HOLLOW BAR SOIL NAILS

Review of Corrosion Factors and Mitigation Practice

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U.S. Department of Transportation
Federal Highway Administration

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
12300 West Dakota Avenue
Lakewood, CO 80228

FOREWORD

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Hollow bar soil nails (HBSNs) have been used in the United States in earth retention systems for over 10 years. HBSNs are commonly used in place of solid bar soil nails (SBSNs) when the solid bar installation would require temporary casing of the hole. A state-of-the-practice (SOP) document was prepared by FHWA in 2006 to identify (a) the various peculiarities of HBSNs in comparison with the conventional SBSNs, and (b) areas of further research, evaluation and testing that would help agency personnel and design professionals understand the potential of HBSNs as a mainstream technology for permanent soil nail applications. This report concentrates on one of the specific areas of research identified in the 2006 report as related to corrosion mitigation. The scope of this report is limited to the preparation and distribution of a survey questionnaire, evaluation of various parameters for HBSNs as they relate to corrosion, preparation of a summary of the responses to the questionnaire, and a review of existing corrosion guidance.

for F. David Zanetell, P.E., Director of Project Delivery
Federal Highway Administration
Central Federal Lands Highway Division

Notice

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16. Abstract

Hollow bar soil nails (HBSNs) have been used in the United States in earth retention systems for over 10 years. HBSNs are commonly used in place of solid bar soil nails (SBSNs) when the solid bar installation would require temporary casing of the hole. A state-of-the-practice document was prepared by FHWA in 2006 to identify (a) the various peculiarities of HBSNs in comparison with conventional SBSNs, and (b) areas of further research, evaluation and testing that would help agency personnel and design professionals understand the potential of HBSNs as a mainstream technology for permanent soil nail applications. This report concentrates on one of the specific areas of study identified in the 2006 report as related to development of corrosion mitigation guidance.

This report presents the results of an industry-wide survey including agencies, designers, consultants, manufacturers and contractors related to installation of HBSNs and practices with respect to corrosion aspects. Based on the responses it was found that a lack of guidance on corrosion protection is limiting the use of HBSNs for permanent applications in corrosive environments. There are numerous contributing factors that may lead to corrosion of HBSNs. These factors are identified in this report along with a review of the current corrosion mitigation guidance. Parameters to be evaluated in formal corrosion studies are outlined. Finally, recommendations for interim corrosion mitigation guidance and further studies are provided.

17. Key Words

HOLLOW BAR SOIL NAILS, CORROSION, MITIGATION, TESTING

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Value assigned to a parameter for assessing ground corrosion potential
AASHTO	American Association of State Highway and Transportation Officials
A_c	Cross-sectional area before corrosion loss
A_{ceff}	Effective cross-sectional after corrosion loss (computed)
ADSC	Association of Drilled Shaft Contractors – The International Association of Foundation Drilling
A_{eff}	Effective cross-sectional after corrosion loss (computed)
ASTM	American Society for Testing and Materials
BS	British Standard
C	A value that defines the criticality of structure (see Table 5)
CALTRANS	California Department of Transportation
CEN	Committé Européen de Normalisation [European Committee for Standardization]
CFLHD	Central Federal Lands Highway Division
DCP	Double corrosion protection
d_{eff}	Effective diameter after corrosion loss (computed)
d_i	Nominal (average) inner diameter before corrosion loss
DIN	Deutsches Institut für Normung [German Institute for Standardization]
d_o	Outer diameter before corrosion loss (computed)
DOT	Department of Transportation
D_G	Diameter of grout body
D_N	Outside diameter of hollow bar soil nail
E	Modulus of elasticity
EN	Euronorm, European Standard
f_c	Compressive strength of grout
FIP	Fédération Internationale de la Précontrainte [International Federation of Prestressing]
FHWA	Federal Highway Administration
FpreEN	Final Draft European Standard
ft	foot (feet)

ft^2	Square feet
F_U	Ultimate strength of hollow bar soil nail before corrosion loss
F_{Ueff}	Effective ultimate strength after corrosion loss (computed)
F_Y	Yield (nominal) strength of hollow bar soil nail before corrosion loss
F_{Yeff}	Effective yield strength after corrosion loss (computed)
GEC	Geotechnical Engineering Circular [developed by FHWA]
G-G	Grout-to-ground bond
gr	Grams
G-S	Grout-to-steel bond
HBSN	Hollow Bar Soil Nail
ID	Inside diameter
I_{eff}	Effective moment of inertia after corrosion loss (computed)
in	Inches
ksi	Kips per square inch
kPa	Kilo Pascal
m	meter
m^2	Square meters
mils	Milli inches (= 0.001 inch)
MPa	Mega Pascal
MSE	Mechanically Stabilized Earth
MTL	Maximum Test Load
NCHRP	National Cooperative Highway Research Program
OD	Outside diameter
oz	Ounce (ounces)
p_c	Confining pressure
psi	Pounds per square inch
PTI	Post Tensioning Institute

PVC	Poly Vinyl Chloride
r	Roughness of the grout-to-ground (G-G) interface
R	Rope-thread designation
R_{GG}	Grout-to-ground (G-G) bond (shear) resistance, e.g., kips/ft (or kN/m)
R_{GS}	Grout-to-steel (G-S) bond (shear) resistance, e.g., kips/ft (or kN/m)
SBSN	Solid Bar Soil Nail
SCP	Single corrosion protection
S_{eff}	Effective section modulus after corrosion loss (computed)
SI	Systéme Internationale (metric system)
SIA	Schweizerischer Ingenieur- und Architektenverein [Swiss Society of Engineers and Architects]
SOP	State-of-Practice
T_F	Tensile force in nail, e.g., kips (or kN)
TRL	Transport Research Laboratory
TUM	Technical University of Munich
US	United States
ΣA	Global Index
~	Approximately equal to

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Several manufacturers, contractors, and designers provided valuable information through their responses to the questionnaire included in Appendix B and additional supplemental information. This support was invaluable in developing this report and is gratefully acknowledged.

CHAPTER 1 – INTRODUCTION

Hollow bar soil nails (HBSNs) have been used in the United States (US) in earth retention systems for over 10 years. HBSNs are commonly used in place of solid bar soil nails (SBSNs) when the solid bar installation would require temporary casing of the hole. For permanent structures in corrosive environments where failure of the structure could result in loss of life, personal injury or significant property damage, the general approach has been to not use HBSNs. For such applications the use of SBSNs with factory-installed encapsulation-type of corrosion mitigation measures is preferred. However, regardless of these concerns, the use of HBSNs has increased steadily. Therefore, the FHWA initiated a systematic evaluation of HBSNs. As a first step, a state-of-the-practice (SOP) report was prepared by the authors for the Federal Highway Administration (FHWA) in 2006 (FHWA, 2006) to identify (a) peculiarities of HBSNs in comparison with conventional SBSNs, and (b) areas of further research that would help agency personnel and design professionals understand the potential of HBSNs as a mainstream technology for permanent soil nail applications. Chapters 1 and 2 of FHWA (2006) provide information on HBSN and SBSN technologies. The reader should review FHWA (2006) to gain a better appreciation of the two technologies. A free copy of the FHWA (2006) document can be downloaded from http://www.cflhd.gov.

FHWA (2006) identified a number of specific areas for further study and research. One of these areas was corrosion mitigation guidance. Based on the 2006 FHWA report and the additional studies performed by FHWA in collaboration with the Association of Drilled Shaft Contractors – The International Association of Foundation Drilling (ADSC), it is recognized that the surrounding grout body and/or bar coatings cannot be reliably counted on to protect HBSNs in corrosive environments. Therefore, the study in this report was commissioned to investigate the efficacy of various corrosion mitigation measures in the context of HBSNs.

In general, both HBSNs and SBSNs are encased in a grout body, which is understood to provide one level of corrosion protection. Centralizers are typically used to assure that the grout cover has a minimum thickness over the length of the nail. However, even if centralizers are used, HBSNs will probably not have the same degree of grout cover uniformity as SBSNs given the fundamental differences in the way each type of nail is installed. As noted in FHWA (2006) the grout body can crack under tensile strains regardless of whether HBSNs or SBSNs are used for retaining walls. Bending stresses can further contribute to the cracking of the grout body. Once the grout body has cracked, the cracks that penetrate the full depth of the grout can provide pathways for corrosive elements to reach the steel bar. In the case of SBSNs, encapsulation in corrugated sheaths can provide positive protection against corrosion, but in the case of HBSNs any coating or galvanization may be suspect because it might be damaged during the installation processes. The potential for corrosion in HBSNs may be further enhanced by the fact that greater pullout resistances are often assumed for HBSN applications that may result in greater tensile loads and associated strains leading to an increased potential for cracking of the grout body. Thus, the corrosion issue takes on more importance for HBSNs. The purpose of this study is to explore corrosion issues with respect to HBSNs. It may be noted that some of the issues explored in this report are equally applicable to SBSNs, e.g., cracking of the grout body under tensile strains. Thus, the recommendations developed herein may also be considered for walls with SBSNs.

SCOPE OF THE WORK

This work concentrates on the collection of existing data related to corrosion and corrosion mitigation of HBSNs and on providing guidelines to evaluate the corrosion phenomena in HBSNs. The scope of the work for the present study is as follows:

- Preparation and distribution of a questionnaire to evaluate various parameters for HBSNs as they relate to corrosion,
- Preparation of a summary of responses to the questionnaire and observed trends,
- Review of existing corrosion mitigation guidance and issues, and
- Identification of parameters to be considered in HBSN corrosion studies.

ORGANIZATION OF THE REPORT

Chapter 2 identifies the various factors that can affect the corrosion of HBSNs. In Chapter 3, the questionnaire development and its distribution are discussed. Chapter 4 presents a summary of the responses to the questionnaire. Chapter 5 presents an overview of the existing corrosion guidance and issues related to soil nails in the US and international practice. Chapter 6 identifies parameters that should be considered in HBSN corrosion studies. Conclusions and recommendations are presented in Chapter 7.

As alluded to earlier, this report builds on the information presented in FHWA (2006). Therefore, it is assumed that the reader is familiar with the 2006 report. If not, then the reader should obtain a copy of the 2006 report and study it in conjunction with this report. As noted earlier, a copy of the 2006 report may be obtained from Central Federal Lands Highway Division (CFLHD) of the FHWA located in Lakewood, Colorado, USA, or from its website http://www.cflhd.gov/.

Units

English units are the primary units in this report. SI units are included in parenthesis in the text. Where SI units are reported in referenced material they are maintained as primary units, e.g., the CEN (2009) reference shown in Tables 5 and 6 in Chapter 5. In this case, the English units are included in the parenthesis. In either event, all unit conversions are “hard,” resulting in rounded and rationalized values.

CHAPTER 2 – FACTORS AFFECTING CORROSION OF HBSNs

Unlike the conventional "drill-and-grout" process used to install SBSNs, the HBSNs are installed using a process that involves the concurrent activities of drilling, placing the reinforcement, and grouting. In general, the concurrent activities may result in faster installation of the soil nails although the actual rate is dependent on the grout loss into the soil formations during drilling. Due to several factors, the HBSN technology leads to more uncertainties as related to long-term corrosion protection. Based on the information in FHWA (2006), the major factors that can affect corrosion aspects are as follows:

- Soil corrosivity
- Coatings
- Soil abrasiveness
- Sacrificial steel
- Grout properties
- Cracks in the grout body
- Grouting procedures
- Grout cover, drill bit size, and centralizers
- Stress in steel
- Thread types
- Nail head
- Couplers
- Proof testing
- Metallurgy of HBSN steel

The purpose of this chapter is to provide the reader with an objective review of the various factors and the work done to date; no specific recommendations for the use or non-use of HBSNs is made or intended. In the discussion, it is assumed that the reader is familiar with the corrosion process in metals and its terminology. Appendix A contains a brief description of the corrosion process in metals and its terminology.

SOIL CORROSIVITY

Corrosion of metals is an electrochemical process that results in the return of metals to their native state such as oxides and salts. The rate and magnitude of corrosion is a direct function of the environment in which the metal is placed. In the case of soil nails, the primary environment of interest is the soil. Soil is generally a three phase medium that consists of solid particles, liquids and gases, all of which can serve as electrolytes. An electrolyte is any substance containing free ions that behaves as an electrically conductive medium. In soils, for practical purposes, the liquid may be considered as water and the gas as air. Depending on the mineralogical composition of the solid particles in conjunction with the dissolved salts or pollutants in the water phase and the oxygen in the air phase, a variety of corrosive environments can develop in nature. For metals in soil and/or water, corrosion is typically a result of the contact of the metal with soluble salts. In general, the most corrosive soils contain relatively large concentrations of soluble salts in the form of sulfates and/or chlorides. There are many other factors that can contribute to corrosion including, but not limited to, the state of stress in the steel, metallurgy of steel, the texture and density of the soil, microbial activity, and stray currents. The key issue with respect to HBSNs is to prevent contact of any of the 3 phases of the soil mass with the soil nail. In this regard, it is important to test the soil for its electrochemical properties (e.g., pH, soluble salts, resistivity, etc.) and provide a protective cover around the nail to prevent contact of corrosive elements with the soil nail. This protective cover generally consists of some type of coating applied directly to the soil nail or encapsulating grout or a combination of both. However, until testing can demonstrate that either the surrounding grout body and/or bar coatings can be counted on to protect HBSNs the only reliable corrosion mitigation method currently available for HBSNs is to use sacrificial steel in the design.

Drilled soil nails, whether SBSNs or HBSNs, are encased in cementitious grout. As indicated previously, centralizers are typically used to assure that the grout cover has a uniform thickness over the length of the nail. However, even if centralizers are used, HBSNs will probably not have the same degree of uniformity of grout cover as SBSNs given the fundamental differences in the way each type of nail is installed. This is not to say that a uniform grout cover around SBSNs can be guaranteed. If an intact (i.e., uncracked) and uniform grout body is assumed, corrosion of soil nail steel will occur only after carbonation of the cementitious grout as explained in Appendix A. Once the grout cover has carbonated, the rate of corrosion will depend on the type of coating (e.g., hot-dip galvanized, metalized, epoxy-coated, etc.) and the soil corrosivity. Coatings are discussed next.

COATINGS

A variety of coatings are used to mitigate the corrosion of metals. The two basic coatings for soil nail applications are (a) a layer of zinc, and (b) a layer of fusion-bonded epoxy. The corrosion protection mechanisms of the basic coatings are significantly different as briefly discussed below:

- **Zinc coatings**: Depending on the environment, zinc has a rate of corrosion which is 10 to 100 times slower than that of ferrous metals (AGA, 2006). When applied as a thin film on ferrous metals, zinc provides a barrier between steel and the environment and also protects the base metal cathodically. This is because zinc is anodic compared to iron and steel and will preferentially corrode and protect the iron or steel against rusting when the zinc coating is damaged. Many different types of zinc coatings are commercially available and each has unique characteristics. For reinforcing bar type applications such as soil nails, the two common types of zinc applications are hot-dip galvanization and metallizing. These two applications are briefly discussed below:

  - In hot-dip galvanization a zinc coating is applied by immersing the steel in a bath of liquid zinc after the steel is cleaned of any surface contamination such as oils, greases, rust, etc. Because the material is immersed in molten zinc, the zinc flows into recesses and other areas difficult to access, thereby thoroughly coating all areas of deformed bars for corrosion protection. The zinc coating is metallurgically bonded to the steel substrate, with the coating integral to the steel. The strength of the bond, measured in the range of several thousand psi, results in a very tightly adherent coating (AGA, 2006).

- In metallizing, also known as zinc spraying, the steel is coated by high velocity spray from a heated gun in which zinc is melted. Heat for melting is provided either by combustion of an oxygen-fuel gas flame or an electric arc. Abrasive cleaning of the steel is required before metallizing. Metallizing can be applied to materials of nearly any size, although there are some limits depending on the configuration of the structure being metallized in terms of access of metal spray to recesses, hollows, and cavities. In contrast to the tightly adherent zinc coating in the hot-dip galvanization procedure, the coating adherence in the case of the metallization procedure is mostly mechanical, depending on the kinetic energy of the sprayed particles of zinc. Furthermore, the coating thickness and consistency is dependent on operator experience, therefore coating variation is always a possibility. Coatings may be thinner on corners or edges than on flat or round surfaces and the metallizing process is not suitable for coating recesses and cavities. Based on these considerations, the hot-dip galvanization is the preferable coating method from the perspective of soil nails, particularly for nails which have sharper threads such as those on deformed reinforcing bars.

Based on tests performed on Mechanically Stabilized Earth (MSE) wall reinforcements (FHWA, 1990) in slightly corrosive ground as defined in Chapter 5, galvanization may be consumed in 10 to 20 years assuming zinc application at the rate of 2 oz/ft^2 (~ 610 gr/m^2). Based on data published by AGA (2008) and using the ISO 12944-2 definitions for classification of environments, the service life of the zinc layer applied by the metallization process is about one-third to one-fifth of that for galvanization in environments ranging from "dry indoor spaces" to "seacoast (or heavy industrial)," respectively.

- **Fusion-bonded epoxy coatings**: In contrast to hot dip galvanizing and metalizing, fusion-bonded epoxy coatings are dielectric, which means that they cannot conduct current, i.e., they act as insulators. Therefore fusion-bonded epoxy coatings deprive the corrosion mechanism of a path for galvanic current to flow, essentially terminating the corrosion process.

  The determination of the life of epoxy coated bars is not as straightforward as that for galvanized bars. There is a variety of epoxy coatings available depending upon the material to be protected, the degree of protection required and the type of environment against which the protection is needed. The characteristics of and specifications for these various coatings are available from manufacturers. The most common coatings used on steel rebar are colored-coded green, gray and purple. The green coating is flexible and is applied to rebar that will be bent afterwards. Bars with green colored epoxy coatings are sometimes used in soil nail applications, especially for SBSNs. The gray and purple coatings are applied after fabrication of the steel rebar with the understanding that the bar will not be bent. The purple colored epoxy coating has greater chemical resistance than the green coating and is better suited for marine or harsh environments. That is why it is sometimes referred to as a "purple marine" coating in soil nail applications. It is typically used for HBSNs. Theoretically, undamaged epoxy coatings can provide protection for significantly longer periods than galvanization. However, epoxy coatings are prone to damage even during factory application. Therefore it is reasonable to assume that the epoxy coating will be damaged. NCHRP (2006) provides the following description of the behavior of epoxy coated bars:

> "Epoxy is a very effective barrier because it does not allow deleterious species to permeate through it. However, the epoxy uptakes some amount of moisture, which results in temporary reduction in bond between the epoxy and the steel surface. The effectiveness of the epoxy as a barrier is not impacted by the reduction or loss of bond; it is impacted by the presence of coating damage or defect in form of holidays, mashed areas, and bare areas. The defects in the coating are normally generated during application of the coating, storage and handling, transportation to site, placement in forms, and placement of concrete. Corrosion on epoxy-coated rebars initiates at defects in the form of crevice corrosion and can spread by undercutting the coating. The rate of corrosion is controlled by availability of cathodic sites and chloride ions. In addition, the coating may deteriorate with time, and more defects may appear on it. To account for corrosion spreading under the coating and deterioration of the coating, the amount of damage on the coating is varied with age. At age 0, the percentage of exposed surface area (i.e., damage or defect in the epoxy coating that exposes the steel surface) is assumed to be that allowed by the governing specifications or whatever the user believes it may have been. At the time of field evaluation, cores that contain one or more epoxy-coated rebar sections are extracted, and the percentage of exposed surface area on each extracted section is documented. The average percentage of exposed steel observed on extracted sections of epoxy-coated rebars is then used to determine the growth rate of deterioration. It is assumed that the rate of growth is linear, and this rate is used to determine when 100% of the surface of the epoxy-coated rebar will be exposed (i.e., no epoxy coating is left on the rebar). This rate of increase of deterioration is used by the model, and it is assumed that the rate will remain the same in the future. The model allows corrosion initiation on epoxy-coated rebars in the finite elements that have suffered epoxy coating damage. A probability distribution is used to determine if the epoxy coating in the finite element has suffered damage or not."

From the description of the deterioration model by NCHRP (2006), it is apparent that an assessment of the amount of initial damage to the epoxy coating is the basis for estimating the service life of epoxy coated bars. The rotary "whipping" action during installation of HBSNs ensures that the epoxy coating will be damaged by abrasion resulting from its contact with the soil mass into which the HBSN is being installed and/or by impact with centralizers during installation. Figure 1 shows photographs of green and "purple-marine" epoxy coatings damaged during installation in a dense gravelly soil. For practical purposes, the damage to the epoxy coating should be considered significant, which may severely reduce its useful service life. It is realistic to assume that as soon as the grout cover is carbonated or cracked, the underlying carbon steel is potentially in danger of corrosion. When cracks in the grout cover occur near or at locations where the epoxy coating has been damaged, corrosion can be expected to begin in a very short time. In this sense, it is better to concentrate on improving the effectiveness of the grout cover in resisting carbonation or cracking and preventing early access of deleterious substances to the nail steel than trying to improve the physical/chemical properties of the epoxy coating itself. Steel bar epoxy coatings were developed to provide corrosion protection for statically placed rebar in concrete. The installation of SBSNs is analogous to that application. Therefore epoxy coatings can be expected to provide similar corrosion protect for SBSNs. However, the effectiveness of epoxy coatings in providing reliable corrosion protection for HBSNs has yet to be demonstrated.

In some cases, a combination of galvanization and fusion-bonded epoxy coatings, known as a "combi-coating," is used. In this case the galvanization is performed first and then the epoxy coating is applied. Thus, the intent is to increase the service life of the zinc coating and thereby increase the corrosion protection of the underlying metal. However, given the rigors of the installation process, it is likely that the epoxy coating is damaged. Therefore the use of costlier combi-coatings for HBSNs is also questionable.

SOIL ABRASIVENESS

As noted previously, HBSNs are subjected to a rotary "whipping" action during the installation process. As the bar spins rapidly, it makes contact with the surrounding soil medium and with the soil mixed grout flowing past it as the grout is circulated back to the collar (top location) of the drill hole. This contact causes abrasion damage to the coating. The coarser the soil, the more abrasive the soil is and the more potential there is for the coatings to be damaged during installation, which increases the potential for corrosion. The abrasiveness also increases with increasing angularity of soil particles. When centralizers are used, the degree of the damage due to abrasion is also a function of the size of the annulus space relative to the size of the soil particles. Therefore, the coating on an HBSN, regardless of its type, is likely to be damaged during installation due to abrasion from the soil.

SACRIFICIAL STEEL

Since coatings have a finite life, the corrosion of the underlying metal is inevitable. Therefore, provisions are often made in design to account for the reduction in the cross-section of HBSNs due to corrosion by increasing the required cross-section with a predetermined amount of "sacrificial steel." The rate of corrosion loss is an important parameter to estimate the magnitude of the steel loss over the design life of the soil-nailed structure. The rate of corrosion is a function a variety of factors as discussed in Appendix A. Use of sacrificial steel is the most common mechanism to mitigate the detrimental effects of corrosion over the design life of the structure as discussed and referenced in FHWA's state of the practice document (FHWA, 2006). However, even the use of sacrificial steel may not be entirely effective when corrosion is localized at crack locations where pitting corrosion may occur or at stress concentrations where stress corrosion could develop. Guidance on estimating steel loss is discussed in Chapter 5.

Figure 1. Photo. Damage to epoxy coatings (Courtesy: Schnabel Engineering/ADSC).

GROUT PROPERTIES

Soil nails installed by using drilling procedures are always encased in grout regardless of whether they are HBSNs or SBSNs. As noted in a study by the Fédération Internationale de la Précontrainte (FIP,1986), cement grout provides a highly alkaline environment in the pH range of 11 to 13 that helps protect the steel in the absence of aggressive anions. At this pH, a passive film forms on the steel that reduces the rate of any further corrosion to minimal levels. Thus, the cement grout cover provides chemical as well as physical protection to the steel. However, this protection works only if the grout cover is intact, i.e., there are no fully penetrating cracks in the grout. Another important property of the grout cover in terms of corrosion is its permeability. The lower the permeability of the grout, the more the grout slows the migration of corrosive elements towards the steel. The relative permeability of grout generally decreases as the water:cement ratio decreases and more thorough mixing techniques are used. In granular soils the water:cement ratio of the in-place grout may be less than the as-mixed water:cement ratio due to the passage of bleed water into the soil (pressure filtration). It should also be noted that during HBSN installation, the grout is contaminated by mixing with the native materials. This issue can be addressed by the requirement to completely flush full strength grout once the HBSN has been installed to its target depth. Grout flushing is discussed in more detail in FHWA (2006).

CRACKS IN THE GROUT BODY

Grout can crack due to a variety of reasons including, but not limited to, shrinkage of the grout and tensile strains in the soil nails. Cracks can be localized near the ribs of deformed reinforcing bars ("rebars") or can extend through the grout body. The area around couplers is particularly vulnerable to grout crushing/cracking because of reduced grout cover in that area as well as the smooth interface between the coupler and the grout; these conditions are discussed later under "Couplers." Localized cracks are referred to as internal cracks while cracks that extend through the grout body are referred to as primary cracks, as shown in Figure 2. The two crack types, i.e., internal and primary, are very different in their behavior. Internal cracks can affect the grout-steel (G-S) bond resistance while primary cracks provide avenues for corrosive elements to make contact with the steel. Internal cracks have an important influence on the size and frequency of primary cracks depending on the deformation patterns on the rebar, e.g., diagonal lug, lateral lug, wavy lug, etc. (Goto, 1971). Since all soil nails have a deformed surface with different lug patterns, the grout body surrounding any nail, *whether solid bar or hollow bar*, will ultimately develop cracks once the tension and/or bending forces have reached a threshold value for the type of thread on the bar and the strength of the grout body surrounding it (FHWA, 2006). Thus, this discussion applies to all tensioned elements that use grouts or other similar agents as a bonding mechanism. Once the primary cracks have penetrated the entire grout body and made contact with the bar, the potential for corrosion exists in corrosive environments as discussed in Appendix A.

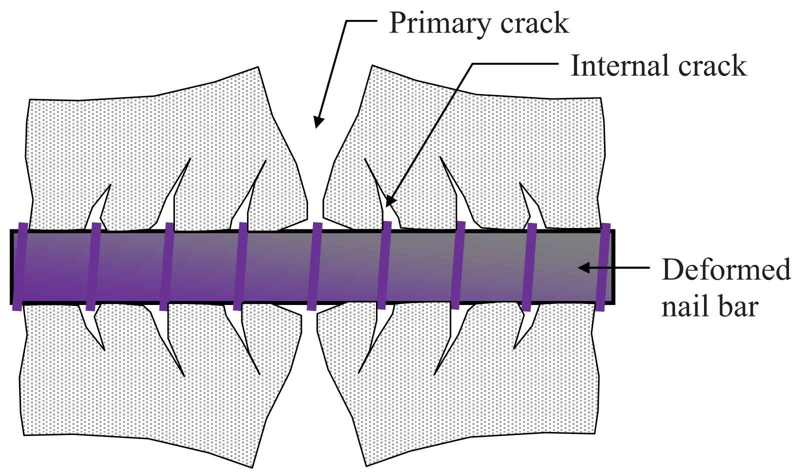

Figure 2. Schematic. Lateral crack pattern close to deformed reinforcing nail bar in tension (after Goto, 1971; FIP, 1986).

Studies by Goto (1971), Beeby (1978), FIP (1986), Zilch and Müller (1997), Schießl (1999), and Hegger and Roeser (2006), indicate that primary cracks larger than 0.1 mm (~ 4 mils) allow for the migration of corrosive elements from the soil through the cracks to the bar steel. Depending on the type of environment, e.g., marine, soil, etc., and the application, e.g., bridge decks, soil nails, etc., there is some disagreement in the literature regarding the size of the crack that is of concern with estimates varying between 0.1 mm (~ 4 mils) to 0.3 mm (~ 12 mils). With respect to soil nails, CEN (2009) indicates the use of 0.1 mm (~ 4 mils) as a limiting criterion for crack width because for cracks smaller than 0.1 mm (~ 4 mils) the grout can be considered to be a relatively impermeable barrier given that the grout can be self-healing. Once a fully penetrating crack forms, corrosion cells can develop at the nail-grout interface. The next level of protection is the directly-applied coating, which has a finite life as discussed previously.

The lateral crack formation mechanism shown in Figure 2 is based on a consideration of axial tension, which is the primary loading mechanism for soil nails. Longitudinal cracks can also form. In addition, soil nails can be subjected to flexural stresses particularly near the failure surface within the soil nailed mass. The grout body can crack at low flexural stresses, particularly when combined axial and flexural loading occurs. In the US practice, it is common to neglect the bending resistance of the soil nails in design, which results in a reduced possibility of significant flexural stresses developing within the soil nails. However, neglecting the effect of bending in design does not mean that bending does not occur in reality. The effects of bending should be considered in the evaluation of corrosion because they could play a role in crack development. The potential effect of bending on grout cracking requires further research.

In addition to increasing the size of the grout body, the development of cracks may be mitigated by adjusting the properties of the grout mix (e.g., water:cement ratio, using non-shrink grout, geosynthetics fibers, chemical additives in the grout to improve tensile strength, etc.) to control the strength of the grout and by limiting the tensile stresses in the soil nail as discussed in FHWA

(2006). Each of these steps to adjust the properties of the grout mix attempts to do one or more of the following: increase crack resistance through increased grout tensile strength (both material strength and reinforced strength), lower nail tensile stresses, or improve the stiffness of the grout body to accept greater strain prior to crack initiation.

Finally, it should be realized that the neat cement grout from the batch plant gets contaminated with in situ soil formations during installation of HBSNs. Such contaminated grout may have more variable properties than neat cement grout because the soil particle sizes are usually larger than the cement particle sizes. Such grout bodies may be susceptible to cracking at the interface of the cement paste with larger particle sizes in the soil formations through which the HBSNs are installed. From this perspective, it is necessary to flush neat cement grout through the HBSN assembly after the nail has reached it target depth. The flushing should be continued until clear cement grout is observed to flow from the collar (top location) of the drill hole. While this may not completely mitigate the contamination of the neat cement grout with native soil particles, it does address the concern to a large extent. The reader is referred to FHWA (2006) for discussions on grout flushing during HBSN installations. Additional discussion on grouting procedures is provided in the next section.

GROUTING PROCEDURES AND EQUIPMENT

The structural integrity of the grout body and its resistance to cracking is dependent to a large extent on the grouting procedures. As noted in FHWA (2006), grouts of two consistencies are often used in the drilling and installation of HBSNs. These grouts are referred to as "flushing" grout and "final" grout. The main purpose of using two different grouts is to reduce costs, with flushing grout being used during drilling when the continuous flow of grout is being flushed out of the drill hole, and final grout being injected to fill the drill hole only after the soil nail has reached its target penetration. Flushing grout has a greater water:cement ratio than final grout and is, therefore, weaker in strength. The final grout is full strength grout, which may provide the best chance to mitigate cracking.

There are varying opinions in the industry on the use of flushing vs. final grout and what these grouts mean relative to nail strength and corrosion performance. Some feel that there is a strong performance-based reason for using flushing grout and that it should be utilized exclusively to ensure proper corrosion protection. Their logic is that the flushing grout is a thinner mix, and therefore is able to permeate the soil mass easier than final grout. Greater permeation of the soil mass allows for a larger conglomerate of soil around the steel element. Others suggest that flushing grout causes undue erosion and abets final grout loss into deep cracking and fissures. The issue of grout consistency involves grout strength. Intuitively, greater grout strength and reduced grout contamination within situ soil formations is equated with less cracking. However, stronger grout, with its greater modulus of elasticity, is more brittle than weaker grout and could conceivably crack more than weaker grout with its lower modulus of elasticity. Weaker grout may also creep more under load, which is preferable when considering cracking. Clearly, these issues, which pertain exclusively to HBSNs, require further research.

Another consideration related to the structural integrity of the grout body and its resistance to cracking may be the type of mixer used for preparing the grout. High-speed, high-shear mixers produce better quality grouts than paddle mixers, which likely results in grouts having better corrosion protection. High-speed, high-shear mixers do a better job of wetting cement particles, decreasing bleed, and increasing strength. Paddle mixed grout, especially at high water:cement ratios, can create channels and pockets of bleed water. This is especially true when the grout is encapsulated or holes are drilled in clay, rock, or other low permeability materials. However, most HBSNs are installed in granular (caving) soils with high permeabilities. As indicated previously, excess bleed water can easily permeate the soil mass (pressure filtration) so that the water:cement ratio of the in-place grout may be less than the as-mixed water:cement ratio. On the other hand, since paddle mixers are not as efficient as high-speed, high-shear mixers at wetting cement particles, their use may result in the presence of more unhydrated cement in the grout body, which could actually be beneficial when the grout cracks. Autogeneous healing of microfractures can occur when water enters the crack and reacts with unhydrated cement (Burrows, 1998). Autogeneous healing cannot occur if there are no un-hydrated cement particles left after mixing.

The practical benefits of using high-speed, high-shear mixers to prepare grout are as follows (after Houlsby, 1990; Reschke, 2000):

- The combined effect of the highly efficient mixing action and the ability to mix at low water: cement ratios allows for reductions in the cement content for a given strength requirement and also reduces permeability of the grout cover.

- Cement particles in the mix are thoroughly wetted by the high speed shearing action of the mixer and formation of flocs or clumps is minimized. This wetting results in better hydration of cement particles leading to greater strength and durability.

- The grout mix is nearly immiscible in water. Immiscibility allows the mix to resist washout or contamination with other water sources.

- The mix is stable and fluid enough to allow it to be pumped considerable distances.

- The grout permeates uniformly into voids.

- Segregation of sand, if incorporated in the mix, is virtually eliminated.

- The grout has less settlement, i.e., bleed of the cement when stationary.

In addition to the use of high-speed, high-shear mixers, consideration may be given to physical and chemical additives to modify the strength and stiffness of the grout, which in turn will mitigate the development of cracks and reduce permeability. Physical additives may be in form of geosynthetic fibers that do not react with cementitious grout and do not create problems with the pumpability of the grout, e.g., if proper care is not taken the drill bit aperture could plug easily with the fibers. The authors have used such geosynthetic fibers successfully on two of their projects where open-graded soil formations were resulting in large grout losses; the use of geosynthetic fibers led to successful grouting of the HBSN boreholes.

There are a variety of chemical additives in the marketplace to improve the strength of grout. However, chemical additives should be carefully evaluated with respect to their chemical compatibility with steel in terms of corrosion as well as pumpability and set characteristics with respect to the grouting procedures and equipment.

GROUT COVER, DRILL BIT SIZE, AND CENTRALIZERS

Although many factors such as soil type, flushing volumes, jetting pressures, drill speed and advance rates, affect the final thickness of the grout cover, it is the drill bit size that primarily dictates the thickness of the grout body. Because of the jetting action at the drill bit, the diameter of the grout body for HBSNs is often larger than the drill bit size (FHWA, 2006). The larger the diameter of the grout body, the more resistance to corrosion due to less probability of cracks extending through the full depth of the grout cover. To ensure a consistent thickness of grout cover, consideration may be given to the use of centralizers.

Centralizers may be both good and bad for HBSNs. Centralizers encourage uniform grout coverage around the bar, generally result in straighter drilling (minimizing bar stress), and minimize the whipping of the bar during drilling, which may damage coatings. Fixed, plastic-type centralizers that are commonly used for SBSNs are typically not suitable for HBSNs because they tend to get damaged during the rotary "whipping" action of the HBSNs during installation. Therefore, mobile metal centralizers are used that have an inside diameter (ID) larger than the OD of the HBSN but smaller than the OD of the couplers. There are several concerns related to the use of mobile metal centralizers as follows:

- The outside diameter of the centralizer should be recommended such that the centralizer has a minimum of 1-inch greater OD than that of the coupler. Drill bit diameter selection should take this oversize into consideration.

- During the installation of HBSNs, there is a high probability that the mobile metal centralizers will damage the epoxy coatings and thereby reduce the corrosion protection.

- A non-metallic protective sleeve within the ID of the centralizer can be used to minimize the steel centralizer damage to the HBSN's coating.

- The centralizer metal is different from the nail metal. This difference creates the potential for galvanic corrosion, i.e., corrosion due to contact between dissimilar metals. This possibility may be further compounded by the possibility that the edges of the centralizer may be in contact with the soil, which may be corrosive. Due to concerns related to galvanic corrosion and damage during installation, it appears that there is a need to develop centralizers made from durable non-metallic materials (e.g., thick nylon).

- During the installation process, mobile centralizers will tend to migrate to coupler locations. There is a possibility that cuttings and pockets of air may be trapped at this location, which may make this area susceptible to corrosion. Retracting and advancing the HBSNs by 4 to 5 ft (1.2 to 1.5 m) once they have reached the target depth may help alleviate this problem. Perhaps a larger grout body is the more positive mitigation option in this case.

- Centralizers may represent a grout body inclusion along the bar that promotes cracking.

There are varying opinions in the industry on the role of centralizers in corrosion mitigation. Some feel that centralizers are an important feature of the designed and installed soil nail system and that the benefits of the potentially uniform grout cover they provide outweigh the possible side effects of the centralizers on corrosion due to compromising of the epoxy coating. Others feel that that the potential damage to epoxy coatings due to centralizer impacts during the installation of HBSNs far outweighs any benefits from potential improvement in the uniformity of the grout cover since the effect of centralizers in improving grout cover uniformity has yet to be demonstrated. All seem to agree that further research is needed before any definitive statement can be made about the efficacy of centralizers in HBSN corrosion mitigation.

STRESS IN STEEL

The major effect of tensile stress in soil nails is that of producing cracks in the grout body due to tensile strains in the steel. As noted earlier, flexural stresses can also contribute to the development of cracks particularly near the failure surface within the soil nailed mass. Therefore, the level of steel stress at which cracks are produced is of importance with regard to corrosion in view of the crack-corrosion correlation discussed earlier. The development of cracks has the effect of setting up corrosion cells that tend to produce pitting (Houston, et al., 1972). Pitting corrosion can rapidly decrease the cross-sectional area of steel in a localized area thus increasing the stress levels in the steel leading to potentially unsafe structural conditions. On the other hand, the use of sacrificial steel reduces the resulting stress in an element and the likelihood of cracking grout as well as providing added resistance in the steel element. It should be noted that these observations about the stress in soil nail steel apply to both HBSNs and SBSNs.

THREAD TYPES

As noted in FHWA (2006), there are two primary types of threads: rope threads (“R”) and sharper threads. The R-thread is a smooth thread, while the other type of thread is comparatively coarser having an inclined shoulder that meets the general requirements of ASTM A615. While the R-thread is manufactured and distributed by all HBSN manufacturers, two manufacturers, Con-Tech Systems, Ltd. (CTS) and Willams Form Engineering Corp. (WF), also distribute HBSNs with sharper threads. German studies by Zilch and Müller (1997), Schießl (1999), and

Hegger and Roeser (2006), using neat cement grout bodies of various diameters in conjunction with CTS HBSNs, suggest that sharper-threads help mitigate the development and propagation of cracks better than smoother threads. The information in German studies is not new in the context of effect of thread types on cracking of surrounding cementitious bodies. Indeed, studies done a couple of decades earlier in rebar industry (e.g., Goto, 1971) had already demonstrated this observation which led to the development of various threads in the rebar industry as well as various standards such as ASTM A615 or AASHTO M 31. In any event, while German studies as well as other studies in the rebar industry indicate that sharper threads may mitigate development of cracks, there are several factors specific to the HBSN technology which could have an influence on the development and propagation of cracks and therefore need to be studied, e.g., effect of couplers and in situ grout composition. Such studies have not yet been performed by the FHWA and an industry-FHWA collaborative effort in this regard is clearly warranted to address this important issue.

NAIL HEAD

Once corrosion is initiated at a given location it spreads along the nail and all its accessories. In this context, one particularly sensitive area for local corrosion in a soil nail system is the nail head location which is generally encased in shotcrete. Before shotcrete is placed, care should be taken to completely encase the nail in the ground by periodically topping off the grout and then shooting shotcrete in any remaining opening around the nail. When a PVC sleeve is installed over the HBSN, care should be taken to ensure that the sleeve is grouted properly and so that it will be free of air, water or diluted cement grout. This can be done by use of a grout tube that allows grout injection from the lower end of the PVC sleeve so that grout is expelled out the top end. Simply shoving a PVC sleeve into wet grout does not ensure adequate grout encapsulation. Use of a 5 ft (~ 1.5 m) long section of PVC and grout encapsulated HBSN may be considered near the nail head location. Such sections can be easily pre-fabricated and shipped to the site as part of a regular order (Aschenbroich, 2009). However, it should be realized that the grout-ground (G-G) bond within the length of the encapsulation may be compromised depending on whether the encapsulation sleeve is smooth or corrugated.

COUPLERS

Couplers are an essential element of any HBSN application. Because HBSNs are manufactured in lengths of 4.9 ft (1.5 m) and 9.8 ft (3 m), couplers serve to connect the various manufactured lengths to obtain the nail lengths required based on the internal stability requirements of the pullout and tensile breakage modes of failure. In this context, the tensile strength of the coupler must meet or exceed that of the bars that it connects. The connection is achieved by mated threads wherein the internal threads of a coupler mate with the external threads on the reinforcing bar elements being connected by the coupler. This is also an area where coating thicknesses are minimized or eliminated by manufacturers to maintain threadability. Because of the connection configuration, the outside diameter of the coupler is larger than the diameter of the reinforcing bars. Therefore the grout cover is smaller at the coupler compared to that of the grout cover at the location of the reinforcing bar elements that are being connected by the coupler. Furthermore, the outside surface of the coupler is smooth. Because of the larger diameter, reduced grout cover, and smooth steel-grout interface, the grout within the length of the coupler is particularly vulnerable to crushing and/or cracking. Thus, couplers represent a concern in terms of corrosion. This concern is further exacerbated by the consideration that the coupler location is highly stressed because of thread-to-thread intersections. Once corrosion is initiated it tends to accelerate in areas of high stresses. Thus, while thread types may have an effect on the initiation and propagation of cracks, coupler locations may be of larger concern because of the various reasons mentioned herein.

PROOF TESTING

During proof tests the maximum test load (MTL) is carried to 150% of the design load. For identical bars, the test load may create more and/or wider crack widths in the grout body than the design load, thus rendering the nail more prone to corrosion. However, at this time there is insufficient information and test data on relative crack sizes vs. stressing. The interactions at the bar/grout interface and grout cover/soil interface are complex in terms of bar strains vs. grout strains vs. minimum crack strain/stress levels particularly when one considers the highly irregular grout body in case of HBSNs. These aspects need further study. As noted in FHWA (2006), use of larger diameter production bars that are sized for proof test loads may mitigate this concern and at the same time provide more sacrificial steel to compensate for corrosion. Other precautionary alternatives are to increase the number of verification tests to compensate for not performing proof tests and/or to conduct proof tests on sacrificial production nails.

METALLURGY OF HBSNs

Based on a comparison of various HBSN products currently available on the market, it is readily apparent that HBSNs have yield stresses ranging from 60 ksi to over 90 ksi. It is well-known that the metallurgy of steel can have a significant impact on its behavior. For example, if the steel has a relatively high (e.g., > 0.2%) carbon content, then it can lead to an increase in the strength of steel, but it may also cause a reduction in its ductility. At this time, the metallurgy of steel for HBSNs is not regulated and is not clearly understood with respect to their performance in soil-nailed walls. Furthermore, it appears that various HBSN manufacturers are using steel from different international sources whose properties may not be consistent with US standards. Since HBSNs are essentially reinforcing bar ("rebar") elements subjected primarily to tensile stresses, it is recommended that HBSN steel should meet the requirements of ASTM A615 (AASHTO M 31) as is the case with SBSNs. In ASTM A615 (AASHTO M 31), the ductility aspects are indirectly controlled by the requirements for elongation and bending. While the thread types of HBSNs vary and R-threads are not addressed by ASTM A615 (AASHTO M 31), all of the requirements for the metallurgy of steels in ASTM A615 (AASHTO M 31) should be implemented for HBSNs.

SUMMARY

Based on the above discussions, it is evident that HBSN technology is much more complex than SBSN technology. Clearly there is much more uncertainty in the HBSN installation processes than in the SBSN process. This uncertainty, when coupled with the inherent uncertainties associated with caving soil formations, leads to a final product that is difficult to quantify in terms of its behavior under stresses and associated strains as well as to establish its level of corrosion protection. Therefore, a comprehensive questionnaire was developed to survey the industry's practices and the published corrosion mitigation guidelines. Chapter 3, Appendix B, and Chapter 4 present information regarding the questionnaire and the responses. Chapter 5 presents information on published guidance regarding corrosion mitigation measures for soil nails and provides recommendations for future practice. Chapter 6 identifies parameters that should be considered in any HBSN based corrosion study and Chapter 7 presents conclusions and recommendations.

CHAPTER 3 – THE QUESTIONNAIRE

A comprehensive questionnaire was developed and distributed to seek industry input on various topics related to HBSN practice. A copy of the 4-page questionnaire is included in Appendix B. The questionnaire consisted of questions in the following 12 categories of interest:

1. Preparer/general information
2. Coatings
3. Sacrificial steel
4. Grout
5. Evaluation of soil corrosivity
6. Field corrosion test programs
7. Laboratory corrosion test programs
8. Thread type/configuration
9. Encapsulated HBSNs
10. Drill bit size/centralizers
11. Knowledge of existence of other HBSN corrosion-related studies.
12. Additional input and/or suggestions for developing corrosion mitigation guidance.

The categories include one or more of the fourteen factors related to consideration of corrosion in design and construction that were discussed in Chapter 2.

The questionnaire was distributed to owner agencies, manufacturers (US and international), design-build contractors, engineers/consultants, trade associations and one university selected on the basis of known faculty interests. Geotechnical engineers from the FHWA Resource Center were responsible for gauging the level of use of soil nails with their State DOT contacts. State DOTs with specific experiences in the use of soil nail technology, particularly as it pertains to HBSNs, were forwarded the questionnaire. Table 1 summarizes the distribution list.

Table 1. Summary of the distribution of the questionnaire.

Category	Contacts
Owners/ Agencies	FHWA and its resource centers All state DOTs (Departments of Transportation)
Manufacturers	AGL Manufacturing, Ltd. Atlas Copco Con-Tech Systems, Ltd. Dywidag Systems International (DSI), USA, Inc. Friedr. Ischebeck, GmBH SAS Stressteel Williams Form Engineering
Design-Build Contractors	DBM Contractors, Inc. Drill Tech Drilling and Shoring, Inc. Foundations Specialties, Inc. (FSI) Hayward Baker Inc. Mays Concrete, Inc. Nicholson Construction Yenter Companies
Engineers/Consultants	Geosystems, L.P. Schnabel Engineering
Trade Associations	ADSC – The International Association of Foundation Drilling Deep Foundations Institute (DFI)
Universities	University of Wyoming (Laramie, WY)

CHAPTER 4 – SUMMARY OF RESPONSES TO THE QUESTIONNAIRE

A total of 15 responses were received. Two respondents were from different offices of the same manufacturer (Williams Form Engineering). Two other respondents were from closely affiliated companies, one a manufacturer (Friedr. Ischebeck GmBH) and the other a distributor (Con-Tech Systems, Ltd.). The replies of the respondents from these same or closely related entities were not always in agreement probably because practices might be different in the different geographical regions in which the respondents were located, e.g., North America and Europe and east and west coasts of the US.

A summary of all the responses is included in Appendix C. Since most responses were hand written, for the sake of clarity and uniformity all responses were reproduced in typed format. Also, in order to limit the number of pages in Appendix C, multi-lined responses were paraphrased by the authors and only the paraphrased versions, indicated by an asterisk, are included in the summary presented in Appendix C. Seven of the respondents were contacted for clarification of their responses. Appendix C includes the clarified responses. The original questionnaires and the full responses are available from CFLHD.

A summary of the responses, organized in the order of the questions in the questionnaire, is presented here. Information that was requested to be kept confidential by the respondents was omitted. Since not all the questions were answered by every respondent, in summarizing the responses only the "useful" answers are reported below, i.e., responses that provide a direct answer to the question being asked. Therefore, blank spaces and answers of "N/A", "?" or "-" were not counted because it is not clear whether those responses were due to a lack of experience with HBSNs or a lack of knowledge about a specific aspect of the question being asked. In some instances the respondents did not answer the question but provided a comment. These comments, although useful in themselves, are not included in this summary since they do not provide a direct answer to the question.

1. General Information

- Eleven of the respondents indicated that they had experience with both temporary and permanent HBSN applications to varying degrees. Respondents from state agencies, except for the California Department of Transportation (CALTRANS), seem to have had very limited or no experience with HBSNs.

- Of the fifteen useful responses, eleven respondents indicated that lack of corrosion guidance is a major impediment to their use of HBSNs, particularly in permanent applications.

- Of the twelve useful responses, eleven respondents indicated that if clear corrosion guidance was available they would consider using HBSNs more frequently.

2. Coatings

- Of the thirteen useful responses, seven respondents indicated that they use nails having purple marine epoxy coating with a common thickness of 7 to 8 mils (~ 0.18 to 0.20 mm), except for CALTRANS who indicated use of 12 mils (~ 0.30 mm) without specifying whether or not the bars are for permanent or temporary installations.

- Of the thirteen useful responses, three respondents indicated use of green epoxy coating with a common thickness of 3 mils (~ 0.08 mm).

- Of the thirteen useful responses, eight respondents indicated use of galvanization with thicknesses ranging from 4 to 10 mils (~ 0.10 to 0.24 mm). One respondent (Ischebeck from Germany) indicated use of a "combi-coating," which consists of an epoxy coating on bars that have been previously coated with 3.5 mils (~ 0.09 mm) of galvanization.

- Of the thirteen useful responses, four respondents indicated that they had experience with observation of exhumed nails. One of those respondents indicated that the epoxy coatings he observed had been damaged.

3. Use of Sacrificial Steel

- Of the fourteen useful responses, seven respondents indicated that they used sacrificial steel.

- Two respondents indicated that they assume approximately 63 mils (~ 1.6 mm) for loss of steel section. One respondent indicated the use of one bar size larger than the size required by design.

4. Grout

- There were nine useful responses regarding the typical thickness of grout cover over the bar. The range of grout cover thickness was reported to be 0.75 to 3.0 in (~ 19 to 75 mm) with seven of the nine responses being in the range 1.0 to 2.0 in (~ 25 to 50 mm).

- There were nine useful responses regarding grout strength with reported values ranging from 3,000 to 6,000 psi (~ 20 to 40 MPa).

- There were ten useful responses regarding the cement type. Three of the respondents indicated use of Type I cement and four indicated use of Type I/II (general purpose) cement. One respondent indicated use of Type K (non-shrink) cement while two respondents indicated use of Type III (high early strength) cement.

- There were nine useful responses regarding water:cement ratio with values reported to be between 0.40 and 0.50. Six of the nine respondents reported a value of 0.45.

- There were ten useful responses regarding mixer type. Eight of the ten respondents indicated use of a high speed-high shear colloidal mixer for preparation of grout. One respondent indicated use of paddle mixers and one respondent reported using both types.

- There were ten useful responses regarding the use of diluted grout (flushing grout) for initial drilling and full strength grout (final grout) once target depth was reached. Six of the ten respondents indicated that they use both. Two respondents indicated use of full strength grout throughout the drilling process. One respondent indicated use of full strength grout throughout the drilling process in soil, and water for initial drilling in rock. One respondent reported that usage varies with soil type.

5. Evaluation of Soil Corrosivity

- There were seven useful responses regarding the use of assumptions or data for evaluating soil corrosivity. Three respondents indicated that they make assumptions; three indicated that they do both, and one respondent uses data only.

- There were nine useful responses regarding the use of guidance in GEC #4 (FHWA, 1999). All respondents indicated that they do not use GEC#4 (FHWA, 1999).

- There were ten useful responses regarding the use of guidance in GEC #7 (FHWA, 2003). Five respondents indicated that they used GEC #7 (FHWA, 2003) and five indicated that they did not.

- There were nine useful responses regarding the use of other guidance. Two of the nine respondents indicated use of the German standards (DIN [Deutsches Institut für Normung], 1985) for evaluating corrosion, one respondent used personal experience based on mechanically stabilized earth (MSE) walls, one respondent used the guidelines of the Post Tensioning Institute (PTI, 1996), one respondent used guidance on culvert criteria, and one respondent used guidelines in the Manual for Design & Construction Monitoring of Soil Nail Walls (FHWA, 1996).

6. Field Corrosion Testing Program

- There were thirteen useful responses regarding field corrosion testing. Of the thirteen respondents, seven had not performed a field corrosion testing program. Two respondents indicated that they had performed a field testing program and referred to an on-going field testing program in Switzerland. One respondent referred to an ADSC/FHWA field testing and exhumation program in Salt Lake City, and another respondent indicated an on-going ADSC study. The other two respondents that reported having conducted field corrosion tests did not comment about them. Final reports were not available for any of these studies.

7. Laboratory Corrosion Testing Program

- There were thirteen useful responses regarding laboratory corrosion testing. Of the thirteen respondents, ten had not performed a laboratory corrosion testing program. Two respondents indicated that they had performed a laboratory testing program and referred to an on-going testing program in Switzerland. The final report on the Swiss study was not available.

8. Effect of Thread Type/Configuration

- Thread type/configuration was singled out in the questionnaire even though it is just one of many factors that could influence crack development such as: the non-uniformity of the grout body, soil type, nail load, ground stresses within the finished reinforced mass, couplers, centralizers, etc. From the way the question was posed in the questionnaire, there were thirteen useful responses regarding the effect of thread type/configuration on corrosion rates. Nine of the thirteen respondents indicated that they did not think thread type (the R-thread versus the sharper thread) made a difference in corrosion rates. Two respondents (Con-Tech and Ischebeck), indicated otherwise and referred to studies done in Germany, which indicate that the sharper CTS/TITAN type threads reduce crack widths in the grout body thereby offering better protection against corrosion. One respondent answered affirmatively but indicated that the data show no difference in the cracks. One respondent answered affirmatively but had no data to support that answer.

9. Encapsulated HBSNs

- There were thirteen useful responses regarding awareness of encapsulated HBSNs. All but four respondents were not aware of encapsulated HBSNs.

- There were eleven useful responses regarding the feasibility of encapsulated HBSNs from an economic and construction viewpoint. Seven of the eleven respondents indicated that encapsulated HBSNs are likely not economically feasible or constructible. The four affirmative respondents conditioned their responses with comments regarding application and construction techniques e.g., the use of short lengths of encapsulated HBSNs near the face of the wall to mitigate corrosion near the nail head location.

10. Drill Bit Size and Centralizers

- There were nine useful responses regarding drill bit size. Six of the nine respondents reported values for the drill bit: HBSN OD ratio ranging from 1.6:1 to 4:1. Two respondents indicated use of drill bit sizes that were 2.0 in (~ 50 mm) larger than HBSN outside diameter (OD) for sand and 3.0 in (~ 75 mm) larger than HBSN OD for gravels.

One respondent indicated that the size varies by bit type and/or manufacturer, e.g., 3.0 in (75 mm) to 6.0 in (150 mm) for R38 bar.

- There were eleven useful responses regarding the use of centralizers. One respondent reported that they do not use centralizers. Seven of the remaining ten respondents reported use of centralizers on from 50 to 100% of their jobs. One respondent did not use centralizers on all projects and one indicated they use centralizers only when required. One user expressed concern about metal centralizers damaging the epoxy coating during installation of the soil nail. As indicated in Chapter 2 under the discussion of grout cover, drill bit size and centralizers, there is a need to develop centralizers made from durable non-metallic materials (e.g., thick nylon) that can withstand the extreme conditions imposed on the bar and centralizers during the installation of HBSNs.

- There were seven useful responses regarding distance between centralizers. Five respondents indicated 10 ft (3 m), one respondent reported a range of 8 ft (2.5 m) to 10 ft (3 m), and one respondent indicated 5 ft (1.5 m).

11. <u>Other Corrosion Studies</u>

- Of the fourteen useful responses regarding awareness of other corrosion studies, eight of the respondents were unaware of other corrosion studies. One respondent referred to an NCHRP proposal for research on the use of HBSNs for slopes or walls, but after follow-up discussions with the respondent it was found that the research was not funded. Three respondents referred to studies in Europe. One respondent referred to the PTI recommendations for anchors. One respondent referred to an ADSC/FHWA study by Schnabel Engineering.

12. <u>Additional Input and/or Suggestions</u>

Eleven respondents provided additional input and/or suggestions. These responses are a combination of recommendations and concerns. When taken together they provide a sense of the respondents' expectations from FHWA regarding corrosion guidance. They are presented here almost verbatim for the sake of accuracy. Where similar suggestions or comments were made by multiple respondents, the suggestion that was worded most clearly is reported.

- Follow German criterion that requires a minimum of 35 mm (~ 1.4 in) of grout cover for permanent soil nail applications. This criterion does not apply to HBSNs used as compression members such as micropiles.

- Use the sacrificial steel method.

- Consider using stainless steel for aggressive ground conditions.

- Be careful while dealing with the corrosion issue. Biggest concern is installation damage of any coating. Starting to see a number of MSE wall failures due to corrosion of steel reinforcements.

- Use combi-coating (epoxy-coated galvanized bars) for permanent applications in non-corrosive soils. HBSNs should not be used in aggressive, corrosive soils for permanent applications. The level of soil aggression must be well established by ASTM and CALTRANS standards.

- Need specific guidance because currently some users ignore corrosion while some suppliers/users promote sacrificial steel.

- Ensure drill bit is at least 1.5 in (~ 38 mm) larger than bar diameter.

- Use HBSNs only in non-aggressive ground.

- Use galvanized coating instead of epoxy coating from a durability standpoint since galvanization is a sacrificial coating.

- Need to develop better understanding of the size, shape and quality of resulting grout column for the proper selection of design assumptions for permanent wall design. Evaluate if there is a build-up of cuttings at the couplers, with or without the centralizers that will create porous pockets for increased corrosion there. Evaluate if there is a shrink sleeve durable enough to protect the couplers and threads on the bars adjacent to the couplers after installation.

- Need to be careful with use of metal centralizers since they would damage the epoxy coating during installation.

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).

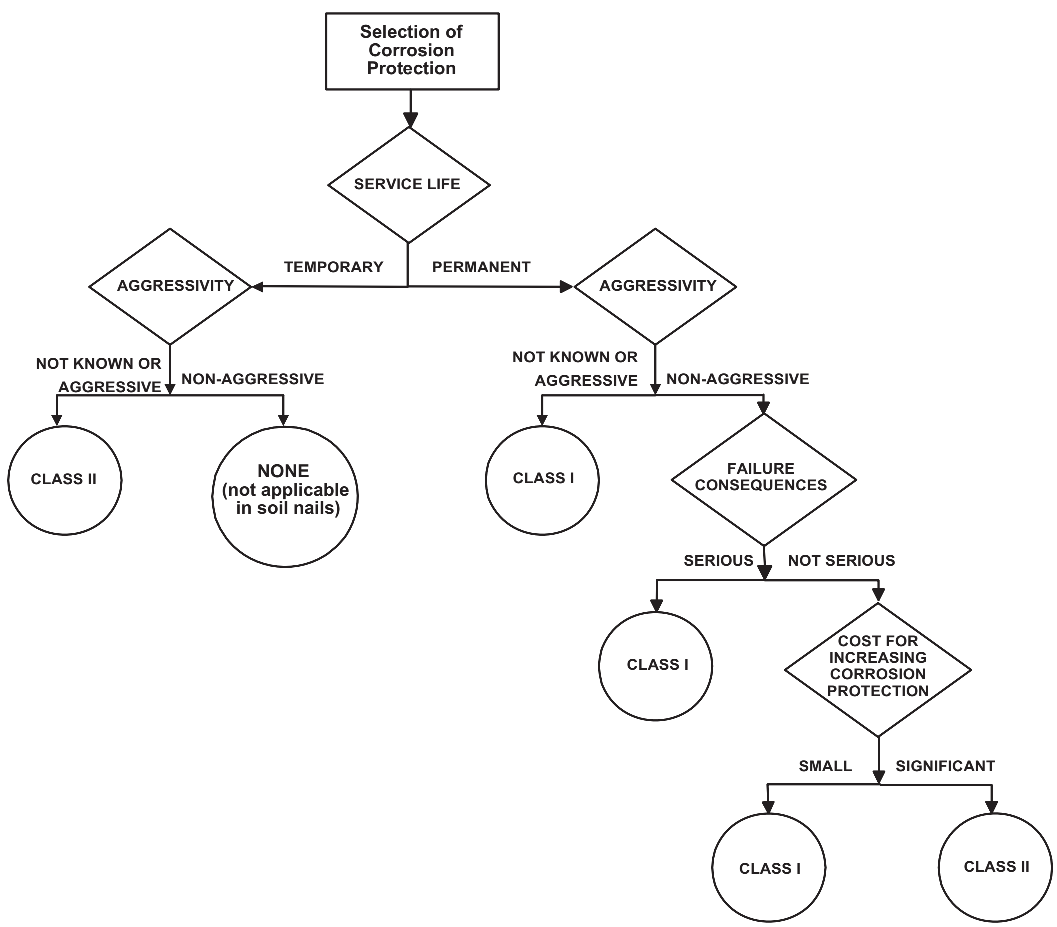

Figure 3. Flowchart. Criteria for selection of SBSN corrosion protection (FHWA, 2003)

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, $\Sigma A + C$ (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.

CHAPTER 6 – PARAMETERS TO BE CONSIDERED IN HBSN CORROSION STUDIES

Ideally a corrosion study for HBSNs should consist of a combination of field, laboratory and numerical simulation studies to evaluate the effect of the various factors presented in Chapter 2 on the corrosion of HBSNs. These factors may be categorized as “natural” or “mechanical.” Soil corrosivity and soil abrasiveness fall into the natural category while the other factors can be categorized as mechanical. The properties of the natural factors can be measured by appropriate testing as noted in Chapter 5. Most of the mechanical factors can be controlled by selecting appropriate equipment and installation procedures. Once the nails are installed the two basic considerations in a corrosion study for HBSNs are:

1. Mechanisms that provide an avenue for corrosion, i.e., causative mechanisms.
2. Corrosion of metals, i.e., metallurgical considerations.

The corrosion of metals is a well known and well documented phenomenon, as summarized in Appendix A. It is the causative mechanisms that should be the primary focus of a program of study to address the corrosion from the practical aspect of soil nail installation. For HBSNs, the primary means for controlling causative mechanisms is by preventing the formation of cracks in the grout body so that corrosive elements do not contact the HBSN. Variables that may affect crack formation include:

- Diameter of the grout body, D_G
- Compressive strength of grout, f_c
- Yield (nominal) load of steel, F_Y
- Tensile force in the nail, T_F
- Grout-to-ground (G-G) bond (shear) resistance, R_{GG}
- Grout-to-steel (G-S) bond (shear) resistance, R_{GS}
- Thread type, depth and spacing, e.g., rounded rope thread vs. deformed sharp thread
- Roughness of the grout-to-ground interface, r
- Confining pressure, p_c
- Bending and shear forces

As noted earlier, the testing program should ideally consist of a combination of field and laboratory studies. However, there are practical limitations to field studies. For example, a large number of field installations in various types of ground (soil type, density, moisture content, etc.) would be necessary. Furthermore, it would not be practical to conduct field tests in all possible soils. Therefore, it is recommended that consideration be given to a comprehensive laboratory study along with a limited field study. Before conducting the field study it is recommended that numerical simulations be performed to verify and extend the findings of the laboratory studies. Such numerical simulations will also help in the development of a design model after the field study. Consideration should also be given to a limited numerical study before the laboratory study to streamline the testing program.

CHAPTER 7 – CONCLUSIONS AND RECOMMENDATIONS

This report presents the results of an industry survey related to the use of HBSNs with respect to various criteria currently used to identify corrosion potential and current practices to protect against corrosion. Based on the responses it was found that there is a lack of guidance on corrosion protection, which is limiting the use of HBSNs for permanent soil nail wall applications. For example, the answers to some of the questions suggest that there is an overall lack of consistent assessment of corrosivity and an absence of any application of corrosion mitigation. Many respondents admitted to not even testing for or addressing soil corrosivity. This suggests that procedural guidance is critically required.

There are three major considerations related to the corrosion of HBSNs:

1. Performance of protective coatings during the installation process,
2. Cracking of the grout body, and
3. Metallurgy of HBSN steel.

Based on the results of this study, the following conclusions are made:

1. A coating, whether by fusion bonded epoxy, galvanization, metallization, or a combi-coating, has a finite life that may be less than the routine design life of 50 to 75 years for a permanent retaining wall even under ideal conditions. From the photos in Figure 1 it is apparent that damage to epoxy coatings is inevitable due to the rotary “whipping” action of HBSNs during installation. The same type of damage may be expected in other coatings. Therefore, the effective service life of coatings may be severely shortened in HBSN applications. The potential for excessive coating damage during installation seems to be the biggest differentiator between the SBSN and HBSN applications for permanent walls. This is not to say that coatings of SBSNs are completely free of damage due to nicks and scratches during handling and installation. If corrosion protection of HBSNs can be assured by some other means, then more confidence can be developed in the use of HBSNs for permanent applications on a par with the use of SBSNs. The obvious options for HBSNs are to concentrate on the grout body and its performance in addition to the use of sacrificial steel.

2. The potential for corrosion of HBSNs because of damaged coatings can be minimized by assuring that the grout body is not compromised. The development of cracks in grout appears to be a function of a variety of factors. These factors are identified in the report. Once cracks form in the grout body, corrosive elements can migrate through the cracks and initiate corrosion of the soil nail steel if the coating has been compromised. Of course, the corrosion potential in the bar is also a function of whether or not the cracks in the grout body occur at or near the location of damage to the coating. However, since damage to coatings due to the installation process is random and cannot be quantified reliably, an assumption has to be made the probability of the occurrence of a crack at the location of coating damage is great enough so that the onset of corrosion cannot be discounted. In this context, the

cracking of the grout body becomes very important since it is applicable to both SBSNs and HBSNs because both are susceptible to some level of coating damage.

3. At this time the metallurgy of HBSN steel is not regulated and the source of HBSNs available in the marketplace today can be traced to a variety of international sources, which may not be regulated in accordance with US standards. Thus, although high strength is claimed by various manufacturers, the HBSNs available in the US marketplace may have distinctly different behavior in terms of ductility and corrosion characteristics.

4. Numerous sources of information and personal communications reveal that there are several on-going studies in Europe related to corrosion mitigation that are at an advanced stage. Based on the review of US and international practice presented in Chapter 5, it appears that the European guidance in this regard is superior to the current US guidance in terms of scope and clarity in assessment of soil corrosivity (Tables 3 and 4) as well as in the estimation of the magnitude of steel loss (Table 5) and thickness of grout cover (Table 6).

In view of the uncertainties related to the current US practice for corrosion mitigation and the lack of uniform procedural guidance in this regard, the following recommendations are made:

1. It is recommended that field, laboratory and numerical simulation studies be performed to assess the factors that influence the development of cracks in grout as discussed in Chapter 6. In this context, it is recommended that formal contact be initiated with researchers in Europe to further understand their on-going experiments. Knowledge of the details of their investigations and an independent evaluation of their results may help to define the details of the study program described in general in Chapter 6.

2. At this time it seems to be more appropriate to concentrate on the concept of sacrificial steel as the preferred method of corrosion mitigation for HBSNs. Therefore, it is recommended that the guidelines in Tables 3 through 6 based on European studies described in Chapter 5 be considered as the interim guidance for corrosion mitigation in the US. Use of larger nail cross-sections to account for corrosion loss over the design life of the structure will also help limit the potential for the formation of grout cracks due to tensile strains in nails during proof testing.

3. For all HBSN projects the performance of at least one suite of all applicable tests noted in Table 4 for each geologic unit anticipated to be encountered within the soil nailed mass should be made mandatory as a part of the soil nail design process. The distribution of the geologic units may be determined based on the recommended subsurface investigation program outlined in FHWA (2003).

4. The requirements of ASTM A615 (AASHTO M 31) should be made mandatory for all HBSNs. This will serve to regulate the metallurgy of HBSN steel to be conformance with the US standards.

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APPENDIX A – BASICS OF CORROSION OF METALS

Metals are commonly created by refining naturally occurring stable ores and minerals by using large amounts of heat energy (e.g. blast furnace). The reconfigured ores and minerals in the form of metals are in an unstable state compared to their naturally occurring stable states. Corrosion is nature's way of returning metals to their unrefined naturally occurring forms as ores and minerals. The product of the corrosion process in iron-based metals is rust (ferric oxide) and hence corrosion is also known as rusting. The corrosion process releases the energy the metal gained during its refining in the form of electrical energy (FHWA, 1990).

For corrosion to occur, the following three conditions must be satisfied:

1. Presence of an electrolyte, such as water, which can conduct electrical current. Sometimes gases can also serve as electrolytes.

2. Presence of dissolved substances in electrolyte. Examples of dissolved substances include gases such as oxygen and chlorine and/or dissolved hydrogen ions.

3. The development of a "corrosion cell" wherein two portions of like or unlike metal surfaces become electrically connected via an electrolyte

The corrosion process is a natural electrochemical process where electron flow occurs in the steel and at the same time hydroxide ions are conducted through an electrolyte. This completes an electric circuit. The completed circuit is known as a corrosion cell. A schematic of a typical corrosion cell is shown in Figure 4. A corrosion cell is an electrochemical cell that acts very much like a battery. As shown in Figure 4, the corrosion reaction consists of simultaneous cathodic and anodic reactions. The steel acts as an electrode that couples the two reactions as discussed below (Hamilton, et al., 1995; Key to Metals.Steel, 2009):

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^-$

Cathodic reaction: $2H_2O + O_2 + 4e^- \rightarrow 4(OH^-)$

Hamilton, et al. (1995) note that in sound, uncracked and uncontaminated grout these reaction rates are depressed to a sufficiently low level because of the protective oxide layer that forms over the surface. The amount of iron lost to corrosion is insignificant over the life of a typical structure. An environment with an elevated pH (>13) and oxygen is required for this protective or passive layer to form. The presence of sodium, potassium, and calcium hydroxides derived from the reactions between the mix water and Portland cement provides an environment suitable for the passivation of the steel. Consequently, grout can provide excellent corrosion protection in two ways, (1) by maintaining the alkaline environment surrounding the surface of the grout necessary to passivate the steel, and (2) by providing a tough barrier to the external elements. However, the problems begin when the grout is no longer sound and/or contaminated.

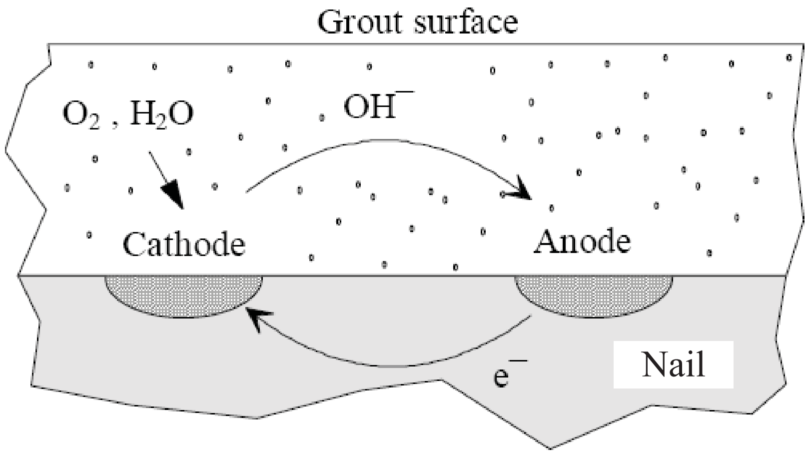

Figure 4: Schematic, Representation of corrosion of steel in uncracked grout (after Hamilton, et al. 1995).

The structural durability of this mechanism is a function of the grout quality and the depth of cover. It is important that the pH not be reduced because corrosion accelerates when the pH approaches a value of 7.0 (Houston, et al., 1972). The pH can reduce (a) by carbonation wherein the cementitious grout reacts with various corrosive elements or (b) by direct access of corrosive elements to steel via cracks in the grout body. Carbonation occurs when carbon dioxide combines with moisture in the pore structure of the grout to form carbonic acid which neutralizes the alkalinity of the grout by reducing the pH to less than 9. The following simplified equation describes the process:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

in the presence of H_2O and NaOH

When the pH is reduced, the passive film is destroyed, which leads to steel corrosion and the formation of rust. Rust occupies a volume approximately 10% greater than the steel from which it formed. Therefore, rust exerts expansive stresses on the surrounding grout. Because the grout has low tensile strength, these expansive stresses can cause cracking and spalling, which, in turn, permit faster ingress of water, oxygen, and chlorides, into the grout thereby accelerating corrosion further.

In a corrosion cell, these reactions can continue in a cycle. The total reaction will normally be under cathodic control. Figure 5 illustrates the corrosion cell in the event of the grout cover being carbonated by corrosive agents. If the grout cover is cracked and the cracks extend to the steel bar, then the steel exposed in the bottom of a crack becomes the anode in a galvanic cell. In this case the reinforcement in the uncracked grout becomes a cathodic area and this is very large compared to the area of steel in the crack. Thus, the cathodic capacity would be large, giving a very high current density on the anode; i.e., extremely rapid corrosion occurs (Fidjestol and Nilsen, 1980). This is the reason why cracked grout is a major concern in tensioned elements such as soil nails.

The corrosion can be uniform or localized. Uniform corrosion causes a uniform loss of metal across the entire surface of the element, while localized corrosion causes pitting at a specific point on the element.. In either case, the rate at which the electrons move out of the metal is the principal factor controlling the corrosion rate and is of primary interest in the corrosion process.

Many factors affect the development and rate of corrosion. These include soil resistivity, moisture content, soluble salts, chlorides, sulfates, sulphides, pH, redox potential, soil texture and density, oxygen transfer, organic material and soluble iron content.

For a more detailed discussion on corrosion of soil reinforced structures, the reader is referred to FHWA (1990).

APPENDIX B – QUESTIONNAIRE

A copy of the questionnaire discussed in Chapters 3 and 4 is presented in this appendix.

Corrosion Mitigation Guidance for Hollow Bar Soil Nails

QUESTIONNAIRE

(In this questionnaire "HBSN" refers to "**H**ollow **B**ar **S**oil **N**ail")

1. **Preparer/General Information**
   a. Firm:____
   b. Prepared by/Title:________________________________
   c. Phone/E-Mail:__________________________________
   d. What approximate percentage of your practice in the area of soil nail walls includes use of HBSNs as compared to conventional solid bar soil nails? (a) for permanent applications ________ %, (b) for temporary applications _________ %
   e. Is lack of understanding about corrosion issues an impediment to use of HBSNs for permanent applications? (Yes/No) ________
   If Yes, would you use more HBSNs if clear guidance on corrosion protection measures were available? (Yes/No) _________
   f. Can we contact you for more information? (Yes/No)______

2. **Coatings**
   a. Do you use purple marine epoxy coated HBSNs? (Yes/No):______
   If Yes,
      i. What is the minimum thickness of purple marine epoxy coating that you use? ______ mils
      ii. What is the typical application? (Permanent/Temporary): ____________________
   b. Do you use HBSNs with the conventional green epoxy coating? (Yes/No):_______
   If Yes,
      i. What is the minimum thickness of green epoxy coating that you use? ____ mils
      ii. What is the typical application? (Permanent/Temporary): ____________________
   c. Have you used galvanized HBSNs? (Yes/No):___________
   If Yes,
      i. What is the minimum thickness of galvanization that you use? _________ mils
      ii. What is the typical application? (Permanent/Temporary): ____________________
   d. Have you exhumed HBSNs after installation to verify damage to coatings due to nail installation processes? (Yes/No):_________
   If Yes,
      i. Would you be able to provide information on your findings? (Yes/No) _________
      If Yes, please provide information (use additional sheets as necessary) _________
      ____
      ____
      ____

QUESTIONNAIRE

3. Sacrificial Steel

a. Are you aware of sacrificial steel being used in lieu of coatings? (Yes/No):______
   i. If Yes, what is the typical sacrificial thickness that has been used?: ______ mils

4. Grout

a. What is the typical grout cover that you have used? _______ inches
b. What is the typical unconfined compressive strength of grout you have used?_______ psi
c. What is the typical cement type that you have used for grout? ______________________
d. What is the typical water cement ratio that you have used for grout? ________________
e. What type of mixer do you use for mixing grout? (e.g., high-speed high-shear colloidal type mixers, low-speed low-energy paddle type mixers) __________________________
____
f. Do you use final strength grout from the start of the drilling or do you use diluted grout for initial drilling and then final strength grout after the drill hole has reach target depth?
____

5. Evaluation of Soil Corrosivity

a. Is soil test data available to assist in determination of required level of corrosion protection or are assumptions frequently made? ________________________________
____
b. How do you evaluate soil corrosivity for HBSN applications?
   i. Use the corrosion criteria in Chapter 6 of GEC #4 (Ground Anchors and Anchored Systems)? (Yes/No): __________
   ii. Use the corrosion criteria in Appendix C of GEC #7 (Soil Nail Walls)? (Yes/No): __________
   iii. Use something else? (Yes/No): __________
   If Yes, please provide reference to publication or provide criteria (use additional sheets as necessary) ____
   ____
   ____
   ____

Note: "GEC" refers to "**G**eotechnical **E**ngineering **C**ircular" which is a publication prepared by the FHWA (Federal Highway Administration). If you do not have GEC #4 and/or GEC#7, you can download them for free at following weblink: http://www.fhwa.dot.gov/engineering/geotech/library_listing.cfm

Corrosion Mitigation Guidance for Hollow Bar Soil Nails

QUESTIONNAIRE

6. Field Corrosion Test Programs

a. Has your firm conducted or are you aware of field corrosion test programs for HBSNs? (Yes/No) __________

i. If Yes, is a copy of the report available and can it be provided for this study? (Yes/No)__________

7. Laboratory Corrosion Test Programs

a. Has your firm conducted or are you aware of laboratory corrosion test programs for HBSNs? (Yes/No) _________

i. If Yes, is a copy of the report available and can it be provided for this study? (Yes/No) __________

8. Thread type/configuration

a. Have you observed or do you have data that the thread type/configuration, e.g., a smooth rope (or R) thread vs a sharper (coarse) Titan bar type thread, on a HBSN has any effect on corrosion rates? (Yes/No) _______

i. If Yes, please provide explanation and supporting information (use additional sheets as necessary)____

9. Encapsulated HBSNs

a. Are you aware of HBSNs with encapsulation corrosion protection systems similar to ground anchors? (Yes/No) _________

i. If Yes, please provide information for such bars (use additional sheets as necessary) ____

b. Do you believe encapsulated hollow-core bar soil nail systems are feasible from an economical as well as constructability viewpoint? (Yes/No) __________

i. If Yes, please provide additional information as necessary (use additional sheets as necessary) ____

Corrosion Mitigation Guidance for Hollow Bar Soil Nails

QUESTIONNAIRE

10. Drill Bit Size/Centralizers

a. Based on your practice, what is the typical ratio of the drill bit diameter to the outer diameter of the HBSN? ___________

b. Do you use centralizers on HBSNs? (Yes/No) ___________

If Yes,

i. What percentage of your soil nail jobs have you used centralizers on? ____ %

ii. Please provide additional information on size and type of centralizers and the typical distance between centralizers along the HBSN (use additional sheets as necessary) ________________________________

11. Is there any other information (US or international) about corrosion related studies specific to HBSN earth retention structures that you are aware about and can provide?

(Yes/No) _______

i. If Yes, please provide additional information as necessary (use additional sheets as necessary)________________________________

12. Do you have any additional input and/or suggestions for developing corrosion mitigation guidance for HBSN earth retention structures?

(Yes/No) _______

If Yes, please provide input/suggestions (use additional sheets as necessary): _____________

THANK YOU FOR YOUR TIME AND EFFORT

APPENDIX C – SUMMARY OF RESPONSES TO QUESTIONNAIRE

This appendix presents a tabulated summary of the responses to the questionnaire (see Appendix B). The following points should be noted with respect to the information in this appendix.

- Descriptive answers and comments have been paraphrased for brevity. These paraphrased responses are indicated by an asterisk [“(*)”] in the forms presented in this appendix.
- Where no response was provided, “--” is used in the summary responses.
- Six of the respondents were contacted for clarification of their responses. The information included in this appendix contains the clarified responses.
- The original questionnaires with the full responses are available from CFLHD.
- Information that was requested to be kept confidential by respondents has been omitted from the summary.

A synthesis of the responses is presented in Chapter 4.

1:	PREPARER/GENERAL INFORMATION	#1		
a	Firm	Con-Tech Systems LTD.		
b	Name/Title	Horst Aschenbroich, Pres./CEO		
c	Phone/E-mail	604.946.5571/ horst@contechsystems.com		
d	% HBSN use: temporary, permanent	90%	90%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Yes	8 mils	Permanent
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	Yes, with problems	10 mils	Permanent
d	Have you exhumed HBSNs and could you provide findings?	Yes	Yes, many tests in Europe/North America shows 100% grout cover with Titan nails	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	See Con-Tech brochure for guidance on sacrifical steel	
4:	GROUT			
a	Thickness	1.5 inches minimum		
b	Strength	3000 psi		
c	Cement type	Portland Cement, Type I		
d	Water:Cement (W:C) ratio	0.45 for final grout		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Both in non-cohesive ground, diluted (w:c ratio=0.7 for flushing) and final (w:c ratio=0.4)		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Assumptions		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	No		
d	Use guidance in some other reference?	DIN 50 929-3, Table 7(*)		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Yes	Yes (by Ischebeck)	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	Yes	Yes (Swiss Test)	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	Yes	See Brochure (Test by TUM, Germany)	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	Yes	Only with additional coating. Sometimes w/ corrugated short HDPE sheath	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No	With proper boring/grouting, grout cover is guaranteed over nail length; near top of nail encapsulated HBSN could be used	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	2" larger for sand; 3" larger for gravel		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	100%	Max Distance = 10'
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	Yes	Switzerland	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	In Germany min 35mm grout cover is used for permanent applications. Use INOX steel for extremely corrosive ground (*)	

1:	PREPARER/GENERAL INFORMATION	#2		
a	Firm	Friedrich Ischebeck GmbH		
b	Name/Title	Ernst Ischebeck		
c	Phone/E-mail	0049.2333.8305-0/ ischebeck@ischebeck.de		
d	% HBSN use: temporary, permanent	90%	10%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Yes (blue epoxy aka "combi-coating")	@3.5 mils galvanize+@5 mils epoxy	Permanent
b	Use of green epoxy coating, thickness, application	No		
c	Use of galvanization, thickness, application	Yes	@3.5 mils	Permanent
d	Have you exhumed HBSNs and could you provide findings?	Yes	Yes (see 2007 ICE London Conference presentation by Ischebeck)	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No		
4:	GROUT			
a	Thickness	20-50 mm (0.8 - 2.0 inches)		
b	Strength	35 N/mm2 (5076 psi)		
c	Cement type	Portland or HS-Cement		
d	Water:Cement (W:C) ratio	0.4 - 0.5		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Both, diluted (w:c ratio=0.7 to 1.0 for flushing) and final (w:c ratio=0.4 to 0.5)		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Water anlaysis and ranking as per DIM 50 929-3 Table 7		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	No		
d	Use guidance in some other reference?	DIN 50 929-3, Table 7		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Yes	Yes, but study incomplete (by Ischebeck)	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	Yes	Yes (Swiss Test)	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	Yes	See Brochure (Test by Schiessl)	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	Yes	Only with additional coating. Sometimes w/ corrugated short HDPE sheath (*)	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No		
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	50 mm (2") larger for Sand; 75 mm (3") larger for Gravel		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	100%	Max Distance = 10'
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No		
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	In Germany min 35mm grout cover is used for permanent applications, Use DIN 50 929-3, Table 7 for guidance, use INOX steel for more corrosion resistance (*)	

1:	PREPARER/GENERAL INFORMATION	#3		
a	Firm	DBM Contractors, Inc.		
b	Name/Title	Tom Armour		
c	Phone/E-mail	206.730.4591/ tarmour@dbm.com		
d	% HBSN use: temporary, permanent	0%	10%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	No	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	No		
b	Use of green epoxy coating, thickness, application	No		
c	Use of galvanization, thickness, application	No		
d	Have you exhumed HBSNs and could you provide findings?	No		
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	62.5 mils	
4:	GROUT			
a	Thickness	3 inches		
b	Strength	4000 psi		
c	Cement type	Type I/II		
d	Water:Cement (W:C) ratio	0.45		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Both, diluted and final strength		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Both		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	No		
d	Use guidance in some other reference?	Yes, Personal Experience with MSE walls		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	No		
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No		
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No	Call Horst (604.946.5571)	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No		
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No		
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	4:1		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	No		
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No	Call Horst (604.946.5571)	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	Be careful, starting to see a number of MSE walls failures due to corrosion. Biggest concern is installation damage (*)	

1:	PREPARER/GENERAL INFORMATION	#4		
a	Firm	DYWIDAG Systems International, USA		
b	Name/Title	Lucian Bogdan, Chief Engineer		
c	Phone/E-mail	562.531.6161/ lucian.bogdan@dsiamerica.com		
d	% HBSN use: temporary, permanent	1%	5%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Yes	7 mils per ASTM A934	Permanent
b	Use of green epoxy coating, thickness, application	Yes, very rarely	7 mils per ASTM A775	Permanent
c	Use of galvanization, thickness, application	Yes	5 mils per ASTM A123	
d	Have you exhumed HBSNs and could you provide findings?	No		
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	There are no US standards; concern at coupler areas (*)	
4:	GROUT			
a	Thickness	N/A (not involved in grouting as a manufacturer)		
b	Strength	N/A (not involved in grouting as a manufacturer)		
c	Cement type	N/A (not involved in grouting as a manufacturer)		
d	Water:Cement (W:C) ratio	N/A (not involved in grouting as a manufacturer)		
e	Type of mixer	N/A (not involved in grouting as a manufacturer)		
f	Final strength or diluted for drilling	N/A (not involved in grouting as a manufacturer)		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	--		
b	Use guidance in GEC #4?	--		
c	Use guidance in GEC #7?	--		
d	Use guidance in some other reference?	Yes, PTI Rock and Soil Anchor Rrecommendations (*)		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	No		
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No	Check with CALTRANS for their study	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No	There is no clear evidence	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	Yes, but used very rarely	Pregrouted encapsulation was never used. At top end of bar pump grout in 3-ft long HDPE over bar in field (*)	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No	Encapsulation may be damaged during drilling; does not cover coupler area (*)	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	2.33:1		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes, if req'd		
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	Yes	European/BS standards for solid bars (*)	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	Galvanized+epoxied bars for permanent applications in non-corrosive soils. Define soil aggressivity. Do not use HBSNs in corrosive soils for permanent applications (*)	

1:	PREPARER/GENERAL INFORMATION	#5		
a	Firm	Hayward Baker, Inc.		
b	Name/Title	John Wolosick		
c	Phone/E-mail	770.442.1801/ jrwolosick@haywardbaker.com		
d	% HBSN use: temporary, permanent	20%	25%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Yes	7-12 mils	Permanent
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	Yes	4-7 mils	Permanent
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No	--	
4:	GROUT			
a	Thickness	0.75 inches (rock bit) - 2.25 inches (clay bit)		
b	Strength	6000 psi		
c	Cement type	Type I/II		
d	Water:Cement (W:C) ratio	0.45 with water reducer		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Both, or drill with water only and pump grout at the end		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Usually only when we ask for it		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	Yes		
d	Use guidance in some other reference?	No		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	No		
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No		
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No		
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	Yes	See CALTRANS detail at top of nail; can also use a trumpet as in ground anchors	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	Yes	Only for top 5 ft or so	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	Varies by bit type/manufacturer. 3-6" for R38 bar		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	No	80%	8-10 ft on centers; PVC spider types (*)
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	Yes	PTI recommendations for anchors	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	Afraid to use metal centralizers due to concern with damage to epoxy during installation	

1:	PREPARER/GENERAL INFORMATION	#6		
a	Firm	FSI Geo-Con (Foundation Specialties, Inc.)		
b	Name/Title	Paul Gintonio		
c	Phone/E-mail	479.263.2969/ paul_gintonio@fspecinc.com		
d	% HBSN use: temporary, permanent	0%	100%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	No	--	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	No	--	--
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	No	--	--
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No	--	
4:	GROUT			
a	Thickness	3 inches		
b	Strength	5000 psi		
c	Cement type	Type I		
d	Water:Cement (W:C) ratio	0.45		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Water in rock, full strength in soil		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Use assumptions		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	No		
d	Use guidance in some other reference?	No		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Yes		
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No		
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No		
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No		
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No		
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	2.5:1		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	100%	Titan centralizers every 10'
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No		
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	No	Corrosion seems dependent on the soil/rock material	

1:	PREPARER/GENERAL INFORMATION	#7		
a	Firm	Nicholson Construction		
b	Name/Title	Tom Richards, Chief Engineer		
c	Phone/E-mail	412.677.2224/ trichards@nicholsonconstruction.com		
d	% HBSN use: temporary, permanent	15%	0%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Only for a test	Use supplier standard	Test nail
b	Use of green epoxy coating, thickness, application	No		
c	Use of galvanization, thickness, application	Only for a test	Use supplier standard	Test nail
d	Have you exhumed HBSNs and could you provide findings?	Yes	Contact Gary Lange (contact information not provided)	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	63 mils (only on one job)	
4:	GROUT			
a	Thickness	Depends on bit size provided by supplier		
b	Strength	5000 psi		
c	Cement type	Type I/II		
d	Water:Cement (W:C) ratio	0.45		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Typically final grout strength from start		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Typically not		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	Yes, if data is available		
d	Use guidance in some other reference?	No		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Yes	ADSC/FHWA Study in Salt Lake City	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No		
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No		
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No	Except PVC for free length	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No		
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	Supplier provided; depends on ground & desired bond		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Sometimes		
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	Yes	ADSC/FHWA study by Schnabel	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	Need more guidance because currently some ignore corrosion, some use sacrificial steel, some use with various justifications in permanent walls and GEC7 does not allow HBSN in permanent walls. (*)	

1:	PREPARER/GENERAL INFORMATION	#8		
a	Firm	Williams Form Engineering		
b	Name/Title	Tom Bird, VP-Sales		
c	Phone/E-mail	303.807.9945/ tbird@williamsform.com		
d	% HBSN use: temporary, permanent	15%	25%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Yes	7 mils	Permanent
b	Use of green epoxy coating, thickness, application	Yes	7 mils	Permanent
c	Use of galvanization, thickness, application	Yes	4 mils	Permanent
d	Have you exhumed HBSNs and could you provide findings?	Yes	Yes, ADSC study, noted severe scratches on coating (purple/green/galvanized)	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	1 size larger	
4:	GROUT			
a	Thickness	1-inch		
b	Strength	3500 psi		
c	Cement type	Portland Type I/II		
d	Water:Cement (W:C) ratio	0.45		
e	Type of mixer	Paddle is most common, I recommend colloidal		
f	Final strength or diluted for drilling	Varies by contractor		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	?		
b	Use guidance in GEC #4?	?		
c	Use guidance in GEC #7?	?		
d	Use guidance in some other reference?	?		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Yes, ADSC	Not yet	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No		
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	Yes, but....	Data shows no difference in cracks	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No		
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	Yes	Drill to depth, extract 5'-10' replace with CALTRANS Soil Nail (3') DCP	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	2:1		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Not usually	5%	10' before couplers
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	Yes	EN 14490 soil nail spec	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	(1)Use only in non-aggressive ground; (2) galvanize or hot zinc spray (HZS); (3)evaluate galvanization vs HZS; (4)use DCP; (5)Use sacrificial steel; (6)verify grout strength; (7)ensure drill bit is 1.5" min larger than bar diameter	

1:	PREPARER/GENERAL INFORMATION	#9		
a	Firm	Williams Form Engineering		
b	Name/Title	John White, VP East Coast Sales		
c	Phone/E-mail	616.866.0815/ jwhite@williamsform.com		
d	% HBSN use: temporary, permanent	0%	5%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	No	--	--
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	Yes	4-5 mils	permanent
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No	--	
4:	GROUT			
a	Thickness	--		
b	Strength	4000 psi		
c	Cement type	Type K (non-shrink)		
d	Water:Cement (W:C) ratio	0.4 - 0.45		
e	Type of mixer	Both		
f	Final strength or diluted for drilling	Both		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Unknown		
b	Use guidance in GEC #4?	--		
c	Use guidance in GEC #7?	--		
d	Use guidance in some other reference?	--		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Yes	No	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	Yes	Enables fast production rates in granular or problematic soils that are not conducive to open hole drilling	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	1.6:1 (min) to 2:1 (more common)		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	--	Steel centralizers,10' before couplers
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No	--	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	We recommend galvanization instead of epoxy from a durability standpoint and since galvanization is a sacrificial coating.	

1:	PREPARER/GENERAL INFORMATION	#10		
a	Firm	CALTRANS		
b	Name/Title	Kathryn Griswell, Earth Retaining Systems Specialist		
c	Phone/E-mail	916.227.7330/ kathryn_griswell@dot.ca.gov		
d	% HBSN use: temporary, permanent	Small % (*)	Small % (*)	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	Yes	12 mils	Temporary
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	No	--	--
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No	--	
4:	GROUT			
a	Thickness	2 inches		
b	Strength	930 lbs/cy Type II w/ 5 gal per sack		
c	Cement type	Type II		
d	Water:Cement (W:C) ratio	5 gallons to 94 pounds		
e	Type of mixer	Do not specify		
f	Final strength or diluted for drilling	Drill diluted first then flush with final strength		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Test for permanent walls, assumption for shoring systems		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	Yes (this is similar to CALTRANS guidance)		
d	Use guidance in some other reference?	Yes, guidance on culvert criteria for soil corrosion test		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	No	--	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	Yes	Maybe economical but durability issues need to be addressed	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	No typical value		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	100%	5' spacing based on regular systems
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No	--	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	Need better understanding of the size, shape and quality of grout column for proper selection of design assumptions for perm walls. Concern with build-up of cuttings at couplers creating porous pockets that promote corrosion (use heat shrink sleeve?) (*)	

1:	PREPARER/GENERAL INFORMATION	#11		
a	Firm	Iowa DOT		
b	Name/Title	Robert Stanley, Soil Design Engineer		
c	Phone/E-mail	515.239.1026/ robert.stanley@dot.iowa.gov		
d	% HBSN use: temporary, permanent	0%	0%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	No	Have not used HBsN	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	--	--	--
b	Use of green epoxy coating, thickness, application	--	--	--
c	Use of galvanization, thickness, application	--	--	--
d	Have you exhumed HBSNs and could you provide findings?	--	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	?	
4:	GROUT			
a	Thickness	Have had only 1 soil nail project, was not HBsN		
b	Strength	--		
c	Cement type	--		
d	Water:Cement (W:C) ratio	--		
e	Type of mixer	--		
f	Final strength or diluted for drilling	--		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Soil can be tested if needed		
b	Use guidance in GEC #4?	Have not used HBSN		
c	Use guidance in GEC #7?	--		
d	Use guidance in some other reference?	--		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	Not used HBSN	--	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	Not used HBSN	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	Not used HBSN	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	Don't know	--	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	Have not used HBSN		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	--	--	--
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No	--	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	No	--	

1:	PREPARER/GENERAL INFORMATION	#12		
a	Firm	Missouri DOT		
b	Name/Title	Kevin McLain, Geotechnical Engineer		
c	Phone/E-mail	573.751.1044/ kevin.mclain@modot.mo.gov		
d	% HBSN use: temporary, permanent	0%	0%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	--	--	--
b	Use of green epoxy coating, thickness, application	--	--	--
c	Use of galvanization, thickness, application	--	--	--
d	Have you exhumed HBSNs and could you provide findings?	--	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	--	--	
4:	GROUT			
a	Thickness	--		
b	Strength	--		
c	Cement type	--		
d	Water:Cement (W:C) ratio	--		
e	Type of mixer	--		
f	Final strength or diluted for drilling	--		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	--		
b	Use guidance in GEC #4?	--		
c	Use guidance in GEC #7?	--		
d	Use guidance in some other reference?	--		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	--	--	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	--	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	--	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	--	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	--	--	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	--		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	--	--	--
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	--	--	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	--	--	

1:	PREPARER/GENERAL INFORMATION	#13		
a	Firm	New Hampshire DOT		
b	Name/Title	Charles Dusseault, Geotechnical Engineer		
c	Phone/E-mail	603.271.3151/ cdusseault@dot.state.nh.us		
d	% HBSN use: temporary, permanent	0%	0%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	No	
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	No	--	--
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	No	--	--
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No	--	
4:	GROUT			
a	Thickness	--		
b	Strength	--		
c	Cement type	--		
d	Water:Cement (W:C) ratio	--		
e	Type of mixer	--		
f	Final strength or diluted for drilling	--		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Yes		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	No		
d	Use guidance in some other reference?	FHWA-SA-96-069/FHWA-SA-93-068		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	No	--	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	No	--	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	N/A		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	--	--	--
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	Yes	NCHRP proposal (not funded)	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	Yes	Long-term monitoring of a HBSN slope that used green epoxy per AASHTO M284 requirements	

1:	PREPARER/GENERAL INFORMATION	#14		
a	Firm	South Carolina DOT		
b	Name/Title	Jeff Sizemore, Geotechnical Design Support Eng.		
c	Phone/E-mail	-/ sizemorejc@scdot.org		
d	% HBSN use: temporary, permanent	<1%	N/A	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	Yes	Yes	
f	Could the preparer be further contacted?	No		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	No	?	--
b	Use of green epoxy coating, thickness, application	Yes	?	Permanent
c	Use of galvanization, thickness, application	No	--	--
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	No	--	
4:	GROUT			
a	Thickness	1 inch		
b	Strength	3000 psi		
c	Cement type	Type I or III		
d	Water:Cement (W:C) ratio	0.4 - 0.45		
e	Type of mixer	Colloidal		
f	Final strength or diluted for drilling	Final strength from start		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Assumptions		
b	Use guidance in GEC #4?	No		
c	Use guidance in GEC #7?	Yes		
d	Use guidance in some other reference?	--		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	--	--	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	--	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	--	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	--	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	--	--	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	?		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	100%	--
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No	--	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	No	--	

1:	PREPARER/GENERAL INFORMATION	#15		
a	Firm	Tennessee DOT		
b	Name/Title	Len Oliver, Civil Engineering Manager		
c	Phone/E-mail	615.350-4130/ Len.Oliver@state.tn.us		
d	% HBSN use: temporary, permanent	10%	50%	
e	Is lack of corrosion guidance an impediment to HBSN use? Would clear corrosion guidance help?	No		
f	Could the preparer be further contacted?	Yes		
2:	COATINGS			
a	Use of purple marine epoxy coating, thickness, application	No	--	--
b	Use of green epoxy coating, thickness, application	No	--	--
c	Use of galvanization, thickness, application	Yes	Unknown	Semi-permanent landslide repair
d	Have you exhumed HBSNs and could you provide findings?	No	--	
3:	SACRIFICIAL STEEL			
a	Aware of use of sacrificial steel? What thickness?	Yes	Unknown	
4:	GROUT			
a	Thickness	1.5 inches		
b	Strength	Unknown	--	--
c	Cement type	Unknown	--	--
d	Water:Cement (W:C) ratio	Unknown	--	--
e	Type of mixer	Paddle mixers		
f	Final strength or diluted for drilling	Unknown		
5:	EVALUATION OF SOIL CORROSIVITY			
a	By Assumptions or Data?	Can do tests, on 1 project, assumptions were made		
b	Use guidance in GEC #4?	--		
c	Use guidance in GEC #7?	Yes		
d	Use guidance in some other reference?	--		
6:	FIELD CORROSION TESTING PROGRAM			
a	Conducted a field program and have copy?	No	--	
7:	LABORATORY CORROSION TESTING PROGRAM			
a	Conducted a lab program and have copy?	No	--	
8:	THREAD TYPE/CONFIGURATION			
a	Effect on corrosion rates? Supporting information?	No	--	
9:	ENCAPSULATED HBSNs			
a	Aware of encapsulated HBSNs? Have info?	No	--	
b	Are encapsulated HBSNs feasible from an economical and construction viewpoint?	Unknown	--	
10:	DRILL BIT AND CENTRALIZERS			
a	Drill bit:HBSN OD ratio	2:1		
b	Use centralizers? What % of jobs? Distance between centralizers and other info	Yes	90%	--
11:	AWARENESS OF OTHER CORROSION STUDIES			
	Aware of other corrosion studies? Where?	No	--	
12:	ADDITIONAL INPUT AND/OR SUGGESTIONS			
	Do you have additional input and/or suggestions for corrosion evaluation? Provide input/suggestions	No	--	