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HOLLOW-CORE SOIL NAILS STATE-OF-THE-PRACTICE



Memorandum

Subject: **INFORMATION:** FHWA Hollow-Core
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April 2006

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In Reply Refer To: HIBT-20

To: FHWA National Geotechnical Team Members

FHWA is interested in the hollow core soil nail technology and would like to see hollow core nails used on transportation projects where they would add value. We believe that the technology is different enough from the traditional drill-and-grout soil nail that study is needed to develop specific hollow core soil nail guidelines. FHWA is interested in developing such guidelines and in collaborating with others in doing so.

With this interest in mind, FHWA is pleased to provide a recently completed report on the current state of practice for hollow soil nail use on transportation projects. This report does not present FHWA guidelines, rather it summarizes the state of the practice and identifies areas where further study and guideline development would be beneficial... These areas can be broadly classified as follows: 1) determining capacity of test nails; 2) assuring quality of production nails, and 3) long-term performance. We plan to prioritize the study areas listed in the report and to look for ways to get the priority issues addressed and to develop published guidance on hollow core soil nail technology. We welcome your thoughts on priorities and ideas for collaboration.

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Mr. Geordie Compton, Executive Director, Deep Foundations Institute (DFI)
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Mr. Tom Bird, ADSC, Chair Soil Nailing Committee
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FOREWORD

Hollow core bars have been used in the United States as self-grouting soil nails for approximately 10 years. This method has advantages over solid bar nails primarily because fewer installation steps are involved, especially where the solid bar technique would require temporary casing of the hole. The applicability of some aspects of the current FHWA soil nail wall design/construction/inspection procedures is affected by this type of bar and installation and this report provides guidance on how these aspects are currently being addressed.

This report identifies areas of design and construction where the hollow bar method differs most from conventional solid bar methods, and where further research, evaluation and testing would have the greatest impact in assuring quality of hollow bar soil nails and soil nail walls. Hollow bars were initially used for temporary installations and experience gained here suggested that hollow bars could in some instances be advantageous for permanent installations. This report discusses temporary and permanent installations, and recommends issues to address and resolve so that good opportunities for hollow bar installations are not missed and the hollow bar technology is deployed wherever it is advantageous.

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16. Abstract A commentary on the use of hollow-core bars for soil nail walls is presented in this report based on the authors' experience. The basic technology of hollow-core soil nailing is presented and several issues related to that technology are raised. Topics for further study are recommended. Some guidance is provided on how to proceed with the use of the hollow-core nail technology until the issues are studied in detail. It is recommended that along with the evaluation and resolution of the various issues, the FHWA should develop a construction inspector manual that applies to the hollow-core nail technology. Preliminary guidance for construction monitoring and QC/QA is also provided in this report.			
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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
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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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF SYMBOLS AND ABBREVIATIONS

A_u	Ultimate (nominal) adhesion (grout-to-ground) e.g., kN/m (or kips/ft)
D_D	Diameter of drill bit
D_G	Diameter of grout body
D_H	Diameter of drillhole
DL_T	Design Load for temporary walls
DL_P	Design Load for permanent walls
F_Y	Yield (nominal) strength of hollow-core bar
F_U	Guaranteed Ultimate Tensile Strength (GUTS) of hollow-core bar
G-G	Grout-to-ground bond
G-S	Grout-to-steel bond
GUTS	Guaranteed Ultimate Tensile Strength of hollow-core bar
ID	Inside diameter
ISO	International Organization for Standardization
L_R	Length of the nail in the resisting zone
L_A	Length of the nail in the active zone
L_T	Total length of the nail
MSE	Mechanically Stabilized Earth
MTL	Maximum Test Load
OD	Outside diameter
QA	Quality Assurance
QC	Quality Control
P_R	Pullout resistance over the length of the bar in the resisting zone
R	Rope-thread designation
SG	Specific Gravity of neat cement grout
TUM	Technical University of Munich
w/c	Water/cement ratio by weight
~	Approximately equal to

CHAPTER 1. INTRODUCTION

There are many techniques for supporting ground excavations. These excavation support (also known as shoring) techniques may be broadly classified as external and internal (FHWA, 1999). External support techniques rely on resistance provided by elements outside the face of the excavation and include the use of elements such as berms, rakers, anchors, cross-lot bracing and cantilever walls. Internal support techniques rely on the installation of reinforcement into the existing ground and include the use of elements such as soil nails.

While shoring techniques are well established, new construction equipment and techniques have emerged in the last few years that have demonstrated faster construction processes compared to the traditional techniques currently recognized by the Federal Highway Administration (FHWA). These newer construction technologies can lead to optimization of the design, which in turn results in significant cost savings for the owners and contractors. This document is focused on one such newer technology wherein soil nails are installed by use of the hollow-core soil nailing technique.

The soil nailing technique is described in two recent FHWA documents (FHWA, 1996, 2003). Both FHWA documents concentrate on the use of the “drill-and-grout” soil nailing technique wherein a solid-bar nail is placed in a pre-drilled hole and then tremie-grouted. A typical nail installation sequence using the solid-bar nailing technique is shown in Figure 1. In the hollow-core soil nail construction technique, the drilling, installing and grouting of nails (Steps 2 and 3 in Figure 1) are combined into one step, which may be attractive to contractors. Initially this technique was used primarily for temporary shoring. As better equipment and field Quality Control (QC) and Quality Assurance (QA) procedures were developed and as the experience base of the hollow-core soil nails expanded, the state-of-the-practice (SOP) has been extended to construction of permanent walls.

The purpose of this document is to present a SOP summary on the use of the hollow-core nail technology. The scope of this document is limited to the use of hollow-core nails in soils. Where appropriate, guidance for use of this technology and suggestions for further studies are provided. The intent is that this document will stimulate appropriate discussion and research by practitioners, academicians, and the FHWA and other organizations such as the International Association of Foundation Drilling, Association of Drilled Shaft Contractors (IAFD – ADSC).

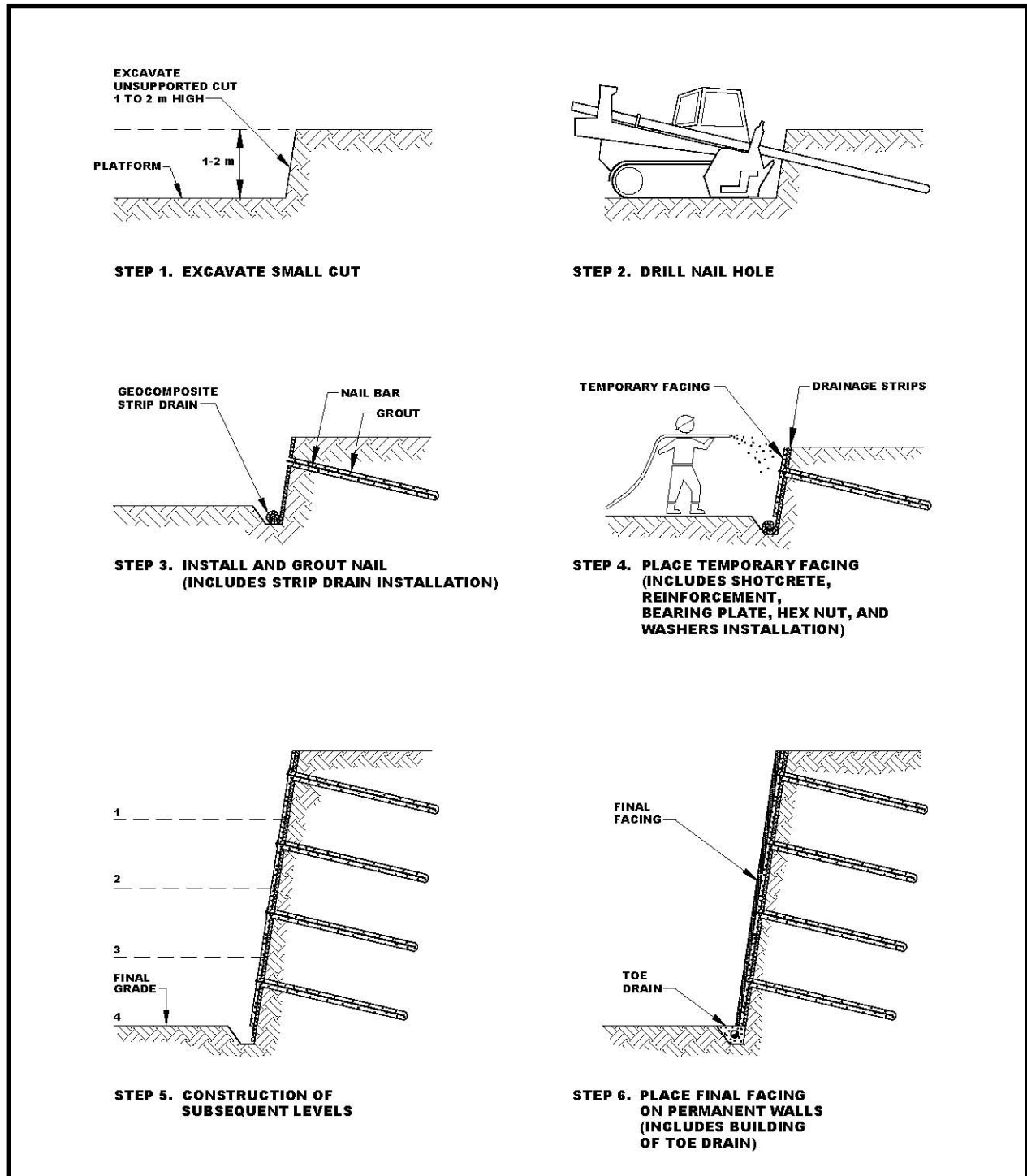


Figure 1. Typical “drill-and-grout” construction technique using solid-bar nails (FHWA 1994, 2003)

CHAPTER 2. THE HOLLOW-CORE SOIL NAIL TECHNOLOGY

The conventional solid-bar nail installation technique using the “drill-and-grout” approach is most efficient in soils where the open-hole drilling method is possible. In caving ground conditions, such as in running or raveling sands and loose soils with cobbles and boulders, casing would be required to support the drill-hole excavation. Use of casing makes the solid-bar soil nailing process slower and therefore costlier.

An alternate to installation of solid-bar nails in pre-drilled holes was developed in Europe in the 1980s and has been used in the United States since the mid-1990s. This alternate technique involves the use of hollow-core bars instead of solid-bars and is shown schematically in Figure 2. The hollow-core bar is fitted with an over-sized sacrificial drill bit that serves as a cutting tool to advance the hole. The drill bit is equipped with 2 to 5 holes with the configuration of the holes based on soil types through which the hollow-core bar is to be advanced. Grout is pumped through the hollow-core of the nail to the drill bit where it comes out of the holes and facilitates the drilling process. The nail is rotated during this operation and advanced using a percussion hammer. Grout pressure then forces the grout back along the outside of the bar to the ground surface. Once the hollow-core bar is advanced to the target depth, it is left in the hole as the nail reinforcement along with the drill bit.

Thus, in this process, the hollow-core bar serves as a grouting conduit as well as the nail reinforcement, while the injected grout and the bar provide the support to maintain the hole open. In other words, Steps 2 and 3 shown in Figure 1 for the conventional “drill-and-grout” process are combined in the case of hollow-core soil nail installations. This concurrent activity of drilling, installing and grouting the nail is generally faster than the conventional “drill-and-grout” technique of installation of a solid-bar nail where casing would otherwise be required.

Grout-to-Ground (G-G) Bond

A better grout-ground interface bond is generally obtained with the hollow-core nailing technique because of the grouting process. The dynamic rotary pressure grouting characteristic of the hollow-core soil nailing technique permeates the grout into the geomaterials around the drillhole further than the gravity head characteristic of the “drill-and-grout” technique, resulting in an improved bond between the geomaterials and the grout. Based on the authors’ limited observations, the thickness of the “permeation” zone varies and appears to depend on the type of the geomaterial being penetrated. For example, in cohesive soils, the “permeation” zone appears to be minimal while in caving and open-graded geomaterials, such as gravelly and cobbly soils, the “permeation” zone is generally thicker. This is generally consistent with the hydraulic conductivity (permeability) of these geomaterials to fluids such as water. In caving and/or open-graded soils, the grout is mixed into the soils at the drill hole perimeter as the hole is trying to collapse. This mixing further enhances the grout-to-ground interface bond. Therefore, for a given hole diameter (D_H in Figure 2b), the pullout resistance of hollow-core soil nails may be expected to be greater than that obtained with solid-bar nails for most soils. This also leads to stiffer load-deformation behavior that is commonly observed during pullout testing of hollow-

core nails. The magnitude of the increase in bond and the stiffness characteristics should be studied further based on side-by-side comparison of nails installed using the hollow-core construction technique and the conventional “drill-and-grout” technique in a given geomaterial.

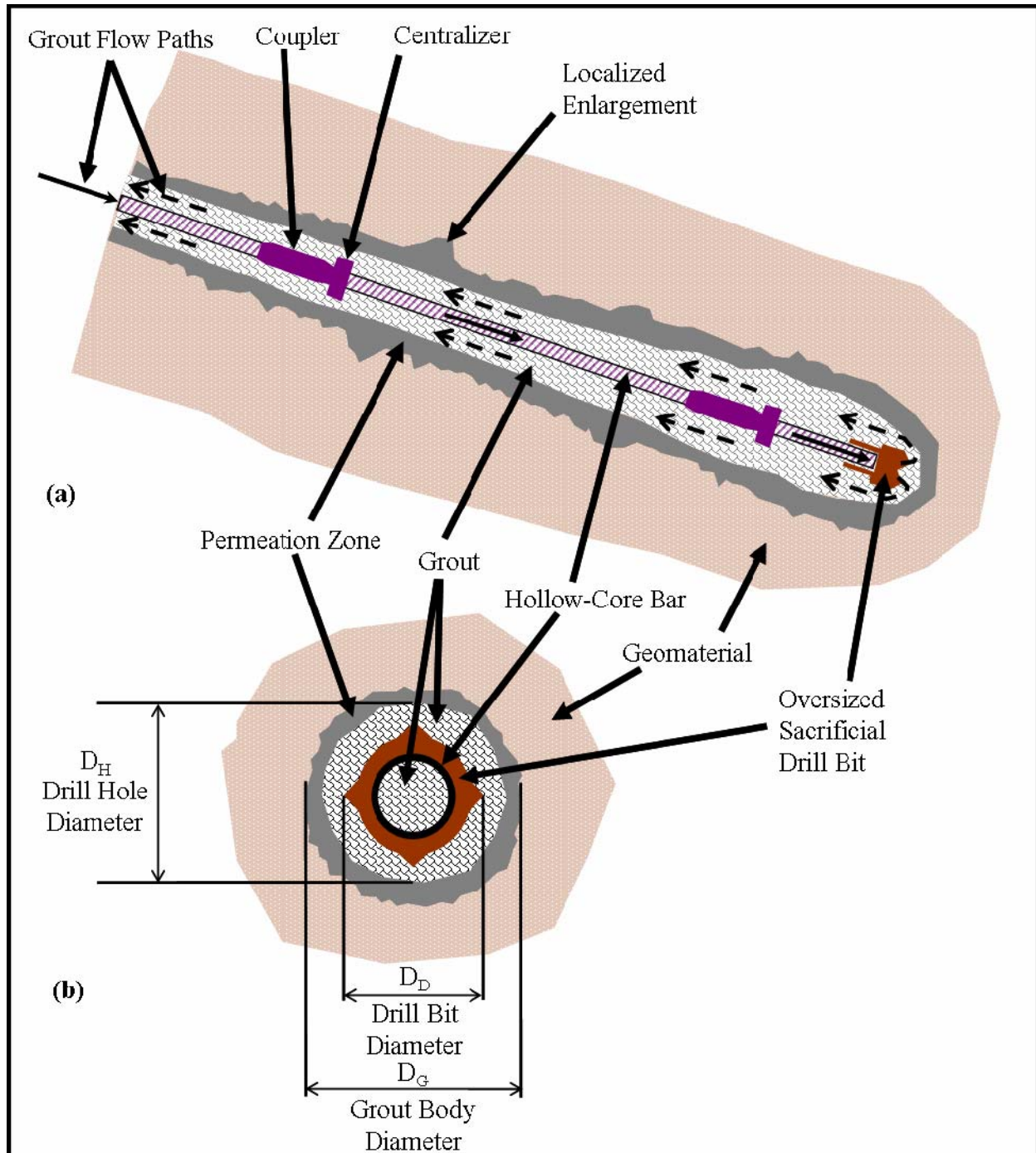


Figure 2. (a) Schematic of hollow-core soil nail installation and grout paths, (b) Schematic of a cross-section of hollow-core soil nail and the grout body.

Expression of Pullout Resistance

As can be seen from Figure 2, the shape of the grout body can vary significantly along the length of the hollow-core soil nail. This makes it difficult to reasonably define the area over which the pullout resistance is developed. The situation is further complicated by the general observation that at the final nail bit location, the grout column may be shaped like a bulb that can offer passive resistance to pullout. Depending on local enlargements, passive resistance may be developed at other locations along the grout column. Due to these observations regarding the shape of the grout column, units of force per unit length (F/L), e.g., kN/m or kips/ft, are utilized rather than expressing the interface bond in terms of stress units, as is commonly done in the case of nails installed using the conventional “drill-and-grout” technique.

Organization of the Document

As can be surmised from the above discussions, the hollow-core soil nail technique may be sensitive to various parameters. The chapters of this report where the parameters are addressed are listed below:

- Nail thread types (Chapter 4)
- Drilling equipment (Chapter 5)
- Grouting (mix, pressure and equipment) (Chapter 6)
- Drill bits and experience of drill crew (Chapter 7)
- Nail accessories (couplers, centralizers, etc.) (Chapter 8)

The hollow-core soil nailing technology is different enough from traditional “drill-and-grout” soil nailing that the applicability of the traditional analytical methods and field testing procedures needs to be considered. These issues are discussed in Chapters 9 and 10, respectively. Corrosion issues and QC/QA related to this construction technique are discussed in Chapters 11 and 12, respectively. Finally, Chapter 13 provides recommendations for further studies.

CHAPTER 3. EXPERIENCE AND RESEARCH BASE

As part of the preparation of this document, the authors relied on their own experience and research (Nowatzki and Samtani, 2004; Samtani, 2003; NCS, 2005) as well as discussions with manufacturers of hollow-core soil nails and specialty contractors who install hollow-core soil nails. The authors have been involved in the design and construction of over 25 permanent soil nail structures using the hollow-core soil nailing technology. A summary of the range of various parameters of the walls with which the authors have been involved is provided below:

- Wall heights: 3 m (~10-ft) to 20 m (~65-ft) (see Figure 3)
- Wall slopes: vertical to ½ H:1V (H: Horizontal, V: Vertical)
- Wall configuration: single height to multiple-bench (tiered) walls
- Nail spacing: 1.5 m x 1.5 m (~5-ft x 5-ft) to 1.83 m x 2.74 m (~6-ft x 9-ft)
- Required (design) minimum nail hole diameter: 76 mm to 102 mm (~3- to 4-inches)
- Nail Lengths: up to 15 m (~50-ft)
- Nail corrosion protection systems: grout only to fusion-bonded purple marine epoxy-coated (ASTM A 934) nails encapsulated in grout
- Nail configuration: rectangular to diamond (quadrilateral)
- Facilities behind top of wall: none, roadways, bridge abutments with deep foundations (piles and shafts), swimming pools, buildings
- Type of soils: running sands, clayey sands, sandy clays, lean clays, silty sands, gravelly soils, cobbly soils, variably-cemented soils, compacted embankment fills, existing embankment fills, MSE wall backfill, and weak sandstone
- Nail testing: proof testing (on production and sacrificial nails), verification testing and ultimate (pullout) testing
- Measured nail adhesion values: 11 kN/m (~0.75 kip/ft) to 117 kN/m (~8 kips/ft).

In some of the above applications, hollow-core soil nails were used for repairs of slope and MSE wall failures. Many of these walls were monitored for lateral and vertical deformations by inclinometers and surface survey monuments (NCS, 2005).

As indicated earlier, the authors solicited input from the manufacturers of hollow-core soil nails. These manufacturers included Con-Tech Systems, Ltd (Con-Tech), DYWIDAG Systems International-Lang (DSI-Lang), and Williams Form Engineering Corporation (Williams). Information on the hollow-core soil nails manufactured by each of these three manufacturers was collected and discussed with their representatives. It must be noted that the hollow-core soil nails available from these three manufacturers are manufactured outside the United States. This may be a procurement issue related to the requirements of the “Buy American Act.”

Since most of the original research was performed in Germany and is documented in the German language, an effort was made to verify the manufacturers’ claims in their brochures. In this

regard, Dr. Wolfgang Fritz, PE, of NCS Consultants, LLC, translated the German literature on hollow-core soil nails to English. He also communicated directly with researchers in Germany to verify the published literature and the latest German and European standards on hollow-core soil nails (Fritz, 2005).

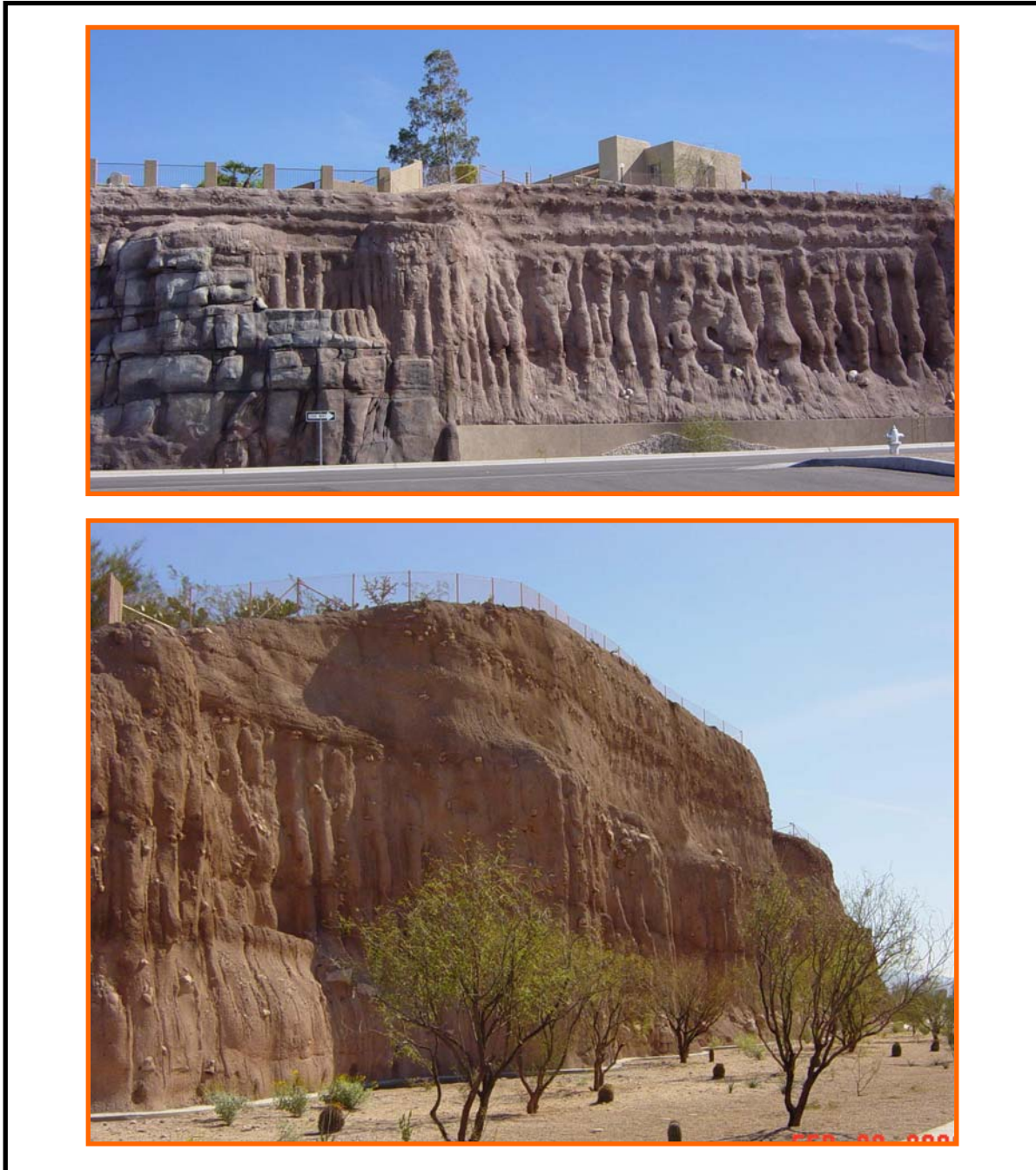


Figure 3. Photos of 20 m (~65-ft) high soil nailed walls in Tucson, AZ, constructed using hollow-core soil nails (Nowatzki and Samtani, 2004; NCS 2005).

CHAPTER 4. STEEL AND THREAD TYPES

As with solid-bar nails, the steel for the hollow-core soil nails must meet the requirements of ASTM A615. Grade 60 is the minimum requirement for the soil nails, although higher grade steels are available and commonly used. Within these ASTM requirements, two types of hollow-core soil nails are available at this time. The primary difference between the two nails is in the type of the thread on the exterior of the nail, see Figure 4.

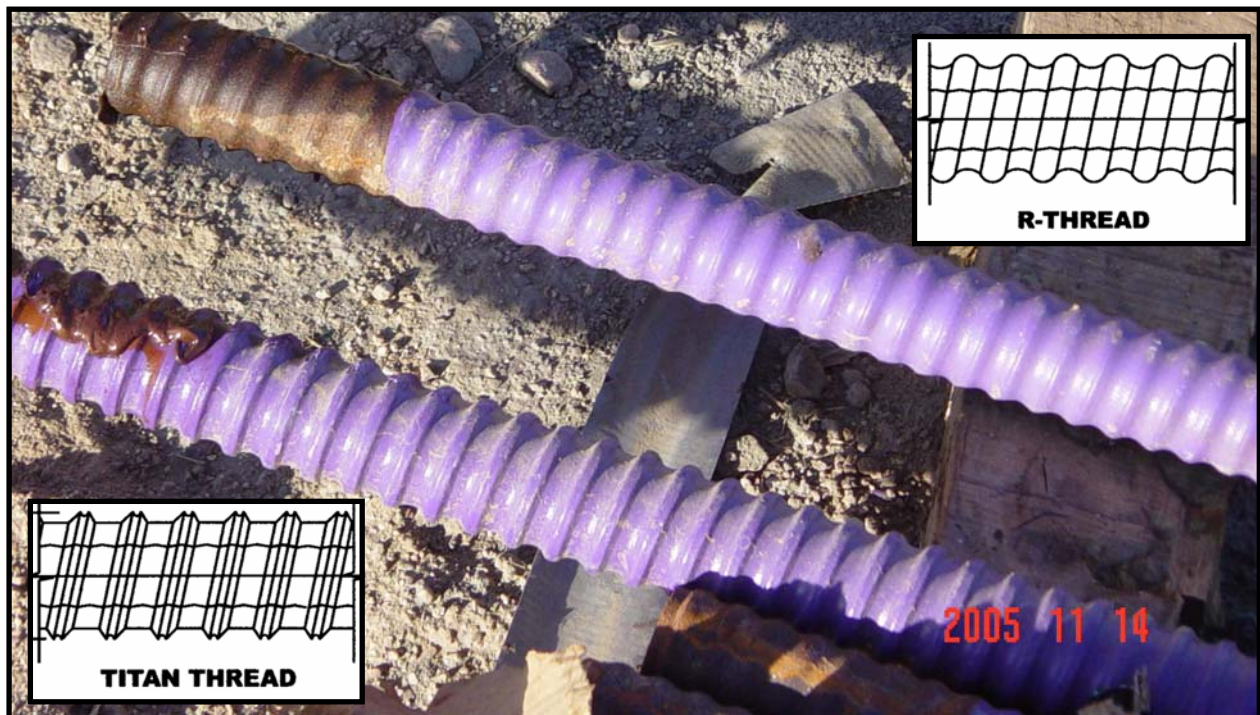


Figure 4. Available thread types for hollow-core soil nails. Upper nail is Rope (R-) thread and lower nail is Titan thread. The purple color is due to the “purple-marine” epoxy coating used to protect against corrosion.

One thread type is the “rope” thread or the R-thread (see upper nail in Figure 4) that is the standard thread in the drilling industry for continuously threaded drill rods. The R-thread is characterized by smoother (rounded) threads to permit easy and fast splicing of the drill rods and couplers. The R-thread is continuous along the entire bar length and is cold-rolled from heavy wall steel tubing. Hollow-core bars with R-thread are available from all three manufactures, i.e., Con-Tech, DSI-Lang and Williams. The R-thread bar sizes available from these three manufacturers vary. The designations of R-thread bars follow the ISO (International Organization for Standardization) rope thread designation, e.g., R 25 where the number indicates the outside diameter (OD) of the bar in mm. In general, hollow-core bars with an OD greater than 52 mm (~2-inch) have right-handed threads and smaller bars (≤ 52 mm (~2-inch) OD) sizes have left-handed threads.

The other thread type is similar to that used on continuously threaded deformed reinforcement bars. At this time, only Con-Tech manufactures this particular thread type for their Titan hollow-core bars. Therefore, this thread is known as the “Titan” thread. Unlike rope threads, the Titan thread (see lower nail in Figure 4) is a sharper thread with thread shoulders varying from 40- to 70-degrees similar to deformed rebar meeting the requirements of ASTM A615. Furthermore, the Titan thread is characterized by a depressed groove at the crown of the thread (refer to schematic insert in Figure 4). Similar to the rope-thread, the Titan thread is continuous along the hollow-core bar. Although the Titan thread is continuous, it should be noted that the thread configuration and spacing vary with the size of the bar (see Figure 5).



Figure 5. Various CTS-Titan hollow-core bars (Aschenbroich, 2005).

The implications of the different thread types is that under tension and/or bending, the grout body surrounding a hollow-core bar cracks at different magnitudes of loading depending on the thread type, grout body size and grout strength. Based on our preliminary evaluation of published data from the Technical University of Munich (Zilch and Müller, 1997; Schießl, 1999), it appears that the Titan thread mitigates the development and propagation of cracks in the grout better than the R-thread for a given size bar. However, it must be noted that the grout body surrounding any nail, *whether solid-bar or hollow-core bar*, will ultimately develop cracks once the tension and/or bending has reached a threshold value for the type of the thread on the bar and the strength of the grout body surrounding it. Once the cracks have penetrated the entire grout cover and made contact with the bar, the potential for corrosion exists in corrosive environments. Further discussion on this issue is presented in Chapter 11.

CHAPTER 5. DRILLING EQUIPMENT AND DRILL CREW EXPERIENCE

The drill rig used on soil nailing projects using hollow-core bars has the capacity to adapt to various sizes of hollow-core bars and drill bits. Hydraulic rotary or rotary-percussion drill rigs are commonly used. The rigs can be track-mounted (Figure 6) or excavator-mounted (Figure 7). The mast of the drill rig is usually articulated and can access tight areas as shown in Figure 8. The versatility of the drill rigs and the concurrent drilling, installing and grouting procedure of hollow-core soil nails has worked well for remote access areas or areas with tight access.

Drill rigs with the following minimum capabilities have performed effectively (Aschenbroich, 2005):

- Rod rotation up to 160 rpm,
- Torque of approximately 2,500 N-m (~ 1.84 kip-ft),
- Percussion energy of 610 Joules (~ 450 ft-lbs).



Figure 6. Track rig installing hollow-core soil nails on a slope.



Figure 8. Mobile rig under a bridge end-span.



Figure 7. Excavator-mounted drill rig installing hollow-core soil nails to repair a rockery wall in a remote area.

CHAPTER 5 – DRILLING EQUIPMENT AND DRILL CREW EXPERIENCE

For bar sizes up to 52 mm (~2-inch) OD, the drill rigs have left turn motors since the bars are left-threaded. For bars larger than 52 mm (~2-inch) OD, the threads are right-handed, therefore a drill rig with a right hand motor is used. Common drill rigs currently being used include those manufactured by Klemm, Casagrande, Davey Drill, Interoc and SoilMec.

While experience is important for the installation of “drill-and-grout” nails, it is critical that the installation of hollow-core soil nails be performed by pre-qualified and experienced drill crews not only because the equipment must meet the specific requirements, but also because the crew must be familiar with the intricacies of the grouting procedures discussed in Chapter 6. In addition to the drill crew, it is important that qualified and experienced personnel are inspecting the construction of the soil nail wall using hollow-core soil nail procedures. It is the state-of-the-practice for the owner and/or the designer to require a certain minimum level of experience to protect the integrity of the design and construction processes.

CHAPTER 6. GROUTING

While grout is an important component of the “drill-and-grout” installation process, the grout and grouting processes are even more critical for the hollow-core soil nailing process. Since the “drill-and-grout” soil nail installation process is predicated on an open-hole concept, the grout is a discrete step in installation of the nail. In contrast, the grout and grouting is a continuous part of the entire hollow-core nail installation process. Therefore, the performance of hollow-core soil nails is dependent on grouting procedures that are complicated by the fact that grouting occurs during drilling and the grout serves more than one function. Details of grouting operations may vary from region to region, but based on the authors’ experience with hollow-core soil nail projects (specifications and field observations) the following criteria generally apply to grouting operations for hollow-core soil nails.

- Grouts are designed to provide high strength and stability, but they must also be pumpable. Typical water/cement (w/c) ratios are in the range of 0.45 to 0.6 by weight. In terms of a 42.64 kg (94-lb) cement bag, a w/c ratio of 0.45 to 0.6 by weight translates to 1 cement bag per 19.2 liters (~5 gallons) to 25.6 liters (~6.8 gallons) of water, respectively.
- Neat cement-water grout mixes are typically used. Design (28-day) compressive strengths of 20.7 MPa (~3,000 psi) to 34.5 MPa (~5,000 psi) can reasonably be attained with properly produced neat cement grouts with w/c ratios between 0.6 and 0.45, respectively (see Figure 9).
- Grouts are produced with potable water, to reduce the danger of reinforcement corrosion.
- Bagged Type I/II cement conforming to ASTM C150/AASHTO M85 is most commonly used.

The critical importance of the grouting operation is underlined by the fact that the placed grout is required to serve a number of purposes:

- It transfers the imposed loads between the reinforcement and the surrounding ground.
- It serves to protect the steel reinforcement from corrosion.
- Its effects may extend beyond the confines of the drill hole by “permeation”, densification and/or fissuring.
- It provides a medium for flushing the cuttings and supporting the borehole without clogging the openings in the drill bit.

The grout, therefore, needs to have adequate properties of fluidity, strength, stability, and durability. The need for grout fluidity should not be achieved by an increase in the water content

because that can lead to a negative impact on the other three properties. Of all the factors that influence grout fluidity and set properties, the water/cement ratio is the most dominant.

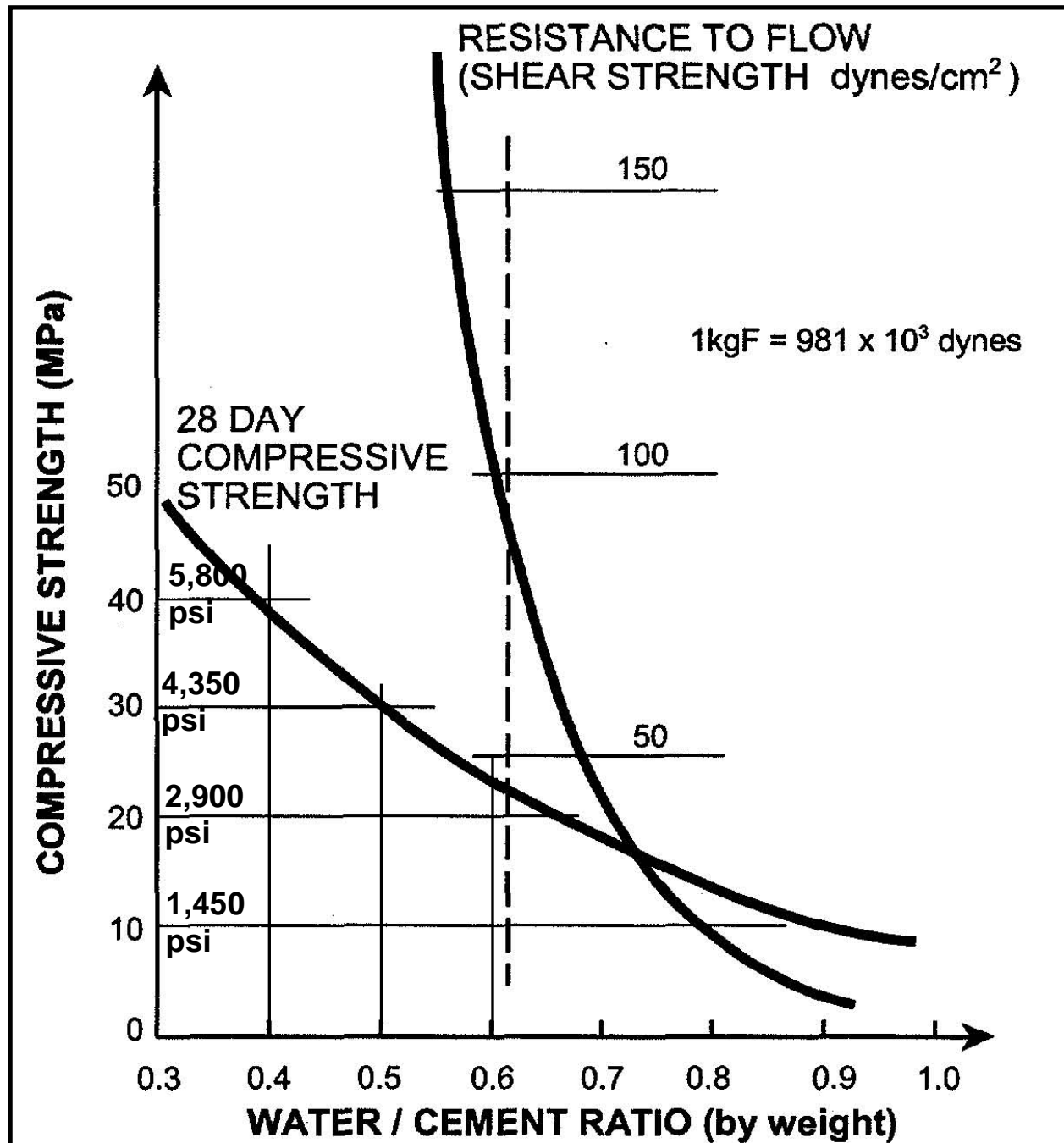


Figure 9. Effect of water/cement ratio on grout compressive strength and flow properties (After Barley and Woodward, 1992). [1 MPa = 145 psi, 1 dyne/cm² = 0.0021 psf].

Because the grout is such a vital component of the hollow-core soil nail method of installation, close attention must be paid to its control and quality. The standard-of-the practice is to implement a grout quality control plan that, as a minimum, includes cylinder or cube compression testing and sometimes includes grout density (water/cement ratio) testing.

Flushing and Final Grout

During the advancement of a hollow-core soil nail to its target depth, the grout is used as a flushing medium. To prevent waste of cement and reduce cost, the grout during the advancement of the nail (termed “flushing grout”) does not necessarily have to be full strength. In most granular soils, diluted grout with a w/c ratio of 0.7 to 0.9 (approximately one 42.64 kg (94-lb bag) per 30 liters (~8 gallons) to 38 liters (~10 gallons) of water, respectively) is used as a flushing medium. Typically, the full strength final grout is used for flushing when the nail is within 1.5 m (~5-ft) of its target depth to ensure a good grout-ground interface. Once the target depth is reached, flushing with full strength grout should be continued while rotating and working the hollow-core bars in and out about 1.5 m (~5-ft) in granular soils and 3 m (~10-ft) in cohesive soils until the grout emerging from the drill hole is observed to be of the same consistency as the neat full strength grout being pumped into the drill hole. The recommendation for working the bars for a longer length in cohesive soils is due to the fact that the “permeation” zone in dry cohesive soils may actually introduce a weaker zone at the perimeter of the grout body as the diluted grout is absorbed in such materials. Therefore, the longer length for final grouting will mitigate the detrimental effects of initial flushing with diluted grout. Based on these considerations, the authors, in their practice, have started using final grout throughout nail installation for all cohesive soils.

Grout Equipment (Mixer and Pump)

In general, any plant suitable for the mixing and pumping of fluid cementitious grouts may be used for the grouting of hollow-core soil nails. The best quality grouts, in terms of both fluidity and set properties, are produced by high-speed, high-shear colloidal mixers (Figure 10) as opposed to low-speed, low-energy mixers, such as those that use paddles (Figure 11, 12). Preferably there should be two mixers or two holding tanks, one for the diluted flushing grout and the other one for the full strength final grout.

Most equipment can be driven by air, diesel, or electricity. Mixers are available in a wide range of capacities and sizes from many manufacturers. In any event, the grout pump should (a) ensure thorough mixing of the grout to avoid blockages at the drill bit, (b) provide continuous delivery of the grout, and (c) maintain sufficient pressure during drilling. Although recommended, the use of an automatic logging system for measurement, recording and documentation of grout volume and pressure is not yet widely prevalent.

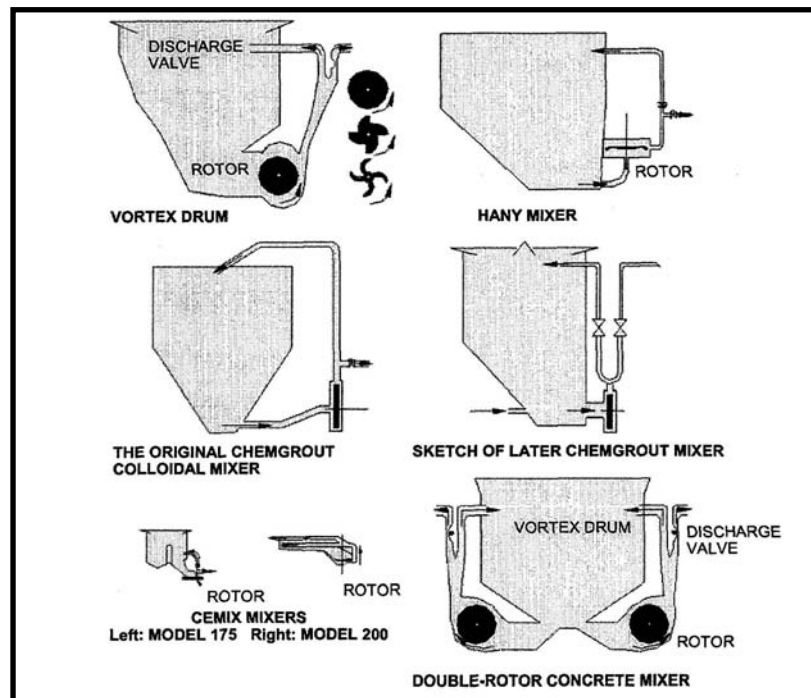


Figure 10. Various types of colloidal mixers (FHWA, 2000).

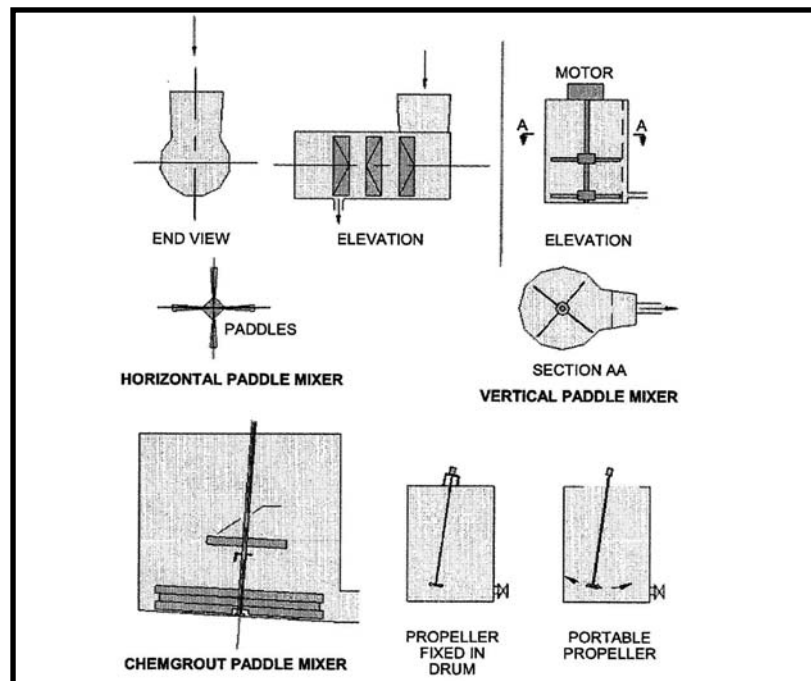


Figure 11. Various types of paddle mixers (FHWA, 2000).



Figure 12. A typical paddle mixer with a holding tank.

Grouting Pressures

Grouting pressures are regulated to maintain circulation at all times such that grout egress from the mouth of the hole is observed at all times. If grout is not coming out of the mouth of the hole then it is flowing elsewhere in the formation and is not providing an effective bond between the grout and ground nor corrosion protection along the entire length of the nail. It is also possible that the drill hole may have caved locally and temporarily blocked the grout return. In such events, the grouting is continued, sometimes with increased pressures, until the return flow at the mouth of the hole is established. If grout flow is not established in a few minutes, then a further evaluation of the subsurface conditions may be warranted to determine whether undetected subterranean voids might be the cause. In one case, where the ground consisted of cobbles and small boulders in a loose soil matrix, the authors used fiber-reinforced grout that did not flow easily into the soil matrix and flow at the mouth of the hole was maintained.

To maintain continuous circulation and egress of the grout, the grout has to pass through the pump, hoses, the hollow core of the nail and then back up through the annulus between the nail and the drill hole. This circuitous path adds resistance to the grout flow. As shown in Figure 9, the resistance to flow of the grout mixes increases significantly for w/c ratios below 0.6. Since the final grouting is typically performed with w/c ratio between 0.45 and 0.6, the resistance to flow will be much higher than 100 dynes/cm^2 ($\sim 0.01 \text{ kPa} \sim 0.21 \text{ psf}$). Thus, to maintain grout flow and a continuous circulation and grout egress from the drill hole, higher pressures are needed to simply pump the grout from the grout mixer to the drill bit. To assure higher pressure capability during final grouting, a piston or plunger pump with about 120 liters/minute (~ 4.3 cubic feet/minute) volume and 0.5 MPa to 1 MPa (~ 72 to 145 psi or 5 to 10 bars) pressure

capability is needed in practice. Sometimes, pressures up to 10 MPa (~1,450 psi or 100 bars) are needed to clean out grout or dirt blockages in hoses or hollow-core bars. Blockages at the drill bit can occur in clayey (cohesive soils) and can be minimized by using drill bits with side-discharge openings that are recessed such that grout flow back towards the mouth of the hole is promoted, as discussed in Chapter 7.

The use of a higher pressure to pump the grout does not necessarily mean that the higher pressure is being applied at the drill bit openings because (a) pressure losses occur in the lines, and (b) the drill hole grout overflow point at the ground surface is open to atmospheric pressure and it serves to relieve excess build-up of grout pressure in the drill hole. Nevertheless, for a given soil, the grout pressure at the drill bit serves to control the diameter of the grout body. Therefore, it is extremely important to use the same grout pressures during installation of production nails in a given soil as was used during installation of the verification test nail(s) in the same soil.

Grout Mixing

A measured volume of water is usually added to the mixer before the cement is added. The water is typically batched into the mixer by means of a calibrated tank or flow meter. Cement is typically batched by the number of 42.64 kg (~94-lb) bags required to attain a desired w/c ratio. On large jobs, the cement may be batched by weight of bulk cement from a silo. In any case, it is generally recommended that grout be mixed for a minimum of two minutes and that thereafter the grout should be kept in continuous slow agitation in a holding tank prior to being pumped to the hollow-core soil nail. The grout should be injected within a certain specified time after mixing. The “safe workability” time should be determined on the basis of on-site tests, as it is influenced by many factors, but it is typically not greater than one hour.

In hot climates, such as in the desert southwest, flash setting of grout can occur and it is recommended that the temperature of the grout be kept less than 32.2 °C (~90 °F). Under these conditions, shaved ice is often added to the water before mixing cement to control the grout temperature and, even then, the “safe workability” time for self-drilling nail installations is generally less than 15 minutes. Additional precautions may include covering the mixing tanks with wetted cloths and spraying the grout hoses and nails with water to cool them because, as the grout passes through these hoses and the hollow-core of the nails, it can flash-set. If flash-setting occurs within the hollow core of the nails, then these nails should be discarded.

The water content in grout is the prime control over grout properties and is most frequently checked through specific gravity measurements. The specific gravity, SG, of neat cement grout can be determined by the Baroid Mud Balance Test (API RP 13B-1). This test is extremely quick and inexpensive to perform using mud-balance equipment shown in Figure 13. A mud-balance essentially compares the unit weight of fluids with that of water. Several equivalent scales are provided on the mud-balance equipment as seen in Figure 13. Each of these scales can be correlated with w/c ratio. The following approximate relation, based on the data provided in

PTI (2004), has been found to be beneficial and can readily be used to monitor the w/c ratio of the grout mix based on measured specific gravity, SG (in kg/m³).

$$\text{w/c (by weight)} = 4.4 (\text{SG}/1000)^{-3.6}$$

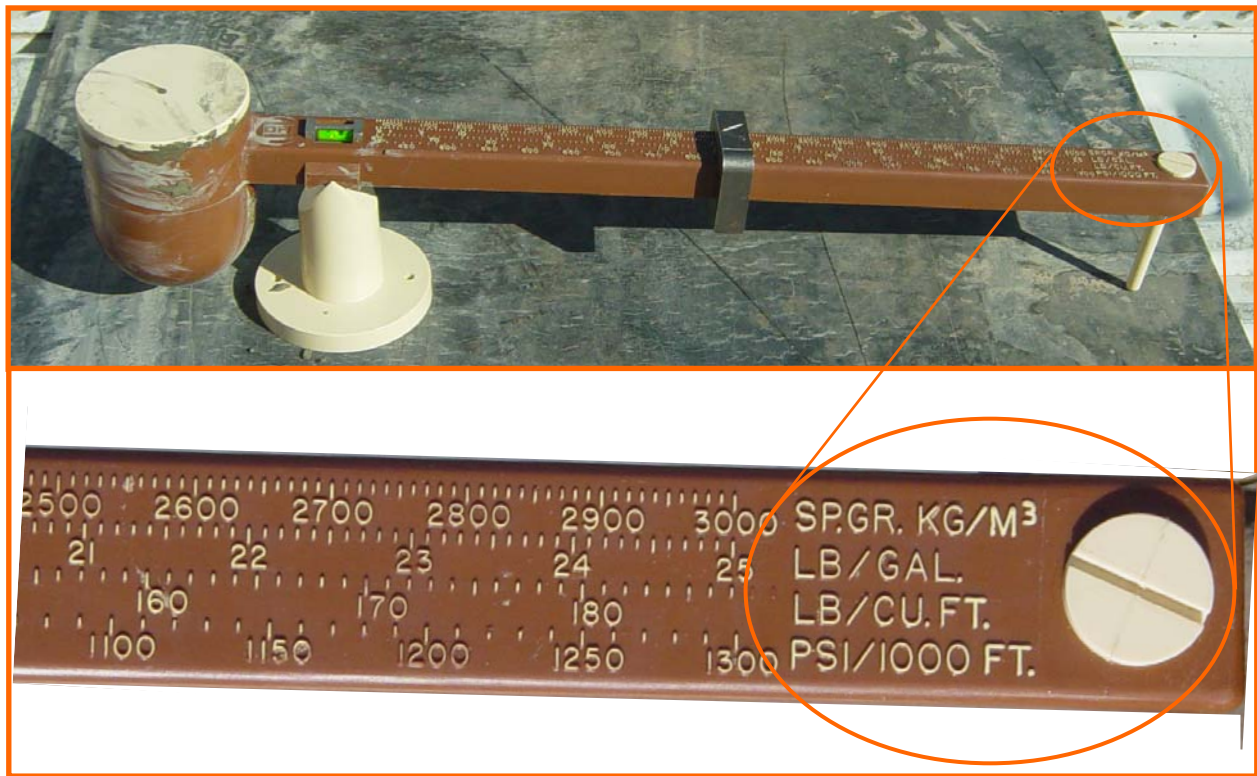


Figure 13: Typical mud-balance equipment (lower photo shows the quantities that are typically measured during the test).

Frequent checking is recommended. By monitoring the w/c ratio during grouting, the inspector can ensure that the grout is being prepared according to the mix design specified for the project. Simple tests such as mud-balance tests that allow quality assessment prior to installation are valuable since they permit immediate reaction in case of anomalies. Unfortunately, other measures of grout quality cannot be assessed prior to installation such as values of compressive strength that can be established only 48 hours after the sampling at the earliest. It is good practice that initial values for these measures of grout quality to be determined on the design grout mix during verification testing to provide the owner's representative confidence in the mix design prior to production drilling.

The grout and grouting processes are much more involved for the case of hollow-core soil nail installation in comparison with the "drill-and-grout" installation process. The state-of-the-practice is to put considerable emphasis on grouting because the success of this technology is heavily dependent on grout and grouting procedures.

CHAPTER 7. DRILL BITS

As discussed in Chapter 2, a sacrificial drill bit is screwed on to the front of the threaded hollow-core soil nail bar (Figure 14). The three manufacturers of hollow-core nails offer a variety of drill bits to permit drilling through different geomaterials including sands, clays, gravels, cobbles, soft rocks, weathered rock and hard rocks. The choice of an appropriate drill bit is critical to the success of the hollow-core soil nail procedure. The following general rules may be used in the selection of the proper drill bit:

- Use cross-cut bits with front and side discharge openings for mixed soils (sands and gravels).
- Use “fish-tail” bits with side-discharge nozzles for clays.
- Use button type bits with front and side discharge openings for cemented soils, weathered soft rock and gravelly/cobbly formations.
- Use carbide (hardened) offset cross-cut bits for hard rocks such as granite, dolomite, and sandstone.
- Use carbide tipped button bits for concrete or very hard rocks such as quartzite.

The locations of the openings in the drill bits vary based on the type of the soils and the drill bits. The openings are usually somewhat recessed between the cross-cuts (see Figure 15, 20) and/or buttons and are located such that the grout can flow back around the bit and towards the top of the drill hole at the ground surface. Bits with side-discharge openings are preferred in clayey soils since bits with frontal openings are prone to plugging in such soils.

The diameter of the drill bit size, D_D , is instrumental in controlling the diameter of the grout body, D_G . As a minimum, $D_G = D_D$, is attained although sometimes centralizers are needed in raveling soils to maintain a minimum D_G equal to D_D . However, since the openings in the drill bit generate grout jets which erode the drill hole perimeter (similar to jet-grouting), a drill hole diameter larger than D_D is often attained (see Figure 2). For granular soils (sands, sandy silts, and gravelly formations) $D_G \sim 1.5$ to $2D_D$ is commonly attained (see Figure 16). For weathered rock and clays $D_G \sim D_D$, since the grout jets which are under relatively low pressures (typically < 700 kPa (~100 psi)) are not able to erode the cohesive geomaterials.

Theoretically, D_G is also a function of the number of nozzles; however, since the grout jets are at relatively low pressures they do not significantly increase D_G as would be the case for high pressure jets (up to 34.5 MPa (~5,000 psi)) that are used in jet grouting. For a given pressure, jet velocity can be increased by reducing the diameter of the openings in the drill bits.



Figure 14. Drill bit attached to a hollow-core soil nail.

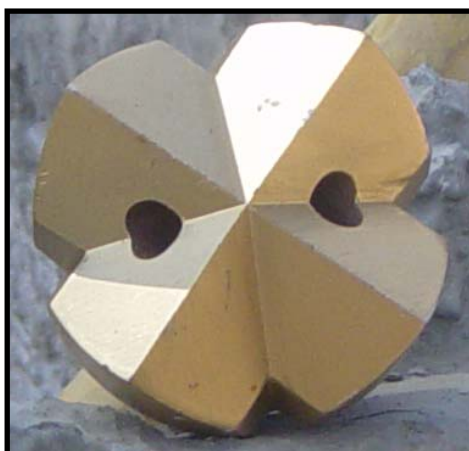


Figure 15. A typical cross-cut bit with two discharge openings.



Figure 16. A 152 mm (~6-inch) diameter grout body generated by a 76 mm (~3-inch) cross-cut drill bit on an approximately 25 mm (~1-inch) outside diameter hollow-core soil nail.

CHAPTER 8. HOLLOW-CORE SOIL NAIL ACCESSORIES

Accessories for hollow-core soil nails are the same as those for solid-bar nails and include the following:

- At the nail head: beveled washers, nuts and bearing plates (see Figure 17, 18),
- Along the nail length: couplers (see Figure 1, 20) and centralizers (see Figure 1,20)



Figure 17. Headed stud bearing plate with a spherical hex nut.



Figure 18. Headed stud bearing plate with a beveled (wedge) washer and a straight hex nut.

While the nail head accessories and the couplers for hollow-core soil nails are similar to those for solid-bar nails, the couplers and centralizers are different as described below:

Couplers

The strength of the connection at the coupler should be equal to or greater than the ultimate strength of the hollow-core bars. Since grout is being flushed through the nail, the couplers should have internal seals to prevent loss of grout pressure during nail drilling. This is important in order to achieve the required flushing and grout injection pressure at the drill bit so that the required drill-hole diameter and ground improvement can be accomplished consistently.

Centralizers

For solid-bar nails, the conventional PVC “bulb” type centralizers are affixed to the nail (see Figure 19). However, these fixed “bulb” type centralizers are not suitable for the hollow-core soil nails because the rotary motion of the bar during the installation process tends to damage this type of centralizer. When damaged, the centralizer can create impediments for grout flow in the drill hole. Therefore, hollow-core soil nails require a mobile “star” type centralizer shown in Figure 20. These mobile centralizers are made of steel and have an ID greater than the OD of the hollow-core bar but smaller than the OD of the coupler. Thus, these “star” type centralizers are free to rotate as well as move along the bar during the nail installation process and their shape

allows the grout to flow freely past them. Since the common length increments for hollow-core bars are 1.5 m (4.92-ft) or 3 m (9.84-ft), one centralizer within a given nail segment between couplers is sufficient to centralize the nail in the hole. The minimum OD of the mobile “star” type centralizer should be equal to the diameter of the drill bit. The actual OD should be such that the centralizer provides a minimum chosen grout cover over the nail.

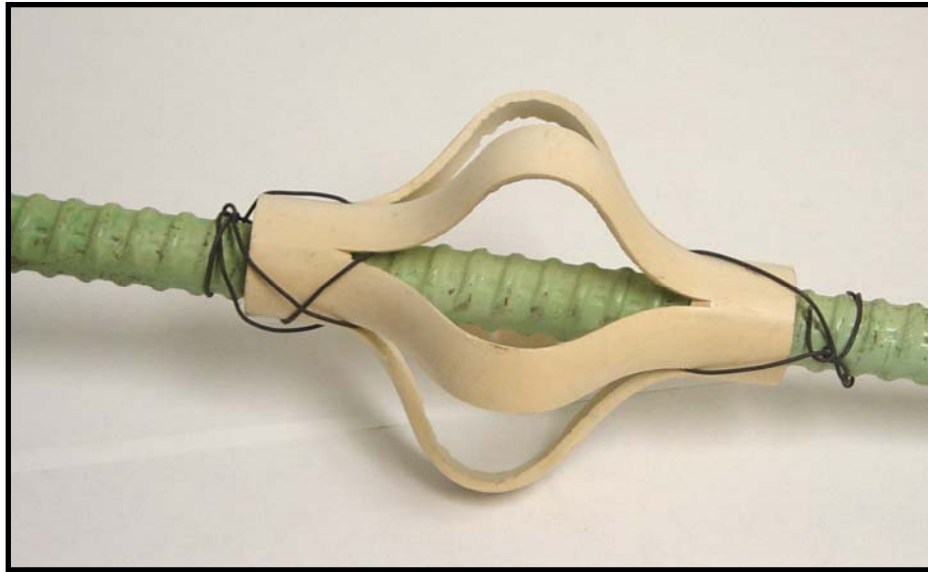


Figure 19. Conventional “bulb” type PVC centralizer tied to a solid-bar nail.

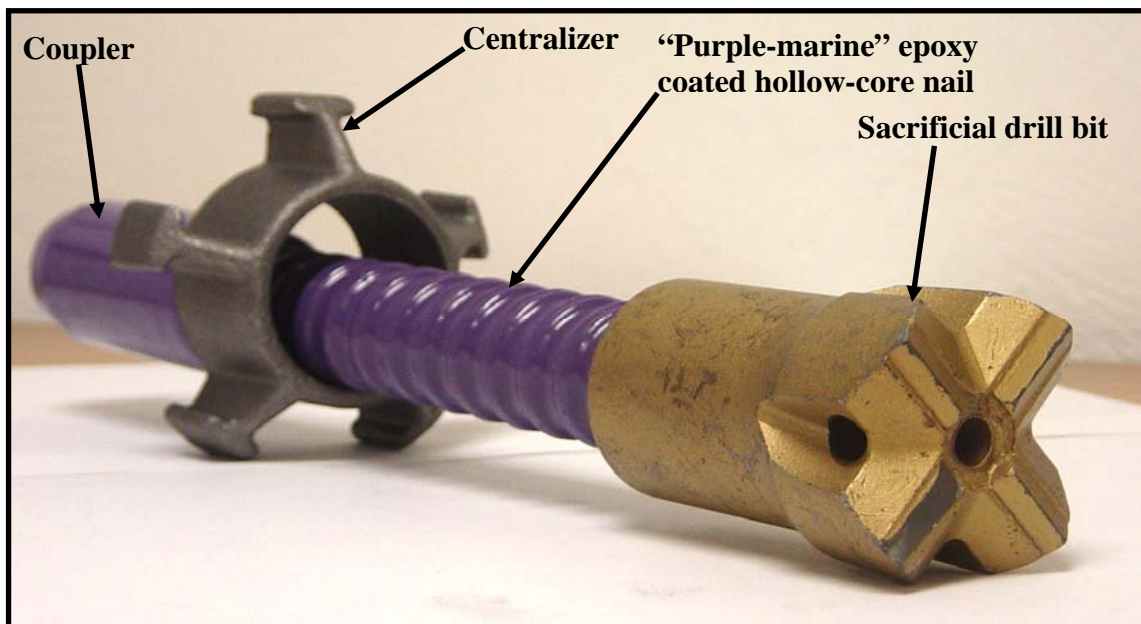


Figure 20. Mobile “star” type steel centralizer on hollow-core soil nail.

CHAPTER 9. FHWA ANALYTICAL MODEL AND HOLLOW-CORE SOIL NAILS

The basic analytical model for soil nail walls that has been adopted by the FHWA is shown in Figure 21. This model was based primarily on experience with “drill-and-grout” installation technique. According to this model, the reinforced soil mass is partitioned into two zones by an assumed failure plane. These two zones are referred to as the active zone and the resistant zone. At incipient failure the distribution of tension along the nail is assumed to be in opposite directions on each side of the failure plane. The length of the nail within the resistant zone is effective in resisting the loads from the active zone and is essentially instrumental in holding up the soil nail wall. For a given set of structural and geotechnical safety factors, the resisting force is equal to the active force to maintain internal stability of the wall. When an analytical program such as GOLDNAIL (Golder, 1993) or SNAILz (CALTRANS, 2006) is used, the nail size is based on the resisting force as well as the contribution of reinforced structural shotcrete at the face of the wall. The effect on nail size, nail spacing and shotcrete of the potentially higher bond resistances (or stiffer load-deformation response) achieved with the hollow-core soil nail technology is discussed next.

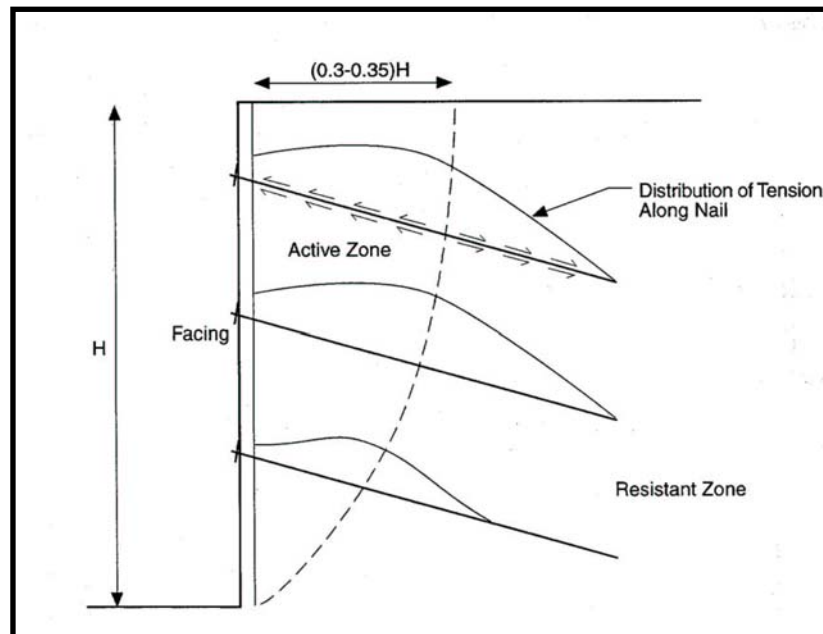


Figure 21. Basic analytical model adopted by the FHWA for soil nail walls (FHWA, 1996, 2003).

Effect on Nail Size

From the basic analytical model shown in Figure 21, it can be seen that for constant length nails, the resisting length varies from the top to the bottom of the wall with the resisting length being generally smaller towards the top of the wall. For the purposes of discussion, the following terminology is used:

CHAPTER 9 – FHWA ANALYTICAL MODEL AND HOLLOW CORE SOIL NAILS

- A_u = Ultimate (nominal) adhesion (grout-to-ground) e.g., kN/m, kips/ft
- L_R = Length of the nail in the resisting zone.
- L_A = Length of the nail in the active zone.
- $L_T = L_A + L_R$ = Total length of the nail.

The pullout resistance (force), P_R , mobilized over the length of the nail in the resisting zone, L_R , can be expressed as follows:

$$P_R = (A_u) (L_R) \quad \text{in units of force (e.g., kN or kips)}$$

The nail is sized to provide this resisting force with an adequate reduction factor (commonly 0.55) against the nominal (yield) load, F_Y , of the bar and a factor of safety of 2.0 on the ultimate adhesion. The key point to realize is that the nail is sized for the resistance in the resisting zone only.

In the testing of nails installed by the conventional "drill-and-grout" nailing technique using solid-bars, the bonded length can be adjusted by simply limiting the extent of the bar that is tremie grouted such that the test load does not exceed the maximum permissible test load of the solid nail which is commonly $0.8 F_U$ or $0.9 F_Y$. However, since the hollow-core soil nailing technique is predicated on continuous grout egress from the mouth of the drill hole, it is not possible to prevent grout-to-steel (G-S) bonding in the length of the nail in the active zone, L_A , which then transfers the tensile load to the ground through the grout-to-ground (G-G) bonding. Thus, during testing the total (full) length of the hollow-core bar, L_T , is effective in resisting the test load instead of just the resisting load. Since $L_T > L_R$, the test load may be limited by the size of the bar depending on the $L_T:L_R$ ratio. Therefore, a meaningful proof or verification test cannot be performed unless somehow the G-S and G-G bond is broken over a certain length of the nail or, in other words, an adequate unbonded length is provided.

Some of the common practices used to overcome this dilemma in the industry have been (a) to offset the effect of grouting the entire length of bar by installing larger nails for testing, (b) to test sacrificial nails with limited length. Neither of these practices results in a representative test, therefore, neither of them is recommended for the following reasons:

- Use of larger nails necessitates use of larger diameter drill bits that result in a larger diameter of the grout body surrounding the test nail than that surrounding the design nail. As discussed earlier, this practice would result in the mobilization of larger resistance. Since the grout body is not uniform in diameter (see Figure 2), it is not possible to linearly reduce the measured resistance to the smaller diameter grout bodies that will be generated in the production nails.
- The concept of shorter sacrificial nails is based on an FHWA (1996, 2003) recommendation that the minimum bonded length for test nails shall be 3m (~10-ft). This recommendation was developed for solid-bar nails installed in open holes where the bonded length of the nail

could be developed in the resistant zone by controlling the amount of tremie-grouting. However, for hollow-core soil nails, use of a minimum 3 m (~10-ft) bonded length forces the termination of the installed nail in the active zone. Thus, during a test, the shortened sacrificial hollow-core soil nail would test the resistance of the soils in the active zone and not that of the soils in the resistant zone where the actual production nails would be mobilizing their resistance.

The problems described above can be avoided if the production nails are sized for the larger of (a) the maximum test load or (b) the resistance required for maintaining the wall stability. This can be achieved by optimizing the soil nail wall design. Techniques for optimization include efficient use of the nail spacing, wall batter, shotcrete strength and length of the nail (NCS, 2005). For example, for a given geometric configuration of a wall, use of shotcrete with an unconfined compressive strength of 27.5 MPa (4,000 psi) instead of 20.7 MPa (3,000 psi) might increase the nail head capacity and enable use of loads in test nails similar to those in production nails.

Research is needed to solve the problem of obtaining an adequate unbonded zone for the verification and proof testing of hollow-core soil nails.

Effect on Nail Spacing and Shotcrete

Based on a limited evaluation of instrumented walls with nail spacings varying from 1.5 m x 1.5 m (~5-ft x 5-ft) to 1.83 m x 2.74 m (~6-ft x 9-ft) in similar types of materials, the authors have found that walls with wider spacing showed significantly greater horizontal deformations. For the 20 m (~65-ft) high vertical soil nail walls shown in Figure 3, the authors measured, by use of inclinometers, lateral movements at the top of the wall of approximately 6 mm (~ $\frac{1}{4}$ -inch) for nails installed at a rectangular spacing of 1.83 m x 1.83 m (~6-ft x 6-ft) (Nowatzki and Samtani, 2004). On another project in the same general geologic formations within 8 km (~5-miles) of the 20 m (~65-ft) high walls, nails were installed on a 1.83 m x 2.74 m (~6-ft x 9-ft) spacing on 11 m (~35-ft) high walls with batters ranging from 15- to 20-degrees. On these battered walls with larger nail spacing, the authors measured, by use of inclinometers, lateral movements in the range of 25 – 32 mm (~1- to 1 $\frac{1}{4}$ -inches) (NCS, 2005). Given that all other factors such as installation processes and shotcreting were reasonably similar for the two projects, it appears that large nail spacings are not recommended based on considerations of lateral movements. In view of these observations, the authors have limited the maximum spacing of nails to 1.83 m x 1.83 m (~6-ft x 6-ft) in their practice, i.e., 1 nail per 3.35 m² (~36 ft²) of tributary area; this is consistent with the guidelines presented in FHWA (2003).

With regards to shotcrete, a preliminary evaluation by the authors appears to indicate that the larger the spacing of nails, the more likely that the nail head strength is governed by flexure rather than punching-shear. This observation suggests that more reinforcement of the shotcrete between the nails may be required. However, this is a function of several other parameters such as the shear strength of the soils, type of bearing plate, use of headed-studs and type of architectural finish. Further investigation to study this observation is warranted.

CHAPTER 10. FIELD TESTING OF HOLLOW-CORE SOIL NAILS

The testing frequency and procedures for hollow-core soil nails do not vary from those for solid-bar nails described in FHWA (1996, 2003). However, as indicated in the previous chapter, development of the unbonded length for hollow-core soil nails is complicated by the basic requirement that the circulating grout must egress from the mouth of the drill hole. This continuous grout flushing through the drill hole mouth tends to bond the entire length of the nail. The testing is further complicated by the basic analytical model used to design soil nail walls.

Development of Unbonded Length

The procedure commonly used to achieve an unbonded length is pictorially shown in Figures 22 to 26. The procedure involves sliding a PVC tube over the nail before installation so that only the bonded length to be tested is exposed to the grout. The PVC tube must have an internal diameter larger than the outside diameter of the hollow-core bar but smaller than the outside diameter of the coupler. The ends of the PVC tube are duct-taped to prevent ingress of the grout in the annulus between the PVC tube and the hollow-core bar (see Figure 22). The PVC-outfitted hollow-core bar is then attached to the string of hollow-core bar already installed in the ground (see Figure 23). Once the string of hollow-core bars has reached its target depth and the entire nail length is flushed with the final grout as described earlier, the grout surrounding the installed nail is allowed to cure for at least three days. The duct tape at the end of the PVC tube at the mouth of the drill hole is then removed and the PVC tube is trimmed as necessary to permit attachment of the testing setup.

The PVC tube with the duct tape can be used on bar segments between couplers to develop an unbonded zone of the desired length. In this case, the coupler would still be bonded. However, since the exterior of the coupler is smooth (i.e., not threaded) and the coupler length is typically 150 to 229 mm (6 to 9-inches), the pullout resistance provided in the length of the coupler is insignificant compared to that in the bonded length.

The PVC tube technique breaks the grout-steel bond in the unbonded zone since there is no grout in the annulus between the PVC tube and the outside of the hollow-core soil nail. Because of the PVC tube's smooth exterior surface, the bond between the outside of the PVC tube and the grout is usually broken during the first or second increment of the design load. This is also true for the relatively smooth exterior surface of the coupler. Thus, it is often observed that the load deformation curve shows elastic movement less than 80% of the theoretical elongation up to the first or second increment of the test load which is typically 50% of the design load. This is not a reason for concern as long as the elastic criterion is satisfied at maximum test loads.

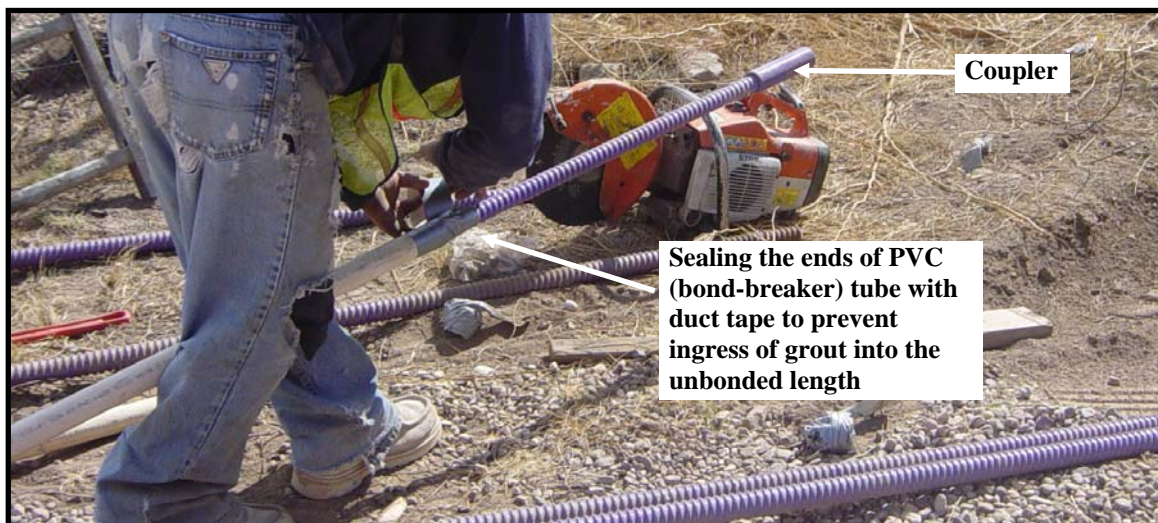


Figure 22. Preparing the unbonded length.

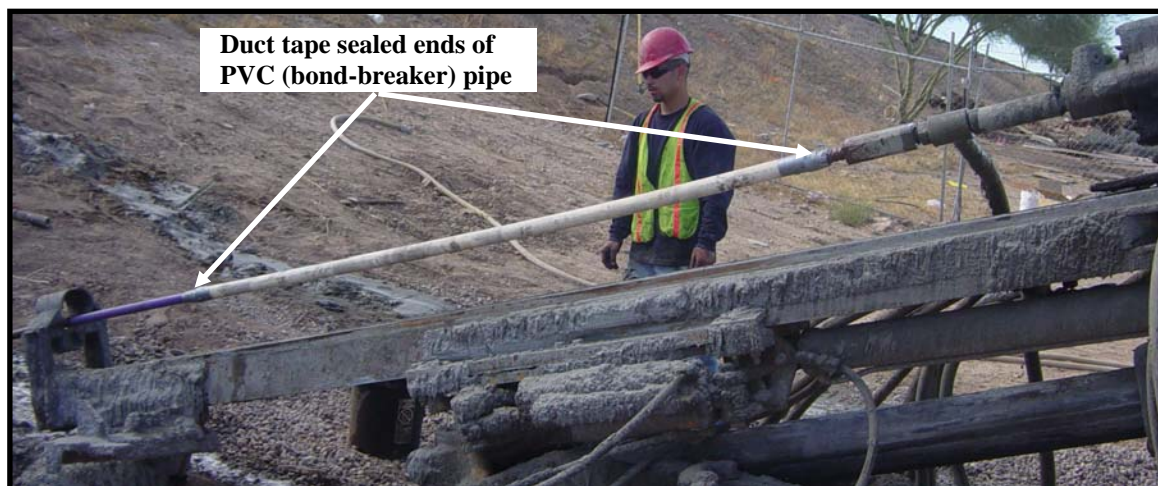


Figure 23. A hollow-core bar being installed with attached PVC tube sealed at both ends.



Figure 24. Front view of finished hollow-core soil nail with PVC tube.



Figure 25. Side view of finished hollow-core soil nail with PVC tube.



Figure 26. Trimmed PVC tube to expose the hollow-core soil nail for testing.

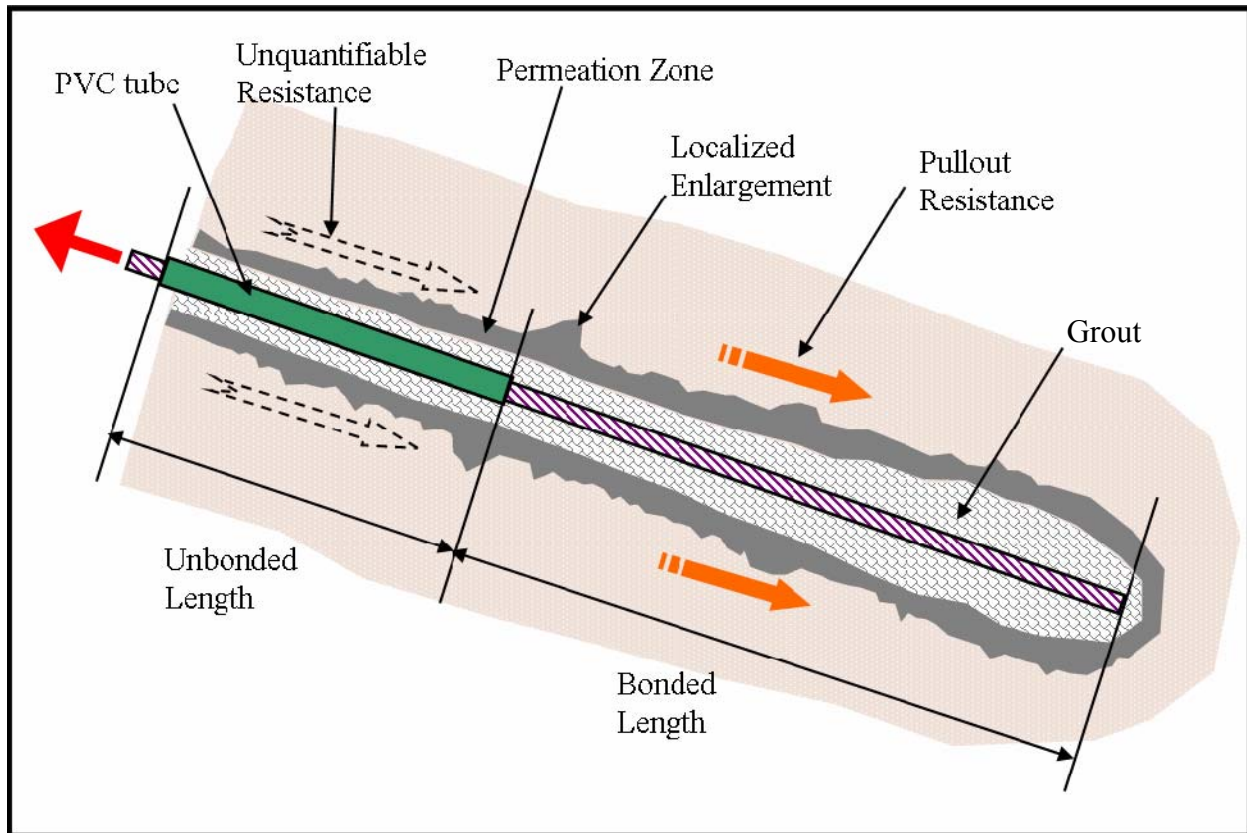


Figure 27: Schematic of unquantifiable resistance in “permeation” zone along the unbonded length (nail head test setup, nail bit, centralizers and couplers not shown for clarity).

It must be realized that even though the grout-steel bond and the PVC tube-to-grout bond is not an issue during the load testing, there is an unquantifiable resistance within the “permeation” zone as shown in Figure 2 and Figure 27. This is because the “permeation” zone as well as the grout body between the PVC tube and the “permeation” zone is continuous along the entire length of the nail even though the PVC tube serves as a bond-breaker between the grout and the nail. This unquantifiable resistance depends on the length of the unbonded zone and the configuration of the “permeation” zone. To minimize this resistance the following options may be considered:

- Option 1: Use only 1 m (~3-ft) of unbonded length as recommended for solid-bars (FHWA 1996, 2003). However, the penalty under this option is that the longer bonded length will necessitate the use of a larger nail than required by analysis. Furthermore, the longer bonded length will include the length of the nail in the active zone and therefore the test may not be representative of the pullout resistance in the resisting zone.

- Option 2: Drill a larger diameter flushing pipe around the PVC tube and use air and/or water to flush out the “permeation” zone in the unbonded length. The penalty under this option is added equipment and materials cost.
- Option 3: Estimate the resistance in the “permeation” zone and add this resistance to the test load. In other words, carry the test to a load greater than the traditional (i.e., that used for nails installed using the “drill-and-grout” technique) maximum test load by a magnitude equal to the estimated resistance in the “permeation” zone. This may not be an easy task since, as indicated in Chapter 2, the profile of the “permeation” zone in the unbonded length is unknown.

The authors have implemented Option 3 on several projects by continuing the traditional verification nail test beyond the required maximum test load (NCS, 2005). Regardless of the option chosen, it is imperative that the annulus between the PVC tube and the hollow-core bar be completely filled with grout or grease following completion of the test to prevent the intrusion of air or water into this void that may promote corrosion. The current state-of-the practice is to use grout to fill the annulus. Use of grease will lead to an anchor type of load transfer mechanism in the production nails that will not be in accordance with the assumed analytical model shown in Figure 21. It should be realized that under field conditions, complete infilling of the annulus may be difficult to achieve. It is probably not possible if the PVC tube technique was used between two couplers. To avoid this problem, it might be better to use a specially prepared bar in the unbonded length that contains grease on the outside of the hollow-core bar and is encased in a heat-shrink sleeve similar to that used in the unbonded zone for ground anchors. Based on our conversation with Mr. Eberhard Heinzemann (2005) of Con-tech Systems, we understand that this type of specially prepared hollow-core bar can be easily fabricated in the factory and shipped to the site as part of a regular order.

Prevention of Passive Failure of Ground at Shallow Depths

Construction specifications for soil nail walls using hollow-core soil nails are often adapted from those included in the FHWA (1996, 2003) documents, which were developed for conventional solid-bar nails installed using “drill-and-grout” techniques. In these specifications, it is often required that verification tests be conducted at an elevation within 1 m (~3-ft) below the top of the wall. The ground in this 1 m (~3-ft) depth is usually adequate to resist the test loads at the nail head for tests based on the lower adhesions for conventional solid-bar nails. However, with the higher adhesions often obtained using the hollow-core soil nailing technique, the test loads are correspondingly higher. Consequently, passive failures such as that shown in Figure 28 can occur. The authors have mitigated or prevented these failures by increasing the angle of inclination of the test nail and placing a surcharge at the ground surface to increase the passive resistance or by specially preparing the timber-cribbing reaction system as shown in Figure 29.



Figure 28. Passive failure where a hollow-core soil nail was tested close to the ground surface (see depression at the cut face and the profile at the ground surface above the soil nail).



Figure 29. Timber cribbing reaction system embedded into slope to prevent passive failure during verification test of hollow-core soil nail.

CHAPTER 11. CORROSION ISSUES

Our independent research (Fritz, 2005) indicates that, based on data from two corrosion-related studies (Zilch and Müller, 1997; Schießl, 1999) performed at the Technical University of Munich (TUM), the 30/11 CTS-Titan bar is allowed for permanent soil nail wall applications in Germany by the German Institute of Construction Technology. Other Titan threads have been allowed on a case-by-case basis at the discretion of the local agencies in Germany and the European Union (EU).

The two TUM studies are summarized in Appendix A. To our knowledge, a formal study similar to the TUM studies has not been performed in the US. However, hollow-core bars of various sizes have been used in numerous permanent soil nail wall applications at the discretion of the local agencies, e.g., Pima County Department of Transportation (PCDOT), Arizona Department of Transportation (ADOT), FHWA Central Federal Lands Highway Division (FHWA-CFLHD) and others. These projects were evaluated by the owner agency and the acceptance of hollow-core soil nails was made on a case-by-case basis. One of the greatest concerns for the use of hollow-core soil nails in permanent applications is related to assurance of long-term corrosion protection.

Corrosion of metallic inclusions in soil is a well known phenomenon (FHWA 1990, 2001, 2003; Murray, 1993; CLOUTERRE, 1993; CALTRANS, 2003). In contrast to Mechanically Stabilized Earth (MSE) walls where controlled fill is used, the phenomenon of corrosion is difficult to control in case of soil nail walls and anchored walls where the metallic inclusions are installed in native ground. For installation of metallic reinforcements in native ground, protection against the detrimental effects of corrosion can be designed for the service life of a structure by utilizing (a) encapsulation of the metallic element in a coating and/or grout, or (b) use of sacrificial steel. Brief discussions of these two options are presented below.

Use of Coating and Grout Cover

A purple-marine fusion bonded coating meeting the requirements of ASTM A934 is used to protect steel in aggressive marine environments. The soil nail industry has typically accepted purple marine epoxy coating as providing one level of protection against corrosion. The grout cover has then been argued to provide the second level of corrosion protection. It may be noted that FHWA and most agencies require two levels of corrosion protection for permanent walls.

It must be realized that the corrosion protection system provided by the purple-marine epoxy coating and the grout cover are valid only if the coating is not damaged during handling and/or installation, and the grout cover remains intact, i.e., does not crack. As discussed in Chapter 4, the grout body surrounding the hollow-core bar cracks at different magnitudes of loading for different patterns of the threads on the bar. Once cracks of sufficient width have penetrated the entire grout cover and made contact with the hollow-core bar the potential for corrosion may exist, particularly if the purple-marine epoxy coating has been damaged at the location of the cracks. Although anecdotal evidence suggests that the purple-marine epoxy coating for hollow-

core soil nails is robust and has been observed to be undamaged after nail exhumation, a detailed scientific, well documented and peer-reviewed study to support the anecdotal evidence is not available and needs to be performed. In the absence of this study, an intact (i.e., not cracked) grout cover can be thought of as the primary source of corrosion protection.

Until detailed studies are performed, the designer of soil nail walls using the hollow-core technique should be cautious in designing permanent walls. Until the issues raised here are resolved, the designer may consider the following guidance based on the experience of the authors:

1. The nominal load of hollow-core bars should be limited to less than that corresponding to the yield strength of the bar, and a certain minimum grout cover should be required.
2. Particular emphasis should be placed on quality assurance/quality control (QA/QC) during construction to assure that grout strengths and grouting procedures are properly implemented. Construction monitoring and QA/QC aspects are discussed in Chapter 12.

Use of Sacrificial Steel

Under this approach, a sacrificial thickness equal to the projected section loss over the service life of the structure is added to the required structural thickness. This approach results in a larger bar cross-section than required by the design, but the cross section is progressively reduced by corrosion over the service life such that at the end of the service life the remaining cross-section is sufficient to service the design stresses. Information on the evaluation the corrosion potential of soils can be found in publications by Murray (1993) and FHWA (2003). A discussion of corrosion rates is beyond the scope of this document, but it appears that in the case of hollow-core soil nails, this sacrificial steel approach may be particularly advantageous given that the test loads often govern the nail size as discussed in Chapter 9. For a given ground condition and $L_T:L_R$ ratio (see Chapter 9), the design of the hollow-core based soil nail wall system can be optimized such that the dual issue of the test loads and corrosion can be addressed together. Use of larger bars will also likely mitigate the issues related to crack width discussed earlier as it will permit higher design loads and the grout body will be larger in diameter. In cases where corrosion was considered to be an issue, the authors implemented this approach in their practice even when the hollow-core soil nails were purple-marine epoxy coated.

**CHAPTER 12. CONSTRUCTION MONITORING, QUALITY CONTROL AND
QUALITY ASSURANCE (QC/QA)**

A flow chart depicting the various construction activities and the responsibilities of the inspector is shown in Figure 30. This chart can be used to monitor the construction activity for both solid-bar as well as hollow-core soil nails. The construction monitoring and related QC/QA aspects for solid-bar nails are described in FHWA (1994). In addition to the guidelines presented in FHWA (1994), the current state-of-the-practice includes monitoring the following items during construction for hollow-core soil nails:

Hollow-Core Soil Nails

1. Verify the nail thread. To the untrained eye the two different types of hollow-core bars look similar (see Figure 4).
2. Check the mill certificates for the hollow-core bars.
3. Check the hollow-core of the bar to verify that it is not plugged.
4. Check the ends of the hollow-core bars to verify that they have 90-degree cut ends.
5. Measure the inside diameter of the nail. All three hollow-core soil nail manufacturers have several hollow-core soil nails whose OD is the same but the ID is different. The larger the ID the smaller the structural capacity of the nail, i.e., the less steel in the cross section.
6. Verify that the nails are properly stored on a dunnage and the ends are wrapped with a covering to prevent dirt from plugging the center hole (see Figure 31).
7. Verify that the nails are lifted by a forklift such that the epoxy coating is not damaged.
8. Before drilling, place the correct length of the bars next to the drill hole so that the correct length of the nail is installed (see Figure 32).



Figure 31. Storage of hollow-core soil nails at site on dunnage.



Figure 32. Placing the correct length of hollow-core nail next to the drillhole.



Figure 33. Example of missing beveled (wedge) washer.

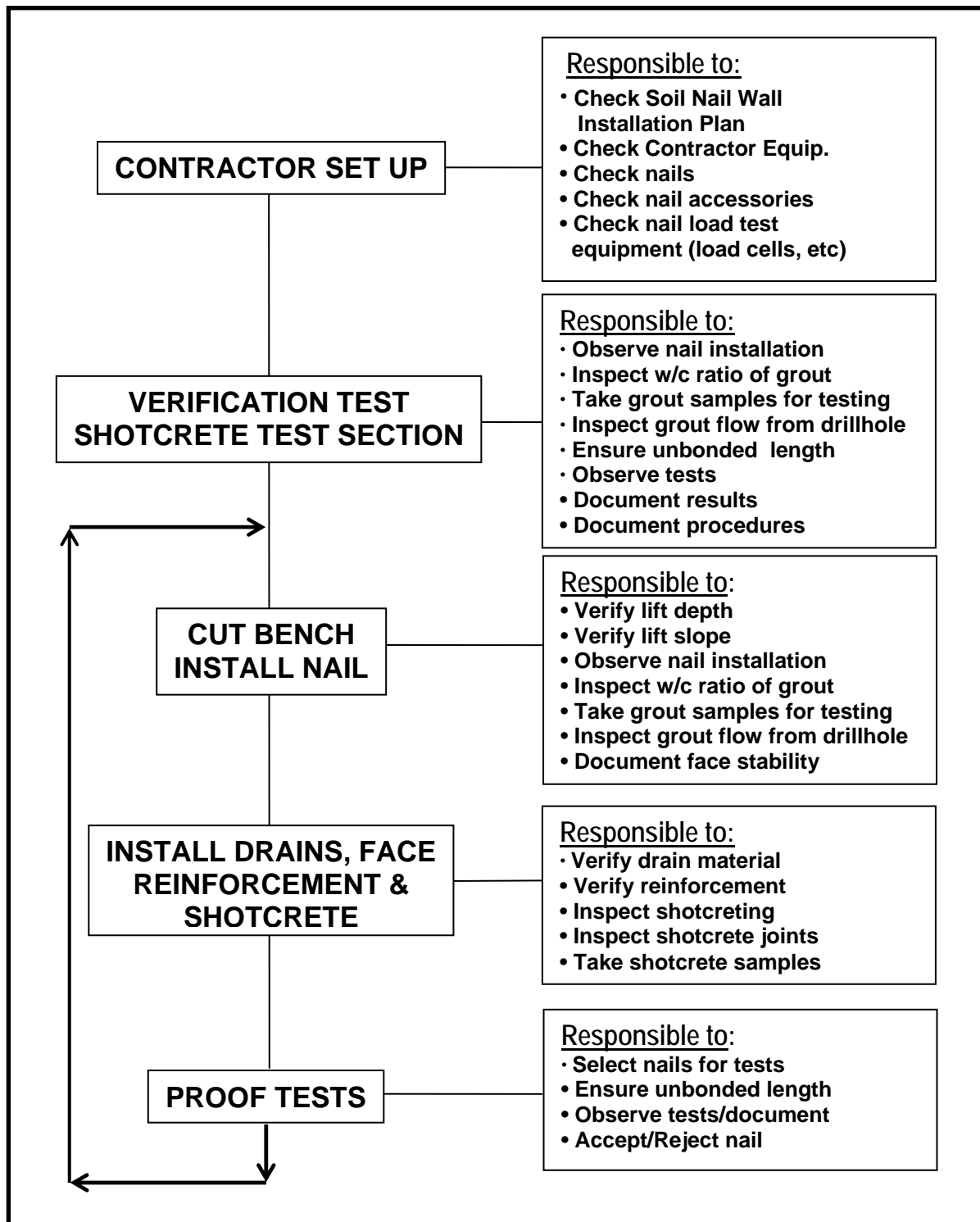


Figure 30. Flow chart of activities and inspector responsibilities during soil nail wall construction (Modified after Samtani, 2003).

Nail Accessories

1. Ensure that all soil nail accessories (washers, nuts, bearing plates, couplers, centralizers, etc.) are available at the site prior to the nail installation and are properly installed.
2. Verify the diameter of the drill bit to ensure the correct drill hole and grout body diameter.
3. Verify that the grout holes in the drill bit are clean and open.
4. Verify that centralizers are used as specified. It is recommended that a centralizer be used near the collar of the hole to support the nail and ensure that it is reasonably centered in the hole.
5. Verify that the bearing plate is flush set in the fresh shotcrete and that the nut is tightened immediately after the bearing plate is set. Ensure that the correct beveled washer is used between the bearing plate and the nut. Figure 33 shows an example of a missing beveled (wedge) washer between the straight hex nut and the bearing plates. It is critical that all nail head accessories are properly installed.

Drilling Equipment

1. Verify that the drill rig has the appropriate motor to install the hollow-core bars. Hollow-core bars equal to or greater than 52 mm (~2-inch) OD have right hand thread. Therefore the drill rig should have a right-turning motor. Conversely, a left-turning motor is required for hollow-core bars having OD less than 52 mm (~2-inch).
2. Verify that a tool such as a clamp or pipe wrench is used to disconnect the hollow-core bar from the flushing head (or swivel). This is necessary to prevent the hollow-core bar from turning out of the couplers below the ground. The point of contact between the tool and the bar should be protected to avoid damage to the “purple marine” epoxy coating used for corrosion protection.

Grout and Grouting

1. Verify w/c ratio by measuring the quantity of water and the cement added to the water. The w/c ratio should be verified both during the flushing stage as well as final grouting. Note that the weight of cement bags may vary by $\pm 10\%$. Therefore, it is advisable to perform mud-balance tests frequently to verify w/c ratio as discussed in Chapter 6.
2. Verify that the temperature of the grout is below 32.2°C ($\sim 90^{\circ}\text{F}$) to prevent flash set within the hose lines and the hollow-core of the nail itself.

CHAPTER 12 – CONSTRUCTION MONITORING, QUALITY CONTROL AND QUALITY ASSURANCE (QC/QA)

3. Verify that an adequate quantity of grout at the proper w/c ratio has been mixed and that there is an uninterrupted flow of grout during installation of the nail. The grout should be agitated continuously during the drilling process.
4. Before drilling the nail, eject some grout through the nail bit to ensure that the lines are full of grout and that there are no air pockets within the grout body.
5. Make sure that grout flushes continuously out of the mouth of the drill hole. If the grout flow out of the drill hole stops then check the grout lines for blockages or the grout level in the holding tank. If no blockages are found in the lines and the grout level in the holding tank is adequate, continue pumping grout while rotating but not advancing the string of bars until grout out-flow resumes at the mouth of the drill hole.
6. Verify that the grout pressures are equal to or greater than those used during approved verification tests.
7. When the nail has reached within 1.5 m (~5-ft) of its target depth in granular soils (3 m (~10-ft) in cohesive soils), ensure that the final grout is being used. Once target depth is reached, retract the bar and re-advance the bar to the target depth while rotating until the final grout is clearly seen at the mouth of the hole.
8. After the nail is drilled, verify the grout level in the hole and within the hollow-core of the nail itself and top-off the grout as necessary. It is particularly important to completely fill the “birds-beak” formed at the collar of the hole due to the nail inclination and the horizontal level sought by the fluid grout. A stiffer grout may be used at this location.

Development of Unbonded Length

1. For development of unbonded length, ensure that the ends of the bond breaker pipe are carefully sealed to prevent ingress of grout in the annulus between the nail and the bond breaker pipe.
2. After the proof-test has been performed, fill the annulus between the bond-breaker pipe and the nail with grout. Note that if the PVC pipes are tight-fitting then filling with grout may not be possible. In this case, the outside of the bar should be greased thoroughly before sliding the PVC pipe on it and the ends of the pipe should be sealed tightly. Grease should also be liberally applied to the coupler since the coupler will not be covered with the PVC pipe. If possible, use of heat shrink sleeves is also recommended before grease is applied.

As can be seen from the above list, there are many more elements to be monitored during the installation of nails using the hollow-core technique compared to the “drill-and-grout” technique. Therefore, it is important that qualified and experienced drill crews and inspectors be employed during the installation of hollow-core nails as discussed in Chapter 6.

CHAPTER 13. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

A state-of-the-practice (SOP) document regarding hollow-core soil nails is presented herein. Issues peculiar to the use of hollow-core soil nails are presented and, where appropriate, a commentary is provided based on the authors' experience.

The hollow-core soil nail technology has been used successfully by the authors and others throughout the United States and elsewhere. Since the hollow-core soil nail technology is a relatively recent development, a sufficiently long track-record is not available. There are several issues that require attention before the hollow-core soil nail method can be accepted as a mainstream technology and regularly used for permanent applications. Some of these issues may be addressed by related literature review while others will require testing and analysis. The issues that are recommended for further studies include the following:

1. Evaluation of the difference in the grout-to-ground bond and stiffness characteristics based on side-by-side comparison of nails installed using the hollow-core construction technique and the conventional "drill-and-grout" technique in a given geomaterial.
2. Possible modification of the current analytical model (FHWA 1996, 2003) to better reflect the behavior of the soil nails installed by the hollow-core bar installation process, where permeation occurs and the grout body is of irregular shape and may contain a larger diameter bulb near the end of the nail.
3. Determination of the extent of the "permeation" zone in dry cohesive soils when a diluted grout is used during nail installation and its effect of the strength of the grout body after final grout is introduced.
4. Evaluation of the nail adhesion as a function of nail advance rate and grouting pressures.
5. Development of a cost-effective method to obtain an adequate unbonded zone for the verification and proof testing.
6. Evaluation of the effect of nail spacing on thickness of shotcrete and the amount of shotcrete reinforcement required as a function of the shear strength of the supported soils, the type of bearing plate and the use of headed-studs.
7. Determination of the effect of the hollow-core soil nail method of construction on the integrity of corrosion protection coatings such as the "purple-marine" epoxy and other coatings available today.
8. Evaluation of the difference in load capacity between different bar types. For example, a larger nail bar with R-thread may not be necessarily better than a smaller bar with a sharper continuous thread such that on a Titan bar.

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9. Evaluation of the limiting crack width at which grout ceases to provide an effective corrosion cover.
10. Determination of the stress in steel at which limiting crack width develops for a given pattern of thread and size of nail, grout strength and configuration of grout body. This would follow-up on the work done by Zilch and Müller (1997) and Schießl (1999) at the Technical University of Munich, as summarized in Appendix A.
11. Determination of whether or not an acceptable corrosion loss rate can be established based on electro-chemical characteristics of the ground.
12. Evaluation of the effect of corrosion loss on the shape and size of the thread and its implications on grout-steel interface bond.
13. Evaluation of the effectiveness of the fusion-bonded epoxy coatings for corrosion protection and development of specifications for coating thickness. Consideration should also be given to new products combining galvanization and epoxy.
14. Determination of the w/c ratio of the flushing and final grout as a function of soil gradation, soil type (e.g., cohesive versus cohesionless soils),
15. Evaluation of the use of higher test loads to compensate for the uncertainty in the unquantifiable resistance in the “permeation” grout in the unbonded zone.
16. Development of a method for protection of the unbonded length after the conclusion of proof tests.
17. Evaluation of the effectiveness of centralizers in terms of spacing, shape and size of centralizers for effective grout cover.

Comprehensive laboratory and field investigations are suggested to evaluate the above issues. Careful exhumation and examination of nails should be part of the field investigations to verify issues such as the extent of corrosion protection offered by epoxy coatings and the amount of protection of unbonded length after nail tests.

The goal of further studies should be the development of a unified model that incorporates different nail types and construction methods and provides limiting values for design, e.g., limiting steel stress values for a given thread type from a crack width viewpoint.

Finally, it would behoove the industry to think of the hollow-core soil nail technology as a specialized grouting technique whereby reinforcement is installed during grouting because the success of this technology is heavily dependent on the grouting procedures. Although the grouting processes are relatively straightforward it is important that qualified construction and inspection personnel are involved in the construction of the soil nail wall using hollow-core soil

CHAPTER 13 – SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

nail procedures. Thus, it is recommended that while the studies suggested above are being performed, FHWA should consider immediate development of a soil nail inspector qualification course similar to the FHWA courses for inspector qualification for drilled shafts, driven piles, MSE walls and subsurface investigations.

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APPENDIX A. CORROSION RELATED STUDIES

In the late 1990s, Ischebeck, manufacturer of the CTS-Titan bars in Germany, funded two studies (Zilch and Müller, 1997; Schießl, 1999) at the Technical University of Munich (TUM) in Munich, Germany, to evaluate the issue of corrosion of hollow-core soil nails. Both studies were performed on the IBO-Titan 30/11 (OD/ID) bar (Heinzemann, 2005). Data from the two studies suggest that if the crack width is less than 0.1 mm (~0.004-inch) then the grout is effective in providing corrosion protection. However, the conclusions regarding the limiting load or stress at which the grout body shows cracks greater than 0.1 mm (~0.004-inch) were different. Since details of these studies are lacking, the exact cause of the difference in limiting stress or load is not able to be determined at this time. The difference may have been due to various factors such as differences in the thickness, strength and/or shape of the grout cover between the two studies. These studies and their implications are briefly discussed below:

Study by Zilch and Müller (1997)

The study by Zilch and Müller (1997) involved unconfined tensile test on 30/11 Titan bars with grout bodies of various diameters on it as follows:

- Laboratory-cast uniform (cylindrical) grout bodies of 100 mm, 200 mm and 300 mm (~4-, 8- and 12-inches) in diameter.
- An irregular grout body from an exhumed nail that was installed using the procedure described in Chapter 2. The study noted that the grout body was asymmetric in relation to the 30/11 bar. For comparison purposes with the laboratory-cast cylindrical grout bodies, the study estimated the approximate equivalent diameter of the grout body to be 150 mm (~6-inches).

The study did not measure the grout strength but indicated that from experience the grout body could have a compressive strength of 50 MPa (~7,250 psi).

The study indicated that the grout crack widths exceeded 0.1 mm (~0.004-inch) at 125% of the design load (~ 87% of the Guaranteed Ultimate Tensile Strength or GUTS) for the 30/11 bar. Using the data published by Con-Tech (2005), we performed an evaluation of this criterion as follows:

GUTS, $F_U = 320 \text{ kN}$ (~72 kips)

Yield load, $F_Y = 260 \text{ kN}$ (~58.5 kips)

Thus, $F_Y = (260/320) (F_U) = 0.8125 F_U$ or $F_U \sim 1.231 F_Y$

The maximum test and design loads for the Titan 30/11 bar are listed as follows by Con-Tech:

Maximum test load, $MLT = 256 \text{ kN} (\sim 58 \text{ kips}) \sim 0.8 F_U \sim 0.985 F_Y$

Design Load for temporary applications, $DL_T = 224 \text{ kN} (\sim 50.4 \text{ kips}) = 0.7 F_U$

Design Load for permanent applications, $DL_P = 192 \text{ kN} (\sim 43.2 \text{ kips}) = 0.6 F_U$

Based on the above data, 125% of the design load to limit the crack width to 0.1 mm (~ 0.004 -inch) can be computed as follows:

1.25 times $DL_T = (1.25) (0.7) F_U = 0.875 F_U \sim 1.08 F_Y \sim 281 \text{ kN} (\sim 63.2 \text{ kips})$

1.25 times $DL_P = (1.25) (0.6) F_U = 0.75 F_U \sim 0.92 F_Y \sim 239 \text{ kN} (\sim 54 \text{ kips})$

It can be seen from the above analysis, that for permanent applications, the load in the 30/11 bar should be limited to less than the yield (nominal) load to limit the crack width to 0.1 mm (~ 0.004 -inch).

Study by Schießl (1999)

The study by Schießl (1999) involved unconfined tensile tests on 30/11 bars (Heinzemann, 2005) with a uniform (cylindrical) laboratory-cast grout cover of 19 mm ($\sim \frac{3}{4}$ -inch) using a grout of 25 MPa (3,625 psi) compressive strength. Thus, the grout body had an approximate diameter of 63 mm (~ 2.5 -inch) since the approximate OD of the 30/11 bar is 26 mm (~ 1 -inch). This study indicated that the grout crack width exceeded 0.1 mm (~ 0.004 -inch) at a limiting steel stress of approximately 275 MPa ($\sim 40 \text{ ksi}$) for thread on a Titan Bar. Published data by Con-Tech (2005) indicates that the cross-sectional area of a 30/11 bar is $446 \text{ mm}^2 (\sim 0.69 \text{ in}^2)$. Thus, for the 30/11 bar the limiting load to prevent cracks larger than 0.1 mm (~ 0.004 -inch) would be $275 \text{ MPa} \times 446 \text{ mm}^2 \sim 123 \text{ kN} (\sim 28 \text{ kips})$. This limiting load is approximately 50% of that indicated in the study by Zilch and Müller (1997).

Comments on the TUM Studies and Suggestions for Further Study

The apparent difference between the limiting loads from the two TUM studies is likely a result of differences in the thickness, shape and strength of the grout bodies surrounding the nails. Note that the diameters of the grout bodies in the 1997 study were much larger than that in the 1999 study. Therefore, one would expect that the tensile loads required to crack the thinner grout body would be less than those required to crack the thicker grout body, which is exactly what was observed. In any event, the important point to note is that both studies suggest that for a given configuration of grout body there would be a certain threshold tensile load in the nail that would cause cracks more than 0.1 mm (~ 0.004 -inch) in the grout body.

Since the two studies at TUM, many other hollow-core bar sizes with both R- and Titan- threads have been introduced into the marketplace. The limiting load for controlling the crack width to less than 0.1 mm (~ 0.004 -inch) depends on the thread configuration as well as steel grade and type. As can be seen from Figure 5, the configuration of the Titan thread varies with the size of the bar. The diameter of the grout body will vary based on the types of soil and size of the drill bit as discussed in Chapter 5. To our knowledge, a comprehensive study involving the

evaluation of crack widths for varying grout body diameters and for various grout strengths has not been performed. Therefore, it is appropriate that further bar-/thread-specific research should be conducted both in the laboratory and in the field (i.e. confined conditions) to evaluate the permissible crack width with respect to corrosion and the effect of perimeter stresses on the crack width.