DURABILITY OF MATERIALS USED IN DIFFERENT ENVIROINMENTS FOR SOIL NAILS


“Tony Barley and Dr Devon Mothersille prepared this paper for publication during 2002/2003. It was first published on this internet in early August 2004. Both authors were invited onto the CIRIA committee for the preparation of CIRIA C 637 “Soil nailing – best practice guideline”

This paper contributed to the first draft of the first CIRIA report. Further work by Barley, Mothersille and much by Alan Phear précised, cut and pasted and the amended original Barley/Mothersille document for incorporation in Section 9 of “Degradation and Durability” of CIRIA C 637. The attached document presents more information than that in the CIRIA document and in a somewhat different format”.
CONTENTS

1.0 Introduction
1.1 Consequential effect of failure
1.1.1 Soil nails in high risk category
1.1.2 Soil nails in medium risk category
1.1.3 Soil nails in low risk category
2.0 Materials – Degradation and Durability
2.1 Introduction
2.2 Uncoated Steel
2.3 Coated Steel
2.3.1 Galvanic Coating
2.3.2 Epoxy Coating
2.4 Stainless steel
2.4.1 Introduction
2.4.2 Selection of the Most Suitable Stainless Steel
2.4.3 Types of corrosion
2.4.4 Experiences with Stainless Steel in the Ground
2.4.5 Three Percent Salt Immersion
2.4.6 Summary
2.5 Composites
2.5.1 Introduction
2.5.2 Resin Types
2.5.3 Fibres Types
2.5.4 Glass Fibres
2.5.5 Carbon Fibres
2.5.6 Aramid Fibres
2.5.7 Durability Testing
2.6 Durability and Degradation of Soil Nail Systems
2.6.1 Steel Nails Directly Within Soil Mass
2.6.2 Coated Steel Placed Directly Within Soil Mass
2.6.3 Steel Surrounded by Cement Grout
2.6.4 Coated Steel Surrounded by Cement Grout
2.6.5 Composites surrounded by cement grout
2.6.6 Stainless Steel surrounded by cement grout
2.6.7 Steel Surrounded by Grouted Impermeable Ducting
2.6.8 Double Corrosion Protection
3.0 Observation and Exhumation
3.1 Case studies in Japan
3.2 Case studies in Hong Kong
3.3 Observations in Singapore
3.4 Observations at Stansted
4.0 Nail heads
5.0 Summary
5.1 Cost and Durability
5.2 Categorisation/Recommendations
1.0 Introduction

Early usage of soil nails in the UK for slope stabilisation generally adopted a conservative approach by the installation of a relative high density of soil nails at close spacing. This ensured a high degree of redundancy such that in the event of failure of a scatter of individual nails the collapse of the slope would be prevented. This conservatism appeared to allow some reduction in the quality requirement of the nails and also the extent of testing of the nail bond capacity.

Increase in soil nail usage lead to conflicting opinions with regard to tolerance of nail corrosion or corrosion protection requirement. One school of thought maintained the safety in number approach with minimum or zero protection, others favoured the incorporation of corrosion protected steel tendons or non-corrodible composite tendons incorporating a lower nail density. However at this time no guidelines had been published to provide Geotechnical Engineers with clear recommendations relating nail quality and nail testing requirements to the consequential effects of slope or face failure.

The British Standard Code of Practice for Strengthened/Reinforced Soils and Other Fills (BS8006) published in 1995 presented categorised levels of risk. (Table One) – Categories of “Low”, “Medium” and “High” provided a classification of the consequences of failure of the reinforced soil structure and related these to the “probability of hazard”. The hazard identifies the potential of loss of life, loss of transportation services, or of utility services in the event of failure. However the Code did not extend its recommendations to address the suitability of nail tendon systems in relation to the specified categories.

This paper endeavours to provide information which identifies factors that contribute the risk of corrosion of steel, coated steel and stainless steel and to the degradation of composite tendons. It then summarises the modes of enhancement of durability of steel and composite tendons and provides information on the cost differences associated with the use of each system. Finally it provides guidance to the suitability of systems appropriate for use in mild and aggressive soil environments in the “Low”, “Medium” and “High” risk categories.

Most UK soils nails are located in part saturated soils, often subject to seepage and seasonal variations in water content and atmospheric exposure creating environmental conditions which may favour corrosion. The durability of a soil nail tendon and its associated components is highly variable and is primarily influenced by the above and the aggressivity of the soil mass into which it is placed. Based on case histories and research, it is probable that the lifespan of an exposed nail, a grout covered nail or a nail isolated by coating or ducts would vary from several months to more than 120 years.

To date, recommendations relating to the choice of soil nail members and components have frequently been influenced by commercial marketing and even the modern codes (Euro Code EN 14491 and BS 8006) have not provided clarification as to what is fit for the purpose and clear identification of purpose, risk and lifespan requirements. Fitness for the purpose demands an intricate knowledge of the soil nail structure, the
soil itself and ground water conditions into which the nails are installed. Also, required is a knowledge of potential changes in surrounding conditions during the design life due to slope movement increasing permeability, fluid entry and change in aggressivity.

In a case where steel soil nails are installed unprotected then some degradation and corrosion may be expected. Unless degradation and some risk of failure can be tolerated, confidence in the understanding of the corrosion rate, the loss of section, the uniformity or non-uniformity of the loss of section is required. Furthermore it should be understood that the rust product formed around the steel member may have a volume expanded up to seven times that of the corroded steel volume. This change of stress field may have serious effects on the long term nail bond capacity even through tensile capacity may be maintained. In the case where the adequacy of the major member and components (couplers) are enhanced by coating or isolation from the environment then the rate of degradation of the protection barriers must also be understood and the effects on the contained materials in the event of coating breakdown.

Composite materials are available as high capacity tensile members and are formed from materials (fibres) of wide range that may or may not sustain degradation in their ground or cement environment. Unfortunately members are generally high in tensile capacity and low in shear and bending. Therefore an understanding of the degradation of the members subject to tensile load and, where appropriate to shear and bending are required.

The above briefly summarises the range of commercially developed soil nails and protective measures available to the industry; some simple, some complex, some stiff, some flexible, some for rapid installation, some for slower installation, the price range varies enormously, probably by a factor in the order of 5.

So what controls our choice and our recommendations relating to the type soil nail to be implemented on any given project. There are basic criteria which govern the choice of any soil nailing ground support system. These may generally be simplified into:

a) Degree of durability or of limited guaranteed durability
b) Installation rates (economy)
c) Tests and performance criteria
d) Consequential effects of failure of the soil nail slope or face
e) Lifespan requirements of the soil nail face or structure

1.2 Consequential effect of failure

Although not always easily definable, slopes and faces upon which the consequences of failure are considered high might involve major breakdown of services and/or loss of life i.e. high cuttings and slopes above motorways, rail tracks and deep foundations. Such structures may be those that a decade ago would have been stabilised by double corrosion protected ground anchorages and not soil nails. However, the fitness of the purpose of the retention system must be proven and compatible for both systems. Furthermore, these circumstances may demand a combination of soil nails and ground
anchorages for overall stability and the ability to apply prestress to the active soil zone - hybrid stressable anchor nails are now available.

In the case of high cuttings and slopes, the consequences of serious failure may be reduced by a reduction in the slope angle or by construction of benches. These measures may prevent a full face serious collapse or to reduce incidents to small failures of proportions in which rapid remedial measures may be executed. This may reduce the consequences of failure to a medium risk position. The selection of retention schemes in the medium risk category is difficult to identify accurately and may be best identified by firstly investigating slopes and failures where consequences of collapse are negligible or low or slope movement can be detected and remedial works promptly addressed.

Over recent years much use of soil nailing techniques may be identified as low risk;

a) Slope faces and cuttings up to 4m or 5m in height where failure would tend to be by spalling or shallow slippage and areas are available below slope/cutting on to which slip volumes can be safely deposited without impedance of services (e.g. lay-bys or in some cases hard shoulders).

b) Slopes that have low usage benches on which on which slip materials can be temporarily and safely deposited.

c) Embankments where past usage has been satisfactory; the major defect surface being merely surface settlement (road or rail). The characteristics of further settlement could be identified and remedial supplementary measures taken. Based on these, assessment the type of soil nail available to facilitate the support requirements may be reasonably recommended (no doubt with much commercial based controversy).

1.2.1 Soil Nails in High Risk Categories

It is likely that a decade ago the retention of faces with high slopes in aggressive ground, or where the consequences of failure was loss of life or destruction of services that permanent ground anchors would be specified. Such anchorages would be need to comply with the BS 8081:1989 which would have incorporated severe testing to demonstrate good long-term performance, durability and load holding capacity.

The use of soil nails in such circumstances should provide a system of comparable integrity. The proposed system would be required to incorporate fully isolation of the steel member from the environment throughout its length (including couplers where appropriate). Systems which isolate the tendon by grout encapsulation only should be subject to investigation of crack patterns which occur within the grout as a consequence of normal outward and downward movement of the soil i.e. non-axial loading. In such circumstances the presence of couplers with low grout cover and with a different stiffness from the remaining tendon plus an end bearing load transfer component may particularly attract extensive cracking and breakdown in the integrity of the grout column.

For composite materials the durability of fibre reinforced vinylester have been indicated as having a high resistance to degradation such that a 120year lifespan may
be realistic. However, the subjecting of such composite materials to axial and non-
axial loading whilst surrounded in grout should be investigated.

1.2.2 Soil Nails in Medium Risk Categories

Use in this category should incorporate members in which loss of section is 
accommodated in the design; coatings of adequate longevity are applied and grout 
cover is designed and demonstrated to be adequate to protect a steel member. Where 
soil nails are coated or grout encapsulated, the accommodation of calculated loss of 
section after failure of the primary protection system may be acceptable.

The use of medium term degradable components such as polyester resin based 
composite tendons may be suitable but further investigations on the nature of 
degradation may be required.

1.2.3 Soil Nails in Low Risk Categories

Tensile members that can demonstrate adequacy of tensile capacity and bond capacity 
in both active and resistant zones may be appropriate for temporary works soil nails 
subject to allowances for a nominal loss of section during the life span. Temporary 
removable soil nails would also fall into this category. In this range the use of cement 
grout may be considered solely as a loads transfer medium and the steel protection 
measure provided by its alkalinity considered as a benefit but not a requirement.
2.0 Materials – Degradation and Durability

2.1 Introduction

The range of environmental conditions to which an in-situ soil nailed structure may be subjected during its service life is extensive. The condition encountered within the buried nail components and by the surface nail components will inevitably be considerably different.

The conditions which exist at the time of construction may be determined with some accuracy; the accuracy being related to that specified for preliminary and on-going investigations. However the conditions which may exist due to environmental changes during the life of the nailed structure may be difficult to predict. In the latter situation it is not unusual to err on the side of caution.

Attempts have been made to identify relatively common environmental conditions which may be reasonably predicted in buried nails:

- a) Nails within a relatively homogenous soil with low salt content and benign water condition.
- b) Nails passing through part saturated soils;
- c) Nails passing through zones of fluctuating ground water levels;
- d) Nails passing through strata of differing character with regard to chemical composition and differences in water or gas content;
- e) Nails installed in saturated clays with low oxygen content and high sulphate content;
- f) Nails exposed to sea-water, or saline ground conditions;
- g) Nails installed in soils, located in the vicinity of chemical factories that have corrosive effluents or are subject to a corrosive atmosphere;

In UK soil conditions it is rare to encounter homogenous soil of adequate depth to contain multiple levels of soil nails. In layered strata it is appropriate to consider the worst encountered condition and provide the same protection system for each level of nails.

It should be appreciated that the existence of a slope necessitating nail usage or the construction of steep faces retained by soil nails, both require movement within the soil mass to mobilise nail loads. Thus it is inevitable that the soil mass will become fissured and more permeable.

In certain situations the soil nail head contributes little to the overall stability, the tying of the active zone to the passive zone being the major contributory factor of the nail. This generally occurs in shallow slopes. As the slope angle increases the nail head contribution increases: initially retaining geogrids, and finally retaining face plates on near vertical structures. Thus the integrity of the corrosion protection at the nail head may, when appropriate, be less stringent than the requirement of the buried nail. The protection offered by the nail head and plate should include that provided below the faceplate - a particularly vulnerable and hidden part of a nail retained structure.
Nail head protection or condition has one particular advantage over that of the buried nail: the nail head can generally be seen and its long-term condition observed.

At the exposed soil nail head the performance of the head components is influenced by a number of factors which, depending on their severity can markedly affect the durability of the soil nail head components. Consideration should be given to the following conditions when selecting a nail head its coating or its encapsulation:

a) Dry atmosphere with relatively constant temperature
b) Moderate humidity with small range of temperature variation
c) High humidity environment with large range of temperature variation
d) Its exposure to run-off water, drainage or seepage.
e) Its complete encapsulation in concrete.

2.1 Uncoated Steel

Exposure to combinations of oxygen and chlorides, anaerobic conditions in presence of sulphates or severely fluctuating and high stress levels all increase the rate of corrosion. These circumstances are not comprehensive and may vary;

- Temporary reinforcing steel elements should normally be expected to last two years in benign conditions (BS8081:1989) and this period should be regarded as the limit for such elements in any circumstances. In very aggressive conditions or where there is a risk of local damage or corrosion by pitting, unprotected reinforcing elements may last only a few weeks.

- It is noteworthy that Recommendations Clouterre – 1991 specifies three definitions for the longevity of soil nails:
  a) Short-term – service life less than or equal to 18 months
  b) Medium-term – service life between 18 months and 30 years
  c) Long-term – service life between 30 and 100 years

- Where practicable, corrosion history of buried metals in the vicinity of the proposed works should be established. This can sometimes serve as a useful guide to the degree of protection required.

The use of a sacrificial thickness of steel as a form of protection is a philosophy that has attracted conflicting views; at one extreme clause 8.2.3 of BS8081:1989 states that the use of thicker metal sections for the tendon, with sacrificial area in lieu of physical barriers, gives no effective protection, as corrosion is rarely uniform and extends most rapidly and preferentially at localised pits or surface irregularities. This is in stark contrast to the view put forward in the European Standard prEN 14490: 2002(E). Section A.4.3.3 states that the concept relies on the cross section of the reinforcing element and other components being over-dimensional to allow for corrosion. The predicted thickness loss due to corrosion is based on historical data taken from nails, sheet piling and corrugated buried steel structures installed in similar environments with varying levels of soil aggressivity.
Whilst there appears to be a conflict of view between these standards it should be borne in mind that BS 8081:1989 refers primarily to steel tendons with high carbon content and which are subjected to prestress loading as would be required in ground anchorage technology. These conditions require a more cautious approach to the provision of corrosion protection. Soil nails generally utilise steel tendons with low carbon content that are not prestressed albeit become stressed owing to ground movement.

The code of practice for strengthened/reinforced soils, BS 8006:1995 covers soil nailing to a very limited extent and does not specify the corrosion protection provision for drilled and grouted nails. However, Section 3.2.2.2. permits non-structural sacrificial thickness to be allowed on the surface of steel elements exposed to corrosion.

The concept described above should be applied to temporary soil nails where ground conditions are not aggressive and the time span is judged to be short term (i.e. less those 18 months).

Where circumstances exist that require the use of soil nails as a permanent feature of the structure then the usage of the sacrificial loss of section concept should be limited to Category I structures and where soil conditions are not aggressive. As a general rule the method is not recommended for soil nail tendons with small cross sectional area or for steels with high carbon content. Furthermore the Euro code EN 14490 recommends that the sacrificial steel concept should generally used for soils nails where the percentage loss of cross section does not exceed half of its initial cross section and where nails are installed at fairly close centres and a degree of redundancy exists.

Recommendations Clouterre 1991 provides guidance on the design of additional thickness of steel required when sizing unprotected tendons. Three indices are identified:

1. Index covering the classification of the structure involved. Two types of structure are identified; the first are critical structures (slopes greater than 10m high, structures supporting high surcharges, structures where deformations may lead to wide-spread damage and structures in aggressive environments. The second type are termed standard structures and these are soil nailed walls that do not have any of the previously mentioned characteristics.

2. Index covering the classification of soils according to their aggressivity

3. An overall index which encompasses (1) and (2).
A summary of the classification system can be found in Tables 2.1, 2.2 and 2.3

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Features</th>
<th>Weight A of Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of soil</td>
<td>Texture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Heavy, plastic sticky impermeable</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>• Clayey-sand</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>• Light, permeable, sandy, cohesion less soils</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Peat and bog/marshlands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industrial waste:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Clinker, cinders, coal</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>• Builders’ waste (plastic, bricks)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Polluted liquids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Waste water, industrial</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>• Water containing de-icing salts</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>P &lt; 1000 Ω cm</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1000 &lt; p &lt; 2000</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2000 &lt; p &lt; 5000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5000 &lt; p</td>
<td>0</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Water table – brackish water (variable or permanent)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Water table – pure water (variable or permanent)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Above water table moist soil (water content &gt; 20%)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Above water table – dry soil (water content &lt; 20%)</td>
<td>0</td>
</tr>
<tr>
<td>pH</td>
<td>&lt; 4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4 to 5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5 to 6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>&gt; 6</td>
<td>0</td>
</tr>
<tr>
<td>Table 2.1 Overall corrosiveness indexes (Recommendations Clouterre- 1991)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Index No. (A)</td>
<td>Soil Feature</td>
<td>Classification</td>
</tr>
<tr>
<td>&lt;13</td>
<td>Highly corrosive</td>
<td>I</td>
</tr>
<tr>
<td>9 to12</td>
<td>Corrosive</td>
<td>II</td>
</tr>
<tr>
<td>5 to 8</td>
<td>Average corrosiveness</td>
<td>III</td>
</tr>
<tr>
<td>&lt; 4</td>
<td>Slightly corrosive</td>
<td>IV</td>
</tr>
</tbody>
</table>

Table 2.2 Allocating index No. and classification to soil features (Recommendations Clouterre -1991)
<table>
<thead>
<tr>
<th>Index No./Classification</th>
<th>Short-term ≤ 18 months</th>
<th>Medium-term 1.5 to ≤ 30 years</th>
<th>Long-term 30 to ≤ 100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 4/IV</td>
<td>0</td>
<td>2mm</td>
<td>4mm</td>
</tr>
<tr>
<td>5 to 8/III</td>
<td>0</td>
<td>4mm</td>
<td>8mm</td>
</tr>
<tr>
<td>9 to 12/II</td>
<td>2mm</td>
<td>8mm</td>
<td>plastic sheath</td>
</tr>
<tr>
<td>≤13/I</td>
<td></td>
<td></td>
<td>Protective plastic sheath must be provided</td>
</tr>
</tbody>
</table>

Table 2.3 Thickness of steel sacrificed to corrosion (Recommendations Clouterre – 1991)

2.2 Coated steel

2.3.1 Galvanic Coating

Probably the most extensive investigative work relating to the degradation of buried steel took place in the USA commencing in 1910. This research related generally to galvanised coated steel pipes but occasionally to bare steel pipes. Other investigative work has been carried out relating to galvanised coated steel in the UK, France and Sweden. This data has recently been studied and summarised by Shiu and Cheung (2002).

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). 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.

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).

\[ X = Kt^n \]  

where \( t \) is time in years, \( X \) is the depth of general corrosion or pit depth in \( \mu m \) 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 \( \mu m \) (Elias, 1997). For galvanized steels, "\( K \)" constants in the range between 5 and 70 \( \mu m \) 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:

\[ X = 25t^{0.65} \] (Average) ........................................... (2)
\[ X = 50t^{0.65} \] (Maximum) ........................................... (3)

and the following equations for corrosion loss of carbon steel:

\[ X = 40t^{0.80} \] (Average) ........................................... (4)
\[ X = 80t^{0.80} \] (Maximum) ........................................... (5)

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

- Zinc corrosion rate for the first two years: 15 \( \mu m/yr \)
- Zinc corrosion to depletion: 4 \( \mu m/yr \)
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 3CCUTS than a los 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-inc 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/m2 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 (Am 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.

Relating more specifically to galvanised soil nails, Recommendations Clouterre 1991 highlights the following:

- This type of protection is currently in low demand in soil nailed structures. The principle is as follows: In the case of galvanized steel, the corrosion by-products of zinc (zinc hydroxides in particular) initially form a protective screen. The zinc coating initially delays the appearance of any corrosion in the steel and, subsequently, slows its development once the zinc has been transformed to dry oxide.
• Zinc is more highly electronegative than steel. If steel is unprotected in places (as a result of accidental damage during handling or because of deterioration caused by corrosion), it forms an electrochemical battery and any adjacent zinc is "sacrificed" in order to protect the iron. As a result of the phenomenon of spontaneous cathodic protection, the zinc also assures some uniformity of corrosion.

• The thickness of the zinc must be sufficient (80 µm minimum) to guarantee efficient protection, but not too thick because it must adhere to the steel properly. Whatever the circumstances, the zinc coating must conform to the French Standard NFA 91121- Hot Galvanizing (Galvanization a chaud).

• However, zinc protection, albeit readily valid in principle, has not yet had the benefit of being widely used in the area of soil nailing. Also, it requires that the same type of steel be used throughout the structure, particularly when it comes to anchorage heads and connecting sleeves (thread). There is also serious risk of damage during installation, particularly for driven nails.

2.3.2 Epoxy coating

Epoxy coating corrosion protection consists of a fusion-bonded epoxy coating applied to the tendon prior to delivery to the construction site. The minimum required thickness of epoxy coating will typically be specified in the contract documents. The FHWA manual (1994) suggests that a minimum thickness of 0.3mm is commonly used in USA practice. Bearing plates and nuts that will be encased in a structural wall facing will be protected by the concrete cover, and typically are not epoxy coated.

In reviewing the historical use of epoxy-coated strand in USA dams Bruce (2003) found that attention to fabrication details are essential for production dependability. The main source of failures resulted from problems of epoxy adhesion to the steel and it was recommended that this should be an area targeted in future research.

The NCE (November 1998) reported that many reinforced concrete bridges in the US have suffered from chronic corrosion through de-icing salts. In attempts to counter the problem, US maintenance authorities had used 200000t of epoxy coated steel rebar in bridge decks since 1987.

2.4 Stainless steel

2.4.1 Introduction

Type 304 and 316 stainless steels are common and readily available steels regularly used for geotechnical applications, they offer the economic combination of performance and life cycle costing. They are available in most types of tendon, coarse threaded bar and as stainless steel rebar and are generally used throughout the soil nailing industry.
All stainless steel has a minimum of 12% chromium, however Type 304 stainless steel contains 17% and 10% nickel and is regarded as the work horse of stainless steels with a wide range of applications. Despite this, experience has shown (Shaffer et al 1994) that it is subject to crevice corrosion and pitting in chloride environment and is susceptible to stress corrosion cracking in some chloride environments at temperatures above 50°C. Although these limitations were not expected to have an impact on ground reinforcement technology it became apparent through both laboratory and field experience with Type 304 that some environments would require even more corrosion resistant materials for permanent rock reinforcement. Development moved from type 304 to Type 306, containing 17% chromium, 11% nickel and 2.5% molybdenum providing greater resistance to pitting, to sulphuric acid and to stress-corrosion cracking. Type 316 also has substantially higher strength in the annealed condition than Type 304.

A benefit not often discussed with the use of stainless steel is its inherent elasticity, in the un-processed state, i.e. low mechanical strengths with the elongation at failure in the region of 40%. Even heavily cold worked (high strength) material will have elongation at failure in the region of 20%. This aspect should be born in mind when mobilising the passive force in the nail and when used as a soil nail or rock bolt in an earthquake sensitive design.

2.4.2 Selection of the Most Suitable Stainless Steel

The relative corrosive nature of some construction sites are such that no single stainless steel grade will cater for every condition so it is reasonable to adopt the following for application. However if the soil analysis can prepare a corrosive index it is possible to make more accurate suggestions. Such proposals are based on the atmospheric conditions in a particular area, which is a reasonable assumption since as the soil profile often reflects the areas atmosphere.
<table>
<thead>
<tr>
<th>Grade</th>
<th>BS EN 10088</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>304 S 31</td>
<td>1.4301</td>
</tr>
<tr>
<td>2</td>
<td>316 S 31</td>
<td>1.4401</td>
</tr>
<tr>
<td>3</td>
<td>Duplex</td>
<td>1.4462</td>
</tr>
</tbody>
</table>

It should be noted that Duplex bars are only generally available to special order.

### 2.4.3 Types of Corrosion

There are four main types of corrosion which may affect stainless steel in a Civil / Geotechnical environment.

- **General corrosion**
  
  This will only take place on a stainless steel nail when the environment is sufficiently acidic; this is most unlikely in a geotechnical or civil environment. (except some severe mining or industrial applications.)

- **Intergranular corrosion**
  
  This will occur particularly after welding, when structural changes occur in the steel, due to the welding process, however Stainless’, which are to be welded, are now specially alloyed to overcome this problem.

- **Stress Corrosion**
  
  For stress corrosion to occur a series of specific conditions need to be present, Chloride irons, elevated temperature (>60°C) High relative stress levels, and pH levels. For geotechnical applications the stress levels are relatively low and the temperature is rarely at such a temperature, so Stress Corrosion is a rare occurrence.

- **Pitting and Crevice Corrosion**
  
  This is the most evident form of corrosion of stainless steel this increases with increasing chloride ions, and should be considered where the nail my be used in a marine environment or anywhere that road salts may be a problem. The resistance of the various steels can be easily compared with reference to the Pitting Resistance number, (PRN), which is a function of the main constituents of the steel.
### Pitting Resistance Numbers (PRN):

<table>
<thead>
<tr>
<th>Number</th>
<th>Material Type</th>
<th>PRN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4003</td>
<td>3Cr12 type of material</td>
<td>Ferritic 11</td>
</tr>
<tr>
<td>1.4301</td>
<td>304 S 31</td>
<td>Austenitic 18</td>
</tr>
<tr>
<td>1.4401</td>
<td>316 S 31</td>
<td>Austenitic 24</td>
</tr>
<tr>
<td>1.4429</td>
<td>Highproof</td>
<td>Austenitic 24</td>
</tr>
</tbody>
</table>

The following tables guide the selection of stainless steel anchors and nails

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rural</td>
</tr>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td>304 S31 / 304L 1.4306</td>
<td>▲</td>
</tr>
<tr>
<td>31631 / 316L / 1.4401</td>
<td>O</td>
</tr>
<tr>
<td>1.4462 / Duplex</td>
<td>O</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Least corrosive conditions within that category, e.g. tempered by low humidity, low temperatures</td>
</tr>
<tr>
<td>M</td>
<td>Fairly typical of that category</td>
</tr>
<tr>
<td>H</td>
<td>Corrosion likely to be higher than typical for that category, e.g. increased by persistent high humidity, high ambient temperatures, particularly aggressive pollutants.</td>
</tr>
<tr>
<td>O</td>
<td>Potentially over specified from a corrosion point of view.</td>
</tr>
<tr>
<td>▲</td>
<td>Optimum choice for corrosion considerations</td>
</tr>
<tr>
<td>X</td>
<td>Likely to suffer from corrosion</td>
</tr>
<tr>
<td>(▲)</td>
<td>Worthy of consideration if precaution are taken, specifying smooth machined surface etc.</td>
</tr>
</tbody>
</table>
2.4.4 Experiences with Stainless Steel in the Ground

Several studies have been completed investigating the use of stainless steel in the ground and the comparative performance of the various stainless steels, some of the comparisons have been in sea water and the atmosphere, whilst the absolute performance of the steel may change with the embedment in the ground the relative performance of each type of steel is still valuable.

Atmospheric pitting corrosion rates on unwashed sheltered stainless steel

<table>
<thead>
<tr>
<th>Geographical site</th>
<th>Estimated time to penetration 1mm (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade 409</td>
</tr>
<tr>
<td></td>
<td>1.4512</td>
</tr>
<tr>
<td>Marine</td>
<td>5</td>
</tr>
<tr>
<td>Semi – industrial</td>
<td>85*</td>
</tr>
<tr>
<td>Rural</td>
<td>65</td>
</tr>
</tbody>
</table>

*Dull polish; others Mill finishes
Avesta E&OE
Status of document unknown

Note: Ferritic stainless is not recommended for geotechnical applications. See photographs of bar

The Nickel Development Institute has completed a series of tests to prove the suitability of stainless steel when used in the ground, this work, completed at BAM, Germany has studied the three rebar materials.

Exposure tests were carried out on partially embedded bar in a range of ground water environments. In all cases some sulphide ions were present.

Tests were carried out in the stressed and unstressed condition for 1000hr; No corrosion was observed on any of the stainless materials in any of the environments.

Subsequent tests in synthetic sea water did show some corrosion of the 304LN and the duplex alloy 2304. No corrosion occurred on the 316LN. The studies are continuing.

Results to date from these studies indicate that from a corrosion point of view stainless steel ground anchors and soil nails are a viable proposition in the severest of ground waters e.g. natural seawater.
<table>
<thead>
<tr>
<th>Ferritic stainless</th>
<th>3Cr12</th>
<th>1.4401</th>
<th>1.4436</th>
<th>Duplex 1.4462</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic Stainless</td>
<td>Nuovinox Austenitic stainless</td>
<td>Austenitic Stainless</td>
<td>Stainless test duration 2 months</td>
<td></td>
</tr>
</tbody>
</table>

Plate 2.4.4. Six types of stainless steel bars illustrating a range of capacities of corrosion resistance and durability
2.4.5 Three Percent Salt Immersion

Of the samples which have been immersed in a 3 % (by weight) salt solution, for 22 months none of the austenitic samples showed any evidence of bulk corrosion or pitting. Whilst this is not a highly scientific study it is a relevant comparison of performance.

1. 400 range Ferritic steel
2. 3Cr 12 Ferritic steel
3. Nuovinox 1.4401 stainless clad steel bar (only available as a reinforcing bar)
4. 1.4301 Austenitic steel
5. 1.4401 Austenitic steel

2.5.6 Summary

It is believed that the range of stainless steel and nickel alloy and soil nails are especially suitable for permanent stabilisation.

The corrosivity of sites will vary significantly, and the selection of the lowest-cost corrosion-resistant alloy suitable for long-term service at a given site may be problematic. However experience has shown that a corrosivity assessment procedure, in which the performance of several stainless materials for permanent service at a specific site can be determined quickly and economically by using a computerised corrosion engineering guide, developed by the Nickel Development Institute.
2.5 Composites

2.5.1 Introduction

Composite tendons, for use in soil nailing technology, comprise a combination of stiff strong fibres embedded in a resin matrix. The fibres are designed to accommodate the desired loads and the matrix to protect the fibres from mechanical and environmental damage.

Four key factors associated with the performance of composite soil nail elements are:

- **Strength**: the element must be of sufficient strength to sustain the force required for the tensile member.
- **Stiffness**: the element must be sufficiently stiff to ensure that the required force is mobilised at a strain compatible with the allowable soil and structural deformation - consider both the initial and long-term stiffness and creep.
- **Durability**: the influence of both environmental conditions and chemical aggressivity should be assessed – including the likely effects of the cement grout on the geotextile reinforcement element.
- **Bond**: the interfacial bond stresses developed must be sufficient to sustain adequate resistance to pull-out.

Composites are typically manufactured using the pultrusion process. In this process the resin matrix is combined with the dry fibre reinforcements. Continuous fibre reinforcements are drawn through a resin bath, which coats each fibre with resin and in certain circumstances with a synthetic veil to provide a resin rich layer for added protection against weathering. The coated fibres are preformed and then drawn through a heated die. Curing of the resin is initiated thermostatically by the heat of the die and enhanced by catalytic action in the resin.

The composite product profile can be produced within the die and the end product is drawn out continuously using reciprocating pullers or a caterpillar haul off system. The controlled nature of the process ensures consistent properties and good tolerance of the product dimensions.

Surface roughness can be achieved by externally sleeving the product throughout the pull-out process. The sleeve can then be stripped off the bar leaving a roughened bar face to enhance interfacial bonding (Plate8.3.5.A).

It is a commonly held view that any material placed in the ground will suffer some from of degradation given time. With composite soil nails there are three primary components that influence durability:

- The matrix
- The fibres
- The fibre/matrix interface
Each of these components are susceptible to attack by various environmental agents and for optimum performance all three elements should retain integrity throughout the design life of the soil nail. Despite this, it is the matrix that must provide a barrier to the environment and offer sufficient resistance to alkalis and chlorides. The choice of resin matrix, the reinforcement type and construction determines the degree of corrosion resistance allowing products to be tailored to exactly suit their operational requirements.

External factors which may influence the effectiveness of this protection include:

- Nature of the environment (pH, molarity)
- Stress on the composite
- Temperature
- Condition of composite (cut ends, damage etc.)
- Quality of composite (surface finish, voids, resin homogeneity)
- Exposure to UV light

Plate 2.5.1 The Sleeve can be stripped off the bar leaving a roughened bar face (courtesy of Weldgrip Ltd)
2.5.2 Resin types

There are currently three different types of resin used in the manufacture of composite soil nails;

- **Polyester resin** – provides good mechanical resistance and electrical properties coupled with reasonable chemical resistance.

- **Epoxy resin** – provides better resistance to alkalis and solvents than polyesters but slightly poorer weathering resistance. The curing process requires a greater degree of control when compared to polyesters. Epoxy resins are 2 –5 times the price of polyester resins.

- **Vinylesters** – have chemical similarities to epoxy resin with the curing mechanism of a polyester resin. Cost and mechanical performance fall midway between that of epoxy and polyester.

Of the main categories of polyester resin, orthophthalic, isophthalic and bisphenol, are normally recommended for use in alkali environments by the manufacturer of the resin. The deterioration that is known to occur is saponification of the chemical cross links by the hydroxyl (OH-ions) present in the alkali solution. This causes loss in rigidity and a 'soapiness' feel to the resin surface.

Holt (et al) 1998 points out that although the outstanding general chemical resistance of a properly formulated and well cured epoxy resin system is widely accepted. Little work has been done on determining their long term resistance to alkalis. Developing a high level of resistance in an alkalis environment depends upon achieving maximum cross-linking of the polyester chains (highly dependent on resin and process quality) and again on the nature of the linkages. The linkage characteristics are determined by the curing agents used and knowledge of this can enable prediction of the resin chemical resistance.

The quality of a composite in terms of its durability performance can be expressed by a number of factors.

- Resin wet out (how well the fibres are covered by resin)
- Absence of cracks (either surface or through thickness)
- Absence of voids (generally smaller and well distributed is better)
- Degree of cure of resin
- Strong fibre/matrix interface
2.5.3 Fibre types

The type of fibre selected for the pultrusion process is determined by factors such as weight, strength, stiffness, thermal and electrical requirements. The key function of the fibres is to carry the tensile load applied to the tendon. They influence the key properties of the element such as tensile capacity, flexure and creep.

In principle, once suitably prepared, any combination of fibres can be put with any other combination of resins. Two or more fibre types can be used thereby constructing a hybrid composite and most resin suppliers now also offer hybrid resin systems. The principle behind hybridising is to produce a material that offers the advantages of the individual components but minimises the less desirable features.

Most GRP soil nails have a textured surface introduced during the pultrusion process allowing bond stresses of 6 to 12 N/mm² to be achieved in resin grouts. Bond stresses ranging from 3 to 7 N/mm² within cementitious grouts established by Edwards (1996).

- The vinylesters are often selected specifically for their corrosion resistant properties and many resin suppliers now offer hybrid resin systems.

- When resin and fibres are combined to form a composite system the performance of the new material contains elements from each of the constituents.

- As fibres are oriented off axis then the creep and fatigue performance becomes less fibre and more matrix dependent. For the majority of soil nailing applications it is likely that fibres are aligned primarily in the loading direction (i.e. axially).

2.5.4 Glass Fibre Reinforced Plastic Composites

Glass Reinforced Plastic (GRP) composite materials comprise three main elements:

- Resin binder
- Fibre reinforcement
- Catalyst

Glass is the most widely used reinforcement and is available in a variety of types. E-Glass is the standard form and is also known as Electrical grade. A-R-Glass is an alkali resistant grade and is often used where protection from corrosive environments is required. Typically used in short fibre reinforcement, this product has only recently been applied to composite bars.

As is the case for most fibre reinforced soil nails, a glass reinforced plastic (GRP) composite soil nail relies primarily on the fibre properties for its tensile performance and the resin matrix for its lateral shear resistance. Glass fibre is the most commonly used reinforcing material giving the pultrusion relatively light weight and stiffness.
For durability, the fibres dominate creep and fatigue behaviour and the matrix is important for environmental resistance. Holt and Sheard (1998) identify five factors which govern the quality of a composite in terms of its durability:

- Resin wet out – how well the fibres are covered by resin
- Absence of cracks – either surface or through thickness
- Absence of voids – generally smaller and well distributed is better
- Degree of cure of resin – if the production process was not well controlled the resin may be insufficiently cross-linked to provide the designed protection
- Strong fibre/matrix interface – incorrect selection of fibre or matrix types or incorrect processing can lead to a poor interface prone to environmental attack.

All the above factors need to be addressed to ensure optimum durability of the composite system and can be determined through assessing the interlaminar shear strength and flexural properties of the GRP soil nail.

2.5.5 Carbon fibre tendons

There are two basic types of carbon fibre, commercially high strength carbon and higher modulus carbon. Carbon fibre is often employed where high performance is required and this enables even stiffer lighter profiles to be used.

Carbon fibre soil nails were first used in the UK for the stabilisation of slopes in railway cuttings. Use was made of carbon fibre soil nails to prevent any possible adverse effects of stray currents on conductive nails.

Generally the manufactures of carbon fibre soil nails highlight the following benefits:

- Superior durability: lower maintenance costs
- Lightweight: ease of transportation – 1/5 of the weight of conventional steel bar of equal diameter
- Improved safety at a slope site with limited space
- Low relaxation characteristics
- High elastic modulus (in comparison to GRP but less than steel)
- High strength: equal or superior to prestressing steel
The typical properties of carbon fibre pultrusions are tabulated below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Unidirectional Carbon/Epoxy</th>
<th>0°, 90° Woven Carbon/Epoxy</th>
<th>0°, +/- 45° Woven Carbon/Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre content (Vol)</td>
<td>%</td>
<td>65</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Density</td>
<td>g/cc</td>
<td>1.58</td>
<td>1.53</td>
<td>1.53</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>MPa</td>
<td>2040</td>
<td>625</td>
<td>240</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>MPa</td>
<td>1000</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>MPa</td>
<td>49</td>
<td>130</td>
<td>-</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>Gpa</td>
<td>150</td>
<td>70</td>
<td>18</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>Gpa</td>
<td>5</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>Interlaminar Shear Strength</td>
<td>MPa</td>
<td>9</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Properties of Carbon Fibre Pultrusion (Courtesy FibreForce)

The durability of carbon fibre compared with Glass Fibre (GFRP) and Aramid Fibre (AFRP) rods is illustrated in Plate 2.5.5

Plate 2.5.5 Durability of carbon fibre rod (Leadline –GA-D8) – Courtesy Chemical Grouting Co. Ltd

2.5.6 Aramid Fibres

The Federal Trade Commission (USA) definition of Aramid Fibres is *a manufactured fibre in which the fibre forming substance is a long-chain synthetic polyamide in which at least 85% OF THE AMIDE (-CO-NH-) linkages are attached directly between two aromatic rings.*

Aramid fibres have a superior strength/weight ratio when compared to glass fibres and also provide excellent abrasion and impact resistance in a composite. They are known
to be poor in compression, and creep. Currently their cost is about 20% higher than that of carbon fibres.

2.5.7 Durability testing

P. Holt (et al) – 1998 reported on an extensive test program undertaken to ascertain the durability of composite bar.

The authors describe ‘The Eurocrete Project’; a four year, £4.5M European collaboration, part provided in the UK by the DTI/EPSRC Link structural composites programme, to develop non-ferrous reinforcement for concrete structures. As well as developing many important aspects concerning design guidance and processing the project pioneered some of the most advanced durability testing techniques in the world.

The environment considered to be most near to a GRP soil nail is the high alkalinity of the cementitious grout. Considerable research effort has been focused on this aspect of durability over the last five years as part of the Eurocrete project.

The laboratory testing addressed three categories of materials; 1) Raw materials (Fibres and Resins); 2) Composite bars and 3) Concrete reinforced with composite bars.

Raw Materials:

Five resin types were assessed in a pH 13.5 simulated concrete pore fluid solution at 20, 50 and 80°C. Over 180 samples were tested throughout a 12 month programme that resulted in the selection of a resin that best retained its original, flexural strength, flexural modulus, elongation to break, Barcol hardness and laminate thinness.

Composite Bars:

The main bar durability test programme used the same standard alkaline solution and concentrated on five main variables; duration of immersion; effect of pH; effect of temperature; influence of stress and effect of ionic content of the solution. Over the three years that the test programme has been running, in excess of 20,000 tests have been initiated across four independent European laboratories.

Concrete Reinforced with Composite Bars:

The concrete test programme was designed to analyse the composite bar pull strengths after exposure to a range of accelerated aggressive environments. A continuing test programme addressed four types of bar reinforced with glass fibre, aramid fibre and carbon fibre. Over the three year test programme in excess of 1400 concrete samples were cast, aged and tested.
Two key points emerged from these tests:

- The assumption made by many that carbon fibres will overcome all the durability issues for composites in alkaline environments is incorrect. The results presented for composites subjected to NaOH, KOH and CaO environments revealed that the carbon fibre bar sustained shear reductions of up to 10% lower than those affected for glass fibre bar.

- The quality, consistency and integrity of the fibre/matrix interface are one of the most important fundamental parameters affecting durability, second only to the ability of the matrix to resist attack. This is achieved through correct selection of the material and optimisation of the manufacturing process.

Accelerated test regimes were set-up both in the laboratory and in the field – results were reported on over a 2 year period. Pull-out test results were compared for bars installed in varying environments.

The overall corrosion performance of a composite soil nail will be a combination of the corrosion resistance of the resin, the rate of ingress of the environment into the composite and the performance of the fibres themselves. It is important to realise that the selection of a durable fibre without due consideration to the resin or its manufacturing process may not result in a durable product.

World-wide there are now many examples of real working structures containing polymer composite reinforcements. The only undisputed way to determine long-term durability is to wait 120 years. However, accelerated test regimes such as those undertaken during the Eurocrete project provide data that can be applied in a safe design framework and enable reliable reinforcement of slopes and rock faces by composite soil nails.
2.6 Durability and Degradation of Soil Nail Systems

2.6.1 Steel Nail Directly Within Soil Mass

Steel nails may be driven, rotated or pneumatically fired into the soil mass for slope stabilisation. The systems offer an economic advantage gained by rapid installation. However there is a dearth of information on the durability of such systems. Steel installed directly into the soil mass will corrode with time and in the long term encounter some loss of steel section.

Section 8.3.2 provides appropriate guidance for the over sizing of a steel nail installed directly into the soil mass for permanent support. No publications have been found reporting on the effect that increased volume of the corrosion product has on bond, or nail pull-out performance. Rust products have been observed in powder form or in the other extreme soundly bonded to adjacent soil particles (Plate 8.4.1A).

Nails of exposed steel would appear suitable for the installation in non-aggressive ground conditions, in low height slopes or structures, or for temporary works.

Plate 2.6.1 Section through exhumed pile with soil deposits bonded to the rust products around the corroded section.
2.6.2 Coated Steel Placed Directly Within The Soil Mass

When considering the durability of soil nails the natural progression from the concept of over-sizing unprotected tendons, in a bid to increase durability, is to consider applying some form of protective coating to the steel tendon. Coatings such as galvanising and epoxy coating offer time-dependant protection of the steel against corrosion. The durability of the coating will, therefore, depend on the thickness and quality of the coating applied and the maintenance of the coating during installation.

Plate 2.6.2 Coated steel rebar

The use of galvanised steel in soil nails is extensive in the UK but generally within grouted bore holes. There is little information provided about the state of galvanic coating after driving.

BS EN 1537: 2000 advocates the use of tar-epoxy, tar-polyurethane and fusion bonded epoxy coatings on steel surfaces provided they are sand blasted and free from any deleterious matter. The code recommends that such measures may be used as corrosion protection to tendons of temporary systems if they are factory applied and the thickness is not less than 0.3 mm and if application faults like pin-holes are excluded by appropriate fabrication control.

Plate 2.6.3 Epoxy coated rebar
There is little information with regard to the use of epoxy coated steel in the UK soil nail industry. In the USA the use of epoxy coated steel is extensive and more recently the use of epoxy coated strand generally contained with cementitious materials. Several major dams in the USA have been stabilised by the use of epoxy coated strand anchors – some anchors containing up to 90 strands. Should the coating be subjected to extensive damage during the installation process the benefit provided by the coating becomes questionable. The integrity of the coating after installation using driven systems should be checked by excavating test nails or by pulling out the nails during test trials.

2.6.3 Steel Surrounded by Cement Grout

The most common methods of installing soil nails is by predrilling holes, installing nails and grouting the bore. Direct driving of a hollow nail using grout as the flush medium is also common practice.

BS 8081 states that grout is considered suitable as a protective medium provided the crack width within a grout cover can be demonstrated not to exceed 0.1mm. However, the presence of cracks that exceed this limiting width does not render the cement grout ineffective since the presence of the alkaline environment (pH 9.5-13.5) will contribute to the retardation of the rate of corrosion.

It should also be noted that cracking encountered in anchor bond length, is due solely to axial movement. This probably occurs in a soil nail bond length in the passive zone but cracking in the active zone is likely to be aggravated by outward and downward movement of the active zone in mobilising tension and shearing in the nail. The awareness of cracking of the cement grout is supported by Recommendations Clouterre 1991 which suggests that the cracking of the cement grout does not necessarily constitute an aggravating factor in terms of its triggering or encouraging corrosion.

Other relevant points from BS 8081:1989 include:

- Section 8.1.2.2: in relation corrosion of steel in concrete and its relation to cracking, corrosion is likely to start first where a bar intersects a crack. In the short term, e.g. 2 years there is a significant crack width on the amount of corrosion found near a crack. In the long term, e.g. 10 years, however, based on observations of 0.05 mm to 1.5 mm cracks, the effect of differences in these widths of crack on the amount of corrosion reduces dramatically.
- Nevertheless, the smaller the crack the lower is the corrosion risk. Whilst there is little field evidence to indicate what crack widths are acceptable in a cementitious protective barrier, an upper limiting crack width of 0.1 mm is proposed for guidance.
- Section 8.1.2.1: states that steel is protected against corrosion when maintained in a high pH environment free of aggressive ions. Such an environment is provided by hydrated hydraulic cement will give excellent protection over the long term while the high level of alkalinity remains. However, loss of protection can occur as a result of lowering the alkalinity,
through cracks or carbonation, or the presence if aggressive ions, especially chloride.

Recommendations Clouterre 1991, Chapter 6 section 4:

- Nails are either installed by driving or by laying them inside a borehole and then anchoring them into the earth using a cement grout. This cement grout will be subjected to tensile stresses, so it is likely that some fine and regular cracking will occur.

- Since it is impossible to assess with any degree of accuracy the width of this cracking, and even though it might only be slight (in the order of tenths of millimetres), it cannot be proved absolutely that the cement grout will form a watertight barrier between the reinforcing bar and the soil. If cracking does occur, the reinforcing nail can come into contact with the electrolyte carried by the moisture in the soil.

- Concentration of the electrolyte should not necessarily cause concern, and by the same token, the cracking in the cement grout would not be able to generate any more severe corrosion phenomena than those resulting from the reinforcement coming into direct contact with the soil.

Cementitious grout around the steel offers some protection against corrosion, therefore the use of centralisers to maintain cover where possible is beneficial. Kendorski (2003) reports on the importance of ensuring a full distribution grout around the tensile member in order to inhibit corrosion.

Plate 2.6.3  Cover to a coated tendon to reduces the risk of damage to the coating during installation (courtesy Grove Distributors)
2.6.4 Coated Steel Surrounded by Cement Grout

The performance of steel nails surrounded by cementitious grout may be enhanced by the inclusion of coated steel, either galvanised or epoxy coated. With careful handling during transportation and installation the risk of coating damage is considerably reduced from that of driven coated steels.

Inspection of coated nails on site can allow detection of defective coatings (often by the exposure of rust colouring at an early stage). Remedial works may be affected by wire brushing and covering the defect with setting fluid such as galvafroid or an epoxy resin. Care in handling cannot be overemphasised. Complete batches of damage control bars are known to have been rejected.

Plate 2.6.4 After handing and storage removal of galvanising coat visible

The use of an efficient spacer/centraliser attached to the coated steel prior to installation can grossly reduce the risk of coating removal during such operations and may ensure the maintenance of a sound protective layer.

The use of epoxy coated nails in the soil nailing industry is a standard practice in South Korea, where massive slopes are steepened and supported by multilevel of soil nails.
Plate 2.6.4.1 Extensive use of green epoxy coated soil nails in South Korea

2.6.5 Composites surrounded by Cement Grout

In order to protect the composite tendon from damage, care should be taken to ensure that non-corrodible spacers are correctly secured and adequately spaced along the tendon length.

2.6.5 A composite threaded bar with end nut and spacer to ensure centralising of the tendon within the duct (courtesy of Weldgrip Ltd)
2.6.6 Stainless Steel surrounded by Cement Grout

The use of non-corrodible spacers may be used to ensure adequate coverage of grout around the stainless steel tendon.

Plate 2.6.6
A Stainless Steel Self Drilling bar complete with drill bit, hollow bar, coupler and head plate (Courtesy Stainless Steel Ltd)

2.6.7 Steel Surrounded by Grouted Impermeable Ducting

The use of impermeable ducting to surround a steel tensile member and its isolation from the environment was developed for ground anchor protection in the late 1960s, BS8081:1989 acknowledges that the protective elements around a tensile member will have to transmit tensile stresses. The code recommends the use of a semi-rigid corrugated duct provided the strength and deformability characteristics have been proved through adequate testing.

EN1537: 2000 demands that all proposed corrosion protection systems shall have been subjected to at least one system test to verify the competence of the system... and after loading the test anchors shall uncovered with care in order to observe the effect of the stressed condition on the corrosion protection system (Clause 6.12).

EN14490 states where used, protective ducts shall transfer load between the reinforcing element and the ground and ducts shall be impermeable to water, and resistant to ultra-violet radiation. Joints between sections of ducts shall be sealed against ingress of water by direct contact or by sealants.

BS8006: 1995 also acknowledges the use of impermeable ducting to protect tendons. It is recommended that all metallic components buried in soil i.e. reinforcing elements, connections, facing lugs and where applicable the facing units, should be of electrolytically compatible material. Where this is not possible, electrical insulation of durability equal to the service life of the structure should be provided between different materials. Nails fully protected in accordance with the recommended for corrosion protection in BS 8081 require no allowance for sacrificial thickness
(Clause 8.2.2.3). Clause 4.3.4.2 states that the risk of attack of aggressive fluids on both metallic and polymeric reinforcements can often be dealt with by using preventative design measures such as the incorporation of impermeable barriers and effective drainage systems.

The above points are all supported in Recommendations Clouterre 1991.

Hence several published documents acknowledge the benefits of isolation of the tensile member in the ground where appropriate and indicate that the performance of the ducting should be demonstrated by preliminary trials and detailed inspections.

Consideration should also be given to the nature of the materials used for impermeable ducting. Corrugated duct corrosion protection most commonly consists of encasing the tendon in a grout filled corrugated PVC (poly-vinyl chloride) or HDPE (high density polyethylene) tubing. The annular space between the tendon and the corrugated tube, commonly specified as a minimum of 5mm, is filled with neat cement grout. Internal spacers are used to achieve the grout cover inside the encapsulation.

Following the guidance of BS8081: 1989 the design bond stresses along the duct to grout interface should not exceed 3.0 N/mm$^2$ unless preliminary pull-out tests prove otherwise. Attention should be paid to pitch, amplitude and profile of the corrugations. Typically the gaps between the peaks of the corrugations on the outer face should exceed 50% of the duct length to ensure adequacy of grout shear capacity in the bond length (Barley 1997 – Development of Double Plastics).

Duct diameters are influenced and controlled by internal grout cover between nail and inner duct face or by grout cover between coupler body and inner duct face. The minimum cover to enable annulus grout and transfer of load is in the order of 2 to 3mm (Barley 1990) when using neat cement grouts.

Plate 2.6.7. 25mm diameter steel nail with 40mm diameter impermeable duct.
These factors generally control duct sizes to 40mm (without couplers – Plate 2.6.7) to a maximum size of 80mm to accommodate the largest couplers (see Plate 2.6.8). Typical duct wall thicknesses to ensure impermeability in these diameter ranges vary from 0.5mm to 1mm.

Plate 2.6.8 Nail in impermeable duct – section through exhumed soil nail illustrating indented duct profile in grout column and nail centralised in impermeable duct (nail and nail centraliser highlighted for clarity).

BS8081: 1989 recommends that centralizers and spacers should be made of materials having no deleterious effect and the tendon itself and the use of metals dissimilar to the tendon should be avoided.

Plate 2.6.9 The incorporation of an efficient centraliser around the impermeable ducting is critical to the maintenance of the duct integrity and hence the durability of the corrosion protection after installation.

Ducts containing the nail bar may be pregrouted or, as is more commonly carried out, grouted whilst nail bar and duct are in situ. It is common practice to install the centralised duct in the borehole, install the steel nail bar into the duct with appropriate
spacer and centralizer and carry out grouting from the top of the duct. The grout will pass down the annulus between the nail bar and the duct returning up the outer annulus. The system generally ensures efficient grouting and all void filling, with the exception of the small isolated air voids in the roof of the corrugations.

Plate 2.6.10 Typical operation after drilling, duct installation, nail installation:
2.6.11 Exhumation of a slope face exhibits a good example of a steel nail grouted and contained within an impermeable duct, itself centralised within the grout column in the drillhole (Courtesy of Keller ground Engineering)

Where soil nail tendons are pregrouted into the corrugated duct, prior to installation into the borehole, each encapsulation system should be checked to ensure adequate internal clearances the passage of the grout.

2.6.8 Double Corrosion Protection

pr EN 14490 (A.4.3.3) suggests for soil nails the general use of protective systems as described above. It does however advise that the main approach for achieving the desired service life may include “a combination of the above”

BS 8081 (clause 8.21) recommends for anchorages: double protection implies the supply of two barriers where the purpose of the outer second barrier is to protect the inner barrier against the possibility of damage during tendon handling and placement. The second barrier therefore provides additional insurance, given the distinction between the degree of protection of the tendon once installed in the ground, and that of the tendon supplied.

Within soil nail systems the most vulnerable protective layers consist of the galvanized or epoxy coating followed by the potential damage to the “impermeable” duct or the potential long term deterioration of a composite or stainless steel tendon. Generally soil nails in comparison to ground anchor tendons are light and general man handle able. Although the latter does not essentially reduce the risk of damage to the protective layers, it is known that particularly heavy multi- strand or bar anchor tendons can through immediate wall contact (“scuffing”) tear the ducting or remove the coating.

It would seem therefore that when nail tendons become particularly long (greater than 20m) and heavy incorporating a number of couplers, the risk of damage to a single
protection layer increases. Thus in the particular high risk category consideration should be given to double corrosion protection.

Double corrosion protection can be provided in a number of systems:

- Coated steel within a single impermeable duct.
- Composite nails within a single impermeable duct.
- Stainless steel with a single impermeable duct.
- Steel pregrouted within two concentric impermeable ducts (as commonly used in anchor practice).

Where double corrosion protection is offered it should extend in principle through the entire length of the working nail i.e. including the nail head.

### 3.0 Observation and Exhumation

#### 3.1 Victorian soil retention system

The effect of section loss due to corrosion in an unprotected steel tendon is illustrated in Plate 3.1 An exhumed section of a steel tendon from a Victorian soil retention system is shown with considerable section loss and deterioration. Such a member will retain little in the way of tensile capacity. Whilst it is acknowledged that this example shows a steel tendon that has been buried for nearly 100 years, it emphasises that the process of degradation will be accelerated if soil and environmental conditions are even mildly aggressive.

Plate 3.1 Exposed tendon form a Victorian soil retention system
3.1 Case Studies in Japan

Shiu and Cheung (2002) reported on investigation work in 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. 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 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. 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.

3.2 Case Studies in Hong Kong

Shiu and Cheung (2002) collected data from investigation work in 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 (Plate 1*). 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.

### 3.3 Observations in Singapore

Barley and Kiat (2002) reported on the performance of a soil nailed stabilised slope in Singapore where 50mm diameter steel rebars were used to stabilise a uniform 45° slope in a medium dense clayey sand. The exposure of the upper length of a few grouted nails indicated that corrosion was mild in the form of surface rust with no evidence of deep pitting even after a 15 year service life. It should be noted however that no nails were exposed below approximately 1 metre and corrosion at depth may have been more severe.

Plate 3.3 Exhumed nail, surrounded by cement grout exhibits only mild surface rust (Barley/Kiat 2003).
3.4 Observations at Stansted M11

During recent soil nail work on the M11 at Stanstead it was necessary in certain areas to excavate into the soil nailed slope. This allowed exposure and inspection of the integrity of the corrosion protection system albeit after only a 3 month life span. The exposure of a well centralised duct within the grout column and fully intact ducting, duct grout and steel bar were indicative of good working practice.

Plate 3.4 Exhumed soil nail and head plate (After Barley, 2002)

4.0 Nail Heads

The performance requirements of nail heads range from zero (generally in shallow slopes) towards attainment of full nail tendon capacity (in vertical nail retained faces). As a consequence the required attention to detail in the degradation/durability of the nail varies enormously. Full capacity nail heads should be provided with the same lifespan (i.e. durability) as that provided for the nail itself. However it must be borne in mind that the exposed nail head environment may differ considerably from the buried nail environment. It may be considerably more aggressive and severe, particularly in the marine environment.

In considering the nail head attention should be paid to the junction between the buried nail, its corrosion protection, and the nail head itself. This is a particularly vulnerable part of the nail where an overlap in protection is required but where the condition cannot be observed. Conditions of a variety of nail heads at periods after installation are provided in the Plates 4.1 to 4.9
Plate 4.1 (a, b and c)

Three exposed soil nail heads on the same site showing a large variation in resistance to initial corrosion after 5 years in saline environment)

Plate 4.2 Nail head in moderate climatic conditions after 15 years in service

Plate 4.3 Bitumen coated nail heads after seven years in service
Plate 4.4  A partially buried soil nail head after 15 years – rusted but still fulfilling its intended purpose (After Barley, 2003)

Plate 4.5  Nail head subjected to extreme climatic conditions of large temperature variations and high humidity – approximately 8 years in service (After Barley 1992)
Plate 4.6  Nail heads fitted with grease filled steel caps following anchor technology

Plate 4.7  Nail heads may be contained in reinforced concrete recess in the Slope
Plate 4.8 Large temporary nail heads required to fulfil a short term usage only

Where composite nails are installed the capacity of the thread connection is typically between 30% and 60% of the tensile capacity of the composite bar. However, since tensile capacities are generally of a high order in the 300kN to 400kN range for 22mm and 24mm diameter bars respectively, the 120kN to 200kN thread capacity are frequency more than adequate.

Plate 4.9
Composite plates on composite bars generally provide a higher resistance to degradation than steel plates. Thread capacities generally range from 120kN to 200kN
5.0 Summary

5.1 Cost and durability

In the majority of areas of construction it is necessary to evaluate the lifespan of a structure against cost. Financial commitment may optimise between a high financial outlay associated with minimum maintenance costs, guaranteed durability, and minimum risk; or a reduced financial outlay with ongoing durability assessment and maintenance costs necessary to reduce the risk of failure. Alternatively failure may be tolerated.

Table 5.1 provides useful information by relating the Index Cost of an uncoated steel nail (25mm diameter) with the material costs of other nails, protected or partially protected or with non-corrodible nail materials. The indices are inclusive of typical nail components such as coupler end plate and nut and consider an optimum nail length of 8m.

The actual total cost per nail installed in a competitive commercial market is difficult to evaluate but for guidance purposes the range of percentage cost of nail and components in relation to the total installed nail cost has been estimated. It has not been possible to evaluate the cost of the maintenance of soil nailed slopes and structures.

<table>
<thead>
<tr>
<th>Material – Tensile Member</th>
<th>Cost Index for Tensile Member</th>
<th>Percentage cost of nail tendon in full nail price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated steel</td>
<td>1.0</td>
<td>8 to 12%</td>
</tr>
<tr>
<td>Galvanised steel</td>
<td>1.7</td>
<td>14 to 18%</td>
</tr>
<tr>
<td>Epoxy coated steel</td>
<td>2.5</td>
<td>18 to 23%</td>
</tr>
<tr>
<td>Stainless steel: Type 304</td>
<td>5.1</td>
<td>30 to 40%</td>
</tr>
<tr>
<td></td>
<td>Type 316</td>
<td>35 to 45%</td>
</tr>
<tr>
<td>Polyester composite</td>
<td>1.6</td>
<td>15 to 20%</td>
</tr>
<tr>
<td>Vinyl composite</td>
<td>2.0</td>
<td>18 to 23%</td>
</tr>
<tr>
<td>Uncoated steel + single plastic duct</td>
<td>1.8</td>
<td>14 to 18%</td>
</tr>
<tr>
<td>Galvanised steel + single plastic duct</td>
<td>2.2</td>
<td>16 to 20%</td>
</tr>
<tr>
<td>Self-drilling steel</td>
<td>3.6</td>
<td>45 to 55%</td>
</tr>
<tr>
<td>Self-drilling stainless steel</td>
<td>9.0</td>
<td>60 to 70%</td>
</tr>
</tbody>
</table>

* Table to be added to

Table 5.1 Cost Comparisons: Steel, Coated Steel, Covered Steel, Stainless Steel and Composite Materials
5.2 Categorisation/Recommendations

Within the Industry there is available a small range of nail installation techniques but an exceptionally broad range of nail tendon systems. These systems can offer tendons with estimated rates of corrosion or degradation, and hence an estimated lifespan; or can provide tendons partially or totally isolated from the environment.

Nails installed by soil displacement methods generally have no cement cover, although some may have post grouting facilities which could enhance protective measures. Displacement nails are proposed for short term usage or can be designed for loss of section with a limited lifespan or for low risk Categories.

The lifespan of coated displacement nails should be greater but loss of coating during installation is a risk difficult to quantify. Table 5.2 provides a general indication of the Categories and environmental conditions which may be appropriate for displacement nail usage.

Self drilling nails are offered in a range of material types: - generally steel, coated steel or stainless steel. Grout cover is generally present although in some circumstances cover cannot be guaranteed. Nails can be driven beyond the grouted zone, couplers can lie on the drilled bore with no cover, and cover may be reduced at the top of the nail bore, unless centralisers are fitted. Furthermore it is likely that the soil mass movement results in the causation of a cracked grout column. However the presence of the alkaline environment is generally of benefit in retarding steel corrosion.

Where self drilling coated nails are installed they are probably subjected to less coating damage than displacement nails by reduction in nail to soil contact. It is beneficial to provide a centraliser system to reduce wall contact and to maintain the integrity of the entire coating during driving albeit damage within the thread length may be inevitable. Stainless steel manufactured from the higher quality materials may offer the most appropriate nail system for longevity using self drilling in conjunction with bore grouting methods. Guidelines to the recommended system usage of self drilled nails are provided in Table 8.7.2.

Soil nails constructed by pre-boring allow installation of soil nail components in a controlled manner. By integration with non – corrosible spacers which isolate interfaces they can offer a wide range of systems and durability. Centralising of bars and couplers ensures minimum grout coverage and a guaranteed alkaline environment.

It should be noted that in many circumstances the grout column will be cracked due to soil mass movement and the consideration of cement grout as a fully protective layer is not advised for long life high risk categories.

Coatings are available to supplement the steel protection of the cementitious environment and the availability of a range of composite nails identifies other options involving greater and lesser durable materials. Stainless steels are generally available in two grades which in effect identify two ranges of durability.
Alternatively in prebored holes steel isolation within the bore can be simply achieved by its containment in a grouted impermeable duct. Care is required to prevent damage to the outer duct face by centralising and to the inner duct face by preventing contact with the steel and couplers during installation. When soil nails become longer and heavier the potential risk of duct damage may increase. Such risk can be reduced by pregrouting the nail within the ducting prior to careful installation.

For increased durability demand it is possible to provide a double protection system grouted in situ whereby in the event of damage to the outer face the inner protection layer remains intact. This may be considered for high risk categories. An option of coated steel or a vinyl ester composite within the impermeable duct provides such a double protection option. In certain circumstances this may also enhance the integrity of the protection at the nail head since the isolation duct must be terminated below the nail head where nail head plates are required.

Where the pre-inspection of the full corrosion protection is required prior to nail installation then the use of pregrouted double protected nails may be required. This is in the form of coated steel or vinyl/ester composite within a single ducting or steel within a two concentric ducts as frequently used in anchor technology.

Nail head durability is generally affected with a different approach from nail protection within the bore. The contribution of the nail head can be essential in walls and steep faces, contributory in steep to medium slopes and a zero contribution when it is considered that the passive zone retains fully the active zone and surface erosion is restrained by other means.
<table>
<thead>
<tr>
<th>TYPE OF SOIL NAIL</th>
<th>CATEGORY I – LOW RISK</th>
<th>CATEGORY II – MEDIUM RISK</th>
<th>CATEGORY III – HIGH RISK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T or P in ME</td>
<td>T in AE</td>
<td>P in AE</td>
</tr>
<tr>
<td>Steel directly in soil</td>
<td>Y Y N</td>
<td>Y N N</td>
<td>N N N</td>
</tr>
<tr>
<td>Coated steel directly in soil</td>
<td>Y Y Y</td>
<td>Y Y N</td>
<td>N N N</td>
</tr>
<tr>
<td>Steel surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y N</td>
<td>N N N</td>
</tr>
<tr>
<td>Self drilled steel surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y N</td>
<td>N N N</td>
</tr>
<tr>
<td>Coated steel surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y N</td>
<td>N N N</td>
</tr>
<tr>
<td>Self drilled coated steel surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y N</td>
<td>N N N</td>
</tr>
<tr>
<td>Polyester composite surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y N N</td>
<td>Y N N</td>
</tr>
<tr>
<td>Vinylester composite surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>Stainless steel surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>Self drilled stainless steel surrounded by cement grout</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>Steel surrounded by grouted impermeable ducting</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>Coated steel surrounded by grouted impermeable ducting*</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>Stainless steel surrounded by grouted impermeable ducting*</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>Steel surrounded by pregrouted double impermeable ducting*</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
<td>Y Y Y</td>
</tr>
</tbody>
</table>

Key: T = Temporary, P = Permanent, ME = Mild Environment, AE = Aggressive Environment, Y = Yes, N = No, ? For consideration

* System particularly suitable for heavy or long nails for permanent works where one of the two protective layers may become damaged during handling or installation. This probably equates to double corrosion protection required for permanent anchorages.

Table 5.2 Summary of recommendations for different soil nailing systems in relation to different categories of risk
6.0 REFERENCES


European Standard EN 1537:2000 The Execution of Special Geotechnical Work – Ground Anchors


FHWA Soil Nailing Field Inspectors Manual, US Department of Transportation, April 1994


Bruce, D.A. (2003), Epoxy Protected Strand – A historical review of its use for prestressed rock anchors – Part II, ADSC December/January 2003


Technical Article, ‘Nailing Down the Problem’ Contract Journal March 1995


Draft prEN 14490: Execution of special geotechnical works – Soil Nailing


Trial soil nail wall using PermaNail corrosion-free soil nails, M J Turner, Director, Applied Geotechnical Engineering; Ground Engineering 1999.
Summary of Keller Colcretes Investigation work into the use of Polymeric Materials in Soil Nails – December 1991 – confidential report

Soil Nailing Case Histories and Developments, A D Barley, Contracts Director Keller Colcrete.

The Practice of Soil Reinforcement in Europe, A D Barley Keller Colcrete, 8 June 1995. Barley, Keller Colcrete (letter & one page synopsis).

US Bridge Tests Glass Fibre Rebar, Article in NCE? Year?


Trial soil nails for tunnel face support in London Clay and the detected influence of tendon stiffness and bond length on load transfer. A D Barley, Keller Ground Engineering, Wetherby, UK M Graham, Balfour Beatty Civil Engineering, Heathrow, UK.

Polymer Composites for Soil Nailing (unpublished chapter); P Holt, Dr P A Sheard (Trend), J Hartley & M Williams (Fibreforce Composites); Barley (1998)


J Oldfield & D Cochane, Stainless Steel in civil engineering.

J Mietz & J Oldfield, The use of austenitic and duplex stainless steel s in ground anchor environments.

Electrochemical investigations of high strength stainless steels for rock and ground anchors.

European Federation of corrosion Publication 18, Stainless Steel in concrete


