Journal of Construction Education
Fall 1997, Vol. 2, No. 3, pp. 156-170

1522-8150/97/$3.00/General Manuscript

Excavation Support Systems for Construction Operations

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Excavation support systems are temporary structures that have a fundamental influence on the safety, quality, speed, and profitability of construction projects that require deep excavations. Despite their great importance, most contractors and members of the construction industry know very little about their design and construction. There is far less technical guidance available for the design of excavation support systems than for permanent structures, or even than for more common temporary structures such as framework. Designers and builders of excavation supports rely heavily on past experience as well as company-specific design and construction guidelines to perform their work. This leaves owners and general contractors somewhat in the dark when it comes to making decisions about excavation support systems. There is a need within the construction industry to clearly define the nature and scope of excavation support systems, and to identify what technical guidance is available for their design, erection, maintenance, and removal. Educating owners and contractors about the current state of practice regarding excavation support systems will improve their ability to work and make decisions with the specialists that they hire to design and install excavation supports. The goal of the research presented in this paper was to perform a literature review of published work in the United States and survey US design firms to identify the current state of the practice in the support of excavations and to identify any inadequacies in present knowledge. A brief review of the systems available for the support of excavations along with the results of the survey of US design firms is presented.

Key words: Temporary Structures, Support of Excavations, Soil Nailing, Survey, Guidelines

Introduction

Excavation supports structures include all means and methods of preventing a collapse of the earth walls that surround an open excavation. Excavation support is an issue of extreme importance to construction safety officials due to the serious threat to life posed by a potential earth cave-in. OSHA has mandated that any excavation or trenching operation that goes 5 or more feet below ground level must utilize an acceptable excavation support technique.

Usually the cheapest and simplest way to support an excavation is to slope back the sides of the excavation to the acceptable angle of repose. OSHA standards clearly indicate to what depths and at what angle of repose a contractor may perform an excavation. These requirements are dependent on the contractor identifying the soil properties of the area to be excavated, so that suitable angles of repose can be determined. As long as the excavation is not too deep, and adequate space exists on the site for the sloping to occur, contractors will generally opt to support excavations in this fashion.

The subject of excavation support becomes much more complicated when deep excavations take place and there is no room to slope back the soil to the required angle of repose. In this type of a situation earth retention systems must be designed which meet the specific requirements of the site and soil conditions. This occurs most frequently in urban settings where tall structures with deep foundations and basements are constructed on sites constrained by adjacent buildings. The issue of excavation support becomes further complicated when excavations may undermine the structural integrity of nearby foundations. The resulting need to underpin the foundations of adjacent buildings becomes the responsibility of the contractor in most cases. Underpinning can either be a separate activity, or can be combined as an integral component of the excavation support structure.

Although there is no universally accepted definition of shallow or deep excavations, this paper will make the distinction between the two at a depth of twenty feet. Twenty feet is generally the limit to which OSHA will allow an excavation to be sloped, or for the contractor to use a trench box. Excavations greater than twenty feet often require an engineered support system. Several design solutions exist for the problem of excavation support, and these solutions will be categorized and explained later in this paper.

Lack of Unified Design Philosophy

Excavation support is the category of temporary structures with the greatest need for technical guidance. An equal or possible greater amount of literature exists on subjects related to excavation support than any of the other temporary structures categories. However, this material is scattered, and the construction industry seems to lack a unified design philosophy for excavation support structures.

The reason for this lack of a unified design philosophy may be the tremendous variety of solutions that can be applied to an excavation support problem. The sheer number of variables makes it hard for a person to decide what approach to take. Codes and project specifications are also of little help.

Four building codes, The National Building Code, the Uniform Building Code, the Southern Standard Building Code, and the South Florida Building Code were reviewed as to their content on excavation support. None of the four offered any specific guidance for design. Nor did they reference the reader to other applicable technical guidance. They simply require the designer to provide safe access and support for excavations.

Excavation support system designers tend to rely most heavily on their past experience. They are also aided by civil engineering and geotechnical texts, manufacturer’s literature, and in the cases of large design-build firms, in-house data. There seems to be no consensus on what sources are needed for the design of excavation supports.

Conventional Systems for the Support of Excavations

Excavation support structures can be divided into three basic categories:

1. Cantilevered Systems
2. Braced Systems

3. Tied Back Systems

Each category has certain advantages and disadvantages, depending on the depth and soil type of the excavation. Builders and designers should be familiar with the variety of systems that are available, so that the best support structure will be utilized every time a deep excavation takes place. Generally, cantilevered applications are used for shallower applications, but in special instances can cover up to fifteen meter (fifty feet) in depth. Braced and tied back systems are used for greater depths where a cantilevered or embedded wall alone is not enough to overcome lateral earth and water pressures (Schroeder, 1984). It is very common for individual support systems to combine characteristics of all three general types. For example, a cantilevered diaphragm wall could be tied back or braced for additional support.

Braced Sheeting

Braced sheeting includes skeleton and continuous sheeting. Skeleton sheeting is a timber application, while continuous sheeting is almost always of steel.

Skeleton Sheeting

Skeleton sheeting can only be done in somewhat cohesive soil and above the water table. The structure resembles the layout of wall forms for cast-in-place concrete. Wooden uprights are spaced vertically along the wall of the excavation and are held in place by horizontal walls backed by braces or struts. Skeleton Sheeting has very limited load-bearing capacity and lacks a standard, defined procedure (Koerner, 1984). Its applications are limited to relatively shallow cuts.

Steel Sheet Piling

Steel sheet piling consists of continuously driven, interlocking steel sections that form an earth retaining wall. These structures can be made watertight, and are therefore very common in marine applications. Steel sheet piling requires an expensive initial investment and very costly pile driving equipment (Illingworth, 1987). Due to its cost and unique requirements, steel sheet piling is one of the most specialized areas of construction. Design specifications and guidelines are generated from within the sheet piling industry. Companies such as Pile Buck, based in Jupiter, Florida, have produced state of the art manuals that describe the various uses, design, and installation of sheet pile walls. The ability of steel to take on different shapes and thicknesses, and to behave at different levels of flexibility, causes steel sheet pile design to be unique from any other type of excavation support structure. Sheet pile walls can be cantilevered, anchored with tie backs, strutted, or a combination of any of these. Cantilevered walls are typically restricted in height to about 4.5 meter (14 feet). This is due to the deflection experienced by the top portion of the wall and the large embedment lengths required to overcome active earth pressure. Anchored sheet pile walls utilize both the passive pressure of the embedded portion and of tie rods near the top of the structure. They are recommended to heights of about 10.5 meter (35 feet). Braced walls are used for the deepest applications. In this method, struts are utilized to handle lateral loads from two opposing sides of an excavation (Pile Buck, 1987).

Soldier Piles and Lagging

The soldier pile and lagging method is one of the oldest and most widely used methods of excavation support in the construction industry. The systems are basically configured of steel H-sections or I-sections that are placed in the ground before excavation ever begins. As the excavation proceeds downward, the exposed earth walls between the piles are sheeted with boards or other suitable materials. The allowable excavation which can take place before the operation must be stopped and sheeted depends on the soil type. In sandy soils the sheeting must be nearly continuous (Illingworth, 1987).

Slurry Walls

Slurry walls are continuous concrete walls that are built beneath ground level before an excavation takes place. They are typically cantilevered systems, although it is possible for them to be braced or tied back as well. The guiding principle behind the construction of slurry walls is that bentonite slurry or driller’s mud immediately replaces the soil that is dug out for wall sections, ensuring that the trench will not collapse before it can be filled with concrete. Concrete is pumped through a tremie starting at the bottom of the wall, and displaces the bentonite slurry as it reaches the top. Sometimes structural requirements call for the placement of reinforcing steel before the wall is poured. The end result of this process is a continuous concrete earth retaining structure that is embedded deep enough below the proposed level of excavation (and/or braced) to resist all resultant lateral pressures. The slurry wall supports the sides of the excavation and often is abandoned in place, or integrated into the permanent structure.

Slurry walls are the most versatile means of excavation support, because they can be used in any soil and to virtually any depth, limited only by machine capabilities (Hajnal, 1984). They serve a variety of functions, potentially providing sheeting, waterproofing, and load bearing all in one structure. Slurry walls can also be constructed in a great many shapes and in varying site conditions. For instance, slurry walls can go in diagonal or curved patterns, and can be built right along side an existing structure. Another benefit of slurry walls is that they do not clutter the site with braces and supports that get in the way of construction.

Despite their versatility and functionality, slurry walls are expensive and complicated structures to build. There are difficulties in containing the bentonite slurry, which has a soupy consistency, and keeping the site neat and pollution-free. The slurry also prevents direct inspections of the walls before they are poured. The construction process requires very costly excavating and pumping equipment, and the wall components cannot be reused, as is the case with some other systems. Slurry walls, also called diaphragm walls, are the most economical solution only when dewatering is involved or when no other solution is feasible (Hajnal, 1984).

Continuous Piling

Continuous piling is an example of a foundation technique that has been adapted for excavation support. Like slurry walls, continuous pile walls are often integrated into a project's permanent structure. The idea behind continuous poling is that standard bored piles can be placed close enough together that they will form a solid wall. The piles are machine augured and poured with concrete before excavation begins. In some cases the secant piling method is used. This is where adjacent piles actually cut into each other to form a watertight wall (Illingworth, 1987).

Underpinning and Dewatering

Underpinning and dewatering are two additional considerations, which often affect the excavation support design process. Underpinning becomes an issue when an excavation occurs near an adjacent structure. Common in urban settings, underpinning involves the stabilization of nearby foundations to prevent any damage resulting from new construction. Some of the methods of excavation support previously discussed perform underpinning functions as well as earth retention. These methods include slurry walls and continuously piling.

Dewatering becomes an issue any time an excavation will proceed below the ground water table. Two basic solutions are available for ground water control. The first is to select a watertight support method such as continuous steel sheet piles or slurry walls. The second option is to temporarily or permanently alter the level of the water table. A common way of accomplishing this is through the use of a well point system. Well points are a series of wells and pumps placed around the perimeter of an excavation that draw water away from the work.

Survey of United States Design Firms

Construction is a profession that is grounded deeply in practical applications rather than theories and books. In order to truly understand the current practice in the design of excavation support structures, it was necessary to go beyond published literature and obtain input from the working professional world. The first challenging step in this process was to identify which design firms around the country are specialized in the design of excavation support systems. After identifying the sample group, a survey was written and piloted. The goal of the survey was to determine the current state of practice in design of excavation support systems in construction, and to identify what research and development should be carried out.

Locating the Survey Sample

The design of excavation support systems remains one of the most specialized areas in the engineering and construction fields. It requires a complete understanding of soils, geotechnical forces, and unique structural requirements. In addition, excavation support almost always involves a certain amount of risk based on the unknown, because subsurface conditions are difficult to predict with complete accuracy. For these reasons and others, very few companies around the country deal with the design of deep excavation supports. Since no comprehensive list of excavation support specialists exists, locating these companies was a matter of trial and error at first.

The process began by making telephone contact with individuals found on the American Society of Civil Engineers' (ASCE) listing of structural engineers. Most of the ASCE members were not themselves designers of excavation supports, but provided excellent references to firms who were. Each firm contacted was usually able to provide other references. Through this process of telephone networking, a national listing of over 30 specialty firms and designers was compiled.

Developing the Survey

There were three main objectives of the survey developed for this project:

1. Determine current practices in the design of deep excavation supports;
2. Identify which sources of technical guidance are being used, and determine if the amount of available guidance is adequate; and,
3. Determine what research needs to be carried out in the area of excavation support design and/or construction.

A seven-item questionnaire was written along with a short cover letter explaining the nature of the research project and the goals of the survey. Before being sent out to the list of designers, the survey was piloted and reviewed based on the following criteria: clarity, focus, time, and codability. The final copy of the survey contained brief instructions and clearly stated its purpose. It was designed to be completed in 5 to 10 minutes, and to provide easily interpretable data.

Analyzing the Results

The overall conclusion that can be drawn from the results of the survey is that very few people in the United States are routinely designing excavation support systems; but hose who do, feel that there is generally enough technical guidance to meet their design needs (see Figure 1). It was also the consensus opinion of those surveyed that an engineer's pervious experience is the most important resource that he or she has for the design job (see Figure 2). The largest firms surveyed, such as Hayward Baker and Haley and Aldridge, indicated that they actually produced and used in-house design standards and criteria. The survey indicated that the designers of conventional support systems, such as slurry walls, soldier piles and lagging, or sheet piles with tiebacks, are not in need of improved technical guidance. Adequate materials already exist to meet their needs.

Question three of the survey asked designers to rank the factors that determine which type of excavation support system they will choose in any given situation. The responses to this question clearly indicated that safety is the most critical issue. Cost and technical feasibility were the next most important considerations. The results of this item are shown graphically in Figure 3. Respondents listed what they thought were the most pertinent research topics to their field. The 20 suggested topics are listed in Figure 4. Each of these topics were reviewed by the research staff to determine its feasibility for further pursuit. It was decided that all topics that required in-situ testing or expensive laboratory equipment would be eliminated. Other suggested topics were eliminated based on a lack of continuity with the original research goals. The topics that remained after this elimination process were numbers 2, 3, 7, and 14.

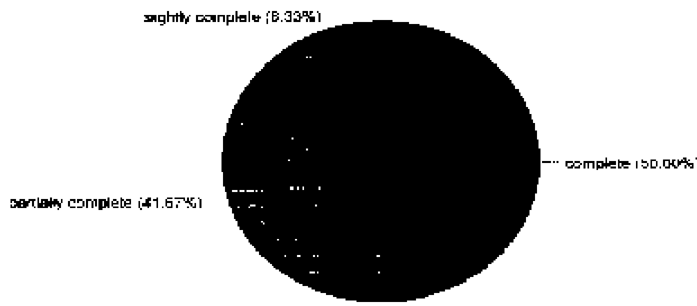

Figure 1. To what extent does the amount of technical guidance currently available to designers meet their needs?

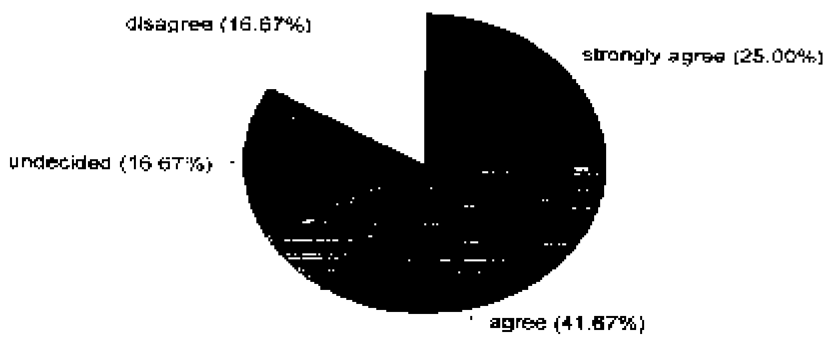

Figure 2. Is previous experience the most important factor or resource available to the designers of excavation support systems?

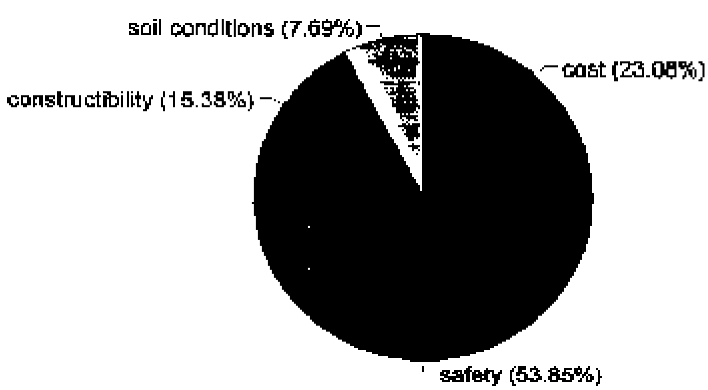

Figure 3. What are the most important factors in selecting an appropriate excavation support system for a particular project?

1. Underpinning methods combined with excavation support.
2. Combining excavation support with ground water control.
3. Designing more rigid support systems (such as soilcrete or grouting) as compared to more flexible systems such as soldier piles or sheet piles.
4. Load distribution data trough walls and support members.
5. Performance data vs. design estimates.
6. Behavior of system below excavation level (deformation of toe of system).
7. Integral discussion of costs vs. risks between members of design and construction team.
8. What are acceptable factors of safety?
9. LRFD design methods.
10. What are acceptable levels of overstress?
11. Areas of overconservation supported by case histories
12. Should designs include seismic loads?
13. Quality (adequacy) of site soil explorations.
14. Practicality and safety of alternate shoring techniques (soil nailing, soil freezing,…).
15. Distribution of loads to anchors for multi-level anchor walls.
16. Accounting for arching behind soldier piles in pressure load determination.
17. Problems with contractor designed (non-professional engineer) systems.
18. In-situ field testing to determine design vs. actual fidel response of support systems.
19. Obtaining good horizontal subgrade information to better model realistic movement.
20. Developing a "cook book" approach for design.

Figure 4. Suggested research topics

Following-up the Survey

Each of the designers who's suggested topics were chosen for further review were interviewed by telephone. The engineers explained the intent of their suggestions in greater detail to aid the research team in selecting one out of the four possible topics. The details of these discussions are outlined in the following section.

Topics 2 and 3

An engineer from Hayward Baker suggested focusing on two ideas. The first was issue of combining excavation support with ground water control. This becomes a key issue when the owner of a project, a municipality for example, does not want to allow dewatering to take place. Possible reasons for this would be the fear of unacceptable settlement around existing buildings or environmental concerns such as ground water withdrawal and recharge. The engineer stated that a technical guide which advises designers on the specific approaches which should be taken when excavation supports are required to control ground water would be very helpful to the industry.

The second topic which was discussed with the Hayward Baker engineer was researching the use of rigid support systems as opposed to more conventional flexible ones. This becomes an issue primarily when excavation supports must also perform as underpinning structures. Flexible systems such as steel sheet piling or soldier piles and lagging are not capable of supporting overhead structures. Conventional rigid systems that have underpinning capabilities include slurry walls and bored pile walls. It was suggested that the underpinning value of less conventional rigid systems, such as soilcreting and grouting be researched.

Topic 7

A designer from Haley and Aldridge suggested an integral discussion of costs versus risks between all members of the design and construction team. This designer feels that the tremendously high cost involved with the support of deep excavation is causing the industry to move toward more risk-based solutions. What this means is that owners are having to decide how much risk they are willing to accept in order to control the costs of a given support system. This has a lot to do with defining the parameters of system failure, and determining what type of specifications to place on a system.

An example of cost/risk issues that owners, designers, and contractors might face would be specifying the allowable movement of the toe of an embedded support wall. Cantilevered systems resist active earth pressures through the passive pressures generated in their embedded portions. Designers are aware that the toe of a cantilevered system almost always experiences some movement. The safest and most expensive option for the owner would be to specify minimal or no movement in the toe of the system. This is also the best case for the designer who must assume liability for his or her design. However, such a specification might be prohibitively expensive. The goal of the research topic suggested by the Haley and Aldridge engineer would be to discuss what trade-offs between cost and risk would be acceptable. This type of a project would have to include case studies where the cost vs. risk issue actually came into play.

Topic 14

The topic suggested by an engineer from Ed Waters and Sons was the one that was eventually selected for the further research on this project. His suggestion was to conduct a comprehensive review of the available guidance, practicality, and safety of alternate shoring techniques. These techniques include soil freezing, soil nailing, grouting, and geosynthetics. The engineer explained that while these techniques may theoretically be cheaper or better options than conventional systems, they must be carefully studied before being used. A soil freezing systems used on the King’s Bay project in Jacksonville, Florida, for example, failed badly due to poor planning and design. Soil nailing was chosen out of all of the possible alternate shoring techniques that could have been studied. There were three main reasons for this decision:
Soil nailing has been used for many years in Europe and is becoming increasingly better known and accepted in the United States.

Soil nailing, more so than the other techniques, is generally used only as a temporary support.
No standard design, construction, or inspection guidelines currently exist in the United States for soil nailing.

New Systems for the Support of Excavations

The introduction of ground anchors and tied-back walls in the 1950's and 1960's served as a catalyst to the development of innovative new systems for the support of excavations. Element walls were introduced that utilized precast or CIP concrete units with tie backs, allowing wall construction to take place simultaneously with excavation. Next, gravity walls were developed that introduced the concept of using reinforced soil or earth as a structural element. The continuation of this process led to the development of soil nailing which employs the soil mass as its main structural element. The advantage of soil nailing over gravity walls is that soil nailing is top-down procedure as opposed to bottom-up process (Stoker and Riedinger, 1990).

The two most notable trends in the industry over the past twenty years are:

1. the increasing use of reinforcing elements to create reinforced soil; and
2. the increasing use of polymeric products to reinforce and control drainage in soils (O'Rourke and Jones, 1990).

Soil Nailing

Soil nailing, like the other systems described in this paper, is a method of supporting the walls of an excavation. The primary difference between soil nailing and these other conventional systems is that soil nailing stabilizes the sides of an excavation through in-situ reinforcement of the soil (Chapman, 1990). For this reason, it is classified as an internally supported system. Systems such as soldier piles and lagging or slurry walls must overcome earth pressures with external structural walls, while soil nailing stabilizes a soil mass by placing reinforcements in and through the potential failure mass of the soil (O'Rourke and Jones, 1990). Soil nailing actually increases the overall shear strength of the soil, restrains its displacements, and limits its decompression (Juran, 1987). This is accomplished through the use of tension elements that are driven or drilled and grouted into the ground. The reinforced ground becomes the system's primary structural element, with a layer of shotcrete applied to support the face of the soil nailed wall.

Since soil nailing is rapidly gaining acceptance in the United States, it is important that engineers and contractors understand how these systems are used and what technical guidance is available for the design and construction of these systems.

A Brief History

Since 1970 the field of excavation support technology has experienced a major increase in the use of reinforcing elements and internally stabilized systems. Soil nailing is generally thought to have evolved from the processes of rock bolting and the New Austrian Tunneling Method. It has become prevalent in France and Germany and is rapidly gaining popularity in the United States. The first recorded use of soil nailing was for the stabilization for a railway cut in France in 1972. The method arrived in the US in 1976, when it was used for the temporary support of a hospital basement cut in Portland, Oregon. By the 1990's soil nailing accounted for 5 to 10 percent of all of the in-situ excavation support construction in the US (O'Rourke and Jones, 1990).

The Function of Soil Nailed Walls

Soil nailing has three major functions within the construction industry. Soil nailed walls have been primarily used to support excavations for both general building construction and highway and heavy construction. The method is thought to be most applicable in cases where tied back walls have been deemed an appropriate means of support. Walls have been constructed to depths of 30 meters (100 ft.). Soil nailing can also be used in the repair and reconstruction of existing structures. Additionally, soil nailing is used for slope stabilization. This final function includes the stabilization of creeping slopes and unstable slopes (Elias and Juran, 1991).

Why Use Soil Nailed Walls?

Soil nailing provides the construction industry with an economical option for the construction of in-situ walls for excavation support. In addition to cost savings of up to 30 percent over more conventional systems, soil nailing offers several advantages including adaptability and technical benefits. Some of the technical advantages of soil nailing compared to conventional systems are listed below:

- requires only light equipment;
- the number of individual nails is so great that failure of one or two is not critical;
- nail diameters are small which makes drilling into rocky soil much easier;
- the system is relatively flexible and can withstand some ground movement; allows for the control of surface deflections (Elias and Juran, 1991).

The Components

As stated previously, the reinforced earth mass is the primary structural element of a soil nailed wall. The soil is reinforced by passive inclusions, or nails, which resist tensile stresses, shear stresses, and bending moments. Nails are generally steel rods or bars of 343 MPa (50 ksi) yield strength, 15 to 46 millimeter (0.6 to 1.8 inches) in diameter. A continuous shotcrete facing is applied to the outside face of the reinforced soil mass to stabilize the ground between the layers of nails. Each nail is attached to the facing by embedded steel plates, cladding, or other methods.

The Construction Process

The basic construction sequence for soil nailed wall is illustrated in Figure 5. It is a top-down process that involves excavation to a specified depth, installation of nails, application of facing, and further excavation. Of course, the presence of groundwater and use of complicated techniques add many more involved steps to this process. The depth of cut which is permissible before the installation of nails and facing depends on the properties of the soil mass. In some cohesive and rocky soils, cuts of approximately three meters (10 feet) can be made preceding in-situ wall construction. Less stable soils such as sand can only be excavated to a depth of about 1.5 meters (5 feet) before the process must be stopped and the soil nailing performed. Very unstable soils may require the placement of shotcrete before the nails are installed. Each section or layer which is excavated and nailed becomes linked to the surrounding sections, and the entire soil mass becomes an interconnected, stable system.

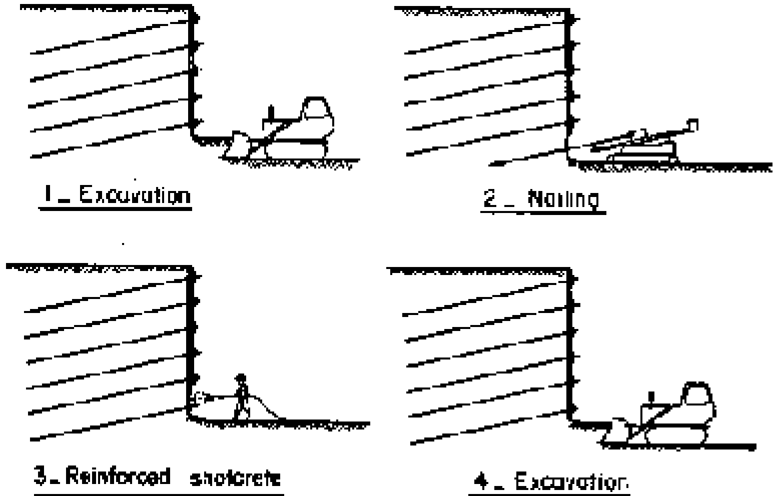

Figure 5. Basic soil nailing process.

Design Methods and Available Standards/Guidelines

One of the difficulties for owners who wish to specify the use of soil nailing is their projects is the lack of universally agreed upon or accepted design process. The three most extensive users of soil nailing, the United States, France, and Germany, each have their own preferred methods. The Germans primarily use a limit analysis method developed by Glassler, et. al. The French use the TALREN or multi-criterion method developed by Schlosser. In the United States the predominant design procedure is the Davis method (Elias and Juran, 1991).

There are several app[roaches to designing soil nailed retaining structures. Each method has been successful at achieving the chief design concern of soil nailing: to ensure that the soil-nail interaction is effectively mobilized to restrain ground displacements and ensure structural stability within an appropriate factor of safety (Elias and Juran, 1991). The industry has not, however, reached a consensus conclusion over the issue of which method is the safest and most effective for given design situations. Furthermore, no general design or construction guidelines currently exist within the United States.

The Federal Highway Administration published a report in 1991 that recommended a design practice that combines several different methods. In addition to recommending design procedures, the report also includes an appendix of construction guide specifications for permanent soil nailed structures. While this report represents the most comprehensive work on soil nailing to date in the United States, it does not qualify as an official adopted design or construction guideline. Clearly, the next step which must be taken in the field of soil nailing is the development of such a standard or guideline.

A recent interview with an engineer from Schanbel Foundations revealed that the Federal Highway Administration (FHWA), in conjunction with the American Association of State

Highway Transportation Officials (AASHTO), has undertaken the project of developing comprehensive design, construction, and inspection guidelines for nailing. In addition, the FHWA project will be developing an educational curriculum to train employees of the agency on the various techniques involved with soil nailing. According to the interviewee, the project is one of the most complete and well-executed undertakings of its kind.

As of the writing of this paper, there is no scheduled date for adoption or publication of the design, construction and inspection manuals. However, the project is well underway and sources working closely with the FHWA claim that the manuals that are being prepared will meet all needs for technical guidance for the design and construction of soil nailed retaining structures.

Soil Grouting

Soil grouting, like soil nailing is quickly gaining acceptance in the United States and is experiencing a rapid increase in use for the support of excavations. There are several varieties of soil grouting, all dealing with the additions of high strength grout to stabilize soil masses. The major classifications of soil grouting include cement grouting, compaction grouting, chemical grouting, and jet routings. Jet grouting is the technique most commonly used in the support of excavation. The other methods are more commonly used for underpinning or foundation improvement.

Soil Freezing

Soil freezing is an innovative technique which utilizes refrigeration pipes to effectively freeze the soil into one solid, stable mass. In cold climates and in situations where only short term excavation support is required, soil freezing is a viable option. Two other important benefits of soil freezing are its ability to halt the flow of ground water and cut off the movement of toxic waste through soil.

Conclusions and Recommendations for Further Research

The investigation performed for this research project showed that adequate technical guidance exists, or being currently developed, for the design of excavation support systems. While approved standards do not exist for the design of excavation supports, specialty engineers feel that they have the resources they need to produce safe designs. Design, construction, and inspection guidelines for soil nailing are currently being developed by the Federal Highway Administration (FHWA). These guidelines will meet the need that currently exists within the industry for improved standards and guidelines for soil nailing.

One of the important conclusions of this project is that the design of excavation support systems is a very specialized field and needs to be performed by an experienced engineer. Most of the large companies working in this field handle the work on a design-build basis, and often use their own in-house design criteria. Any owner or contractor who is considering the construction of a deep excavation support structure needs the service of a geotechnical engineer and specialty contractor, because "design-it-yourself" guidelines do not exist, like they do for other temporary structures such as formwork.

One topic that is becoming increasingly relevant is the questions of whether owners should provide prescriptive or performance specifications. With the upcoming publication of FHWA's design manual for soil nailing, it will be possible for state and federal agencies to provide the design specifications of a soil nailed wall in a construction project's bid documents. The other option open to owner is to leave the responsibility for designing the excavation support system to the contractor, and provide only performance specifications. In this latter case, the soil nailing design manual would simply become a resource or option, not a required guidelines.

There are several advantages and disadvantages to owner-provided design specifications. The trade-off between cost and safety, if any exists, is the key issue in this debate.

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