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.

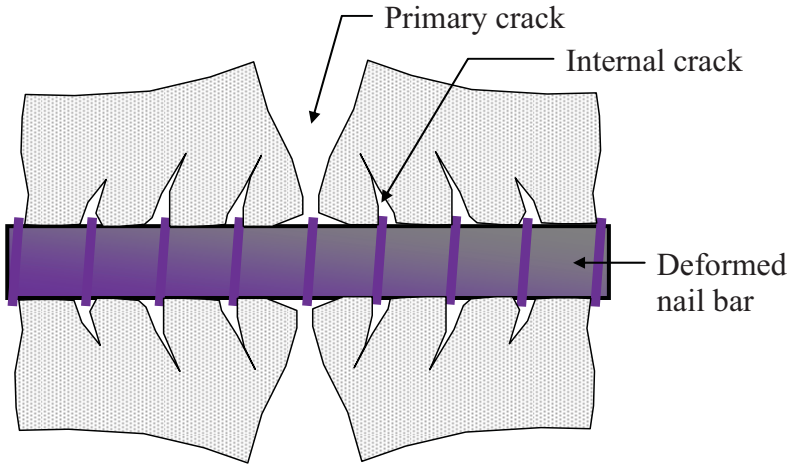

Figure 2. Schematic. Lateral crack pattern close to deformed reinforcing nail bar in tension (after Goto, 1971; FIP, 1986).

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.