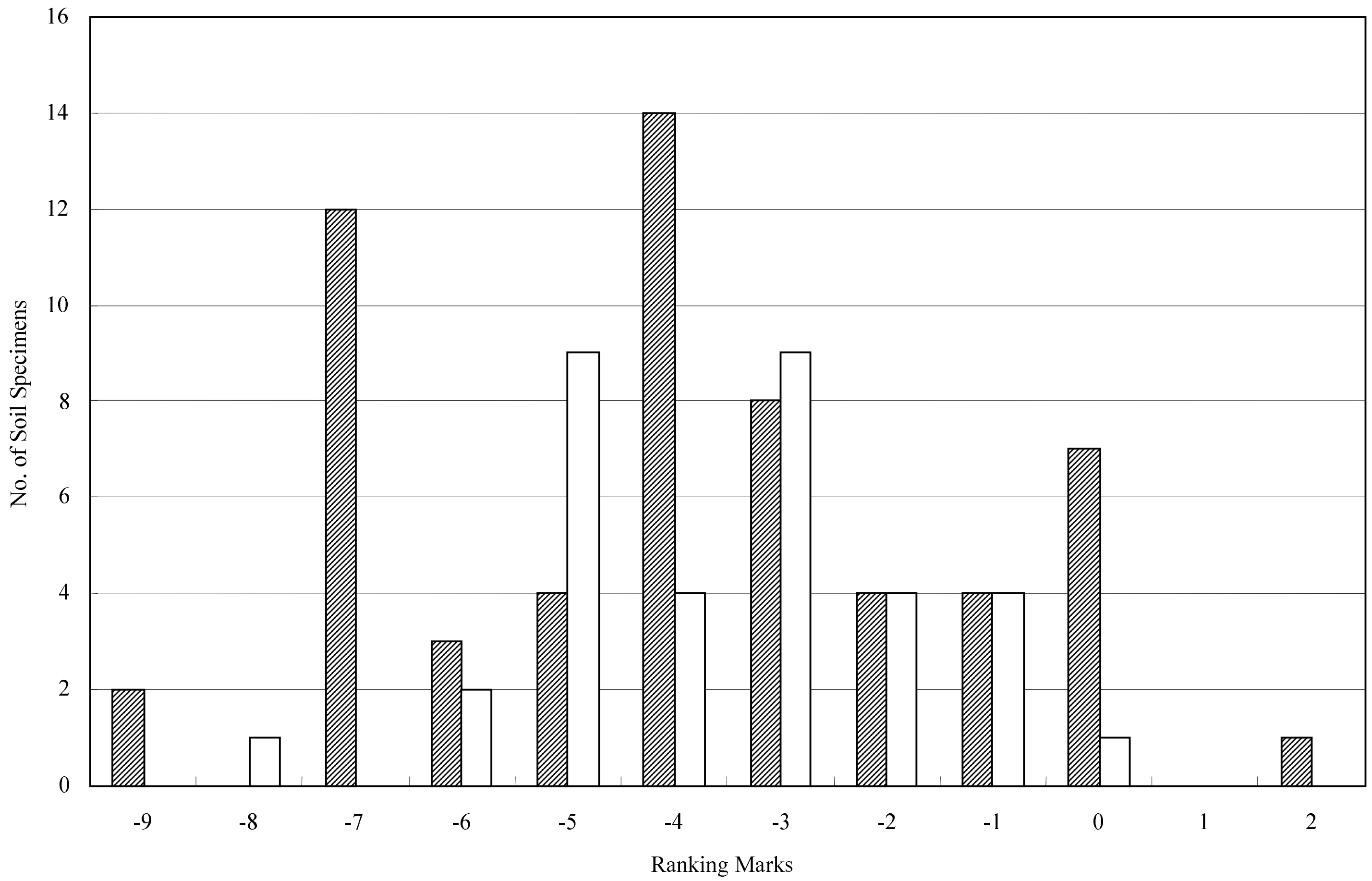


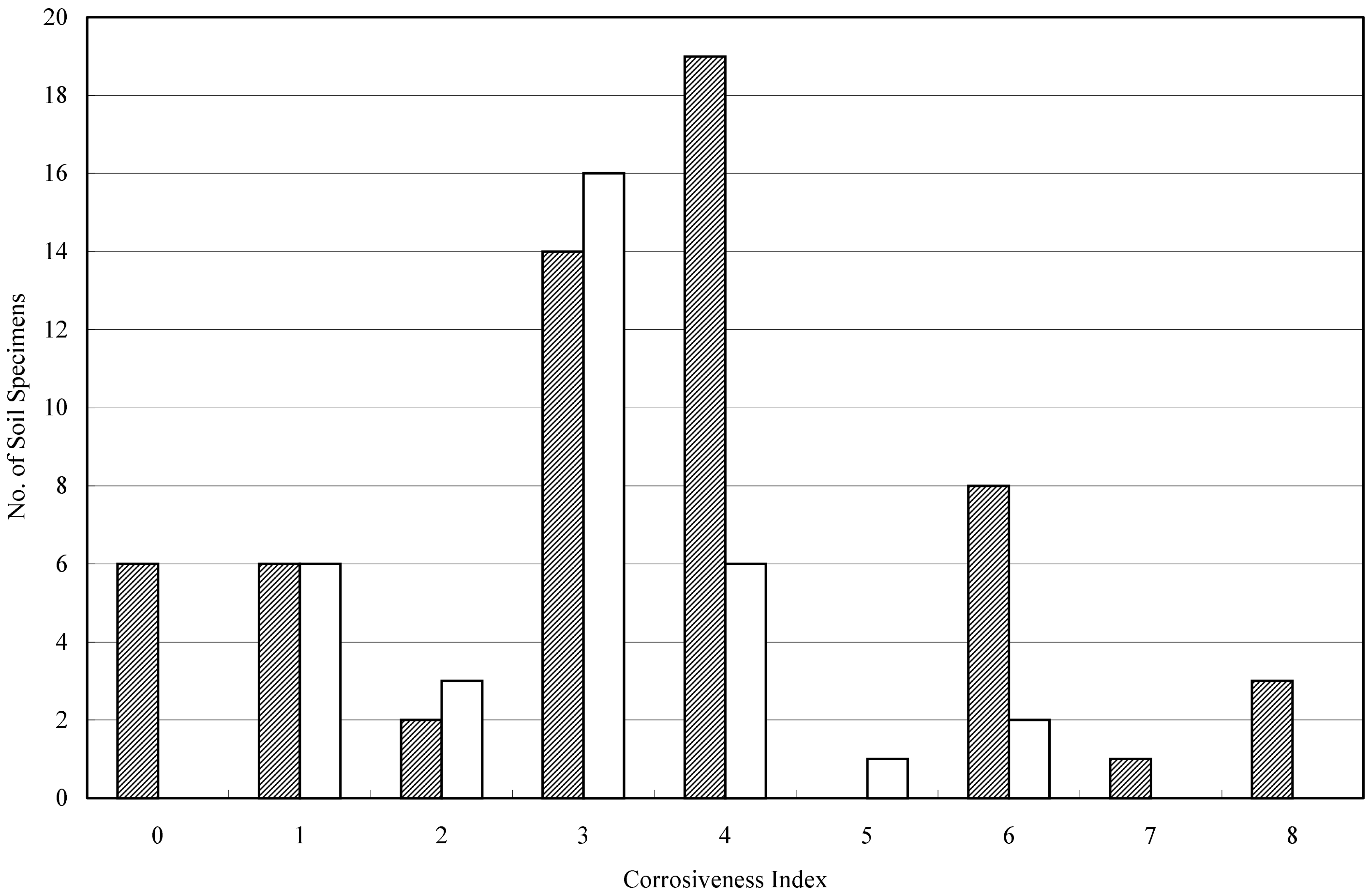
Figure 11 - Distribution of pH Value of the Soil Specimens



Legend:

CDG (59 nos) CDV (34 nos)

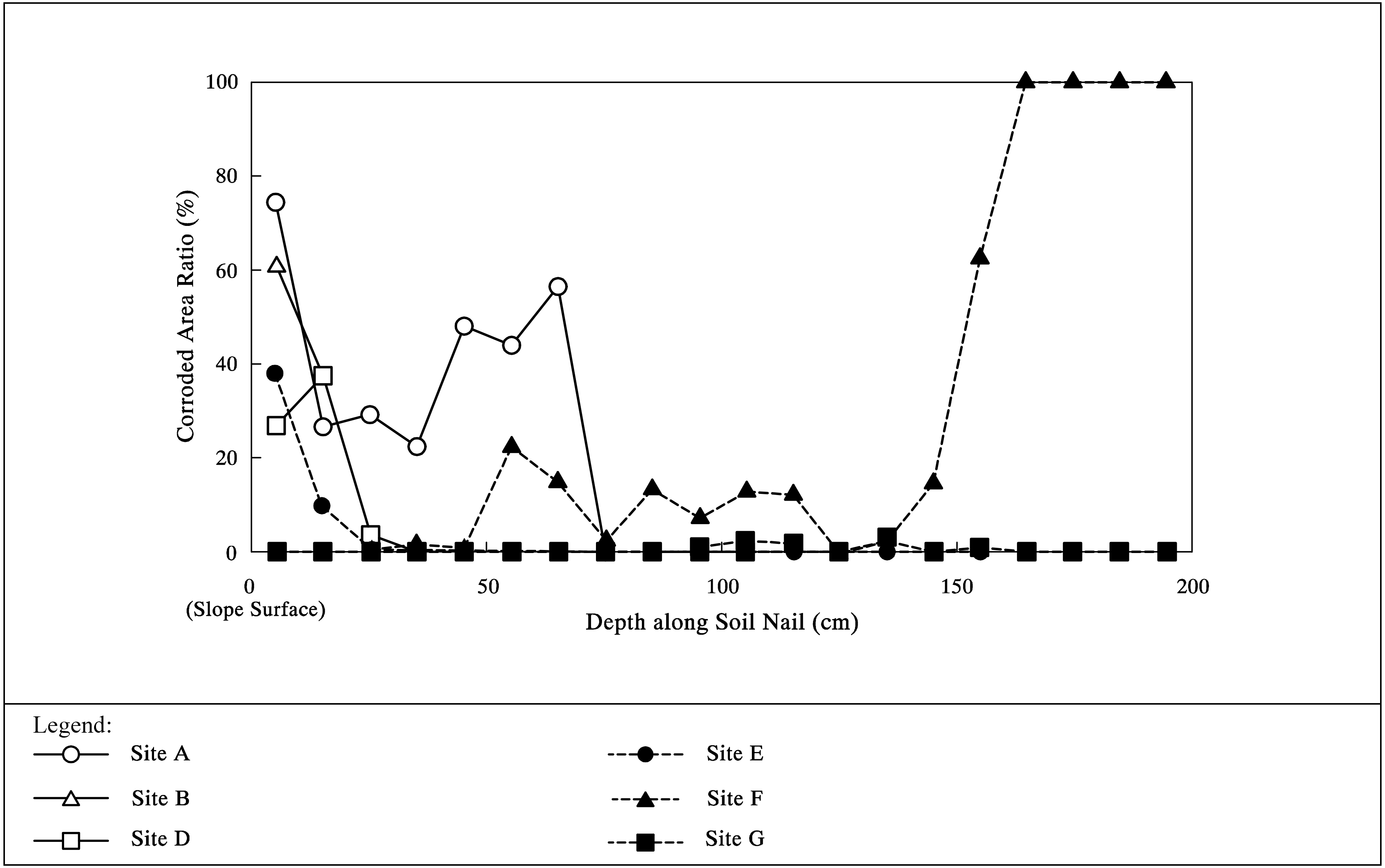
Figure 12 - Distribution of Ranking Marks of the Soil Specimens According to the UK Approach (Eyre & Lewis, 1987)



Legend:

CDG (59 nos) CDV (34 nos)

Figure 13 - Distribution of Corrosiveness Index of the Soil Specimens According to the French Approach (French National Research Project, 1991)



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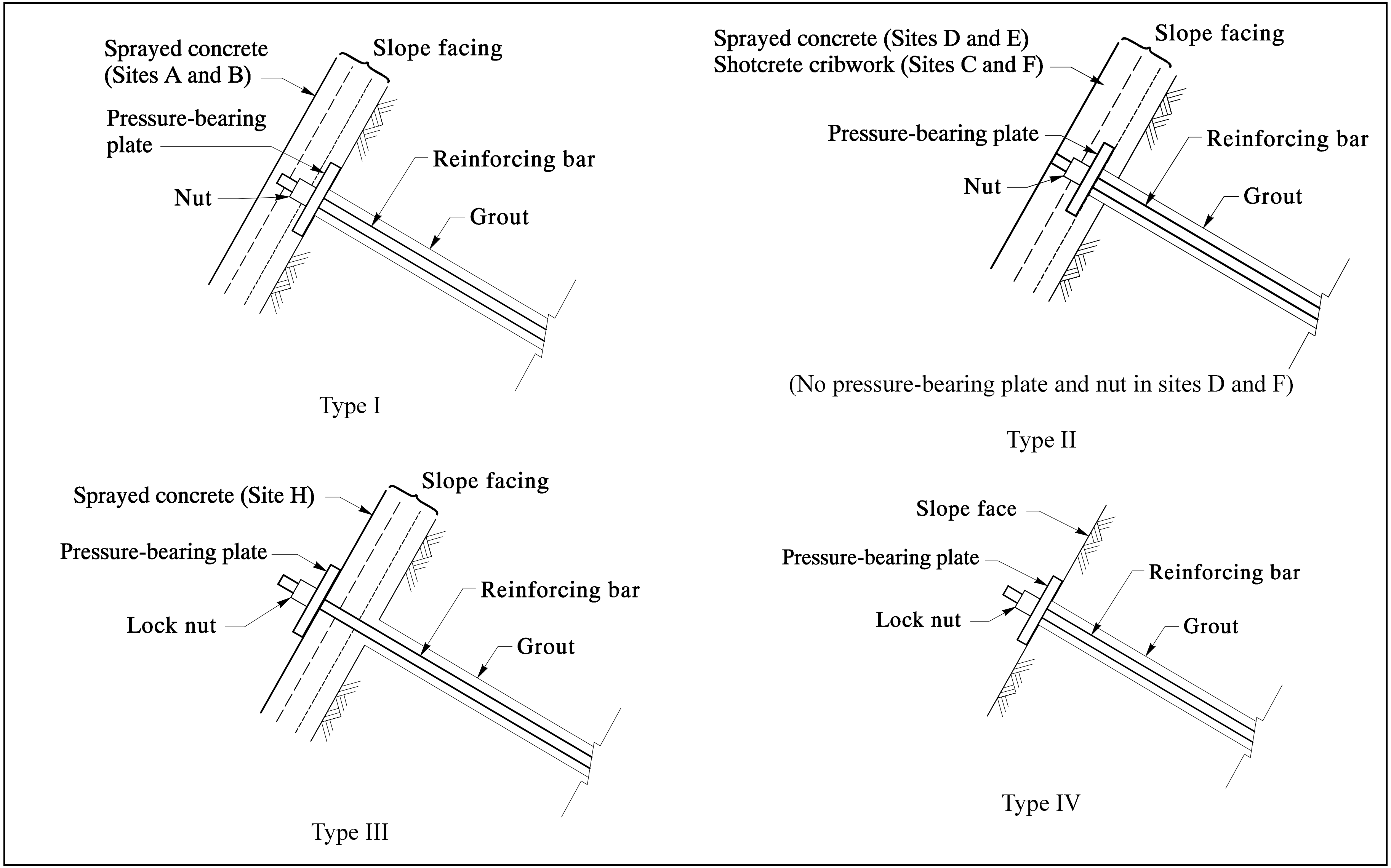

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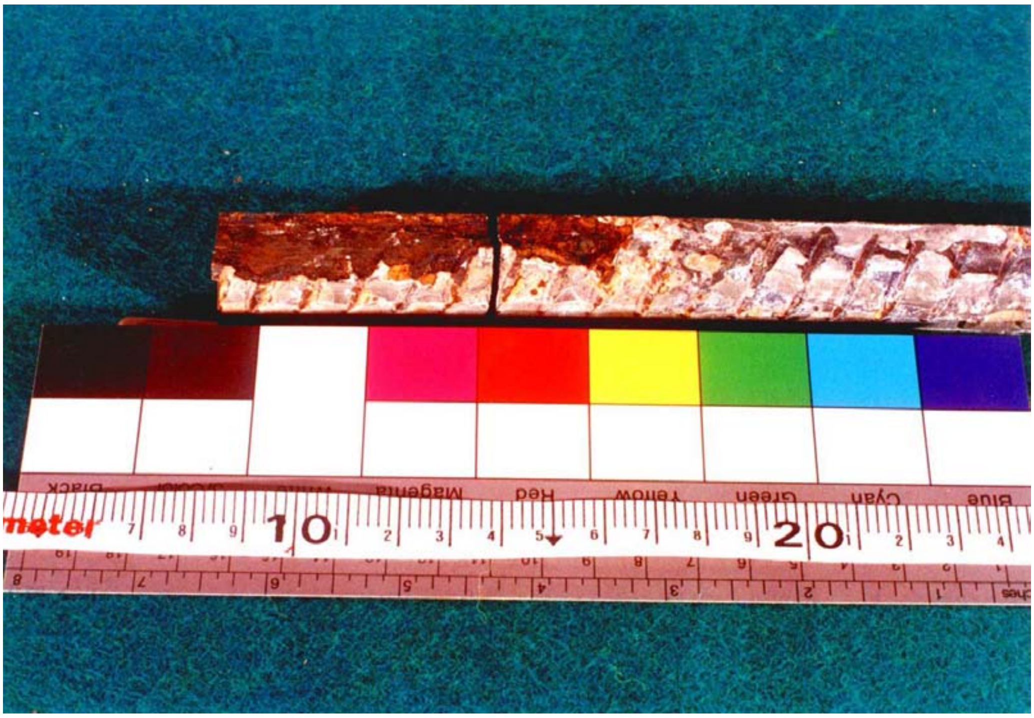

Plate 2 - General View of the Corroded Steel Bar

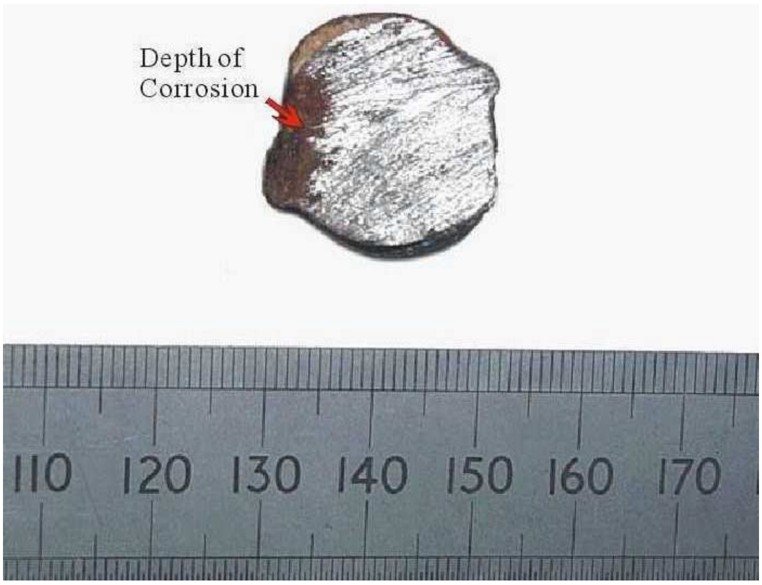

Plate 3 - Cross-sectional View of the Corroded Steel Bar

APPENDIX A

FACTORS AFFECTING THE CORROSIVITY OF SOILS

A.1 Physical Properties

The physical properties of soils that are of importance in soil corrosion are those which determine the permeability of the soil to air and water. Soils with a coarse texture such as sands and gravels permit free circulation of air and water. The corrosion under such conditions is broadly similar to that under exposure in the atmosphere. On the other hand, clayey and silty soils are generally characterized by a fine texture and high water-holding capacity, resulting in poor aeration and poor drainage. These characteristics tend to reduce general corrosion, but make local pitting of the steel more likely to occur and can as a result lead to increase in corrosion rate by keeping the surface wet longer. The pertinent physical soil properties include particle size distribution, Atterberg limits, moisture content, etc. According to King (1977), at 20% moisture content and below, the rate of diffusion of gaseous oxygen could be very high and could result in high corrosion rates. According to Elias (1997), when the moisture content of a soil is greater than 25 to 40%, the rate of general corrosion is increased. Below this value, pitting corrosion is more likely.

A.2 Soil Resistivity

Soil resistivity is defined as the inverse of electrical conductivity of the soil. This is a very important parameter in governing the corrosivity of a soil. It is a measure of the ability of a soil to act as an electrolyte and is related to the development of local corrosion cells as well as the ease of transmission of stray currents. In general, corrosion rate increases as resistivity decreases. However, if the resistivity is high, localized corrosion (pitting) rather than general corrosion is more likely to occur. The resistivity of a soil depends on a number of factors, in particular moisture content, salt content, compaction, temperature, etc.

A.3 Stray Current

Stray currents are present in the ground as a result of electrical leaks, transit rail systems or failure to provide positive and permanent electrical earthing. Stray currents can be an additional trigger of corrosion for a soil nailing system. In general, the effects of stray currents decrease rapidly with distance from the source and become negligible at a distance of about 30 to 60 m.

A.4 Redox Potential

The oxidation and reduction potential of a soil depends on the relative proportion of oxidizing and reducing agents in the soil. It indicates the tendency of a soil to support microbiological activity. The more reducing agents there are in the soil, the lower the level of oxygen and potentially greater the activity of sulphate reducers. Redox potentials are measured in field by measuring the potential of a platinum electrode using a calomel reference electrode.

A.5 pH Value

The soil pH value represents the hydrogen ion (H^+) concentration in solution in the soil water. Soil resistivity mentioned above indicates the ability of a soil to act as an electrolyte for electrochemical corrosion. However, corrosion can also be caused or enhanced by chemical attack and the pH value measurement is used to assess the attack potential. Soils that are extremely acidic (pH < 4) or strongly alkaline (pH > 10) are generally associated with significant corrosion rates.

A.6 Soluble Salts

The amount of dissolved inorganic solutes in the soil water is directly proportional to the solution’s electrolytic conductivity. This electrolytic conductivity is the sum of the individual equivalent ionic conductivities times their concentration. Most soluble salts are active participants in the corrosion process. Chlorides, sulphates and sulphides are identified as the major salts in promoting corrosion. However, carbonate is considered as a corrosion retarder, which forms an adherent scale on the metal surface and reduces corrosion rate.

A.7 Organic Matter

Miro-organisms also affect the chemical properties of a soil through oxidation and reduction reactions. Bacterial activities tend to decrease the oxygen content and replace oxygen with carbon dioxide. Thus, the microbial growth will convert organic matter in soils to organic acids, which when in contact with metal, produce pitting corrosion.

APPENDIX B

CORROSIVITY ASSESSMENT

B.1 Corrosivity Assessment Adopted by TRL in the UK (Murray, 1993)

Step 1: Determination of ranking mark.

The ranking mark of a soil is equal to the sum of marks determined from Table B1a below:

Table B1a - Soil Aggressivity Assessment (Sheet 1 of 2)

Item	Measured Value	Marks
Soil composition	Material containing not more than 10% of particles passing the 63 micron BS sieve size. The material passing the 425 micron BS sieve, when tested in accordance with BS 1377 shall have a plasticity index less than 2	+2
	Material containing not more than 75% and 10% of particles passing the 63 and 2 micron BS sieve sizes respectively. The material passing the 425 micron sieve, when tested in accordance with BS 1377, shall have a plasticity index less than 6	0
	Material for which the particles passing the 425 micron sieve, when tested in accordance with BS 1377, shall have a plasticity index less than 15	-2
	Material for which the particles passing the 425 micron sieve, when tested in accordance with BS 1377, shall have a plasticity index 15 or greater	-4
	Material having an organic content of 0.2% or greater	-4
Groundwater level at buried position	Well drained area	+1
	Poorly drained area	-1
	Above foundation level of structure	-4
Resistivity (ohm - cm)	10,000 or more	0
	10,000 - 3,000	-1
	3,000 - 1,000	-2
	1,000 - 100	-3
	100 or less	-4
Moisture content	20% or less	0
	more than 20%	-1
pH value	6 or more	0
	less than 6	-2
Soluble sulphate (ppm)	200 or less	0
	200 - 500	-1
	500 - 1,000	-2
	1,000 or more	-3
Cinder and coke or made ground	None	0
	Exist	-4

Table B1a - Soil Aggressivity Assessment (Sheet 2 of 2)

Item	Measured Value	Marks
Redox potential	+400 mV or more +400 - +200 +200 - 0 0 or less	+2 0 -2 -4
Presence of sulphate and hydrogen sulphide	None Trace Present High	0 -2 -3 -4
Presence of carbonate	Copious Present Trace	+2 +1 0
Chloride ion (ppm)	50 or less 50 - 250 250 - 500 500 or more	0 -1 -2 -4

Step 2: Classification of aggressivity of a soil.

The aggressivity of a soil can be classified into one of the following four categories according to the ranking mark obtained in Step 1.

Table B1b - Soil Aggressivity Based on Ranking Mark

Soil Condition	Ranking Mark
Unlikely to be aggressive	0 or higher
Mildly aggressive	-1 to -4
Aggressive	-5 to -10
Highly aggressive	-11 or less

Step 3: Determination of corrosion protection works.

The corrosion allowances correspond to a design life of 120 years as adopted in the design of reinforced fill structures. Figure 6 in the Report gives corrosion allowances for soil nails exposed to different soil conditions, for elapsed times varying from 0 to 120 years. However, the corrosion allowance for nails under highly aggressive conditions is not given. This is because permanent soil nailing under highly aggressive conditions is not recommended. In addition to the provision of a sacrificial steel thickness, the corrosion allowance of the zinc galvanization can be determined from Table 4 of the Report.

B.2 <u>Corrosivity Assessment Adopted in Recommendations Clouterre in France (French National Research Project, 1991)</u>

Step 1: Determination of corrosiveness index.

The corrosiveness index of a soil is determined in accordance with the Table below:

Table B2a - Soil Corrosiveness Index Assessment

Criterion	Features	Weight A of Criterion
Type of Soil	• Texture - heavy, plastic, sticky impermeable - clayey-sand - light, permeable, sandy, cohesionless soils • Peat and bog/marshlands • Industrial waste - clinker, cinders, coal - builders' waste (plaster, bricks) • Polluted liquids - waste water, industrial - water containing de-icing salts	 2 1 0 8 8 4 6 8
Resistivity	p < 1000 ohm-cm 1000 < p < 2000 2000 < p < 5000 5000 < p	5 3 2 0
Moisture content	Water table - brackish water (variable or permanent) Water table - pure water (variable or permanent) Above water table moist soil (water content > 20%) Above water table - dry soil (water content < 20%)	 8 4 2 0
pH value	< 4 4 - 5 5 - 6 > 6	4 3 2 0
	Index	Sum of the above : $\sum A$

Step 2: Determination of index C.

Index C is related to the purpose of the structure planned and the consequence of its failure. In practice, for critical structures index C should be greater than or equal to 2 (while the value of C is to be assigned by the designer, a value of 2 is the minimum recommended).

Examples of critical nailed structures include permanent structures of a height greater than or equal to 10 m and permanent structures the excessive deformation or failure of which might lead to large-scale damage. For non-critical structures, C is taken to be equal to 0.

Step 3: Determination of overall corrosivity index, I.

The overall corrosivity index, I, is equal to the sum of the corrosiveness index ΣA and index C as determined from Steps 1 and 2 above.

Step 4: Classification of corrosivity of a soil.

A soil can be classified into one of the following four categories of corrosivity according to the overall corrosivity index, I, obtained in Step 3.

Table B2b - Classification of soil corrosivity

Soil Condition	Overall Corrosivity Index, I
Slightly corrosive	< 4
Average corrosiveness	5 to 8
Corrosive	9 to 12
Highly corrosive	> 13

Step 5: Design of corrosion protection works.

The corrosion allowances for various periods of design life and levels of soil corrosivity are given of Table 5 of this Report. Basically, they include provision of sacrificial steel thickness and/or provision of plastic sheath.

B.3 Aggressivity Assessment Adopted by FHWA in the USA (Byrne et al, 1998)

Step 1: Classification of aggressivity of a soil.

A soil is classified as aggressive if any one of the aggressiveness indicators reaches the following critical values:

Table B3a - Classification of Soil Aggressivity

Soil Property	Critical Value
Resistivity	below 2,000 ohm-cm
pH value	below 5
Sulphate	above 200 ppm
Chloride	above 100 ppm

Step 2: Design of corrosion protection works.

The corrosion allowances for various periods of design life and levels of aggressivity are given in Table 6 of this Report.