CHAPTER 5 – EXISTING CORROSION MITIGATION GUIDANCE

Most of the existing corrosion mitigation guidance is in the form of an assessment of the corrosion potential of soil and the selection of an appropriate corrosion protection system. The US and international (primarily European) guidance both recognize the importance of assessing the soil corrosivity by a suite of electrochemical tests. However, the level of the testing and assessment of corrosivity is different. The US guidance is based on comparing the measured value of each electrochemical property (pH, resistivity, chlorides and sulfates) with a certain threshold value for that property. In contrast, the European practice is based on assigning a numerical rating to a variety of parameters, including electrochemical properties, and assessing the corrosivity of the soil based on the value of a cumulative ranking. Both of these approaches are briefly discussed below.

US GUIDANCE FOR SBSNs

In the US, the formal guidance on corrosion issues is provided by FHWA (2003). The guidance in FHWA (2003) is based on the guidance provided by the Post-Tensioning Institute (PTI, 1996). The California Department of Transportation (CALTRANS, 2003) also presents some guidance, which is very similar to that in FHWA (2003). Basically, the US guidance categorizes ground corrosivity into two categories: aggressive (corrosive) and non-aggressive (non-corrosive) based on 4 electrochemical tests and the presence of stray current. Table 2 presents the criteria for assessing ground corrosion potential based on FHWA (2003).

Table 2. US criteria for assessing ground corrosion potential of SBSNs (after FHWA, 2003).

Test	Units	Strong Corrosion Potential (Aggressive)	Mild to no Corrosion Potential (Non-Aggressive)	ASTM Standard	AASHTO Test Method
pH	-	pH < 4.5 or pH > 10	5.5 < pH < 10	G51	T289-91
Resistivity	ohm-cm	< 2,000	> 5,000	G57	T288-91
Sulfates	ppm	> 200	< 200	D516	T290-91
Chlorides	ppm	> 100	< 100	D512	T291-91
Stray current	-	Present	-	-	-
Note: ppm indicates parts per million; refer to ASTM (2010) and AASHTO (2010) for latest versions of test standards and methods.					

Once the ground is categorized as aggressive or non-aggressive, a corrosion protection system is chosen based on whether the soil nail wall is temporary or permanent as shown in Figure 3. Classes of protection, as defined in Figure 3, are limited to SBSNs at this time. Temporary walls are defined as having a service life of less than 18 months. Walls with a service life greater than 18 months are classified as permanent. The Class I and II protection levels in Figure 3 are understood to be as follows:

- Class I: two mechanisms for "maximum" protection such as grout and an epoxy-coated bar or grout and plastic sheathing encapsulation. Plastic sheathing could be high density polyethylene pipe (HDPE), polyvinyl chloride pipe (PVC) or polyethylene pipe (PPE). A clarification of the Class I protection level was provided by the Post-Tensioning Institute (PTI, 2004) wherein the two mechanisms have to be either water tight corrugated plastic sheathing with inner grout, or water tight hole with epoxy-coated strand. The first of these two conditions is similar to Case I protection in the US. It is also a criterion in the European guidance (CEN, 2009) discussed later.

- Class II: one mechanism for "intermediate" protection such as grout surrounding bare bar.

According to the flow chart in Figure 3, Class I protection is mandated in US practice for permanent walls in non-aggressive soils if the consequences of failure are serious, e.g., loss of life, damage to nearby utilities and structures, structural repairs, and impact to traffic. Such risks are expected in urban areas alongside heavily travelled highways, and areas with problematic soil conditions where slope movements have been experienced (FHWA, 2003).

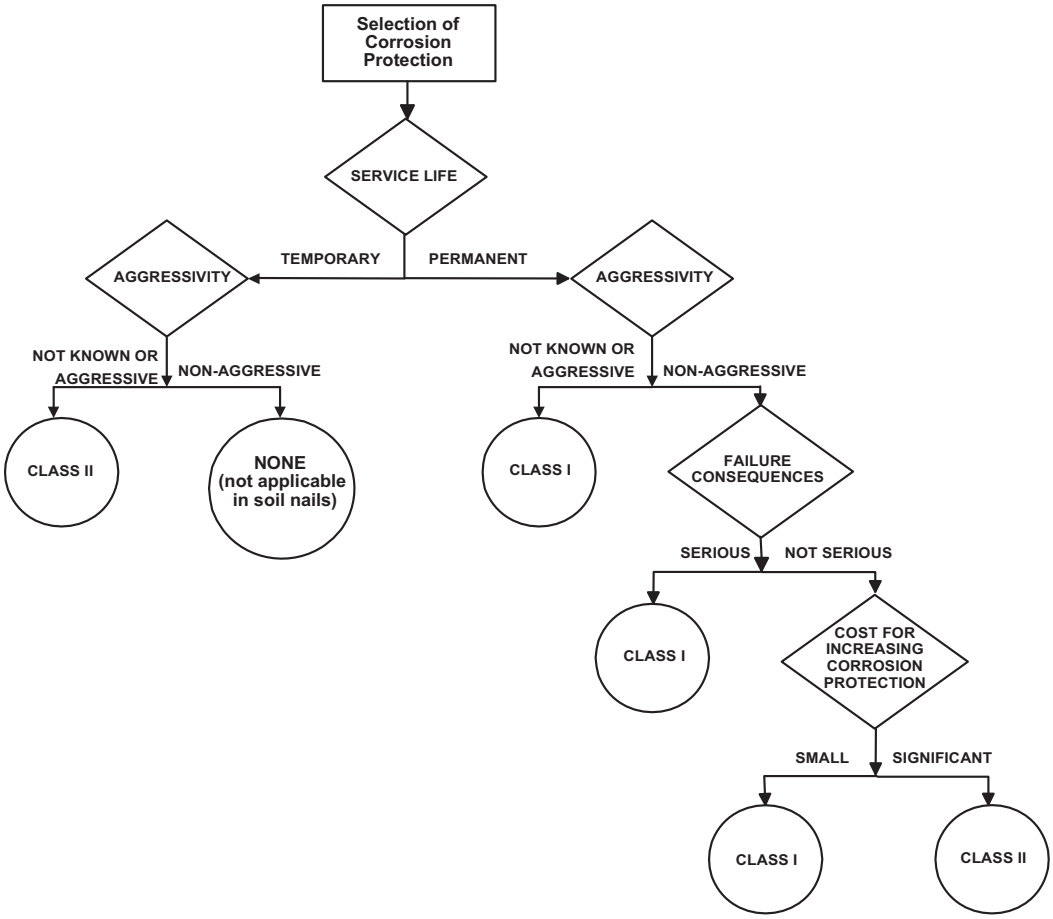

Figure 3. Flowchart. Criteria for selection of SBSN corrosion protection (FHWA, 2003)

In US practice, Class II protection is automatically provided, even if the ground has no corrosion potential (i.e., non-aggressive). Class II protection is often referred to as a single corrosion protection (SCP) system. Similarly, Class I protection, which involves the use of grout in conjunction with plastic sheathing, is often referred to as a double corrosion protection (DCP) system.

INTERNATIONAL GUIDANCE

Internationally, the guidance in various geographical areas is similar, e.g., Germany (DIN, 1985), France (Clouterre, 1993), England (TRL, 1987, 1993), Switzerland (SIA, 2003), and Hong Kong (Geoguide 7, 2008). The Hong Kong guidance is based on TRL (1987); thus, it is essentially a representation of European guidance. The common theme in all of these guidance documents is the assignment of a ranking (or weighting) to various parameters that can contribute to corrosion. The various rankings (weights) are combined to obtain an overall ranking value and the corrosivity of the soil is assessed based on this overall ranking value. The European Committee for Standardization recently finalized and published Document FprEN 14490:2009 (CEN, 2009) for the standardization of soil nailing works. That document takes into account the various previous European guidances. Table 3 presents criteria based on CEN (2009) that use the concept of a Global Index to assess an overall ranking for a site that was originally developed by Clouterre (1993). The Global Index is obtained by adding the values of the various applicable weighting factors for each of the four evaluation criteria presented in Table 4.

Table 3. Criteria for assessing soil corrosivity (after Clouterre, 1993; CEN, 2009).

Soil Features	Classification	Global Index, ΣA
Slightly corrosive	IV	4 or less
Average corrosive	III	5 to 8
Corrosive	II	9 to 12
Highly corrosive	I	13 or greater

The following approaches are commonly used to mitigate the effects of corrosion over the service life of steel soil nail reinforcements:

1. Sacrificial steel
2. An appropriate cementitious material cover (e.g., grout)
3. Surface coatings (e.g., epoxy, zinc, etc.)
4. Grout filled corrugated plastic sheath encapsulation
5. Stainless steel
6. Combination of above

The guidance available for the first 5 approaches is summarized herein. The sixth approach is based on a suitable combination of other approaches, e.g., use of sacrificial steel in addition to an appropriate grout cover.

Table 4. Typical European criteria for assessing ground corrosion potential (after Clouterre, 1993; CEN, 2009).

Evaluation Criterion	Features	Weight A of Criterion
Type of Soil	**Texture**	
	— heavy, plastic, sticky, impermeable	2
	— clayey sand	1
	— light, permeable, sandy, cohesionless soils	0
	Peat and bog/marshlands	8
	Industrial waste	
	— clinker, cinder, coal	8
	— builder's waste (plaster, bricks)	4
	Polluted liquids	
	— industrial waste water	6
	— water containing de-icing salts	8
Resistivity (ohm-cm)	Less than 1,000	5
	1,000 – 2,000	3
	2,000 – 5,000	2
	More than 5,000	0
Moisture content	Water table – brackish water (variable or permanent)	8
	Water table – pure water (variable or permanent)	4
	Above water table – moist soil (moisture content > 20%)	2
	Above water table – dry soil (moisture content < 20%)	0
pH	Less than 4	4
	4 to 5	3
	5 to 6	2
	More than 6	0
	Global Index	See Note 1

Notes:

1. The Global Index is obtained by adding the values of the applicable "A" for each of the four evaluation criteria, i.e., Global Index = ΣA
2. The value of the "A" for "Type of Soil" should be the maximum value applicable to that soil from subgroups "texture," "peat," "industrial waste," and "liquid."
3. The maximum weight for each of the four criteria is less than or equal to 8.
4. Although the terminology for the texture of the soil (e.g., "heavy") is not exactly the same as that in US practice, the terms can be correlated with judgment to those based on the Unified Soil Classification System (USCS) given in ASTM D2487 or the AASHTO soil classification system given in AASHTO M 145, respectively. For example, a soil with a USCS designation "CH" or AASHTO soil group designation "A-7-6" would be assigned A = 2, while a soil with USCS designation "SC" or AASHTO soil group designation "A-2-6" or "A-2-7" would be assigned A = 1.

1. Sacrificial Steel

   This method assumes no surface treatment or grout encapsulation. In other words, it assumes that any coatings or grout encapsulation are rendered ineffective. The method relies on over-sizing the soil nail based on anticipated corrosion over the service life of the structure. Table 5 presents guidance on estimating the loss of steel thickness based on the service life of a structure.

2. Cementitious Material Cover

   In this approach, the corrosion protection is achieved by use of a cementitious material, e.g., cement grout, that provides a highly alkaline ($9.5 < pH < 13.5$) environment that can passivate the steel (see Appendix A for more information regarding role of cementitious materials in corrosion protection). Table 6 provides guidance on the minimum grout cover as a function of service life of the structure. The values in Table 6 are related to grout cover with no other precautions added. In combination with other actions (such as galvanization, corrugated plastic sheaths, etc.) a longer service life may be achieved. The key to this approach is that the highly alkaline environment be maintained. Grout cracking can invalidate the corrosion protection assumed by this approach. According to CEN (2009), research has shown that crack widths controlled to less than 0.1 mm (~4 mils) can be considered to be self-healing. Thus, the guidance in Table 6 should be considered applicable when the crack width does not exceed 0.1 mm (~4 mils).

3. Surface coating

   As noted in Chapter 2, there are a variety of surface coatings, e.g., epoxy, galvanization, etc. In the case of HBSNs, service life of the structure may be compromised by local corrosion due to local damage to the coating during handling and installation of the soil nails.

4. Grout filled corrugated plastic sheath encapsulation

   In this approach grout filled corrugated plastic sheath encapsulation is used in conjunction with grout cover. This is similar to Class 1 protection in US guidance. In this approach, the use of a plastic sheath within the grout cover prevents ingress of moisture or corrosive substances where cracking of the grout occurs. In the case of HBSNs this approach is not practical since similar to damage to surface coatings, the plastic sheath protection system is susceptible to damage during the abrasive installation process

5. Stainless Steel

   There are a number of different types of stainless steel. If stainless steel is used then it is important to prevent direct contact between stainless steel and other steel to prevent galvanic corrosion. Caution should be exercised with stressed stainless steel bars in an environment with high chlorides where corrosion may occur at unacceptable rates.

Table 5. Loss of steel thickness based on level of soil corrosivity and service life (after Clouterre, 1993; CEN, 2009).

Soil Features [Classification]	Overall Index, ΣA + C (Note 1)	Short-term, mm (mils)	Medium-term, mm (mils)	Long-term, mm (mils)
		≤ 18 months	1.5 to ≤ 30 years	30 to ≤ 100 years
Slightly Corrosive [IV]	4 or less	0.0 (0.0)	2.0 (78.7)	4.0 (157.5)
Average Corrosive [III]	5 to 8	0.0 (0.0)	4.0 (157.5)	8.0 (315.0)
Corrosive [II]	9 to 12	2.0 (78.7)	8.0 (315.0)	Note 2
Highly Corrosive [I]	13 or greater	Note 2		

Notes:

1. "ΣA" is the value of global index based on information presented in Table 4. "C" is a value that is based on whether the structure is classified as "critical" or "standard" (i.e., routine). For "critical" structures, use C = 2 and for "standard" structures use C = 0.
2. For all applications in highly corrosive environments and long-term applications in corrosive environments, sacrificial steel approach is not appropriate and plastic sheath type of protection measures should be used. Metal casings are not recommended.
3. The following procedure should be used to calculate the effective bar properties for design based on the loss of steel guidance provided in this table:
   - Obtain the values of cross sectional area, A_c, nominal (average) inner diameter, d_i, nominal yield strength, F_Y, and nominal ultimate strength, F_U, from the manufacturer's data.
   - Calculate the outer diameter, d_o, as $d_o = [(4A_c/\pi) + (d_i^2)]^{0.5}$
   - Reduce the value of d_o by the appropriate value of steel thickness loss listed in this table for the service life and soil features. Call this the effective diameter d_{eff}.
   - Calculate the effective area, A_{ceff}, by using d_{eff} instead of d_o as $A_{ceff} = (\pi/4)\,(d_{eff}^2 - d_i^2)$
   - Calculate the effective section modulus, S_{eff}, and the effective moment of inertia, I_{eff}, for the reduced section as follows: $S_{eff} = [(\pi/32)\,(d_{eff}^4 - d_i^4)]/d_{eff}$; $I_{eff} = (\pi/64)\,(d_{eff}^4 - d_i^4)$
   - Calculate the effective nominal yield strength, F_{Yeff}, and effective nominal ultimate strength, F_{Ueff}, as follows: $F_{Yeff} = F_Y\,(A_{ceff}/A_c)$; $F_{Ueff} = F_U\,(A_{ceff}/A_c)$
4. The procedure in Note 3 is based on the assumption that the inner diameter for threaded bars remains virtually unchanged during the manufacturing process, even for machine cut threads.
5. The reduction in steel thickness should also be taken into account for couplers and nuts. Coupler and nut areas are more susceptible to corrosion because of higher stresses at thread-thread intersections. If the threads at couplers or nuts fail because of corrosion, the entire HBSN based system may be compromised.
6. The following should be noted when the guidance in this table is being applied:
   — This method is not recommended for steels with high carbon content (see discussion regarding metallurgy of HBSN steel in Chapter 2).
   — For soil nail applications the method is generally acceptable when the percentage loss of cross sectional area does not exceed half of its initial cross sectional area. Thus, this method is not recommended for reinforcing elements with small initial cross sectional area.
   — The method is normally used where the nails are installed at a fairly close spacing and a degree of redundancy exists. This can be achieved by using the guidance in FHWA (2003) which indicates that the soil nail spacing should be such that each nail has an influence area less than 40 ft^2.
   — In corrosive and highly corrosive soil conditions, it is important to consider that the soil nail is expected to take not only tension forces but also some shear.

Table 6. Minimum grout cover in mm (~ in) based on level of soil corrosion and service life (after CEN 2009).

Soil Features [Classification]	Service life of the structure (years)				
	5	25	50	75	100
Slightly Corrosive [IV]	10 (~0.4)	20 (~0.8)	25 (~1.0)	35 (~1.4)	Note 1
Average Corrosive [III]	20 (~0.8)	30 (~1.2)	40 (~1.6)	50 (~2.0)	Note 1
Corrosive [II]	30 (~1.2)	40 (~1.6)	50 (~2.0)	75 (~3.0)	Note 1
Highly Corrosive [I]	N/A	N/A	N/A	N/A	N/A

Notes:

1. Special considerations are required for determination of grout cover for 100-yr service life.
2. All values given are minimum and only for guidance. The grout cover for the reinforcing element and any couplers should be greater than the values noted in this table depending on the soil condition and service life. Since couplers are larger than HBSNs, the minimum diameter of the borehole would be dictated by the grout cover at the coupler location.
3. The corrosion protection provided by the alkalinity of hydrated cement grout may be acceptable provided that a high level of alkalinity ($9.5 < pH < 13.5$) is maintained.
4. Cement grout is considered to be acceptable as an impermeable protective encapsulation provided that the crack width within the grout body can be demonstrated to not exceed 0.1 mm (~ 4 mils).
5. The values in this table are related to grout cover with no other precautions added. In combination with other actions (such as galvanization, corrugated plastic sheaths, etc.) a longer service life may be achieved. Similarly, use of pressure grouting techniques may enhance the thickness and quality of cement grout and improves its properties as a corrosion barrier.

COMMENTS ON US AND INTERNATIONAL GUIDANCE

It appears that the European guidance is more comprehensive than the US guidance in the sense that it takes into account more corrosion-related parameters and provides explicit guidance in terms of sacrificial steel as well as grout cover thickness. Conceptually, the China-Hong Kong guidance is similar to the European guidance. It should be recognized that use of the corrosion guidance in Tables 3 to 6 assumes that a suite of all applicable tests required in Table 4 have been performed. It is recommended that at least one suite of all applicable tests be performed for each geologic unit anticipated to be encountered within the soil nailed mass. The distribution of the geologic units may be determined based on the recommended subsurface investigation program outlined in FHWA (2003).

Although the CEN (2009) document acknowledges use of hollow reinforcing elements as soil nails, neither the US nor the European guidance explicitly addresses HBSNs wherein the rotary "whipping" action of the installation process may render coatings and plastic sheath type of protections ineffective. Furthermore, the greater pullout resistances that are often assumed for HBSN applications may result in greater tensile strains leading to larger potential for cracking of the grout body, particularly at the coupler locations, which have a smooth steel-grout interface. Thus, from a practical perspective, it appears that the sacrificial steel allowance approach might be the most prudent method for mitigating the effect of corrosion.