



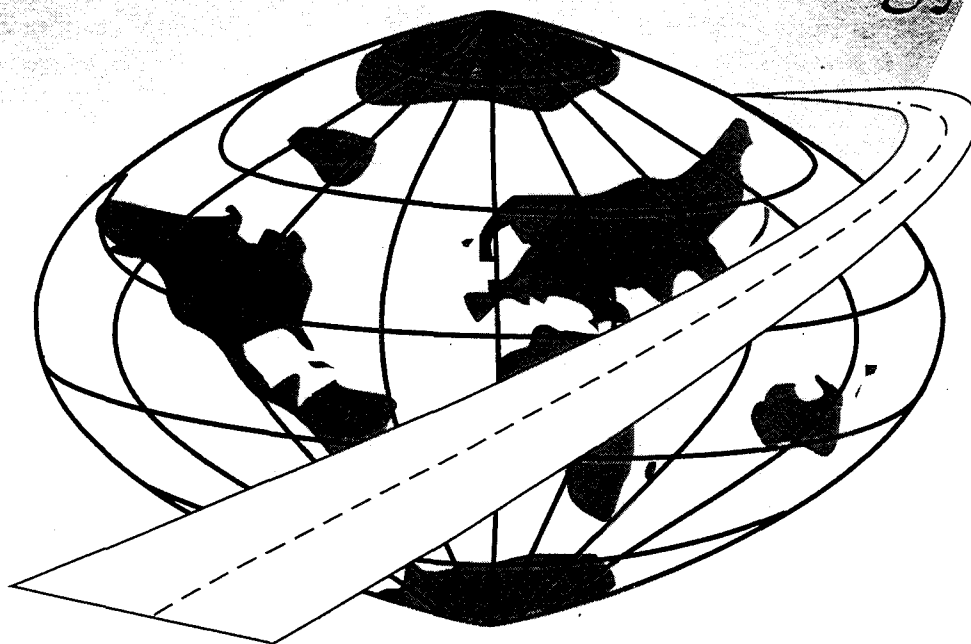
U.S. Department of Transportation
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FHWA Tour for Geotechnology-Soil Nailing

International Technology



FHWA's Scanning Program

June 1993
Revised

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FHWA INTERNATIONAL SCANNING TOUR FOR GEOTECHNOLOGY
SEPTEMBER - OCTOBER 1992

SOIL NAILING SUMMARY REPORT

May 28, 1993

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SOIL NAILING SUMMARY REPORT

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EXECUTIVE SUMMARY

The scanning tour of soil nailing technology described in this report was very informative and productive. Although some of the team members were familiar with much of the technology prior to this trip, there was sufficient new information presented to be of significant value to our current and future efforts. All team members benefited from face-to-face discussions with the leading European researchers and practitioners and from the in-depth review of available European soil nailing information. The new associations developed with some of the top geotechnical specialists in each country will prove very valuable in the future.

The Europeans have established themselves as leaders in the field of soil nailing technology and practice. The on-going and completed research projects have made a major contribution to our understanding of the mechanics of soil nailing behavior. Although we have constructed soil nail walls within North America which are equal in size to some of the largest walls constructed in Europe, the overall scope of soil nailing activity in Europe is considerably larger than in North America. In addition, the Europeans have significant experience with some soil nailing construction techniques which have not been employed in North America. From a technological and a construction practices view, therefore, there is much valuable information to be obtained from the European experience.

During the three week tour of three countries and discussions with representatives at 21 consulting, contracting, teaching, research and public sector organizations, the scanning team focussed on a number of different aspects of soil nailing - design, construction and contracting practices, and research and development activities. The results of our team scanning effort are summarized below.

Design

To date, there has been some considerable diversity among the details of the various design approaches within Europe, with these variations present both within and across national boundaries. A significant factor is the postulated mechanism by which nails are considered to reinforce a soil mass. For nails installed near parallel to the direction of maximum soil tensile strain (e.g., near horizontal nails and a near vertical excavation face), the prevailing opinion is that the reinforcing action is predominantly related to tensile loading within the nails. Under service load conditions, the contribution of shear/bending is considered negligible. As failure conditions are approached, the contribution of shear/bending action is more significant but still small. This has been confirmed by monitoring of test and in-service structures. From a practical point of view, it is however recognized that the soil nails should exhibit ductile behavior under bending in order to minimize the potential for sudden, brittle-type failures.

Where reinforcing elements are used as "dowels" and are oriented near perpendicular to the direction of maximum shear strain (such as when used to stabilize active landslides), the shearing, bending and tensile action of the reinforcement should be considered.

All current European design methods are based on limiting equilibrium or ultimate limit state concepts. Various types of potential failure surfaces are considered, including circular, log spiral, and bi-linear wedge. In general, each of the methods appears to provide a satisfactory representation for design purposes. Consistent with the above, the majority of the European design computer codes consider only the tensile action of the nails, but a minority also permit the consideration of the shear/bending action of the nails.

Almost all of the European design methods do not explicitly consider the potential for pullout of the reinforcing nails within the active block between the facing and the slip surface. It is implicitly assumed that the nail-soil adhesion within this zone, together with the structural capacity of the facing, will be sufficient to prevent this type of failure. Some design approaches offer strict guidelines for the required structural wall capacity in order to prevent such "active zone" failures, but others appear to rely on experience and do not directly address this issue.

A significant range of load/resistance/safety factors have been applied by individual European designers, in considering both ultimate and serviceability limit state design of soil nailed walls. It appears that the proposed new Eurocode 7 requirements will impose a uniform load and resistance factor design approach for Europe and that these requirements will be similar to the recent recommendations from the Clouterre program.

Based on the overall reinforcing requirements determined from the limiting equilibrium design calculations, the nail steel is empirically proportioned. In general, designers use nails of uniform length and cross-sectional area, on a uniform spacing. For drilled and grouted nails, the nail spacing is typically in the 1 to 2 m (3.3 to 6.6 feet) range. For driven nails, much higher nail densities (typically 1.5 to 2 nails per square meter) (0.14 to 0.19 nails per square foot) are used. The nail lengths are typically in the range of 60 to 80 percent of the height of the wall, but may be shorter in very competent rock-like materials and longer for heavy surface surcharge or high seismic or other operational loading.

Facing design requirements are empirically determined using a variety of techniques. German practice requires the use of a uniform facing pressure equivalent to 75 to 85 percent of the active Coulomb loading. The Clouterre recommendations require designing the facing and connectors to support between 60 and 100 percent of the maximum nail loading (for both ultimate and serviceability limit states), depending on the nail spacing. Other techniques which have been used include designing the facing for an equivalent active load corresponding to a soil depth of one to two nail vertical spacings, and specifying standard design wall sections for both temporary and permanent walls. Where the soils exhibit sufficient cohesion and heavily battered slopes are used, significant height nailed slopes have been built without any structural facing, using geosynthetics and vegetation to provide for erosion control of the slope face.

Corrosion protection of nails is an issue of significant concern to European designers. German practice is the most conservative, requiring double corrosion protection (cement grout with a corrugated plastic sheath) in all permanent wall applications. French and English practice permits the provision of a sacrificial steel thickness for other than highly

corrosive ground conditions, with the sacrificial thickness increasing with ground corrosiveness and structure service life.

Construction

Soil nailing is very widely used in Europe, particularly in France and Germany, employing a somewhat broader range of construction techniques than those usually used in the United States. The construction sequence is typically excavate, nail and shotcrete the face. Where face stability is a concern, a flashcoat of shotcrete may be applied before nail installation. The most common method of nail installation in Europe, as in the United States, is the drill and grout method. Most commonly, the steel tendon is installed prior to grouting, although this sequence is sometimes reversed. In France, however, very significant use is also made of driven nails (proprietary) without grouting. Other proprietary specialty techniques for installing nails include jet grout nailing (France), driven nails with an oversize head and subsequent grouting of the annulus (Germany), and compressed air explosive injection of nails (United Kingdom).

Small hydraulic, track-mounted drill rigs of the rotary/percussive type are most commonly used to install nails. These rigs can work in relatively confined surroundings and are therefore compatible with many of the constraints associated with crowded urban environments. Open hole drilling methods are predominant, with cased hole methods used in particularly difficult ground conditions. The most common grouting method used with open hole drilling is the low pressure tremie method with neat cement grout. Where extensive use of casing is required, alternative methods of retaining wall construction are often more cost competitive.

Steel tendons typically used for drill-and-grout soil nails usually consist of 20 to 50 mm (0.8 to 2.0 inch) bars with a yield strength in the range of 420 to 500 N/mm² (60 to 72 Ksi). These steels exhibit ductile behavior under bending action. The driven nails used commonly in France are typically steel angle which shows better ability to deal with subsurface obstructions such as cobbles and small boulders than do circular steel sections.

Drainage is a critical aspect of soil nail wall construction. Face drainage is virtually always used with permanent walls, and very commonly used with temporary walls. Face drainage usually consists of synthetic drainage elements placed between the shotcrete and the retained soil, and may be typically 20-30 cm (8 to 12 inch) wide synthetic strips or perforated pipes. Depending on the site groundwater conditions, face drainage may be supplemented with weep holes through the facing and longer horizontal perforated drain pipes. Control of surface water is also an important element of the drainage system.

Temporary soil nail wall facings generally consist of shotcrete (8 to 10 cm (3 to 4 inches) thick) and a single layer of wire mesh. Permanent shotcrete walls (15 to 25 cm (6 to 10 inch) thick) are very common in Germany and these walls typically incorporate a second layer of wire mesh. For architectural reasons, permanent walls of precast panels and cast-in-place concrete are also used in France and Germany.

Testing and monitoring during construction is an important aspect of soil nail wall construction in Europe. Nail bond testing is almost universally performed, to confirm the assumptions made during design or to enable re-design in the event that the design assumptions cannot be realized. For relatively homogeneous sites, typically 3 to 5 percent of the nails will be tested, depending on the size of the job. Testing is also undertaken whenever changed geologic or construction conditions occur. Wall performance monitoring usually consists of measuring horizontal wall movements during construction. Some contractors make more use of inclinometers for displacement monitoring. Maximum horizontal displacements are typically in the range of 0.1 to 0.3 percent of the height of the wall, depending on ground conditions. Strain gaging of nails, together with the use of load cells at the nail head, are usually reserved for experimental walls.

The level of quality assurance/control monitoring varies significantly. In Germany, for example, the QA/QC inspector might be on the job from 10 percent to full time.

Overall, soil nail wall performance in Europe has been very good. Problems during construction have typically been associated with encountering loose fill, granular soil with no apparent cohesion, water, and man-made obstructions such as utility trenches. Other problems have been associated with the contractor failing to construct the wall in accordance with the plans and specifications (e.g., eliminating nails, overexcavation of lifts). In a couple of instances, frost action on the fully bonded nails has also resulted in the development of very large loads near the head of the nail, where no insulating protection has been incorporated into the wall design.

Contracting Practices

Although procurement and contracting practices vary among the European countries, there are some common elements which tend to distinguish European practices from those in the United States. These include (a) strong industry/academic/government cooperation in research and development to assist the introduction of new technologies, (b) a Partnering approach among all parties involved in a particular project, (c) less litigation and (d) a high level of contractor involvement in the planning and design phases, as well as during construction.

In France, the contractor design-build approach appears to be dominant. For public agency work, a prequalified group of contractors are typically asked to prepare a final design and bid, based on a preliminary design prepared by the Owner or his consultant. Alternative designs may also be prepared by the contractor at this time, and may be selected if they are technically and financially viable and meet the overall performance and scheduling requirements of the project. French contractors tend to be much larger and stronger than their United States counterparts, and the major groups tend to support significant research and development efforts. The contractor/consultant/academic/government cooperation in areas requiring major research and development is particularly well developed in France.

1. INTRODUCTION

Soil Nailing is a construction technique for reinforcing existing ground. This is accomplished by installing closely spaced, passive, structural inclusions, known as nails, into the soils to increase their overall shear strength. The term "passive" means that the nails are not pre-tensioned when they are installed, as with tiebacks. The nails develop tension as the ground deforms laterally in response to continued excavation. Nails may be used to stabilize either existing slopes or future slopes/cuts created by excavation activities at a site. A structural facing connected to the nails is used when the slope angle exceeds some critical value or when the environmental conditions would cause deterioration of the exposed face over its design life.

To date, soil nailing has been used principally for temporary support of excavations at building sites or for slope stabilization along transportation corridors. At building sites, vertical walls are quite common. Permanent applications have been fewer in number, but offer the potential for significant savings over conventional earth retaining wall systems when designed and constructed in appropriate ground conditions. The cost savings are obtained primarily from the expediency of construction and the structural benefits of distributing the face loads over a large number of nails. The elements of the system are presently sized using accepted design techniques which are typically considered to be conservative.

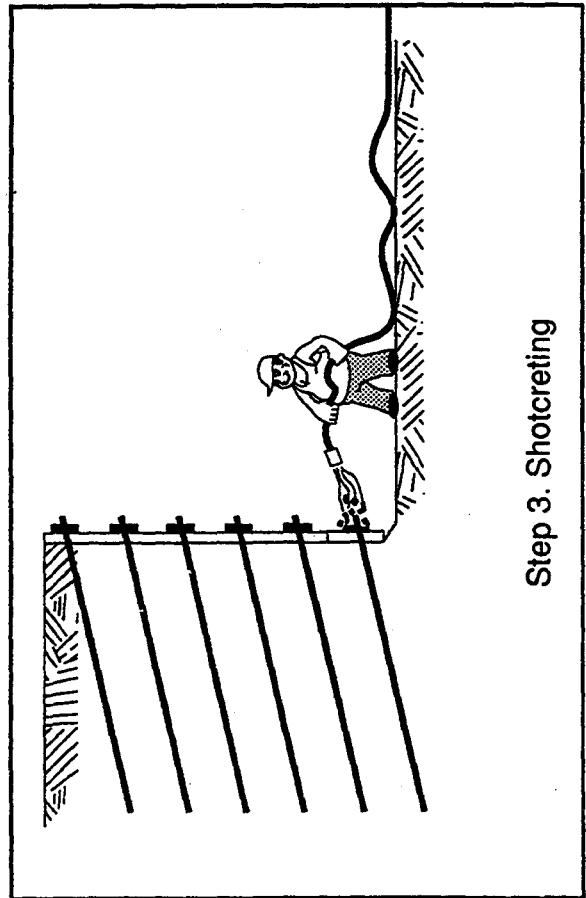
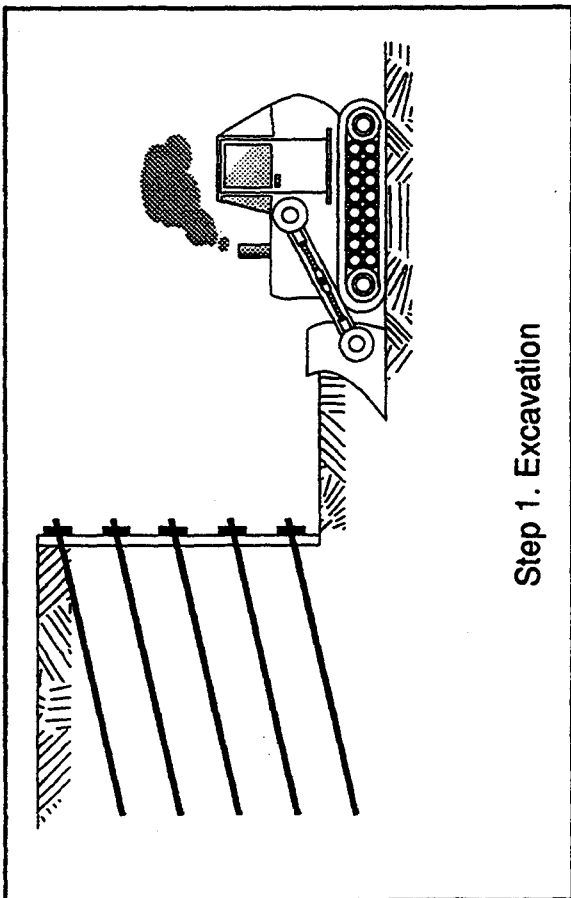
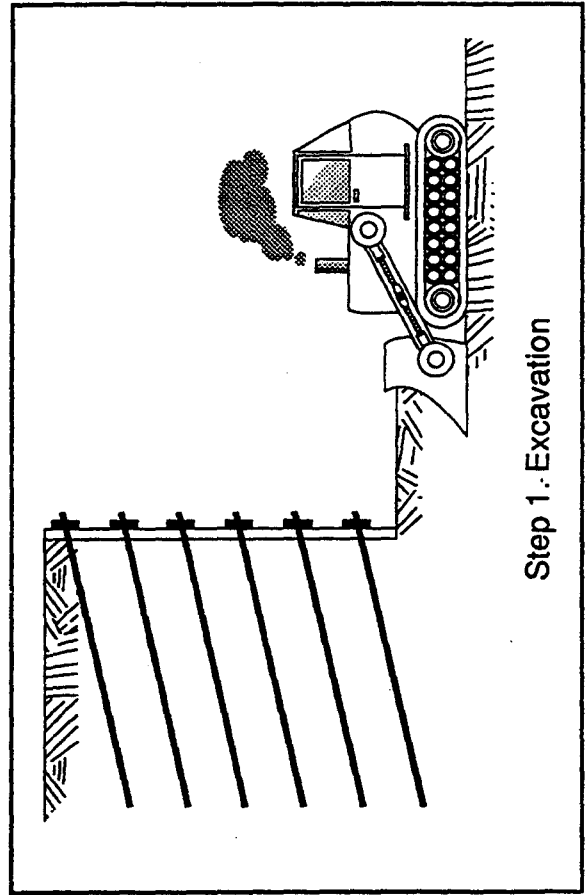
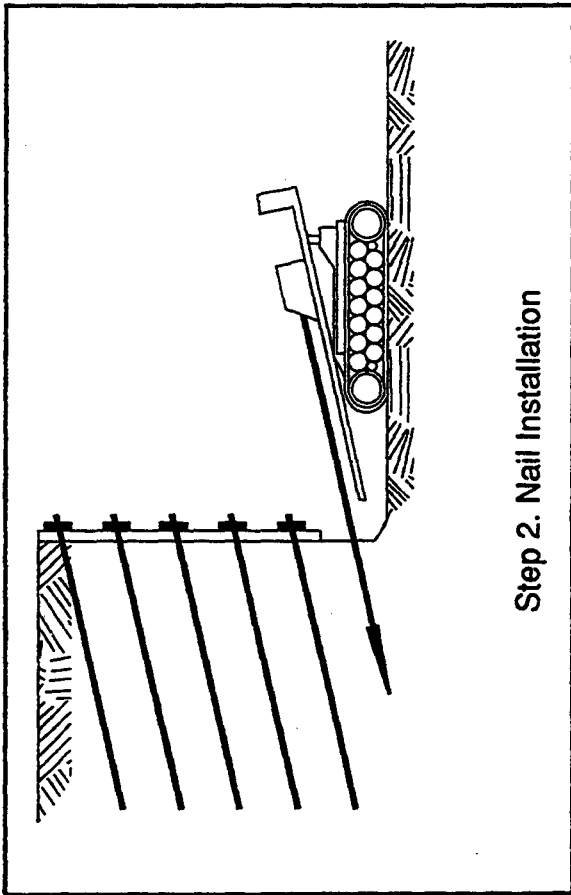
One of the unique features of soil nailed walls is that they are built from the top down, in small (typically two meters/six feet or less) successive, lifts as illustrated on Figure 1, p. 2. The construction of each lift involves three basic steps, which are repeated until the final depth is achieved. These steps are:

- 1) Excavation
- 2) Nail installation
- 3) Shotcreting

Depending on ground conditions, steps 2 and 3 may be reversed. Permanent walls typically include an additional step consisting of placement of a permanent wall facing (cast-in-place concrete, precast elements, or additional shotcrete) over the initial shotcrete layer.

This apparent simplicity of construction masks the complexities of the system. Since nails are not pre-tensioned, the deformation behavior of the wall can be strongly dependent on the site geological conditions and on the details of the construction technique used.

The first soil nailed walls were built in France in 1972 and the first recorded wall built in the United States was in 1976. It was not until the late 1970's in Germany or mid 1980's in France that major research on the performance of the system was undertaken. As a result, the majority of the engineering data developed is located in those countries. After reviewing all the published literature in English on the subject, it was determined that additional information was necessary to resolve detailed design issues faced by American engineers.



In Germany, public agency work is again usually bid on a conceptual or preliminary design prepared by or for the agency, with the contractor required to submit a bid on the original design and also encouraged to submit any alternate design that will provide an equivalent wall at a reduced price. Ultimately, award is made on the lowest cost responsive bid. Soil nailing in Germany requires the involvement of one of a small group of prequalified or "licensed" contractor organizations. As in France, these contractors tend to be technically and financially very strong. Private work, like public work, tends to be awarded on the basis of low bid.

Based on the European, and particularly the French, experience, two main recommendations are offered for encouraging the development of innovative construction methods and improving the construction performance for such methods. First, a stronger and more formal government/academic/industry cooperation should be established to research new technologies and disseminate the information in a non-proprietary manner. This should also include more US-European co-operative programs when the opportunity arises and the information will be of mutual benefit. Second, Alternative Bidding including Contractor Design-Build alternates, performance oriented specifications, and the use of carefully prequalified specialty contractors should be encouraged.

Research and Development

Soil nailing research and development has been actively pursued in Europe since the mid 1970's, particularly within France and Germany. This research and development has included laboratory testing of walls under carefully controlled conditions and testing of those walls to failure under different mechanisms, field-scale testing of test walls under a range of loading conditions, monitoring of the performance of in-service structures, and design computer program development. Some of these programs are continuing. The results of these research and development programs have been significant and have formed the basis for both the design and construction methods, and the proposed codes of practice for soil nailing in Europe.

A number of soil nailing research needs have been identified for the United States, based on the team's understanding of the current state of practice here and abroad. The highest priority needs, in order of importance, are considered to be the following: (a) development of a case history data bank for evaluating design and construction methods and to ensure that the currently available valuable information will be stored in a central repository and not lost, (b) evaluation of current design computer codes to establish points of commonality and difference, and to validate those methods suitable for soil nail wall design, (c) instrumentation and monitoring of in-service walls to gather additional information particularly with respect to maximum nail loads and facing loads, and for walls with unusual configurations or loadings (to support this activity, a generic Guide Instrumentation Plan Details and Specifications Package should also be developed), and (d) establishment of an approach for evaluating the capacity (ultimate and serviceability limit states) of soil nail wall structural facings, including a structural testing program to evaluate the performance of thin shotcrete facings.

The purpose of this report is to document the information obtained from a technical scanning tour undertaken to develop information on current European soil nail design and construction practice. The information developed from the scanning tour and reported herein is part of the database being assembled in support of the planned FHWA Demonstration program on soil nailing.

1.1 Background

Prior to selecting the scanning team for this tour, an extensive literature review was performed and many contacts were made to establish the state-of-the-practice in the United States and, in particular, where information on practical design and construction guidelines was deficient. This study resulted in a recommendation to FHWA Headquarters that a technical scanning team be assembled to review and collect soil nail design and construction information available from within the European community.

1.2 Objectives and Scope of Study

It was quickly recognized that to be effective, a multi-disciplinary team was necessary. The team's objectives would be to gather information and even more importantly help disseminate the team's recommendations to the engineering community after the trip.

The principal objective of the scanning team was to determine the state-of-the-practice and state-of-the-art in Europe of "Soil Nailing" used for permanent excavation support and slope stabilization. The team was also to gather information on "Augercast" or "Continuous Flight Auger" (CFA) piles/shafts and on contracting procedures for underground works, as time and opportunity allowed.

1.3 Team Members

The team was composed of the following FHWA, State Highway, and Industry Representatives:

John Walkinshaw	Team Leader	FHWA San Francisco CA
Ron Chassie	Demo Project Manager	FHWA Portland OR
Jim Keeley	Structural Engineer	FHWA Denver CO
Al DiMillio	Research Engineer	FHWA Washington DC
Ken Jackura	Computer Analysis	CALTRANS Sacramento CA
John Byrne	Facilitator/Recorder	Golder Associates WA
Pete Nicholson	Industry Rep. DFI*	Nicholson Const. PA
Don Bruce	Industry Rep. DFI	Nicholson Const. PA
Ron Chapman	Industry Rep. ADSC**	Schnabel Found. CA
Claus Ludwig	Industry Rep. ADSC	Schnabel Found. CA

*Deep Foundation Institute

**International Association of Foundation Drilling (previously Association of Drilled Shaft Contractors)

1.4 European Contacts

During the three week trip (September 20 - October 11, 1992), the team members met with individuals or groups representing 21 different companies, research facilities, universities and public sector agencies in Great Britain, France and Germany. The principal representatives and their affiliation are summarized below. In Appendix 1, the full addresses, phone/fax numbers are listed along with the names of all technical personnel attending the meetings.

GREAT BRITAIN

Colin Jones	University of Newcastle
Bernard Myles	Soil Nailing Limited, Ryan International Limited
A.D. (Tony) Barley	Keller/Colcrete
David A. Greenwood	Cementation, Piling and Foundations Limited
J. Temporal	Transport Research Laboratory (TRL)

FRANCE

François Schlosser	Terrasol
Roger Frank	Centre d'Enseignement et de Recherche en Mécanique des Sols (CERMES)
Bernard Heritier	Centre Expérimental du Bâtiment et des Travaux Publics (CEBTP)
Jacques Robert	Simecsol
Thao Pham	Bouygues
Michel Gandais	Bachy
Patrick de Buhan	École Polytechnique
Yves Guerpillon	Scetauroute
Claude Louis	CLC S.A./SolRENfor

GERMANY

Günter Gässler	University of Stuttgart
Klaus Pöllath	Züblin Spezialtiefbau GmFH
Herman Schad	Baugrundinstitut Smoltczyk & Partner GmFH (BSP)
Jörn M. Seitz	Bilfinger & Berger Bauaktiengesellschaft
Edelbert Vees	Prof. Dr.-Ing. (consultant)
Manfred Stocker	Bauer Spezialtiefbau GmFH
Thomas F. Herbst	Dyckerhoff & Widmann AG (Dywidag)

All of these contacts were extremely helpful during the visits and many have continued to provide valuable information since the team's return to the United States. In exchange, the team has agreed to send to our hosts, copies of this report as well as future information that we may develop on this subject. With this emphasis on sharing technologies, we hope that long term partnerships may develop and the value of this scanning trip will be further enhanced.

3. DESIGN ASPECTS

3.1 Behavior Mechanism of Soil Nails

Nails are passive elements and there is a range of opinions within the European community concerning their mode of action and their possible application. At one end of the spectrum, the nails are envisaged as elements which bind the soil mass together to form a composite gravity structure and prevent localized raveling and failure. Almost by definition, this point of view considers that nailed structures do not develop any significant facing loads and in fact, in some applications, no structural facing is attached to the nails. Such nail-reinforced slopes are generally battered (Photos 5 and 6, p. 2-3). The nails are considered to be generally low capacity reinforcing elements and where heavy structural support is required, tensioned anchors with structural facing or some equivalent thereof will tend to be used by those practitioners who subscribe to this view of soil nailing. Composite reinforcement system designs have also been employed, wherein tensioned anchors are used to provide overall stability to the soil nailed gravity retaining structure. At the other end of the spectrum, the passive nails are considered to be structural elements in the same way as active tieback anchors, with the nails designed to provide full reinforcing support and attached to structural walls with significant load carrying capacity.

The general consensus among European nail designers appears to be that for near-vertical walls reinforced with essentially horizontal nails, tensile reinforcement is dominant and that the contribution of shear/bending is generally second order. This attitude is a function of the low bending stiffness of typical nail sections. At service load conditions, the contribution of bending/shear is negligible, whereas at the failure condition the bending/shear contribution can be more significant but still small (typically less than 10 percent of the tensile contribution). It is evident that tensile and shear/bending loading within the nails are mobilized at very different relative deformations (typically ten times as much deformation of the soil is required to mobilize shear/bending as to mobilize tension) and that negligible shear and bending contributions from the nails occur at the normal service condition. It appears that the majority of designers therefore ignore the influence of shear and bending, considering the nails to act in tension only, and use design computer codes which explicitly include only the nail tensile loads. An exception to this situation is within France, where some groups using the computer code TALREN can and do incorporate the shear/bending contribution of the nail. Similarly, the computer code CRESOL (United Kingdom) also allows incorporation of the nail shear/bending contribution. This situation appears to have resulted in some confusing terminology problems in that for many, the term nail is used to define a tensile reinforcing element (whereas shear reinforcing elements are termed dowels), whereas for others, the term nail appears to define any small diameter reinforcing element that can act in both tension and shear. Similarly, the confusion appears to extend to the designs themselves, wherein certain designs orient the reinforcing elements approximately parallel to the direction of anticipated maximum tensile strains (nailing action) and others orient the reinforcing elements approximately perpendicular to the anticipated direction of maximum shear strain (doweling action). (Commentary: Although this is obviously an evolving situation, it appears likely that a rational distinction will ultimately be made between nails, defined

primarily as tension elements oriented near parallel to the direction of maximum soil tensile strains, and dowels oriented near perpendicular to the direction of maximum soil shear strains. For nails, as defined above, the contribution of shear and bending to the reinforcing action will not be significant.)

3.2 Overall Design Approach

The European nailing design methods in current use appear to be exclusively based on limit equilibrium design concepts, consistent with the requirements of the various countries' design codes. All methods currently used in Europe examine the stability of free body blocks defined by slip surfaces of circular, log spiral or bi-linear shape. It is generally considered that any of these slip surface shapes can be usefully applied as they can all provide good approximations of each other. The circular slip surfaces are generally used in conjunction with a conventional method of slices (with the slices usually vertical but in at least one case, the slices are taken parallel to the nails themselves), and consider slip surfaces that are contained entirely within the reinforced zone, partially within the reinforced zone, and completely external to the reinforced zone (internal, mixed and external failure modes) (Figure 2, p. 9). The log spiral slip surfaces appear to be used primarily in conjunction with computational methods based on the ultimate limit state concept, wherein a log spiral with a dilation angle equal to the soil friction angle can be shown to give an upper bound solution to the calculated factor of safety. These methods also consider internal, mixed and external failure modes. The bilinear slip surface models used in Germany examine the statics of two wedges, with the upper wedge located behind the reinforced mass and providing an active driving load to the reinforced body, and the lower wedge encompassing the reinforced zone and passing through that zone (mixed failure mode) (Figure 3, p. 10). The German bilinear wedge method appears, therefore, to be somewhat more restrictive in that it does not appear to explicitly consider purely internal failure modes. Those methods based on the method of slices do not generally differentiate between the nail forces and the soil forces on the interslice boundaries, but do explicitly consider the nail forces separately from the soil forces along the slip surface itself.

Where soil nails are used to remediate a pre-existing slide, and a discrete failure surface can be identified, some designers use essentially a "hand calculation" approach to define the amount of in situ reinforcement required to achieve a satisfactory level of stability. Such approaches take explicit account of the shape and location of the identified slip plane, rather than the more general approach which involves analyzing multiple possible slip surfaces.

All design methods compute the required total nail reinforcing force to achieve a specified system or global reliability (expressed in terms of various factors of safety). A nail layout is then determined such that there is sufficient steel (cross-sectional area and length) external to each of the considered slip surfaces to ensure that the computed required nail force can be provided without the nails either breaking or exceeding the bond strength between the nail and the soil. The nail/soil bond strength is estimated for design and almost

2. SOIL NAILING HISTORY AND APPLICATIONS

The first recorded use of soil nailing in Europe was in France in 1972, when the contractors Bouygues and Soletanche constructed an 18 meter (59 feet) high 1.5H:4V battered wall in cemented Fontainebleau sand, in connection with a widening of the tracks for the French National Railways at Versailles (Photo 7, p. 2-4). The nails were relatively closely spaced and grouted into pre-drilled holes. Two years later, the first documented use of driven nails occurred when Bouygues used 40 to 49 mm (1.6 to 1.9 inch) diameter tubes on a Paris Metro excavation. Subsequently, the steel tubes were replaced by angle iron because of their better performance in handling obstructions during driving (Photos 9 to 11, pp. 2-6 and 2-7). The first documented use of a permanent soil nail wall in Germany was a 14 meter-high (46 feet) wall constructed in the Keuper Marl (mudstone) in the city of Stuttgart, in 1979 (Photo 33 p. 2-19).

The first major research program (Bodenvernagelung) on soil nailing was undertaken in Germany by the University of Karlsruhe and the contractor Bauer (1975-1981). This jointly funded program cost approximately \$2.3 million (US\$1=DM1.5) and involved full scale testing of a variety of experimental wall configurations (Photos 30-32, pp. 2-17 and 2-18). Due to the increasing use of soil nailing within France following its initial applications described above, and the perceived lack of a defensible design methodology, the French initiated their own experimental program (Clouterre) in 1986. The Clouterre program was jointly funded by Government and private industry, with a budget on the order of \$4 million and 21 individual private or public participants. The program involved three large-scale experiments in prepared fill (Fontainebleau sand) and the monitoring of six full scale in-service structures. The results of the Clouterre program have recently been published and will form the basis for the future soil nailing design approach to be adopted in France.

Within the 20 years since its first introduction to Europe and the subsequent conduct of the two major national experimental programs, soil nailing has been and is now used very extensively in both France and Germany. The major attractions of the method are its economy, construction flexibility, ability to make use of small construction equipment which is particularly suited for use in urban environments, and its overall adaptability for special applications. Within France, it is estimated that over 100,000 m² (1,100,000 ft²) per year of soil nailed walls are presently being constructed for public works alone, with perhaps hundreds of smaller undocumented walls constructed for private owners. To date, the great majority of these walls have been temporary in nature and have used shotcrete for the structural facing. The highest vertical soil nailed wall in France is believed to be in excess of 20 meters (66 feet). The highest battered soil nailed wall (73 degree face angle) is almost 30 meters (98 feet) high (Dombes tunnel portal, near Lyon). In Germany, over 500 walls are estimated to have been constructed to date, with the majority of these walls being temporary basement walls using structural shotcrete facings. Use of soil nailing in Great Britain has been much less than in France and Germany, with perhaps only a few dozen applications to date. Many of the British applications have involved the stabilization of existing slopes and old, failing gravity retaining walls (Photos 3 and 4, p. 2-2).

Applications of soil nail walls in Europe include permanent and temporary stabilization of natural slopes, renovation of old failing retaining walls, renovation of mechanically

stabilized earth walls that have undergone premature corrosion deterioration of the originally installed stainless steel reinforcing elements (France), temporary shoring for basement excavations, and permanent and temporary support for cuts associated with roads, railways, and tunnel portals. The most common form of nail installation involves grouting the nails into temporarily cased or preferably uncased pre-drilled holes. Within Germany, this installation method is used almost exclusively but there have also been limited applications of a post-grouted driven nail with an oversized head to create an open annulus between the steel bar and the surrounding soil. In France, in addition to the conventional drill and grout installation method, relatively extensive use is also made of percussion driven closely spaced nails without post-grouting (see previous discussion, p. 6), together with the specialist technique of jet nailing. Within Great Britain, there is one specialist contractor using explosive injection of nails by air gun. This last technique appears to have been used almost exclusively for dowelling marginally stable slopes (Photos 1 and 2, p. 2-1).

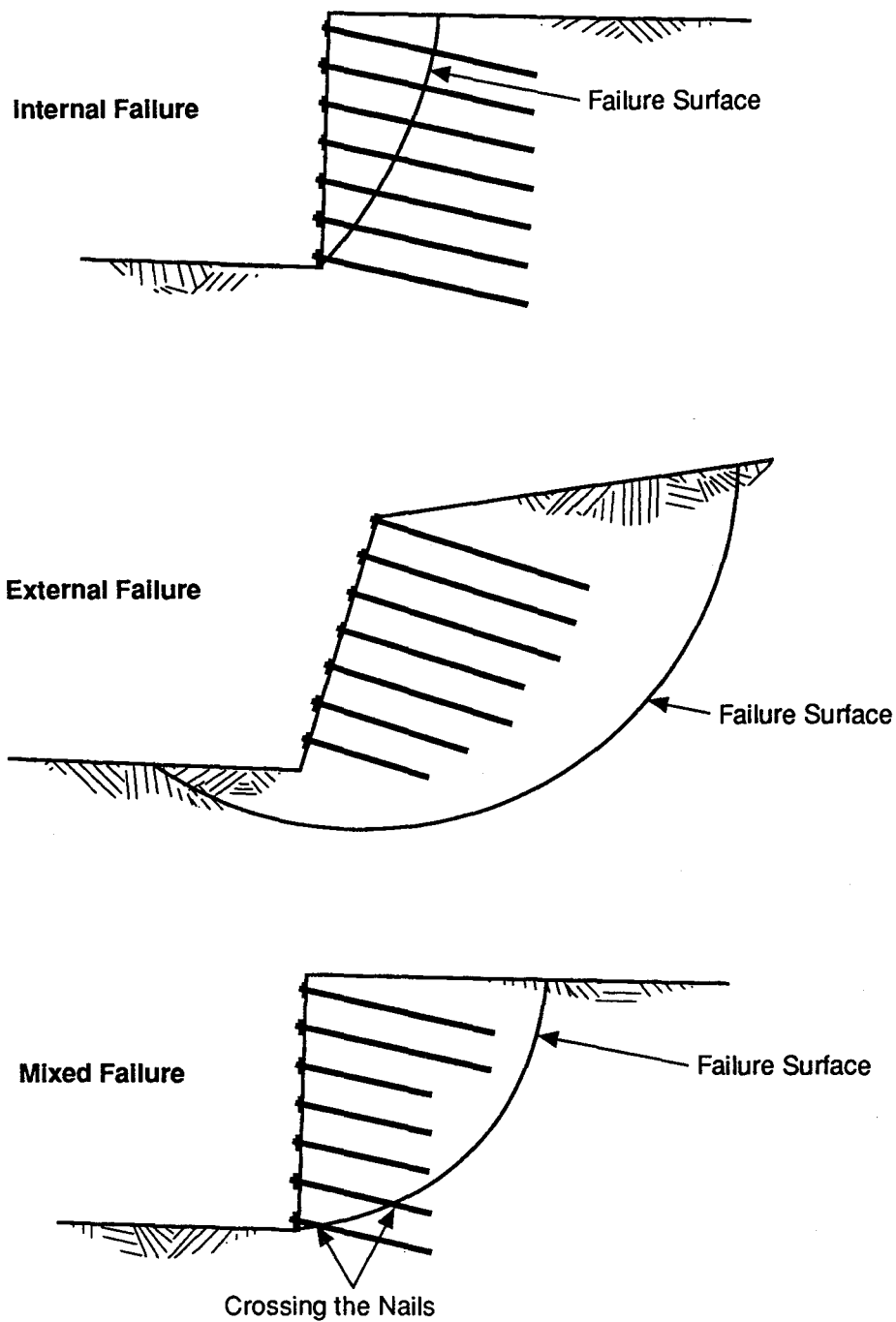


FIGURE 2
DIFFERENT TYPES OF FAILURE SURFACES
TO BE ANALYZED FOR SOIL NAILED WALLS

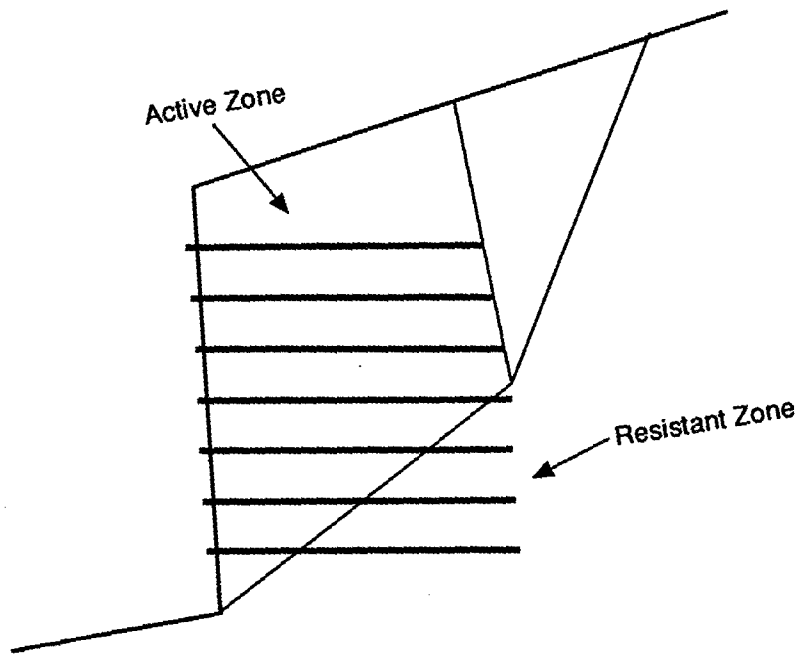


FIGURE 3
GERMAN BI-LINEAR SLIP
SURFACE METHOD

invariably validated during construction by field pullout tests. Correlations between the bond strength and pressuremeter test data are used in France for preliminary design purposes. The bond strength is considered by some designers to be directly correlated with overburden stress for both driven nails and for nails installed in drilled holes. However, the majority of designers consider that, for nails installed in drilled holes, the method of construction effectively destroys the influence of the overburden stress and that beyond a depth of two to three meters, the bond strength is effectively independent of depth, for a given type of soil. The European limiting equilibrium design methods all appear to have the following features in common:

- They consider only overall stability and make no explicit assumptions as to how each of the installed nails should contribute to the overall required stabilizing force. (Commentary: Therefore, from a computational viewpoint, the European design methods make no distinction between, for example, a soil nailed wall and a Mechanically Stabilized Embankment (MSE) wall, even though it is well established that these different structures develop very different load distributions among the reinforcing elements under the service load condition. This difference in service load distribution results from the different methods of construction - top down in the case of nailed walls and bottom up in the case of MSE walls. Limit equilibrium methods of analysis cannot fully address this issue of load distribution among the nails, and if this aspect is to be included in the analysis, it must be incorporated as an additional assumption. It should be noted that, in general, the design methods used in Europe have procedures or general guidelines for apportioning the steel within the ground (discussed below) and that this results in an implicit assumption about the way in which the individual nails contribute to the overall reinforcing force developed.)
- They do not, in general, explicitly consider the potential for pullout or slip of the nails within the free body defined by the slip surface (i.e., no consideration of pullout in the active zone - see Figure 3, p. 10). It is implicitly assumed, based on experience, that the facing attached to the nails will be sufficiently robust as to inhibit this type of failure mechanism i.e., the active block can effectively be considered to be sufficiently strong so as to permit development of the full nail loading along any considered slip surface, with that nail loading defined by the lesser of the nail strength or the pullout resistance of the length of nail external to the slip surface. (Commentary: In certain instances where minimal to no facings are installed, this approach appears illogical. In other instances, where conservative empirical assumptions regarding design face pressures are made, this approach might result in the design of more robust and more costly structural walls than is required for stability.) Only one European designer indicated that he did explicitly consider the potential for face failure and nail pullout within the active block of soil, as part of his limiting equilibrium design approach.
- Consistent with the above, virtually all designers indicated that they have an entirely empirical approach for defining design loads for the wall facing and for the connectors between the facing and the nails. At one end of the spectrum, the facing of nailed walls is considered to have no serious structural role other

than to retain the soil between the nail heads. In these applications, when facing is included, it is designed for only a local active earth pressure between the individual nails. In many applications, nail face support is obviously not required, particularly for heavily battered slopes in slightly cohesive materials where vegetation etc. is used to control erosion. At the other end of the spectrum, where nails are used in a more serious support and reinforcing role such as to support vertical or near-vertical excavations, the facing pressures are defined empirically to equate to either a proportion of the pullout resistance or of the tensile strength of the nails (Clouterre recommendations), or a proportion of the active soil loading for the total height of the wall (German practice). In some cases, there also appears to be some confusion as to whether the empirically derived facing loads are to be considered as ultimate loads for limit design of the facing, or as working loads for serviceability design against cracking. (Commentary. From a limiting equilibrium viewpoint, the minimum required face pressure to ensure that all factors of safety are satisfied will be a function of the slope face batter, soil-nail adhesion in the active zone, surcharge loading, and ground shear strength. Therefore, it is desirable that the limiting equilibrium design method allow computation of the minimum required face pressure as a function of the above variables).

3.3 Computer Codes

Information was gathered on the availability, cost, computational theory, problem complexity, graphics capability and overall user friendliness of the main design computer codes currently in use in Europe. This information is provided below according to country, and includes discussion on only those computer codes exhibiting reasonable sophistication and which are available for public use through purchase or grant. Detailed evaluations involving comparative test runs etc. were not performed as part of this study.

United Kingdom

As noted previously, England has the least experience in soil nail wall design and construction of the three countries visited, but appears to have developed significant computer program capabilities. Two codes are currently available - 'NAIL-Solver' developed at University of Oxford and sold by Oxford Geotechnical Software, and CRESOL developed by the University of Cardiff for Soil Nailing Limited of England.

Program NAIL-Solver uses a bi-linear wedge and force balance for analysis with capabilities for including the effects of water and surcharge loading. The slip surface search technique is unknown. The program is limited in its capabilities in the 1.1 version now available; one soil type, failure exit point only down to the wall toe, uniform nail spacing, uniform surcharges, and non-vertical walls. Earthquake loading features are unknown. The nails are assumed to act only in tension. Graphical display of the cross-section analyzed can be obtained. Results are presented graphically. The partial Factor of Safety method is used. Program cost is unknown. This program is currently being used on a routine basis by a number of British designers.

CRESOL is a new computer program made available for use in the summer of 1992. The program is currently being made user-friendly and will then be sold commercially. It employs a log spiral, moment balance technique for analysis with capabilities for water and surcharge loading. Program search routines are user- and computer-controlled and appear sufficiently flexible to examine a large variety of potential failure surfaces which exit both above and below the toe of the wall. The program is quite versatile with capability for complex subsurface soil profiles as well as complex surface profile geometries. Nail tension and shear/bending resistance are included. Earthquake loading features do not appear to be presently incorporated. Graphical output displays of the cross-section, failure surfaces, inclusions, soil strata and water table can be obtained. The partial Factor of Safety method is used. Program cost is unknown.

France

France has significant experience in soil nailing and has the largest range of, and apparently some of the most versatile, PC programs of the three countries visited. Three programs are available, but only two are receiving country-wide use; TALREN and CLOUDIM. TALREN was developed by the company Terrasol and CLOUDIM by the company Solrenfor. The third program, STARS, has been developed by Professors Patrick de Buhan and Luc Dormieux from the École Polytechnique.

Program TALREN is a comprehensive program that utilizes moment or force equilibrium methods for evaluating circular and wedge type failure surfaces. The program can handle complex surface and subsurface features, water table, inclined or vertical surcharges and reinforcing inclusions consisting of nails, anchors or piles. Reinforcing inclusions can be considered to act in tension, shear, or bending, or any combination thereof. Seismic loading as well as flow net features are accommodated. Diffusion factors accommodate surcharge loads to provide user defined limits to their effect on increasing the normal force on the failure plane. A complete graphics package provides for graphical output of the geometry and data. The partial Factor of Safety concept is generally used. Program cost (English version) is approximately \$12,000 at the time of preparation of this report.

Program CLOUDIM appears similar to TALREN in its overall sophistication. The program offers an interactive mouse-screen display that allows the user to click on a geometry, surcharge, water table and reinforcement inclusions. Screen coordinates provide the scale to properly dimension all features. Program cost (English version) is \$6,000.

Program STARS uses a log spiral, moment balance technique for analysis. Five parallel soil layers can be exhibited, with a cross-sectional surface geometry that may be complex. Surcharges, and water and seismic loadings can be applied. Nail inclusions are considered as tension elements only. Graphics capability illustrates the cross-sections analyzed. A main advantage of this program is its rapid computation time. Failure surfaces can exit above or below the wall toe. The partial Factor of Safety method is used. Program distribution is expected to be sometime in 1993. Cost is unknown.

Germany

Germany, like France, has significant experience in soil nailing projects. There appears to be, however, relatively limited (public domain) computer program capability available for design. Basically, the programs that are available are based on Professor Günter Gässler's (Stuttgart University-FMPA) bi-linear wedge analysis. The analysis is based on a bi-linear wedge failure mechanism with the interslice surface assumed to be vertical and generally located just behind the reinforcement. The bi-linear wedge analysis is a force equilibrium technique that considers reinforcement tension elements in the lower wedge, with no consideration given to bending or shear of the nails. A drawback with this type of analysis is in the assumption that the location of the interslice surface is in a constant, or nearly constant position for all potential failure planes i.e., the geometries of the slip surfaces considered appear to be somewhat more restrictive than those used in other computer codes.

The only commercially available program in Germany, of which the team was made aware, is produced by the contractor Bauer. The program can handle a variety of surface and subsurface geometries and surcharges. Water tables can be included. Capabilities with respect to seismic loading and failures below toe of wall are unknown. The partial Factor of Safety method is used. Program cost is \$30,000 (English version).

Computer Code Summary

In summary, of the three countries visited, France and Germany are the leaders in soil nail wall construction. France, however, exhibited the most sophisticated design computer programs. In some instances, their applications extend significantly beyond the analysis of only soil nail walls, i.e., can include quay walls, sheet pilings, tie-backs, piles, etc.

However, from the standpoint of identifying program needs to satisfy design requirements for purely soil nailing applications, and assuming the European and American program codes are logically written and demonstrate adherence to proper statics, there has been no evidence uncovered that presupposes that United States programs will give significantly different results than the most sophisticated European programs. The French (TALREN) and English (CRESOL) programs allow bending moments/shear forces to be included, whereas the United States programs developed to date do not include this subtlety. There has been much debate concerning the benefits of including shear/bending effects, even within France, but there appears to be a general consensus that conventional nails provide their reinforcing action primarily through the development of tension. German and most English designers are also in the 'tension only' camp.

The English program CRESOL may be competitive with the French program TALREN in terms of its capability of being able to include nail shear/bending. Although CRESOL utilizes a log spiral failure surface instead of a circular or bi-linear wedge failure surface used by most other codes, evidence indicates results are nearly identical.

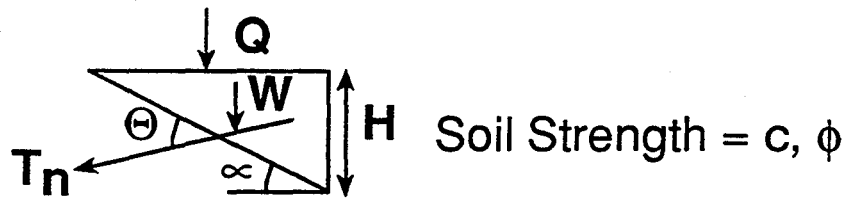
As mentioned previously, the European design computer programs do not appear, in general, to consider the potential for slip of the nails on the active or wall side of the slip surface. Therefore, all possible failure modes do not appear to have been considered.

From a design perspective, this problem seems to be circumvented to a degree by incorporating empirical rules for the facing design pressures and the nail/facing connector design capacities so as to inhibit the development of such failure modes.

3.4 Factor of Safety/Load and Resistance Factor Considerations

The approach to incorporating factors of safety appears to be in a state of transition at this stage, from the more conventional global factor of safety commonly associated with slope stability analyses, to a load and resistance factor approach wherein individual factors are assigned to each component of the driving and resisting forces. The load and resistance factor approach is being driven by the adoption of the concepts in the new Eurocode 7, and there is currently some uncertainty as to what will be the final guidelines. The load and resistance factors are to be chosen and applied to specific characteristic values of the driving and resisting components in order to achieve a reported low probability of failure of 10^{-6} . One difficulty at this stage appears to be not only in defining the factors to be applied, but also in defining the appropriate characteristic design values to be factored (e.g., mean or some other fractile value).

The traditional approach, which has been used by the majority of soil nail designers to date, defines an overall global factor of safety as the ratio of the resisting forces to the driving forces. Alternatively, the factor of safety can be thought of as being applied to the soil shear strength to produce an equilibrium between the driving and limiting resisting forces. However, because of the presence of reinforcing elements, partial factors of safety (or resistance factors) are also applied to the nails both in terms of the tensile resistance or yield of the steel tendons and in terms of the pullout or soil-nail adhesion resistance of the nails. The concept is best explained by reference to the simplified example given on Figure 4, p. 16, with representative European safety (or load and resistance) factors given in Table 1, p. 17 for the design of permanent soil nail walls. The corresponding factors are generally somewhat lower for temporary walls. The first three lines of Table 1, p. 17, show typical load and resistance factors from three different design organizations. It can be seen that there is some significant variation among the different design groups. The fourth line shows the more complete recommendations from the recently completed Clouterre program, in which the global (F_g) and nail yield/pullout resistance factors (F_y , F_p) for ultimate state design are generally somewhat lower than have been used, but soil strength resistance (F_ϕ , F_c) and applied load partial factors (F_w , F_q) are also incorporated. The range of applied load factors for self weight (F_w) and surcharge (F_q) shown in Table 1, p. 17, are specified to account for loadings that can have either a stabilizing or a destabilizing effect. It is anticipated that the load and resistance factors to be adopted by Eurocode 7 will be somewhat similar to those suggested by the Clouterre recommendations.



Driving forces on plane " ∞ "

$$(F_w W + F_q Q) \sin \infty - \frac{T_n}{F_{yp}} \cos \theta$$

Resisting forces on plane " ∞ "

$$\left[(F_w W + F_q Q) \cos \infty + \frac{T_n}{F_{yp}} \sin \theta \right] \frac{\tan \phi}{F_\phi} + \frac{C H}{F_c} \sin \infty$$

Where F_w = self weight load factor

F_q = surcharge load factor

F_c = cohesion material safety factor

F_ϕ = friction material safety factor

F_{yp} = nail safety factor and includes:

F_y = nail safety factor on yield of steel

F_p = nail safety factor on pullout

Also we can estimate a "global" factor of safety as the ratio of the resisting to driving forces:

$$F_G = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

FIGURE 4
LOAD & SAFETY
FACTOR DEFINITION

TABLE 1

LOAD AND SAFETY FACTORS FOR PERMANENT NAIL WALL DESIGN

F _g	F _y	F _p	F _w	F _q	F _φ	F _c	
1.0	1.7	2.0	1.0	1.0	1.0	1.0	Bauer (Germany) ⁽¹⁾
1.5	1.5	2.0	1.0	1.0	1.0	1.0	Louis (France) ⁽¹⁾
1.5	1.5	1.5	1.0	1.0	1.0	1.0	Scetauroute (France) ⁽¹⁾
1.125	1.15	1.4	.95-1.05	.9-1.2	1.2	1.5	Clouterre recommendations ⁽²⁾

⁽¹⁾ Current practice by organization.

⁽²⁾ Recommendations by Clouterre for future practice.

(Commentary: There would appear to be a number of issues to consider with respect to the factors of safety chosen for design analysis of soil nailed systems. First, in general, higher factors of safety will result in more conservative designs. This is true whether the factors of safety are described in terms of a global safety factor or in terms of partial safety factors. Second, the level of conservatism in the design will also depend on the cumulative safety factors built into the analysis. For example, the cross-sectional area of steel required is a function of both the global safety factor (which determines the design loading in the nails) and the nail yield safety factor which determines the degree to which the nail tensile capacity must exceed the design load. Similarly, the lengths of the nails depend on the global safety factor and the nail pullout factor of safety which defines the degree to which the nail length must exceed the minimum length required to develop the design load through nail-soil adhesion. Reference to Table 1 will show that Bauer, for example, uses a global factor of safety of 1.0 and therefore calculates design loads equal to active loads, which is probably quite close to the actual service load condition. The margin of safety incorporated into their designs is then expressed entirely by the yield and pullout factors of safety applied to the calculated service loads in order to size the cross-section and length of the nails. The other examples shown in Table 1 apply a global factor of safety greater than 1.0, which results in nail design loads higher than the expected service loads, and nail yield/pullout factors of safety in addition.)

3.5 Type and Proportioning of Steel

European experience has demonstrated that under normal service load conditions, there will be adequate nail reinforcement capacity to limit top-of-wall deformations to less than a few tenths of one percent of the height of the wall. In the event that a failure condition is approached however, it is desirable that the overall system behave in a ductile rather than a brittle manner. One way of achieving ductility is to use ductile materials. Hence, ductile

steel is to be preferred for soil nailing applications. In particular, steel which retains its ability to carry tensile loads under the concentrated bending effects which can be expected to occur as failure is approached, should be used. The European practice is to specify such steel for nailing applications (e.g., Gewi 500 N/mm² (72 Ksi) yield) and to avoid the use of high ultimate strength steels with low ductility under bending strains.

(Commentary: As noted previously, limiting equilibrium methods calculate a total reinforcing force required to achieve a certain level of system reliability but cannot, in themselves, determine an optimum distribution of steel to provide that reinforcing force. This is because limiting equilibrium methods deal only with total force and/or moment balance. From a limiting equilibrium point of view, therefore, it is possible to provide a wide variety of distributions of reinforcing steel to achieve an equivalent level of total reinforcing support. However, all such distributions of steel will not, in practice, be equally effective in providing an acceptable deformation performance under service load conditions. For example, under the service load state, the reinforcement at the base of a Reinforced Earth or Mechanically Stabilized Embankment (MSE) wall will tend to be the most heavily loaded whereas within a soil nailed wall, that same reinforcement will generally be the most lightly loaded. This would suggest that the distributions of steel within MSE and soil nailed walls should not be identical, even though limiting equilibrium design techniques cannot really distinguish between the two types of support system. Since it is possible to provide many different reinforcing layouts to give the same computed reliability against failure, it would appear rational to take some note of the service condition to help define the optimum layout of the reinforcing elements for a soil nailed or any other type of reinforced soil system).

In general, European practice appears to proportion the steel so that the nails tend to be modestly spaced and of equal length and cross-sectional area through the full structural height. This empirical practice is based on observations of the behavior of nailed walls under service conditions. The spacing requirement is based on the reasonable premise that performance will tend to be enhanced by a large number of more closely spaced nails than by a smaller number of more widely spaced nails. For more conventional systems, where nails are installed in pre-drilled holes, a significant element of the total cost is associated with the drilling and there are therefore economic incentives for keeping the nail spacing as large as practicable (i.e., keeping the number of drill holes as small as possible). For average conditions, a nail spacing on the order of 1.5 meters (5 feet) appears usual, with a typical range of spacing in the 1 to 2 meters (3.3 to 6.6 feet) range. The Clouterre recommendations, for example, attempt to penalize the designer for increased nail spacing by requiring that the face design pressures be increased with increased nail spacing. For alternative installation techniques such as the driven Hurlpinoise technique practiced extensively by Bouygues, much higher nail densities are used (1.5 to 2.0 driven nails per square meter (.14 to .19 nails per square foot) versus a more typical 0.5 drilled and grouted nails per square meter (0.05 nails per square foot)) as a result of the lower cost of each nail installation and the generally lower nail adhesions achieved.

For most European designs, nail lengths therefore tend to be uniform and dependent on factors such as the soil strength, soil-nail adhesion, and the overall geometry and loading of the system (e.g., face batter, backslope angle, surcharge loading). Similarly, bar cross-sectional areas tend to be uniform. For the assumption of uniform bar length and cross-

section, the limiting equilibrium models can then define the required length and bar size to provide adequate safety against either nail breakage or pullout. Notwithstanding design model predictions, minimum design nail lengths tend to be on the order 0.6 times the wall height for vertical walls with no backslope or heavy surcharge. Somewhat lower nail length to wall height ratios than 0.6 have been used with battered walls in more lithified or rock-like materials.

In general, service load monitoring would suggest that equal proportioning of the nails (length and capacity) such as conventionally practiced in Europe, results in a distribution of provided nail support which is somewhat biased towards the lower one-third of the wall whereas in reality, nails in the lower portion of the wall do not typically work as hard in the service state as do the nails in the upper and middle portions of the wall. Arguments can therefore be made that a uniform distribution of nails over the full height of the wall is generally not optimum from the point of view of meeting the service condition. A preferred approach might be, in general, to install somewhat longer and possibly higher capacity nails in the upper two-thirds of the wall. This point of view is acknowledged in the Clouterre report which indicates that concentrating a higher proportion of the total nail length and capacity in the upper part of the wall will tend to reduce wall displacements under the service load condition. Alternative points of view to this position argue that, notwithstanding the service load condition, the full length and capacity nails are also required in the lower wall section to provide support in the event that failure is approached. To support this position, the results of model and prototype walls tested to failure are quoted, in which the lower nails are seen to develop significant loading as the failure condition is approached. (Commentary: This argument is somewhat circular in nature, however, since an alternative nail layout (length and capacity distribution) could give an equally safe but totally different nail load distribution with the approach of failure i.e., the load will go wherever it can be carried. Furthermore, concentrating support in the lower portion of the wall is not considered to be a particularly efficient method of preventing collapse, since near vertical or steeply battered walls can fail in a rotational mode about the toe if reinforcement in the upper portion of the wall is inadequate - see Photos 18 and 19, p. 2-11). The contractor Bouygues, for example, indicated that they will sometimes increase the length of the uppermost nails to minimize movements and the lowermost nails to enhance overall stability.

In summary, the European practice of constructing soil nail walls with nails of equal length and capacity, on a reasonable spacing, is considered sound. Some design and wall performance optimization might be expected with alternative nail load distribution assumptions that are more consistent with measured service load conditions.

3.6 Face and Connector Design Approach

To date, the European design approach for facing and nail-facing connectors appears to range from entirely empirical based on experience and without any formal design, to conventional strength limit state design based on estimated facing and connector loads but without consideration of cracking limitations in the service state, to both strength and serviceability limit designs.

The method for estimating the facing and connector loads appears to be generally empirical, and often unrelated to the limiting equilibrium design method for apportioning the reinforcing steel within the ground. As noted previously, most European designers take no specific account of the role of the facing or of the nail adhesion within the active zone adjacent the facing, within their limit design analyses. At one end of the spectrum, where facing is only considered to perform the function of retaining the soil between the individual nails, design facing pressures are based on the equivalent active earth pressures corresponding to a depth of soil equal to typically one or two times the nail vertical spacing. This approach is often adopted, particularly for temporary walls and occasionally for permanent walls. Alternatively, a standard design wall section such as 8 to 15 cm (3 to 6 inch) thick dry mix shotcrete with a single layer of welded wire fabric placed at mid-thickness will be used for temporary wall facing. Similarly, permanent walls might consist of an additional 15 cm (6 inch) thick shotcrete wall with two layers of welded wire mesh, placed over the temporary facing. (Commentary: The difficulty with the above approaches to nail system design is that while such procedures may be adequate for many nail-reinforced walls, they are not appropriate for all cases and care must therefore be exercised in the application of such "rule of thumb" approaches.)

At the other end of the spectrum, the facing is recognized as a structurally significant component of the overall system, and specific recommendations for facing design pressures are provided. Based on the observations from service load monitoring of nailed walls in practice, the Clouterre program has concluded that nail loads at the facing typically do not exceed 30 to 40 percent of the maximum loads developed in the nail. Their recommended approach therefore consists of designing the facing for a uniform wall pressure corresponding to a load equal to 60 percent of the maximum nail load for a nail spacing of 1 meter (3.3 feet) and equal to 100 percent of the maximum nail load for a nail spacing of 3 meters (9.8 feet) (i.e., a conservative approach compared with the 30 to 40 percent measured in practice). For intermediate nail spacings, the percentage of the nail load varies linearly with the nail spacing. This approach has been specified to encourage designers to limit nail spacings and reduce the possibility of face failures during construction. The Clouterre recommendations are considered by many to be generally quite conservative in terms of facing design.

For temporary walls, the ultimate limit state only is considered. For permanent walls, both the ultimate limit state and the serviceability limit state are considered. For ultimate limit state design, the maximum nail load (and associated nail face load) are estimated by using the appropriate load and resistance factors (see Table 1, p. 17) in a limiting equilibrium analysis. For serviceability limit state design, the maximum nail load (and associated nail face load) are estimated assuming load and resistance factors of unity.

Cast-in-place concrete facings placed over the shotcrete are typically a minimum of 20 to 25 cm (8 to 10 inches) thick for ease of concrete placement. Pre-cast decorative panels may also be attached directly to a shotcrete face. Steel fiber reinforced shotcrete has also been used for constructing permanent walls e.g., an application described in France consisted of a 20 cm (8 inch) thick steel fiber reinforced shotcrete wall which has been in service for about five years and has shown no cracking distress during that period.

The German approach to facing design is also considered by many of the local practitioners to be quite conservative, but is specified in the government "license" and must be followed. Typically, the face design pressure is taken as 75 to 85 percent of the corresponding Coulomb active earth loading applied as a uniform pressure over the height of the wall face. Mesh reinforced shotcrete facings are most common in Germany. Only a few steel fiber reinforced shotcrete wall facings have been constructed in Germany because they have been found to be more expensive than conventional wire mesh reinforced shotcrete.

There is no consistent European approach for checking the service limit state to control cracking and deflections of the wall. Results from laboratory and full-scale testing done in Europe have tended to show that the facing has remained intact during failure of the reinforced soil. One exception occurred as part of the German Bodenvernagelung research program where splitting of the face occurred because of intentional inadequate lapping of the welded wire fabric. There is some concern within the European design community about face cracking due to service stresses from temperature and frost action. There is a general opinion that additional information on wall service loads needs to be developed by additional monitoring of constructed facilities. One of the objectives of the planned French Clouterre 2 program is to examine the performance of soil nail walls under frost loading.

3.7 Corrosion Protection

The approach towards corrosion protection for permanent soil nails is one of the most controversial aspects of soil nailing in Europe. Available techniques include the provision of sacrificial steel, the alkaline environment of cement grout in either a crack controlled or random crack environment, galvanizing, epoxy coating, corrugated plastic sheathing and cement grout, and two concentric corrugated sheaths and cement grout.

The use of sacrificial steel requires confidence in our ability to predict corrosion rates under non-homogeneous field conditions. Similar concerns exist for galvanizing. In addition, chipping of the zinc coating during bar handling can occur and within the threaded length, the zinc coating might be of minimal thickness. Epoxy coatings can probably provide suitable protection but the influence of small pin-holes (holidays) in the coating needs to be assessed. Corrugated sheathing with cement grout in the annulus between the bar and the sheath has been proven as a reliable corrosion protection measure.

The most conservative approach is represented by German practice, in which all permanent nails are protected by so-called "double corrosion protection" usually consisting of encapsulating the steel nail in a corrugated plastic sheath and cement grout annulus. Although the cement grout can be expected to crack under extension loading, use of deformed bars enables crack widths to be limited to less than 0.1 mm (4 mils). The plastic sheathing, of thickness greater than 1 mm (40 mils), provides a water-tight barrier and the cement grout with cracks of limited width functions as a secondary chemical corrosion barrier in the event that the plastic sheath is breached. Epoxy grouts are not used and are considered inferior because of cost (10 to 15 times that of cement), possible environmental concerns, workability problems, and the fact that they represent a second physical barrier

but not a chemical barrier. Minimum grout thickness between the bar and the sheath is 5 mm (0.2 inch) and the bar must be appropriately centered within the sheath to ensure this minimum coverage. Because of quality control concerns, all permanent nails must be prepared under shop conditions rather than at the job site and are typically delivered to the site in steel channels for protection against bending and cracking during transport. For temporary nails in Germany, defined as those with a life of less than 2 years, corrosion protection can generally consist of a cement grout annulus only with a minimum cover of 15 to 20 mm (0.6 to 0.8 inch). In areas noted for highly aggressive ground conditions, double corrosion protection is used for temporary nails as well.

The corrosion protection recommendations of the recent Clouterre program allow for both a sacrificial steel approach and a double corrosion protection approach, depending on the significance and life of the structure, and on the aggressivity of the host ground (Table 2). For the most critical structures and the most aggressive ground conditions, double corrosion protection incorporating a plastic sheath is required for both temporary and permanent structures. For all other classes of ground aggressivity, the double corrosion protection requirement is limited only to those structures in corrosive ground with a life in excess of thirty years. Otherwise, a sacrificial thickness of steel is allowed, ranging from zero for temporary structures (life less than 18 months) in ground of low to medium aggressivity to an additional radial thickness of 4 mm (.16 inch) for more permanent structures with a life to 30 years in corrosive ground or a life to 100 years in ground of medium aggressivity. To date, however, actual design practice in France appears to have been to use no corrosion allowance for temporary applications and to allow a sacrificial radial thickness of 2 mm (80 mils) for permanent nails. Galvanized bars have also been used. One approach suggested by Bouygues as a corrosion monitoring measure is to install extra sacrificial nails during construction and to extract some of these sacrificial nails every 10 years. It should be noted that the French have had a very bad experience with approximately 75,000 square meters (800,000 square feet) of Reinforced Earth, less than 10 years old, which used stainless steel reinforcing strips. These structures are presently being remediated by installing nails through the face panels.

TABLE 2

CLOUTERRE RECOMMENDATIONS FOR CORROSION ALLOWANCE/PROTECTION¹

OVERALL GROUND CLASSIFICATION	SHORT-TERM ≤ 18 MONTHS	MEDIUM TERM 1.5 TO ≤ 30 YEARS	LONG-TERM 30 TO ≤ 100 YEARS
Slightly corrosive	0	2 mm (80 mils)	4 mm (160 mils)
Medium corrosiveness	0	4 mm (160 mils)	8 mm (310 mils)
Corrosive	2 mm (80 mils)	8 mm (310 mils)	plastic sheath
Highly corrosive	Protective plastic sheath must be provided		

¹ Sacrificial thickness refers to diametral thickness.

Within the United Kingdom, one of the reasons given for the relatively slow acceptance of soil nailing is concern over the long term survivability of the nails. Another reason suggested is the British practice of compensating design consultants in proportion to the cost of the project, tending to not encourage such consultants to actively pursue more cost effective alternatives. The Transport Research Laboratory has recently prepared a draft specification which addresses the corrosion issue. Ground is first classified into one of four categories ranging from non-aggressive to highly aggressive. The category determinations are based on the usual factors of soil composition, groundwater conditions, pH, soluble salts (sulfates, chlorides, carbonates, sulfides), and redox potential. For all but the highly aggressive ground category, a sacrificial thickness approach is allowable for permanent structures with design lives to 120 years, with the sacrificial thickness increasing with both the design life and the ground aggressivity. The maximum sacrificial radial thickness for aggressive ground and a design life of 120 years is given as 2.5 mm (100 mils). It is also suggested that where a grout annulus is present (i.e., drilled and grouted as opposed to driven nails), the benefit of the grout may be incorporated by reducing the ground aggressivity rating to the next lowest category. Rates of galvanizing loss are also provided for all but highly aggressive ground.

The justification for allowing a somewhat more relaxed approach towards corrosion in nails than in anchors, for example, is stated to be the lower stress levels in nails and the requirement to use steel grades for nails which are less susceptible to pitting corrosion and hydrogen embrittlement than are the anchor steels. Nevertheless, the sacrificial steel approach is still considered by some British designers to be inappropriate, and they have a strong preference for the German approach of designing to prevent corrosion as opposed to designing for a sacrificial thickness of steel, considering the level of understanding of the processes of corrosion and the uncertainties associated with characterizing the ground aggressivity. Where corrugated plastic sheathing has been used in the United Kingdom, the nails have sometimes been constructed in situ as opposed to being prefabricated and transported to the site in their final corrosion protected form. On-site fabrication is considered to be somewhat technically inferior but substantially cheaper.

Other approaches to corrosion protection have included the use of non-corrodible fiber glass tendons (e.g., Dywidag - see Photo 41, p. 2-24). The relative extendibility of these systems might be an issue, as might their relative brittleness under bending loading. Colcrete (United Kingdom) has also patented a geotextile wrapped woven mat for use in soil nailing applications.

(Commentary: The well documented experience available from permanent ground anchor installations is considered to be totally relevant to soil nailing applications, especially with regard to current practice in protecting the "bonded zone." Nails differ from tiebacks in that nails have only a "bond zone."

The mechanism of corrosion, identification of corrosive soil environments, required field testing, failure case histories, etc. is extensively discussed in FHWA RD-82-047 "Tiebacks," 1982 and FHWA DP-68-1R, "Permanent Ground Anchors" 1988. Zones most susceptible to corrosion and general guidelines to identify the level of required corrosion protection are identified in these documents. These guidelines are considered applicable to corrosion protection schemes for soil nailing.

At the time of writing this report, the following constitutes FHWA guidelines for the nail corrosion protection on U.S. Federal-aid Highway projects.

Corrosion protection, based on tieback practice, for permanent soil nailed structures should consist of:

1. A minimum grout cover of 4 cm (1.5 inches) to be achieved throughout the grout zone for nails that are not fully encapsulated. Centralizers should be placed at distances not exceeding 2.5 m (8 feet) center to center, and the lowest centralizer located a maximum of 0.3 m (1 foot) from the bottom of the grouted drill hole.
2. In non-aggressive ground, the nail section should be resin-bonded epoxied using an electrostatic process to provide a minimum epoxy coating thickness of 0.3 mm (12 mils) in accordance with AASHTO M-284.
3. In aggressive ground or for critical structures (e.g., walls adjacent to high volume traffic roadways or walls in front of bridge abutments) or where field observations have indicated corrosion of existing similar structures, fully encapsulated nails should be used.

Full encapsulation is generally accomplished as with tiebacks, by grouting the nail inside a corrugated plastic sheath. This tube must be capable of withstanding deformations associated with transportation, installation, and passive stressing of the nail. The annular space between the corrugated tube and tendon is usually filled with a neat cement grout containing admixtures to control bleed of water from grout. Under this procedure the outermost grout cover between the tube and the drill hole wall can be reduced to 12 mm (0.5 inches) and the nail need not be protected by an additional coating.

Critical values that define "aggressive" ground are as follows (FHWA RD-82-047):

<u>Test</u>	<u>Critical Value</u>
pH	Below 4.5
Resistivity	Below 2000 ohm-cm
Sulfate	Above 200 ppm
Chloride	Above 100 ppm

The above tests should routinely be conducted on representative soil samples as part of the subsurface investigation for permanent nailed wall applications. When such testing is not done, fully encapsulated nails should be used.

For temporary applications (less than two years) in non-aggressive ground, the grout only will provide adequate protection.)

4. CONSTRUCTION ASPECTS

Construction methods used for the majority of nailed walls built in Europe are very similar to those used in the United States. The German construction methods are most similar to those used in the United States, while in France nail installation and corrosion protection methods are sometimes different. England has built very few soil nail walls but the majority have been built using methods similar to those used in the United States

Soil nailing is used for both temporary and permanent construction. The most significant difference in construction aspects between the two applications is that permanent nail walls have a higher level of corrosion protection on the nails, and more reinforcing steel is used in the wall facing. Temporary walls are generally defined as walls with a required life of less than two years, while permanent walls have a life greater than two years.

The first soil nail wall was constructed in France by Bouygues in 1972. Since then, both driven and drilled nails have been used. Vertical walls have been constructed up to 24 m (79 feet) high and nail lengths up to 28 m (92 feet) have been reported. Battered wall construction is much more prevalent in Europe than in the United States.

In France and Germany, the design methods and construction sequence have been developed principally by a joint effort of government, contractors and consultants. Most contractors design their own soil nail projects so they can incorporate their own construction know-how and equipment capabilities into their designs and projects.

In Germany, the total soil nail wall market is in the range of 25,000-50,000 m²/year (270,000-540,000 ft²/yr), with permanent walls comprising from 10 to 50 percent of the total. Engineers and contractors estimate that over 500 soil nail walls have been constructed in Germany. In France, the total soil nail wall market is estimated to be on the order of 100,000 m²/year (1,100,00 ft²/yr) with permanent walls comprising 10 to 20 percent of the total. Typical job sizes are in the 500 to 2000 m² (5,400 to 21,500 ft²) range, with individual projects up to 20,000 m² (215,000 ft²) reported in France.

The equipment and methods used by contractors to install soil nail walls are generally similar to those used for tieback and mini-pile work.

4.1 Ground Conditions

For soil nail walls to be economical, they are constructed in ground that can stand unsupported on a vertical or steeply sloped cut of 1 to 2 m (3.3 to 6.6 feet) for one to two days, and that can maintain an open drill hole for a few hours.

Soils considered favorable to soil nailing are: weathered rock; naturally cohesive materials (silts and low plasticity clays that are not prone to creep); naturally cemented sands and gravels; and fine to medium, homogeneous sand with capillary cohesion of 3 to 5 kN/m² (60 to 100 psf) associated with a water content of at least 5 to 6 percent (There are sometimes face stability problems with this last soil type, particularly for south facing cuts subjected to drying by the sun.) Soil nailing is also very adaptable from a construction

viewpoint and is therefore appropriate for mixed face conditions, such as competent soil over bedrock.

Soil nailing is not recommended in ground with water pressure present at the face, in soft plastic clays ($PI > 20$), or in clean, coarse sands and gravels that are either uncemented or without capillary cohesion.

4.2 Soil Nail Construction

Drill Rigs. Most soil nailing is installed using small hydraulic, track-mounted drill rigs. These rigs are mostly of the rotary/percussive type that use sectional augers or drill rods. The rigs can work off benches as small as five meters wide, but are more productive if benches are seven meters or more.

The rigs are generally operated by one operator and one or two tenders. The number of tenders used is based on the weight of the augers or drill rods, hole location and hole orientation.

Large hydraulic-powered track-mounted rigs with continuous flight augers have occasionally been used to install nails up to 28 m (92 feet) in length. These rigs have the advantage that they can drill the entire length of the nail in a single pass without having to add sectional augers. Their main disadvantages are that they have a large mobilization cost, and require a much wider work bench than the smaller more common drill rigs.

Drill Methods. Open hole drilling is used to install about 90 percent of drilled-in soil nails. The method most commonly used in Germany to construct open holes is augering. Other drilling techniques used include percussive methods which displace soil by driving drill rods with a knock-off point on the end, and rotary-percussive methods which displace soil by drilling and driving drill rods. These nail holes typically have a diameter of 89 mm to 112 mm (3.5 to 4.4 inch).

Cased hole methods of drilling are used to install only about 10 percent of drilled-in soil nails. This expensive drilling method increases the cost of soil nail walls significantly to the point where alternative wall construction methods such as tieback walls are often more economical.

Cased methods of drilling include the single tube rotary method which involves drilling with a single tube (drill string) and flushing the cuttings outside the tube by air, water or a combination of water and air. The duplex rotary method is also used and is similar to the single tube rotary method except an outer casing is used which allows drill cuttings to be removed through the annular space between the inner and outer casing. Cased drill hole sizes are generally 89 mm to 133 mm (3.5 to 5.2 inch) in diameter.

Other less common methods of soil nail installation include jet grout nailing, self boring injection nails, and driven nails using steel angle. One contractor in the United Kingdom has used explosive injection of steel nails using an air gun. The use of driven nails is most prevalent in France where it was reported by one source that the French market is roughly evenly split among driven nails, conventional drilled-and-grouted nails and jet

grouted nails. Efforts to drive nails using steel tubes in France were reportedly unsuccessful whereas driven angle steel is significantly superior in accommodating subsurface obstructions. In Germany, driven nails are not allowed for permanent walls because of corrosion protection requirements.

Tendons. Steel bars with a yield strength in the range 420 to 500 N/mm² (60 - 72 Ksi), with or without corrosion protection, are typically used for conventional drill-and-grout soil nails. These bars typically have a diameter from 20 mm to 50 mm (0.8 to 2.0 inch). The use of fiberglass, geotextile nails, and steel angle was also reported. High strength bars, commonly used for post-tensioned tiebacks, are not used for soil nails because of concerns about brittle behavior under bending moments.

For temporary walls, corrosion protection generally consists of using a minimum grout cover. For permanent walls, the most common corrosion protection in Germany consists of the steel tendon encased in one layer of corrugated PVC (or similar plastic) sheathing filled with grout. The grout-filled corrugated sheath is normally required to be fabricated in a shop. Other less common methods of corrosion protection consist of using grout cover with sacrificial steel, or galvanized steel. This latter method is more commonly used in France, where corrosion protection did not seem to be as much of a concern as in Germany. In France, the estimated radial steel section loss was assumed to be uniform and on the order of 0.02 mm/yr (0.8 mils/yr).

Centralizers are placed over the tendon assembly on approximately 2 m (6.6. feet) spacing and are used to ensure adequate grout cover over the full length of the nail.

One contractor reported being uncomfortable with using galvanized angle for driving because of the uncertainty of the effect of driving on the galvanized coating.

Nail Layouts. For drilled and grouted nails, nail spacings of 1 m to 1.5 m (3.3 to 4.9 feet), both horizontally and vertically, are typical. For driven nails, however, the spacings are more on the order of 1.5 to 2 nails per square meter (.14 to .19 nails per square foot). The angle of inclination is typically in the 10 to 20 degree range.

Nail rows from lift to lift are commonly staggered to assist with face stability. Sometimes nails in the top row are spaced more closely to provide more stability during the often critical second lift of excavation.

One contractor in France reported sometimes making the lowermost and uppermost nails longer. The uppermost are made longer to minimize initial ground movement and the lowermost longer to safeguard against overall stability. The upper nail is sometimes made longer to account for added surcharge pressure or lack of adequate overburden and associated nail-soil adhesion.

The range of ratio of nail length to wall height is about 0.5 to 1.0, where ratios on the low end of the range might be used on battered wall construction or for higher strength soils.

Grouting. For open hole drilling, the low pressure tremie method is the preferred method of grouting. In Germany, contractors reported using re-grouting from 20 to 50 percent of

the time. Re-grouting is accomplished by installing the nail with a re-grout pipe attached. After initial grouting, grout is placed through the re-grout pipe under pressure, and fractures the initial grout, thereby creating a better bond between the soil and grout. The grout is normally a neat cement grout with a water-cement ratio of about 0.4 to 0.5. Grouting is sometimes performed prior to installation of the tendon and sometimes afterward.

Nail testing. Nail testing for determination of allowable nail-soil adhesions is performed principally on sacrificial nails which are tested either to pullout failure or to typically twice the required design adhesion. One or two French designers indicated that non-sacrificial proof testing of production nails to typically 125 to 150 percent of design adhesions may also be carried out, although this is not common European practice. All designs are ultimately based upon demonstrated pullout values from field testing during construction, although French practice makes extensive use of correlations between pressuremeter test results and nail-soil adhesions at the preliminary or initial design stage.

The frequency of testing varies depending on the size of the job and the uniformity of the field conditions. Typically, for a relatively homogeneous site, 3 to 5 percent of the nails are tested, where 3 percent might be required on larger jobs (greater than 100 nails installed) and at least 5 percent required on smaller jobs. At a minimum, testing is performed during the earliest stages of the wall construction, and again whenever changed conditions are encountered. Testing is performed either at the level currently being excavated or sometimes after the next level is excavated.

A minimum free length of about 1 m is left at the head of the test nail, so that the test nail will not interfere with the reaction plate positioned on the wall. Movement of the nail is monitored by a dial gauge mounted on an independent reference. A small jack and pressure gauge is typically used to apply the load to the nail.

Two nail testing procedures have been used in Europe. The first procedure, used only in France, involves using a constant rate of nail pullout and has the advantage of being a relatively rapid test. The second procedure, used more widely, involves constant load creep testing at various stages in the loading cycle and may occasionally result in testing extending to periods on the order of one day. Where there is concern for the long-term creep response of the soil, longer term nail creep testing will be performed.

Other Issues. There is no requirement for removal of temporary soil nails in any of the countries visited.

Underpinning of existing structures with soil nailing is approached carefully. It appears to be common to install stressed anchors in the upper row or two in order to control horizontal movements in this area. Other forms of support may also be used in conjunction with soil nailing, in underpinning applications. In Paris, for example, vertical bored or jet grouted piles are commonly used to underpin structures which are particularly settlement sensitive, prior to the use of soil nails for lateral support.

4.3 Drainage Construction

Drainage is considered a critical element and is incorporated into all permanent walls and many temporary walls, depending on conditions. Face drainage is most common and generally consists of a vertical drainage element placed between the back of the shotcrete wall and the retained ground. The water is collected at the base of the wall and transmitted away. These vertical drainage elements are installed from the top to the bottom as excavation proceeds downward. The drainage elements are typically 20-30 cm (8 to 12 inch) wide synthetic strips or perforated pipes. The strips or pipes are spaced sufficiently far enough apart (typically 1.5 to 2 meters) (4.9 to 6.6 feet) to provide for adequate surface area for the shotcrete to adhere to the ground. In France, strips as wide as 1 m (3.3 feet) on 3 m (9.8 feet) centers have been used for some battered walls, without encountering shotcrete adhesion problems.

Depending on site groundwater conditions, an alternative approach is to use weep holes through the face with or without longer horizontal, perforated drain pipes. The spacings and depths of the horizontal drains are dependent on the site specific ground water conditions but the drains are typically at 10 m (33 feet) centers and can extend to depths beyond the reinforced zone. One contractor pointed out the necessity to mortar and protect the outlet end of deep horizontal drains to ensure that collected water would be passed through the facing and not recharge the ground directly behind the wall. A surface water collector ditch, sometimes lined with plastic, is usually placed behind the wall to prevent surface runoff from either recharging the ground behind the wall, or flowing over top of the wall.

4.4 Facing Construction

Temporary soil nail wall facings generally consist of shotcrete and a single layer of wire mesh. In Germany, where shotcrete facings are commonly used for permanent walls, two layers of wire mesh are usually used. The two layers of mesh may be over the entire wall face or just at the nail head. Light horizontally reinforced concrete wales are also sometimes used. Some designers indicated that the nail bearing plate and the tendon are not permitted to contact the mesh reinforcing, to minimize the corrosion potential. Both wet and dry methods of shotcreting are used, with the dry method more common at present but the wet method being used more frequently, particularly on larger jobs.

Shotcrete is applied to the face at each lift of excavation. In Germany, shotcrete is used extensively for permanent as well as temporary walls, with the shotcrete left in the "gun finish". Wire mesh is normally 10 cm (4 inch) square and lapped in both the vertical and horizontal directions.

The shotcrete is normally 8-10 cm (3 to 4 inch) thick for temporary walls and 15-25 cm (6 to 10 inch) thick for permanent walls. For permanent walls, the initial shotcrete application is often considered temporary and not part of the permanent facing. Vertical expansion joints in permanent walls are commonly spaced about 10-20 m (33 to 66 feet) on center and vertical crack control joints are typically spaced at 7 m (23 feet).

Fiber-reinforced shotcrete has been used in France and Germany, but this is not common practice.

Cast-in-place concrete facings (Photo 29, p. 2-16) and precast panels (Photo 13, p. 2-8 and Photos 36 and 37, p. 2-21) are also used for permanent soil nail walls. For permanent walls, short soil nails are sometimes installed solely to support formwork during pouring of a cast-in-place facing. When driven steel angle is used for the soil nails, a steel rod inserted through a hole in the angle is used to secure the angle to the shotcrete facing (Photo 12, p. 2-7).

Another type of infrequently used facing is the prefabricated panel attached to the nail heads with plastic coated double screw ties. The gap between panel and shotcrete is backfilled with sand. These panels can be as large as 1.5 m by 10 m (5 feet by 33 feet).

4.5 Construction Sequencing

Excavation for a soil nail wall is normally performed in 1 m to 1.5 m (3.3 to 5 feet) lifts. Any location along a lift must have the nail and shotcrete work completed before excavating to the next lift in that portion of the wall.

Soil nails are typically installed before shotcreting. However, there are times when the shotcreting is performed before installation of the nails, particularly when short term stability of the excavated face is a concern. A thin shotcrete "flash" coat is sometimes applied if short term face stability is a concern. For open hole soil nails, the holes can be grouted before or after placing the tendons in the hole although the latter appears to be much more common.

4.6 Instrumentation and Monitoring

For most jobs, performance monitoring consists of measuring horizontal wall movements. Slope inclinometers, strain gages along the nail length, and load cells at the nail heads are normally used only on the more sensitive structures although some contractors (e.g., Cementation) appear to use inclinometers more commonly.

4.7 Construction Inspection

Quality Assurance/Quality Control (QA/QC) monitoring includes verifying that: 1) work is being installed in accordance with plans and specifications; 2) admissible excavation depths are not exceeded; 3) boreholes have not caved; 4) nail tendons are of the right size and composition; 5) corrosion protection systems are in compliance; 6) grouting, installation of rebar and mesh, and shotcrete are in compliance; and 7) nail pullout testing meets specifications. Normally grout and shotcrete cubes or cores are taken for strength testing for permanent walls. An essential part of the QA/QC process is monitoring of the material being excavated and drilled; this will assist in making design modifications should the material be different from that on which the design was based.

On a typical job for the railroad in Germany, an inspector might be on the job one-half to a whole day, each day of construction. For a reputable licensed specialty contractor in

Germany, an inspector might be on the job two to three hours per week. The German soil nail license requires specialty contractors to perform their own quality control. In Germany, the inspector may also be the proof engineer (the engineer who reviewed the contractor's design). It should be noted that in Germany, only a relatively few contractors are licensed to design and construct soil nail walls.

4.8 Deformations

Measured wall deflections appear to be similar to or slightly greater than those for tieback walls, and are generally in the range of 0.1 percent to 0.3 percent of the wall height. The contractor Bouygues, who performs an extensive amount of driven nail work, reports that the deformation response of driven and drilled nail systems are generally similar.

4.9 Performance/Construction Problems and Constraints

Performance of completed soil nail walls has generally been good with wall movements within acceptable limits. Most of the performance problems reported have occurred during construction when loose fill, granular soil, water or man-made obstructions were encountered, or when excavation limits were exceeded. In many cases, the first excavation lift is difficult because of loose soil or fill (cultural waste) at the top. In these cases, additional nails are often added along the top to increase nail density. At other times, the top of the wall is sloped in order to remove the loose fill material. Alternative solutions to the face raveling problem include pre-injection of grout to stabilize the soil before excavation, driving small diameter steel pipes at close (e.g., 1.2 m (3.9 feet)) centers, the use of slots (i.e., limiting the length of open excavation face before shotcreting), and decreasing the vertical lift thickness. At lower lifts, when loose or more granular material is encountered, or if excavation limits are exceeded, local sloughing has occurred at the face and piping has developed behind the previously applied shotcrete.

On a few projects, utility trenches behind walls have produced weakened planes that have resulted in movement and localized failures. Overexcavation of more than one lift has caused failure by overloading the unsupported face and the previously installed upper nails.

In France, it was reported that for those relatively few projects in which failure occurred, 75 percent happened during construction and 25 percent after completion of construction. In France, a section of wall about 500 m² (5,400 ft²) was reported to have failed after completion of construction due to soil conditions being weaker than those for which the wall was designed (Paris to Bordeaux TGV Lot 21). Frost action was also a possible cause.

Another failure in France occurred where soil nails were angled to miss a tree (Photos 16 and 17, p. 2-10). The failure was attributed not only to the angle of placement of the nails, but also to the absence of centralizers and poor grout quality due to improper methods of grouting the drill holes.

A temporary soil nail wall in Birmingham, England was reported to have failed along a 12 m (39 feet) length when the quantity surveyor eliminated the third tier of soil nails in a four tier system. The wall failed between the second and fourth tiers. Other contributing factors included plugged drains and unreinforced shotcrete.

Performance problems were investigated as part of the French Clouterre project; the project included failing three full-scale soil nail walls in Fontainebleau sand (SPT = 8-15 blows) by: increasing hydrostatic pressure on the wall by flooding behind the wall (Photo 8, p. 2-5); nailing the top two lifts and bracing the bottom three lifts, then removing the braces lift by lift until failure occurred upon removal of the fifth tier brace; and using shortened nails.

It appears that most problems that have been reported can be attributed to: 1) ground conditions being different from those assumed; 2) excavation exceeding design condition limits; 3) and man-made discontinuities behind the wall.

Where grout loss has been a problem during grouting of the nails (e.g., in open work gravels), solutions have included blowing sand into the hole to plug larger voids, using a thickened sand-cement grout, and using a geotextile sock to contain the grout.

4.10 Benefits/Limitations of Soil Nailing

Benefits and advantages of using soil nailing were reported to include: ability to easily follow the building outline (i.e., can zigzag as required); utilization of small construction equipment compared to alternative methods of construction; suited for special applications and remedial work; ability to mobilize to a site quickly; flexibility to make modifications during construction (e.g., can move nails to miss obstructions); and, compatibility with the usual constraints of operating in an urban environment (e.g., reduced noise, small overhead clearance, etc.).

The limitations of soil nailing were reported to include: inability to excavate where groundwater is a problem; difficulties associated with soil ravelling in cohesionless sands and gravels without special, expensive measures; problems with heavy concentrations of utilities, vaults or other underground obstructions behind the wall; and potential problems with high surcharge loading, expansive clays, and frost action. In addition, the wall performance was considered to be relatively sensitive to the method of construction, with best results achieved by experienced, specialty contractors.

4.11 Cost Data

If installed in ground conditions suitable for soil nail wall construction (i.e., no short term face stability problems, use of open hole drilling methods), soil nailing has proven to be a very economical method of constructing retaining walls.

In France, one contractor provided estimated permanent wall costs of about \$140-\$190/m² (\$13 to \$18/ft²) (US\$1=F5.50) for shotcrete and \$130/m² (\$12/ft²) for soil nails. One consultant's estimated cost for a permanent wall was about \$200/m² (\$19/ft²) for shotcrete

and \$160/m² (\$15/ft²) for soil nails. An estimate of about \$400/m² (\$37/ft²) was also given for construction of permanent soil nail walls.

In Germany, estimated costs for temporary soil nail walls were in the range of \$100 to \$230/m² (\$9 to \$21/ft²) (US\$1=DM1.50) and \$200 to \$400 /m² (\$19 to \$39/ft²) for permanent walls. As a comparison, the temporary soil nail wall costs can be compared to costs of \$180 to \$270/m² (\$17 to \$25/ft²) for a temporary Berlin Wall (i.e., soldier beams and tiebacks) which is the major competitor of soil nailing in Germany. It was stated that soil nail walls were generally more economical for cuts up to 5 m to 6 m (16 to 20 feet) in height, for excavations in soil over rock where rock is at or above subgrade, and at sites with difficult access. For greater wall heights, Berlin Walls were more economical. Soil nailing costs were also estimated to be on the order of \$45/m (\$14/ft) for temporary nails and \$65 to \$80/m (\$20 to \$24/ft) for permanent nails, with the facing costs approximately equal to the nail costs.

5. CONTRACTING PRACTICES

A key point is that there is no single "European" approach to procurement and contracting practices: as is detailed below, practices vary among different countries. However, there are some common philosophies which tend to distinguish European practices from those currently common in the United States. These are principally:

- a strong degree of industry/university/government cooperation;
- a high level of contractor involvement in the planning and design phases, as well as during construction;
- a more pragmatic and cooperative spirit between the various contracted parties, similar to our new concept of Partnering;
- consequently, far less of a litigious atmosphere;
- extended warranties on the work executed (occasionally up to 10 years).

Throughout, however, the contractor generally still has to have the low bid to be awarded the project.

5.1 United Kingdom

Practices are typically similar to those in the United States, where the contractor bids work largely designed by the Owner or Owner's consultant. Less frequently, the contractor will employ a consultant to help with his design, in cases where the specification is more of the performance type. This is becoming more popular, where nailing can be proposed as a cost effective alternate to other soil retention methods. Quantity surveyors, employed by the contractor, engineer and/or owner, act to define the quantities of work executed and so the final payment. These people also tend to handle disputes and claims, hopefully to a level of escalation below that of direct legal action.

There is a degree of contractor prequalification, especially for large or difficult projects, but the UK soil nailing market is not particularly large or active, and contractor acceptability tends to depend on other more general geotechnical or financial criteria, rather than specific soil nailing expertise.

Overall, the market is being developed by contractors, looking for an economic edge. Since consultants' fees are usually based on the overall construction cost, there is little incentive for them to be aggressive in pursuing and specifying more economical methods.

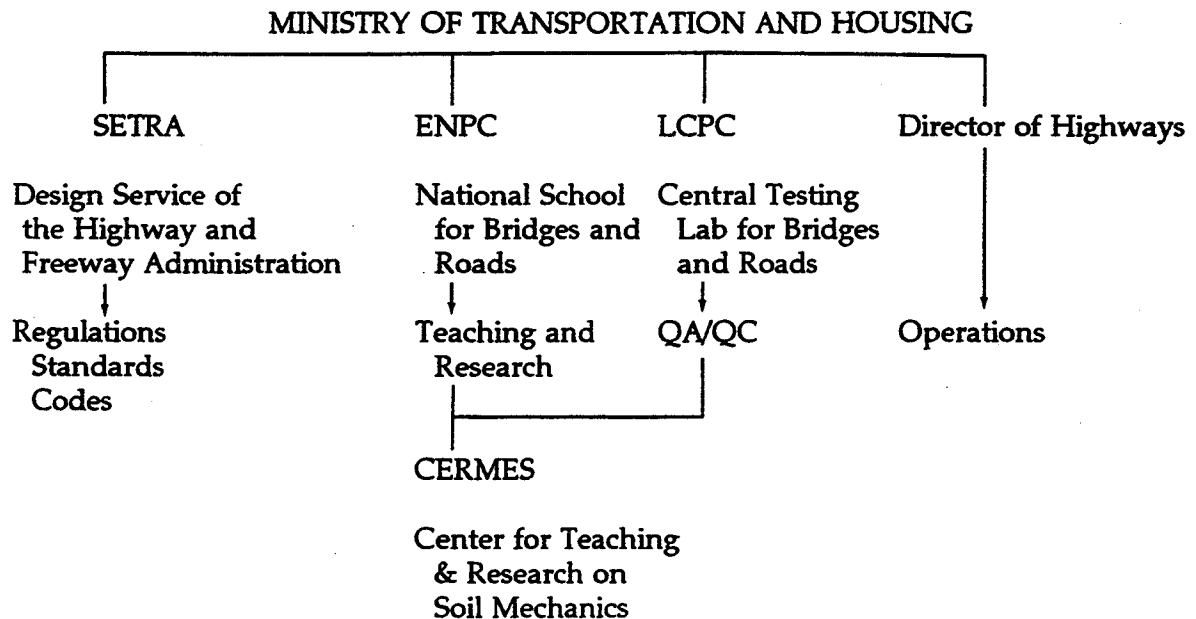
5.2 France

The contractor design-build approach seems to be prevalent. For public works, the Owner or Owner's consultant typically prepares designs to about the 75 percent level. Selected contractors are then given the opportunity to finalize the design and prepare a bid. This can include the preparation of alternative designs. The contractors tend to be larger and stronger than in the United States or the UK, and all the major groups have extensive research, development and technical services teams and budgets. Contractors are provided at the bid stage with all the available geotechnical data and are clearly informed of the nature and goals of the work. They may consider various options, selecting soil

nailing as their final proposal only if it is technically and financially viable and meets the overall scheduling requirements. In France, it was reported that soil nailing was often one-third to one-half less costly than alternative methods of construction. Highly specialized individuals may also be engaged to help prepare designs, especially as related to nail lengths and spacings.

A most significant point in France is the high degree of national cooperation in the research and development of design and construction techniques. The Center for Teaching and Research on Soil Mechanics (CERMES) has a formal structure of interaction with the Universities and with contractor organizations. The National Soil Nailing Research Project, "Clouterre", which is now providing the equivalent of a National Code of Practice, had a formal Board of Directors and was financed both by Government (15 to 20 percent) and by private industry (21 groups of academics and contractors). The largest contributor was the Experimental Center for Research and Studies on Building and Public Works (CEBTP), the contractors' federation, the members of which performed the work and managed the money. The next major such national project - "FOREVER" - will investigate micropiles used for load bearing and as in-situ earth reinforcing. This will be a 5-year project, with a budget of about \$5 million and, hopefully, direct collaboration with the FHWA.

The organization structure for these French National Research Projects appears to be as follows:



There is also a relatively new agency called IREX (Institute for Practical Research in Civil Engineering) which has a permanent board of Government and (mainly) private members, and which is charged with putting CERMES, CEBTP, etc., together to promote future research projects. (Clouterre and Forever fall under this sponsorship.)

5.3 Germany

Companies must have a government license to fabricate and install nails (although it does seem that with respect to installation, it is often not necessary to have a license). Bauer was the first contractor to apply soil nailing in Germany and invested heavily in the '75-81 Bodenvernagelung tests. Since then, however, approximately six other competitors have been accepted, and most of the license requirements are essentially similar. These licenses outline the design, fabrication and installation details to be followed by the licensed organization.

For private work, the contractor is usually either required or at least permitted to prepare his own design/build earth retention scheme. Low price bid almost always wins the work. For public work, the agency's designer generally provides a wall design for bidding purposes. This design will often be for a wall type other than a soil nail wall. The contractors are required to bid on the pre-designed wall. However, the public agency also allows and encourages the contractor to submit any alternate design that will provide an equal wall at a reduced price. The agency then awards the job based on lowest price, including the contractor proposed alternates. In rare circumstances, other factors such as improved scheduling may result in contract award to other than the low bidder. A soil nail alternate design will almost certainly be approved, providing it is designed in accordance with the license requirements. Sometimes the public agency does not provide any wall design (or at most a very conceptual level design), but simply defines geometric requirements and a detailed geotechnical report which outlines the relevant soil parameters and highlights any potential problems. The contractor then produces a design which is in accordance with the geotechnical report design recommendations and with the requirements of his license. The contractor takes responsibility for his design and is expected to inspect and warrant his own work.

A special "checking engineer" may be employed by the owner to check design proposals for acceptability. The designs can be accepted as is, rejected wholly, or can be accepted only with changes. (In this case, if the changes mean extra cost, then the bidder may then not necessarily still be low and negotiations continue). Each checking engineer must also have a license.

For an innovative technology, a special test program can be run and certified. This new concept must be described by the contractor in his bid, in a covering letter.

Again, as in France, the contractors tend to be technically and financially strong, and tend to make use of specialist consultants for their soil nailing designs.

Disputes are rare, with the courts serving only as a last resort.

5.4 Italy

While not part of the detailed scanning tour, personal knowledge suggests that the practices in Italy are very similar to those of France, with a heavy emphasis on design/build, innovative solutions. Contractors therefore have a heavy involvement in the design of the project, from conceptual stage through final design. Alternative bids are

encouraged and widely used. Contractors provide warranties which may be as long as 10 years. Considerable use is made of individuals or small "studios" of highly specialist consultants to aid both the contractor and the general consultant.

5.5 Contracting Overview and Recommendations

Soil nailing may be regarded still as a relatively innovative technology in Europe. Given the examples of France and Germany in particular, it would seem that its current popularity is due to a variety of factors including

- cost effectiveness;
- reliable design methodologies;
- quality construction by prequalified contractors;
- confidence in the performance of finished structure;
- good working relations between the contracted parties.

In addition, there are other more general factors including the availability of soils of the appropriate type, national construction demands, and the overall economy, but these are variables inherent in every country.

The growth of this innovative technology in France and Germany is probably a direct result of the following two special factors:

- a) Transforming the traditional Owner-Designer-Contractor chain into a Partnership in which the Contractor may well also be the Designer, - or he may employ a Designer, - in a Design-Build option. This system benefits all parties:
 - the Owner still gets the lowest prices, but should have a technically superior product, warranted for a specific period by the Contractor.
 - the Designer is still involved, in a wider role, with either the Owner or the Contractor, either as a Designer, a "checker", or a construction monitor.
 - the Contractor has an incentive to innovate, and to refine the quality of the product.
- b) Encouraging very strong, practical links between government, academia and industry. This not only allows innovative geotechnical solutions to be "exposed" across a wide spectrum but it also allows an equitable sharing of research costs for mutual benefit, not to mention the benefit of attracting expertise from all corners of the business.

Using this model, therefore, one can draw two main recommendations for fostering similar innovative geotechnical processes in the United States:

- a) Encourage Alternative Bidding , built around Contractor Design-Build concepts, and promoting the benefits of Partnering. This implies much more performance oriented specifications which can only be bid by carefully prequalified specialty contractors.
- b) Establish a stronger and more formal government-academia-industry cooperation to research and disseminate these processes in a non-proprietary fashion.

Regarding recommendation a), this can be put into effect now for soil nailing projects. For b) the possible cooperation with France on the FOREVER program would be an excellent starting point, while similar research into micro (pin) piles would be equally exciting. There is no compelling reason why cooperative R&D cannot be accomplished in the United States, similar to that practiced in France. All that is required is a strong commitment on the part of government, academia and industry to "make it happen".

6. RESEARCH AND DEVELOPMENT ACTIVITIES

During the technical discussions with each individual/organization visited on the tour, the team indicated its interest in obtaining information pertaining to completed or on-going research projects, together with any ideas they might have concerning future research needs for soil nailing. The main objectives of the research scan were to identify any research projects previously unknown to the team, and to gather any relevant reports and articles pertaining to the research projects of which the team had prior knowledge. Face-to-face discussions with key investigators along with visits to actual research sites were also important objectives.

6.1 Soil Nailing Research Activities in the United Kingdom

Soil nailing in the United Kingdom has not reached the same level as in France or Germany. In some respects it is not as far along as here in the United States. Although the British have not constructed many soil nail projects, they have monitored the progress in the United States, France, and Germany, in order to incorporate the advances of others into their national specifications.

Some of their more notable contributions have been in the areas of design computer program development, monitoring of stresses in nails and soil displacements for both prototype and test walls, centrifuge testing, and shear box testing of soil/nail interactions.

The computer program, "NAIL SOLVER," which was developed by Dr. Richard Jewell in 1990 under a research study, is quite popular with geotechnical engineers in the United Kingdom and was discussed previously. Another design computer code, "GENNAIL", is currently under development at the Transportation Research Laboratory (TRL). It is expected that field data from the various British programs will be made available to the United States program for use in ongoing evaluations of design capabilities of the various available computer programs.

With the exception of some on-going research work at Oxford and Cardiff Universities on shear box testing, there appears to be limited current research in progress, nor do there appear to be any plans to conduct further research on soil nailing. Dr. Colin Jones of the University of Newcastle has recently completed a section of the new British Design Code that deals with Soil Nailing, and Dr. Richard Murray of TRL has developed a draft specification for soil nailing. Copies of both were given to the team for further study.

The objective of the research at Cardiff University under the direction of Dr. Ben Barr is to investigate the fundamental mechanisms associated with soil nailing using driven (non-grouted) bars in a large shear box (2.8 m (9.2 feet) long having a shear plane 1.5 m x 1.5 m (5 ft x 5 ft). They are investigating the increase in shear stress capacity of soil when reinforced by single nails or groups of nails, together with the effect of the inclination of nails to the shear plane on the shear stress capacity of reinforced soil. The nails are instrumented with strain gauges and earth pressure cells are located in the soil adjacent to the nails.

As noted earlier, the British have developed a machine that uses compressed air to shoot soil nails at over 320 km/hr (200 mph) into the ground. The method and the prototype equipment were developed and patented by the Industry Center at Cardiff University. They have granted Soil Nailing Limited an exclusive world wide license to market the system. Mr. Bernard Myles discussed this system with the scanning team and showed the team a site where the explosively injected nails had been used to stabilize a railroad bridge approach fill on one of British Rail's high speed (320 km/hr (200 mph)) rail lines (Photos 1 and 2 p. 2-1).

6.2 Soil Nailing Research Activities in Germany

The Germans were the first to actively pursue soil nailing technology from an applied research standpoint. However, they do not currently have a separate code or manual of practice for soil nailing but instead issue "licenses" to qualified contractors to perform the work.

The first major research project ("Bodenvernagelung") in the world on soil nailing was performed by the Germans during the period 1975-1981. The Federal Ministry of Technology funded part of the research at Karlsruhe University under the direction of Professor Gudehus and a graduate student, Günter Gässler, who is now a professor at the University of Stuttgart. Professor Gässler was our host for the first 2 days in Germany. One of the main presentations he made was on the results of their research project. He noted that Bauer Construction Company furnished a significant part of the funding support and built the test walls. Bauer received the first government license to construct soil nailed walls in Germany. Six other contractors are now licensed.

The German research project involved both model and full-scale tests plus a comprehensive data analysis program (Photos 30-32, p. 2-17 to 2-18). The model tests were conducted in a large box to observe failure mechanisms under a variety of loading conditions. Approximately 100 pullout tests were also performed on nails under various overburden pressures, prior to loading several of the full-scale wall systems to failure. Overall, the full-scale test program involved seven test walls of varying heights and soil types. FHWA has requested copies of the various research reports and raw data files.

The most important conclusions from the Bodenvernagelung program were:

1. The nailed soil structure behaves like a gravity wall.
2. The required nail length for a vertical wall and a horizontal ground surface lies in the range of 0.5 to 0.8 times the height of the wall.
3. The spacing of the nails should be less than 1.5 m (5 feet).
4. The wall face pressure may be assumed uniform with a magnitude on the order of 0.4 to 0.7 times the active Coulomb earth pressure.

6.3 Soil Nailing Research Activities in France

The French have been the most prolific country in the development and utilization of soil nailing technology. Although they were not the first to do research, they have made remarkable advances in soil nailing technology through research and on-the-job innovation.

The centerpiece of their various programs was called "Clouterre," which was a 4-year research project (1986 to 1990) to establish design and construction guidelines for using soil nailing technology. Another important product that came out of their research program is the computerized design method called "TALREN." The recommendations contained in the Clouterre report and the TALREN program are now becoming widely used by the French government and the private sector. Another computer program called "STARS" has been developed at the École Polytechnique in Paris. However, this computer code is very new and has not had a lot of exposure.

The Clouterre research project cost approximately 20 million French Francs (\$4 million United States dollars) and involved instrumentation and monitoring of six in-service walls along with the construction of three test walls at the central research testing site located on the grounds of the CEBTP which is the national Experimental Center for Buildings and Public Works. The CEBTP is a Federation of private contractors and government ministries that initiates and conducts research programs on a national scale. Government agencies contributed about 15-20 percent of the funding, and the private sector furnished the remaining funds to sponsor the research.

The three research test walls at CEBTP, which were tested to failure, were constructed in Fontainebleau sand fill. On one of the walls, failure was induced by flooding the soil mass. The mass was then excavated to observe the deformation of the nails and the soil (Photo 8, p. 2-5). The soil deformations were delineated by incorporating layers of colored sand at each meter of depth in the constructed fill and observing the deformation patterns of these layers following completion of the test.

In a second test, the influence of the nail length in relation to the wall height was examined and failure was induced by progressively shortening the length of the nails. The third test involved inducing failure by progressive removal of the face panels from the lower portion of the constructed wall in order to examine the effect of the height of the unsupported cut on overall wall stability. The lower region of the test fill was not nailed and was constructed against face panels held in place by removable struts. The face panels were removed until a piping-type failure occurred with the soil running out from behind the upper nailed portion of the wall.

The main conclusions from the three walls tested to failure are:

1. The maximum tensile force in the nail is not located at the nail head but at some distance away from the facing. The ratio of the force at the nail head to the maximum nail force decreases as the excavation progresses.

2. The first resisting force mobilized is the tensile force in the nail. Prior to failure, the bending stiffness gives an additional safety factor and prevents a quick collapse.
3. Limit equilibrium methods appear to be capable of accurately predicting the behavior of a soil nailed wall, taken to failure.
4. The vertical height of each excavation stage is critical to stability during construction.

In addition to the three research walls that were load tested to failure at the main facility, the Clouterre program also instrumented and monitored six other nailed walls constructed in various parts of France. Each of the six "in-service" walls was instrumented to monitor the stresses and displacements in the facing wall, individual nails, and the soil mass. Strain gages, load cells, and inclinometers were used to gather these data.

The French are presently developing another soil nailing research project termed "Clouterre 2" which is a 2-year extension of the previous work and is designed to study seismic aspects, frost effects, and deformations in more detail. Clouterre 2 will also look at slope stabilization by soil nailing in more detail because the initial work concentrated on vertical to near-vertical cuts. The FHWA has been asked by the French to consider joint funding support for this additional research work on soil nailing, which is estimated to cost \$2.5 million total. A cooperative research agreement between France and the FHWA Office of Research is expected to be executed by April 1993.

As part of a transition project between Clouterre 1 and Clouterre 2, the French are working on the development of a finite element program to predict soil nail wall displacement. A copy of a recent PhD Thesis from the University of Illinois which presents the results of finite element simulation of soil nail walls was sent to Mr. Philippe Unterreiner for their information and use. The thesis uses a program called SNAP that was developed at the University of Illinois.

The scanning team was also given a presentation on a large research effort on the behavior of micropiles that the French plan to initiate in the near future. The project is called "FOREVER" which is an acronym that stands for "Foundations Reinforced Vertically." The French would also like the FHWA to join them in partnership to perform this 4-year study of the mechanisms of interaction of micropile groups and systems using laboratory tests, centrifuge testing, full-scale field testing, and numerical modeling. Work on this project will be included in the previously mentioned cooperative research agreement to be signed in April 1993. This project is estimated to cost \$5 million in total.

6.4 Future Research Needs

In the opinion of the scanning team, future soil nailing research requirements can be summarized and prioritized as follows:

1. Case History Data Bank

A data base shell or repository should be established for storing information on nail pullout test results and case history projects to include both full-scale and model test

walls, plus any well-instrumented, carefully monitored soil nail walls that have been placed in service. These data will be very useful in evaluating failure mechanisms and computer-aided design methods and developing improved predictive methods for wall deformations.

2. Evaluation of Existing Design Methods

It is not evident at this time which of the many computer-aided design methods are most suitable and what are the major differences among the various methods. A validation study of available design methods needs to be carried out so that suitable design methods for nails and facings can be identified.

3. Instrumentation and Monitoring of Full-Scale Walls

It is expected that the data base will contain significant gaps that can be filled only by implementation of field monitoring of in-service structures. Information such as the magnitude and distribution of maximum nail loads and facing loads are particularly required. Other data needs include wall and ground displacements, response to heavy surcharge loads, and time dependent response.

As part of this monitoring program for in-service structures, we need to develop a generic Guide Instrumentation Plan Details and Specifications Package that can be incorporated into State Transportation Department construction contracts for wall performance monitoring. An R&D effort will also be needed to plot, interpret, and summarize the data gathered from these instrumented in-service walls. This effort should be continued for a period of at least 5 years to include new data from future relevant projects.

4. Wall Facing Design

Procedures for estimating design loadings and approaches for facing design need to be developed, covering both the limiting strength and the serviceability conditions.

Load factors and resistance factors for transition to Load and Resistance Factor (LRFD) design must also be developed. Some limited structural testing of thin 10-15 cm (4-6 inches) facings of shotcrete should be performed, to verify the actual structural capacity of these thinner facings and actual failure modes of nail-wall connections. These test results will be very helpful in developing the recommended load and resistance factors for the LRFD design.

5. Corrosion Protection

The controversy surrounding the use of epoxy coating as permanent protection should be resolved, and other corrosion issues addressed (e.g., what type of protection is required for permanent nails). The use of fiberglass bars as nails should also be evaluated.

6. Consideration of Special Design Events

There is a need to investigate the performance of soil nailed walls to seismic loading, and the effects of freezing, expansive soil behavior, and heavy surcharge loads.

7. Slope Stabilization With Soil Nails

The lessons learned from the research on vertical cuts should be expanded and guidelines developed for the design of flatter slopes stabilized by dowels. Of particular interest is the effectiveness and economy of different nail orientations, i.e., near vertical nails (dowels) acting predominantly in shear versus near horizontal nails acting predominantly in tension.

8. Design Parameter Study

The behavior of the reinforced mass with respect to the relationship of nail spacing and diameter to stiffness and deformation should be studied. The diameter of the nail hole and its effect on design and slope stability should also be investigated.

9. Drainage

There is a need to evaluate the effectiveness of typical drainage details currently being used.

10. Nail Bond

There is a need to evaluate the effect of varying nail bond lengths on the interpretation of the pullout capacity from nail tests.

The anticipated benefits of performing the above programs include a better fundamental understanding of soil nailing behavior, improved design methodologies and specifications, and more cost-effective solutions to many support/stabilization problems.

7. ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1
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APPENDIX 2
PHOTOGRAPHIC RECORD

Project: Soil nail slope stabilization on high-speed rail line near York, England

Description: Failing railway embankment slope (clay soils) stabilized by innovative new development using "fired" nails. Top photo shows nail launcher during "firing" sequence. Machine uses compressed air to propel the nail into the ground at an initial firing speed of 320 km/hr (200 mph). Nails are galvanized 25 mm (1 inch) diameter solid steel bars. Used in this application with nails installed approximately perpendicular across the slide failure plane, the nails function primarily as "shear dowels" or pins. Bottom photo shows revegetated slope approximately two years after nails were installed. The embankment slope on the opposite side of the track was stabilized with a tieback wall approximately five years earlier. The fired nails were reportedly less costly than the tieback wall and offered the aesthetic advantage that the slope could be revegetated after the nails were installed and cutoff at the slope face. Limitations of the launched nails include nail length limited to 6 m (20 feet) and limited penetration depth in stiffer soils – therefore, only applicable to shallow 3 to 4 m (10 to 13 feet) depth slides. *(Photos courtesy Soil Nailing Ltd. and J. Walkinshaw)*

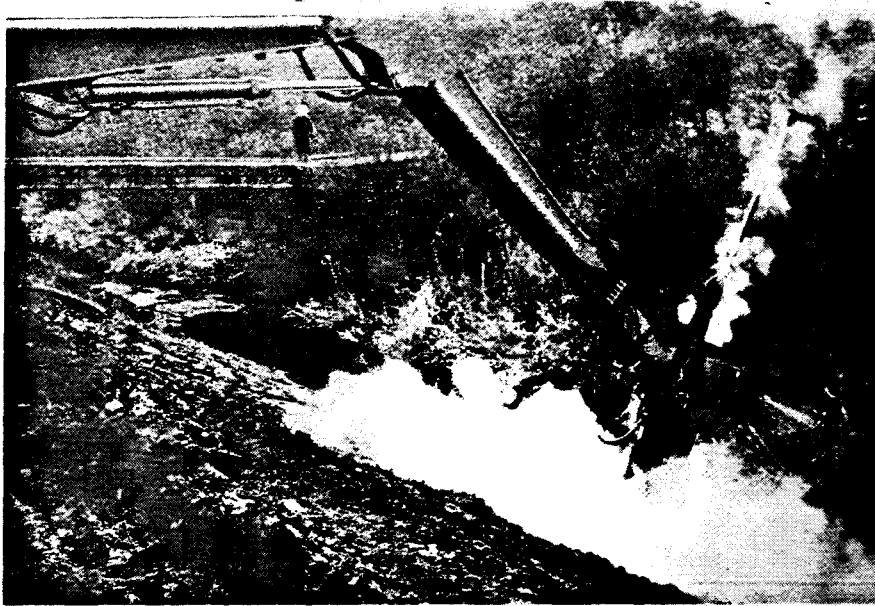


Photo 1



Photo 2

Project: Retaining wall repair, South Wales, England

Description: Permanent soil nails used to repair old failing stone masonry wall next to school building. The wall exhibited cracking and bulging and movement of 5 mm (0.2 inch) had been monitored over a 6-month period. Wall Height = 3 m (9.8 feet); Nail Length = 5-6 m (16.4 to 19.7 feet); Grouted Drillhole Diameter = 100 mm (4 inch). Ninety (90) encapsulated soil nails were installed through the wall in two rows at a spacing of 2 m (6.6 feet) horizontally and 0.75 m (2.5 feet) vertically. After nail installation, nail holes at wall face were grouted flush to the wall face. Illustrates one of the advantages of soil nails -- can be installed with small drill rigs in limited work room. Wall movement was monitored for 14 months after soil nail installation and no movement or further cracking was detected. (Photos courtesy Colcrete, UK)

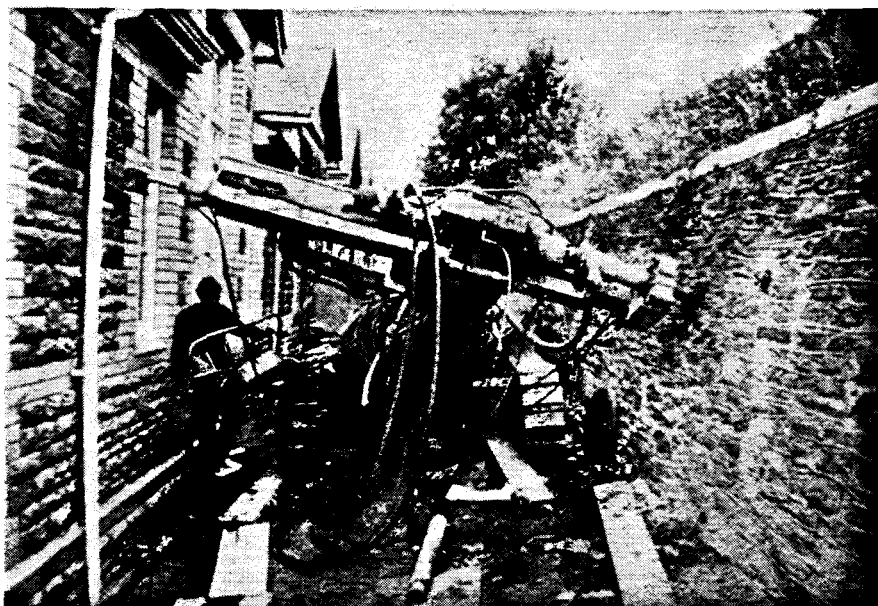


Photo 3

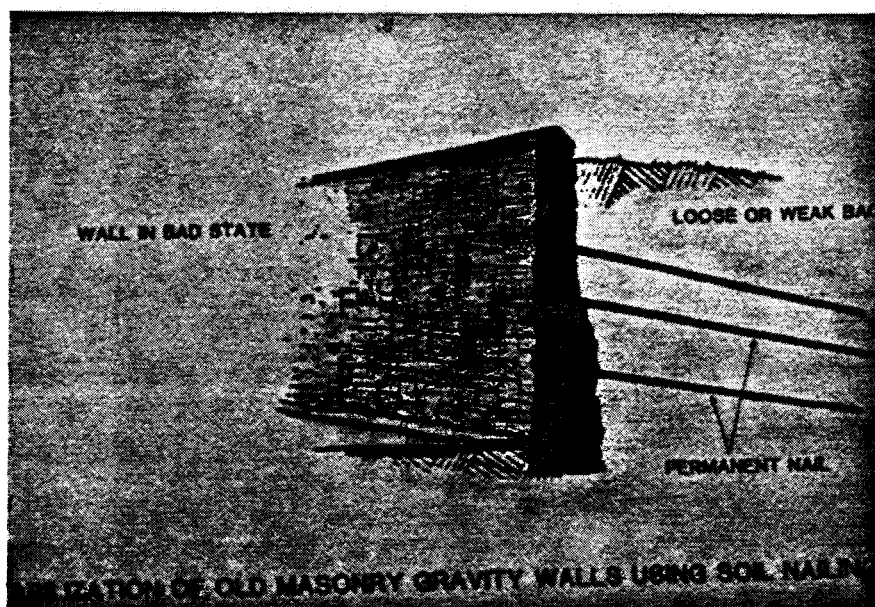


Photo 4

Project: New bank building, Island of Guernsey, England

Description: Slope stabilization with permanent soil nails. Previously existing 50 degree slope was steepened to 70 degrees to make room for a new bank building. Nail support allowed the oversteepening. Total slope height = 20 m (66 feet). Double corrosion protected soil nails were placed into 100 mm (4 inch) diameter grouted drillholes. Soil is dense clayey silt. Slope was faced with geogrid (top photo) and then sprayed to re-establish vegetation (bottom photo). *(Photos courtesy Cementation Ltd., UK)*

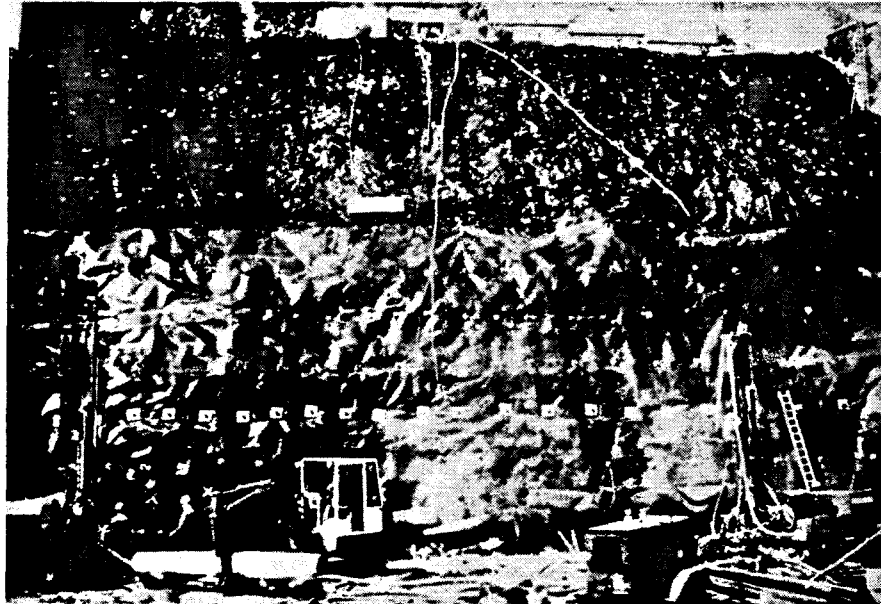


Photo 5

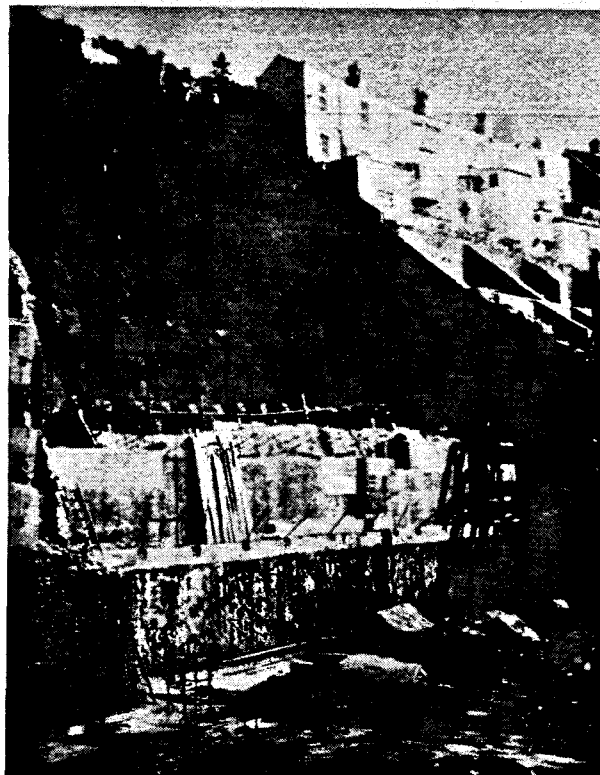


Photo 6

Project: First European soil nailed wall at Versailles, France (1972)

Description: The first recorded European application of soil nailing was in France in 1972, where a nailed wall was used to stabilize a 70 degree cut slope in cemented sand for a railway widening project near Versailles. A total of 12,000 m² (130,000 feet²) of slope face was stabilized by over 25,000 steel bars grouted into predrilled holes up to 6 m (19.7 feet) long. The temporary shotcrete facing was covered with a reinforced concrete wall. The during construction photo below shows the nailed slope with temporary shotcrete facing in the foreground with sections of permanent reinforced concrete facing completed in the background. *(Photo courtesy Bouygues)*

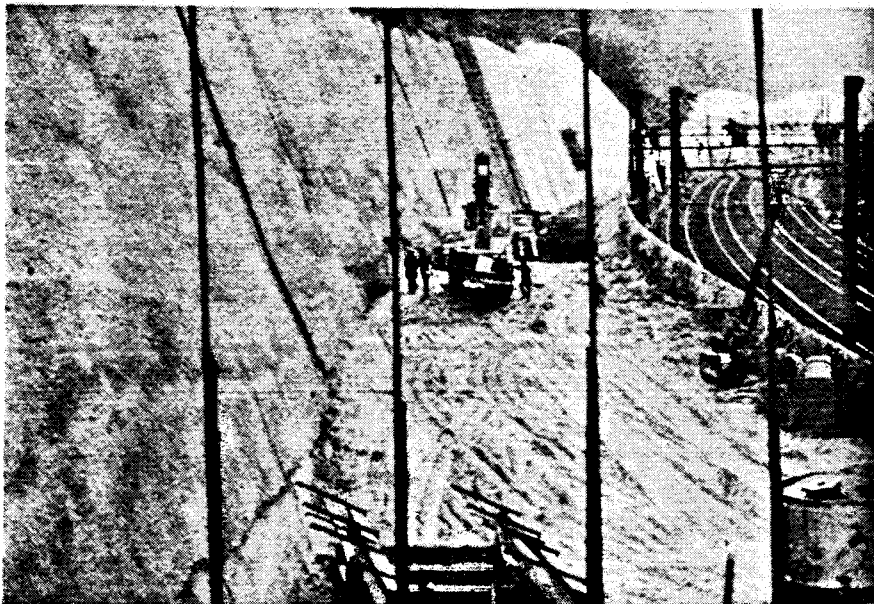
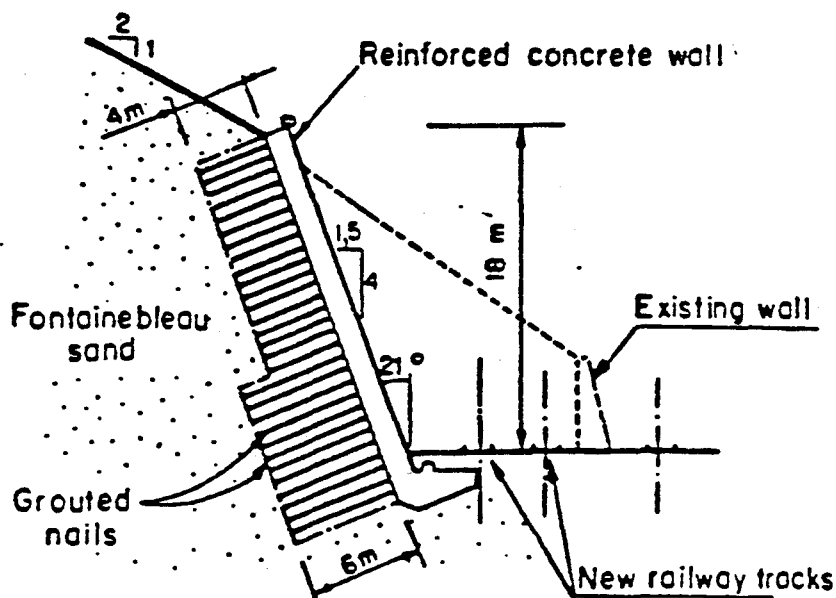


Photo 7



First soil nailed wall at Versailles, France

Project: "Clouterre" Research Project, France (1986-1991)

Description: An extensive five-year soil nailing research project was conducted in France during 1986 to 1991. The project included inducing failure in three test walls and instrumentation of six in-service walls. The photo below is from one of the walls tested to failure. After failure, the wall was excavated to observe the nails. The cross-section below shows the post-failure condition of the first test wall. For this test wall, very flexible aluminum nails were used. The three test walls were failed, respectively, by: 1) saturating the soil backfill, 2) over-excavation, and 3) progressively shortening the nails.

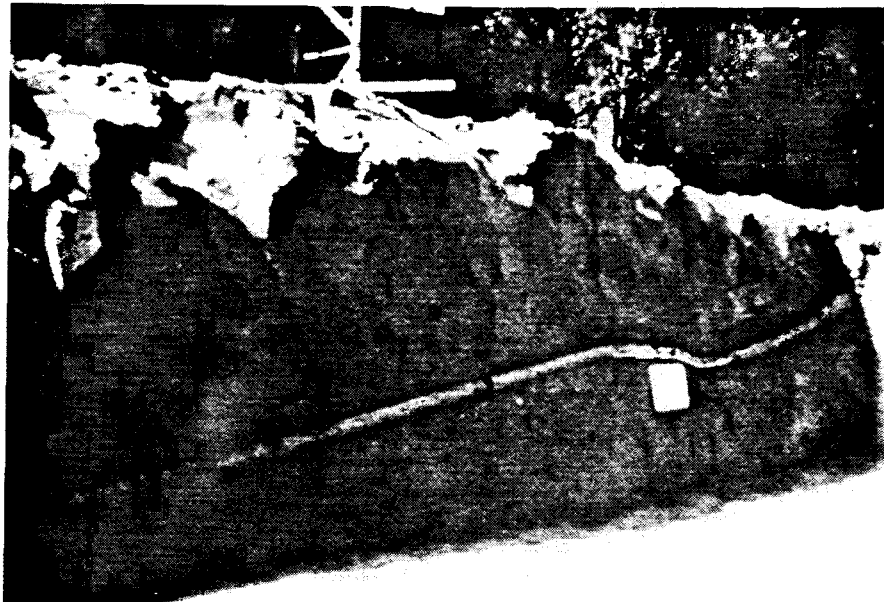
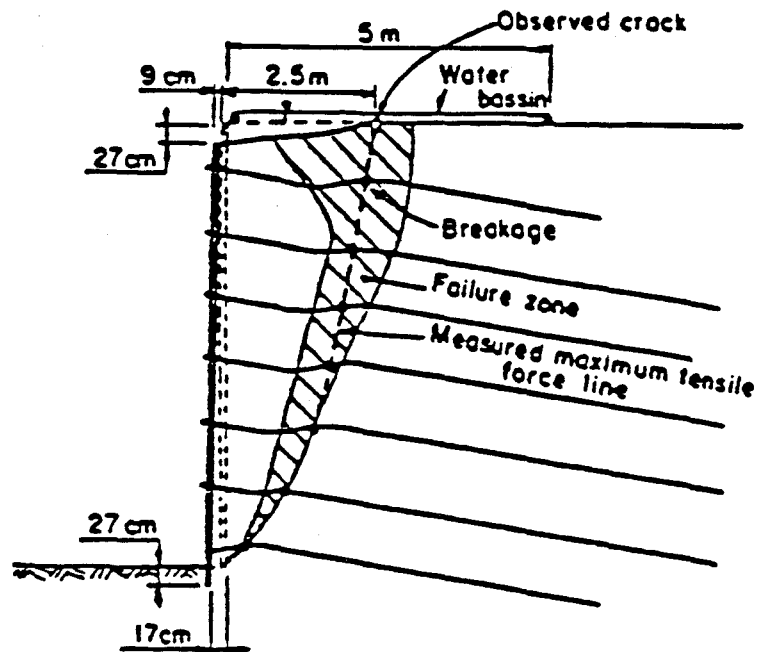


Photo 8



CEBTP Test Wall No. 1: Failed by saturating the sand backfill (CLOUTERRE).

Project: 21 m (69 feet) high soil nail wall at Montpellier, France

Description: A temporary soil nail wall constructed 21 m (69 feet) high using driven nails and one row of tiebacks. The nail wall was used for temporary excavation support to allow construction of a new building adjacent to older historic buildings. Soils are slightly cemented sand. The upper row of tiebacks was used to help limit lateral deflection of the top of the excavation to prevent damage to the settlement sensitive older historic structures. Photos below show an overall view and the 21 m (69 feet) high portion of the wall. The combination of one or two upper tieback rows with nail support below, is common in France for excavations adjacent to structures. *(Photos courtesy Bouygues)*

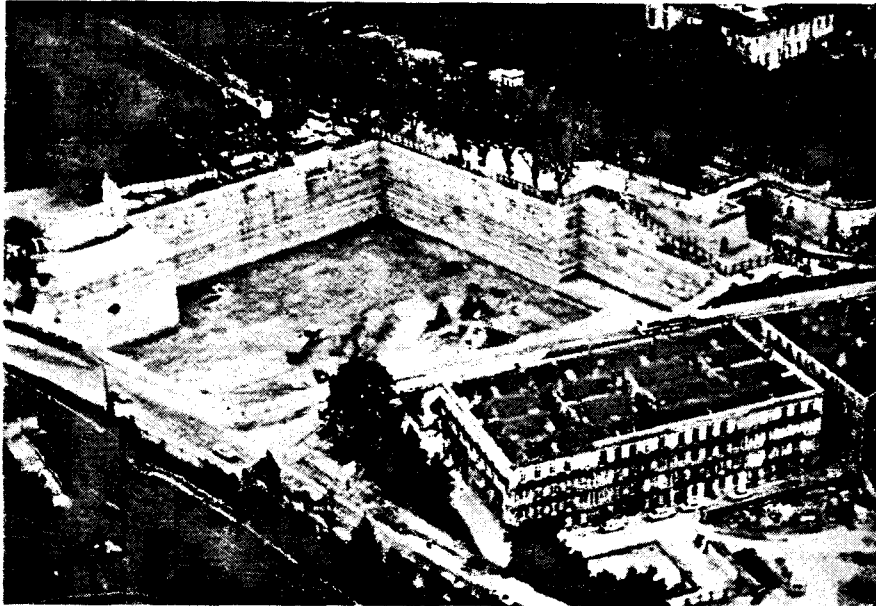


Photo 9

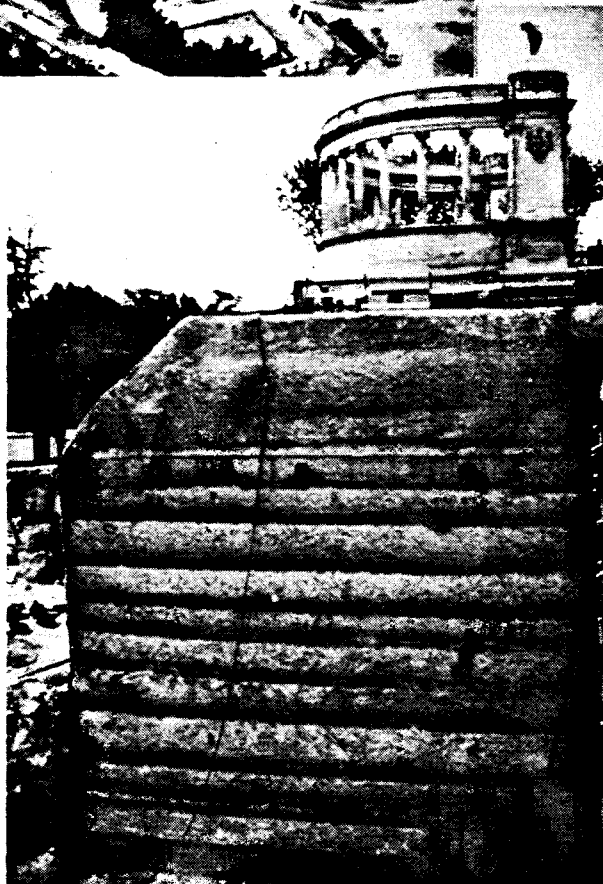


Photo 10

Project: 21 m (69 feet) high soil nail wall at Montpellier, France (cont'd.)

Description: Photos below show the design cross-section and close-up of the excavation face. The nails consist of driven steel angles called "Hurpinoise" which is proprietary to the French specialty contractor Bouygues. A significant advantage of driven nails is that excavation face support can be provided immediately after excavation. The project was completed successfully without damage to the adjacent historic structures. *(Photos courtesy Bouygues and P. Unterreiner)*

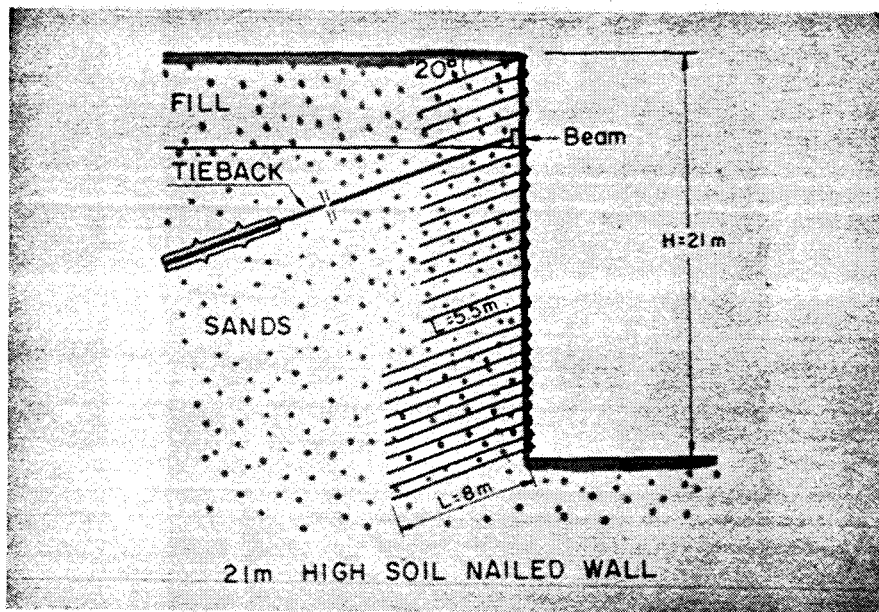


Photo 11



Photo 12

Project: Tunnel Portal stabilization near Lyon, France

Description: Permanent soil nail wall with precast face panels. Face panels have concrete planter boxes cast into them. Constructed 1986. *(Photo courtesy J. Walkinshaw)*



Photo 13

Project: High Speed TGV Rail Line south of Paris, France

Description: Soil nail wall along TGV rail line constructed by Bouygues. Top photo shows vibro-percussion type drill rig used to install "driven" nails (steel angles) Soil is slightly cemented sand. Bottom photo shows the several steps in nail wall construction sequence going on concurrently, i.e. from background to foreground: 1) excavation, 2) installing driven nails, 3) steel reinforcement wire mesh and shotcrete. *(Photos courtesy Bouygues)*

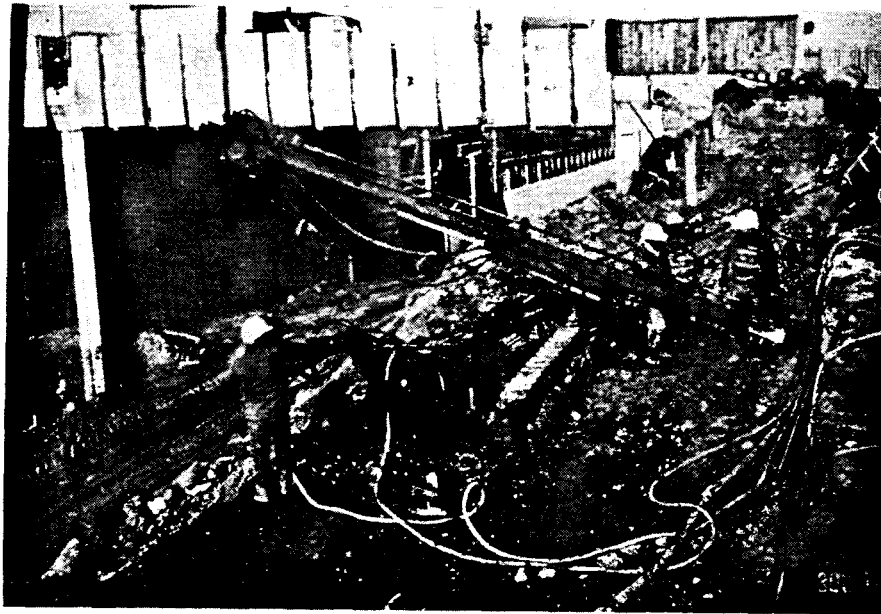


Photo 14

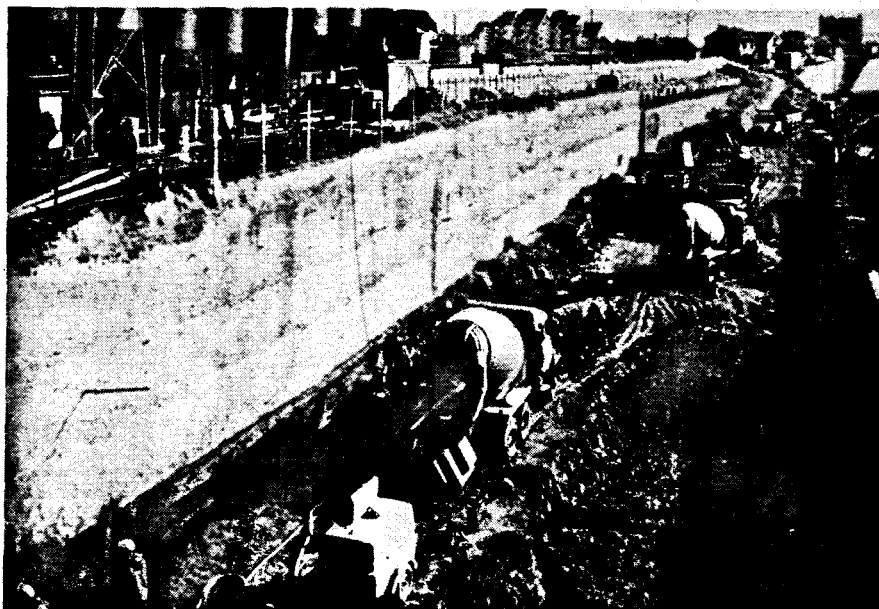


Photo 15

Project: Failure-Temporary soil nail wall -- Champagne, France

Description: A small temporary soil nail wall was used to save a Sequoia tree. Failure occurred when bottom lift was excavated. Cause of failure was attributed to combination of: 1) Nails too widely spaced and angled off to sides to miss tree root zone, and; 2) Lack of adequate grouting around some of nails. French engineers who designed this project stated they would use a sheetpile wall if they encountered this same situation again. *(Photos courtesy Simecsol)*

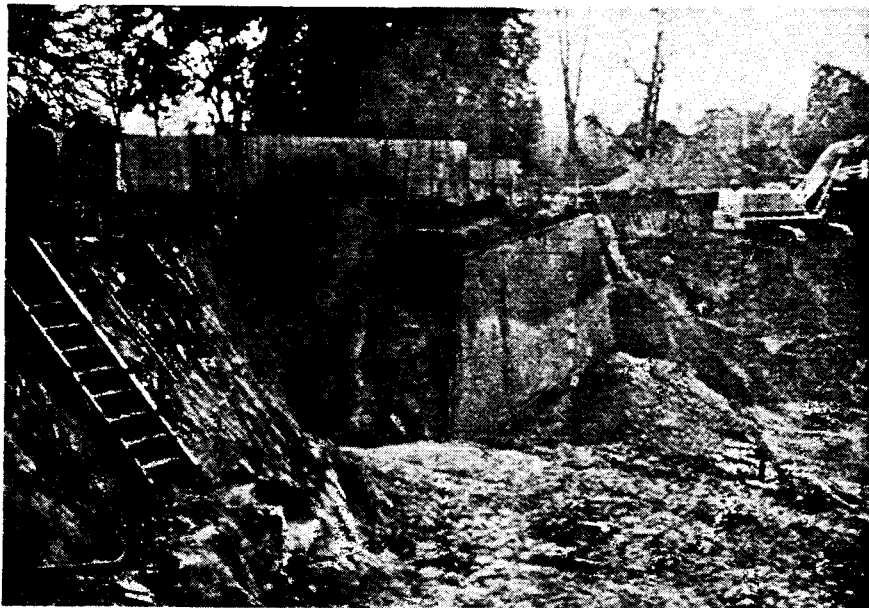


Photo 16



Photo 17

Project: Eparris Wall Failure, 1980, France

Description: Example of soil nail wall failure due to pullout of soil nails. The short, low height wall (with steel grid facing), built in a soft clayey soil, failed after a heavy rainy season. The failure (see photos below) was attributed to reduction in the clay shear strength due to increase in moisture content caused by the prolonged rain. The reduced clay strength resulted in reduced adhesion between clay and nail grout and the wall failed by pullout of the nails. This failure illustrates that this type of pullout failure usually occurs slowly and results in large deformations which eventually tend to stabilize the structure. This particular wall was repaired and permanently stabilized by the installation of additional longer nails. *(Photos courtesy P. Unterreiner)*

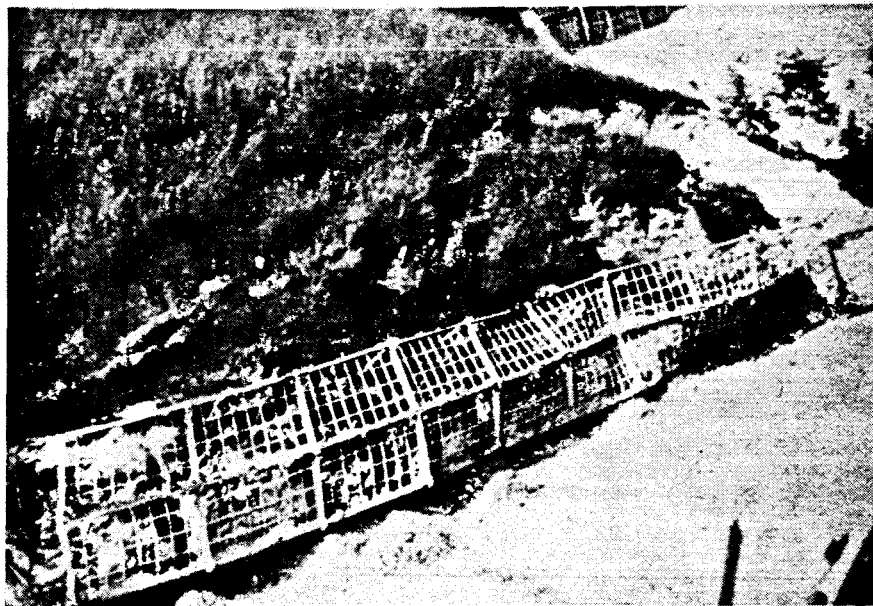


Photo 18

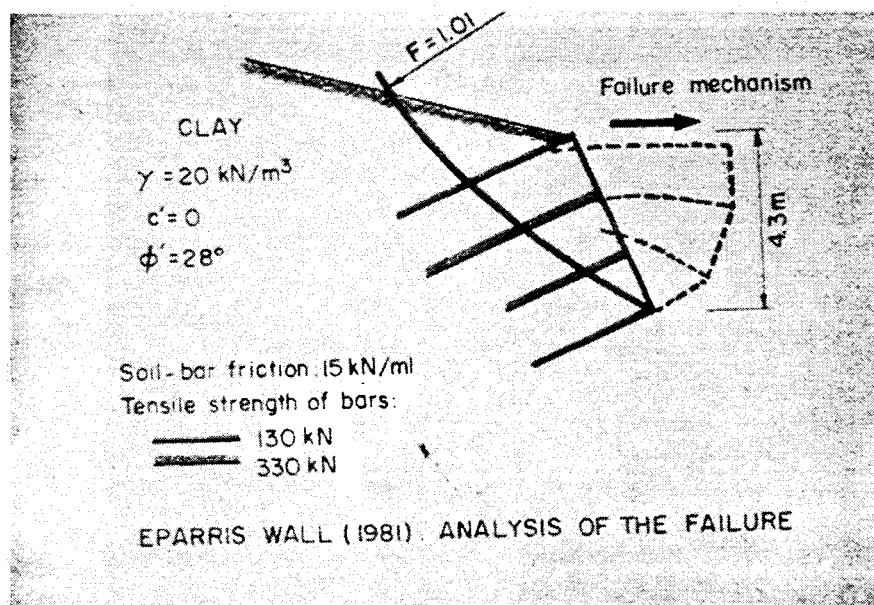


Photo 19

Project: Slope Stabilization using Nails and Micropiles -- A-46 Highway, Lyon, France

Description: Slope failures (top photo) occurred on an active construction project (1992) for a new bypass route near Lyon, France. Glacially consolidated soils exposed in the new cutting consist of clayey sand with gravel containing clay layers and slickensides. The repair scheme, on which construction was nearly completed at time of team site visit, consists of a combination of vertical soil nails ("shear dowels") and inclined micropiles (bottom photo shows design cross-section). A 600-meter (2,000 lf) length of slope was stabilized at a cost of approximately 10 million FFR (\$2 Million). A total of 1,500, 8 to 10 m (26 to 33 feet) long vertical nails and 360, 15 m (49 feet) long micropiles were installed. Nail bars were 32 mm (1.25 inch) $\varnothing$ installed in 125 mm (4.9 inch) $\varnothing$ grouted holes on a 3 m (9.8 feet) spacing. Micropiles have 50 mm (2 inch) $\varnothing$ bars installed in 200 mm (8 inch) $\varnothing$ grouted holes, on a 2 m (6.6 feet) spacing. (Photos courtesy Scetauroute)



Photo 20

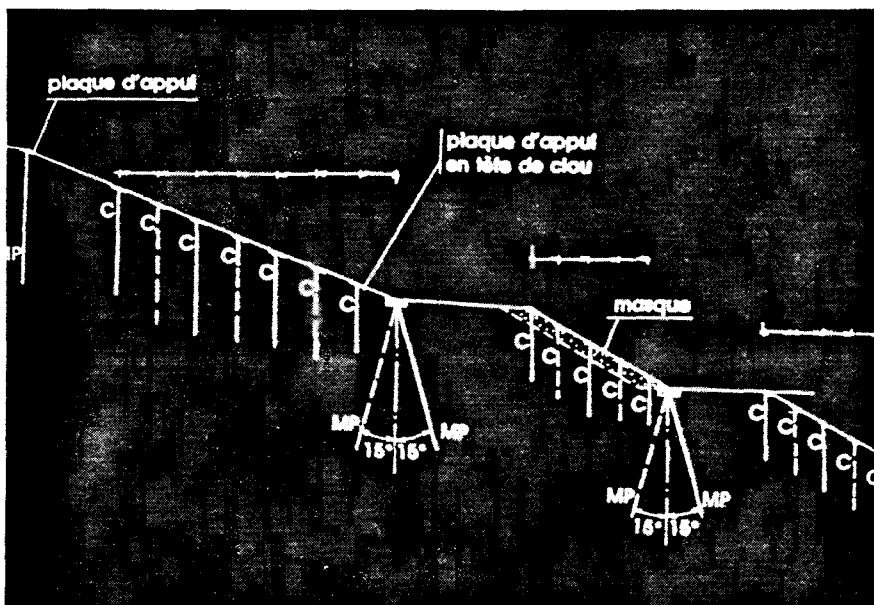


Photo 21

Project: Slope Stabilization using Nails and Micropiles -- A-46 Highway, Lyon, France (cont'd.)

Description: Photos below show nail drilling and completed nail head assemblies on slope face. Slope will be revegetated. The stabilization scheme was designed to provide a 10 to 15 percent increase in slope stability factor of safety. The nails are intended to increase the factor of safety against shallower slope failures and the longer micropiles provide increased factor of safety against deeper seated failures. A concrete cap beam was poured to connect the tops of the micropiles. Blockouts were cast into the cap beam to provide for later installation of tiebacks if long-term slope monitoring shows that additional support is needed. *(Photos courtesy Scetauroute and J. Walkinshaw)*

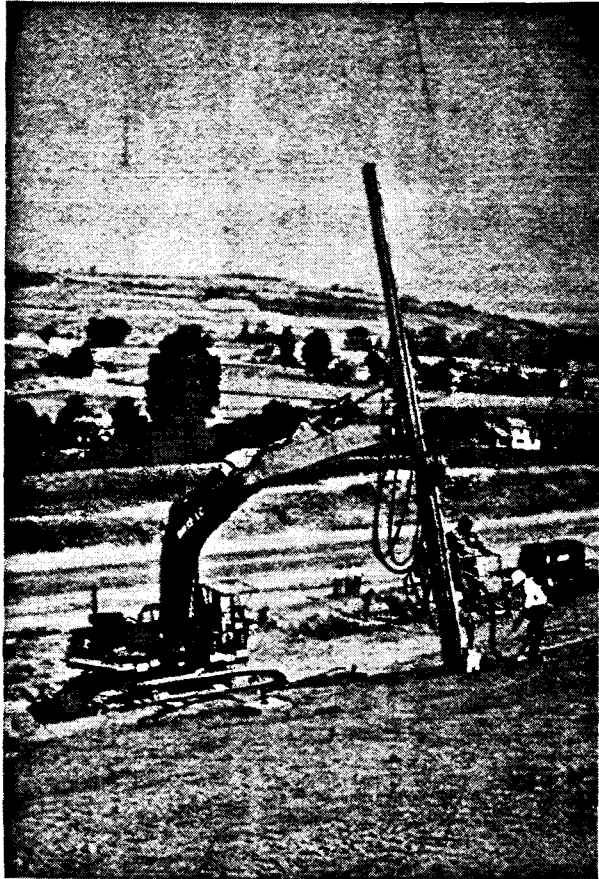


Photo 22



Photo 23

Project: A-40 Highway, Nantua Valley, Southern France

Description: This project was completed approximately three years ago and is on the Paris to Rome motorway crossing the Jura mountains. The project is located in very rugged environmentally sensitive mountainous terrain. Ground conditions consist of loose slope talus debris - (see before construction - top photo) - and limestone bedrock. The 30 km (19 miles) long completed project includes extensive use of tunnels, viaducts, and retaining walls (bottom photo) to reduce environmental impact. (Photos courtesy Scetauroute and J. Walkinshaw)



Photo 24

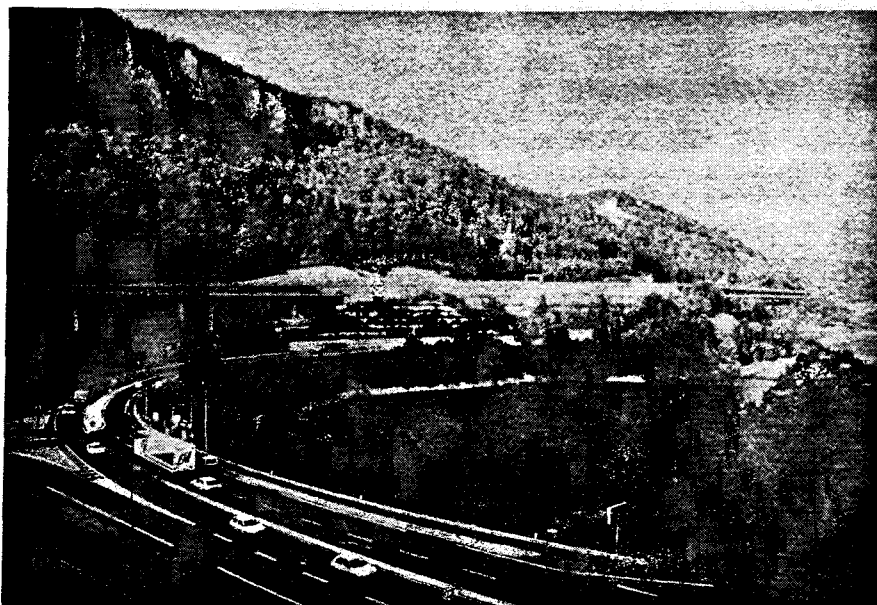


Photo 25

Project: A-40 Highway, Nantua Valley, Southern France (cont'd.)

Description: The 30 km (19 miles) length project included approximately 120,000 m² (1,300,000 ft²) of retaining walls (≈ 50 percent Reinforced Earth fill walls; 25 percent anchored (tieback) walls; and 25 percent nail walls). Anchored walls were used to retain cuts in the loose talus debris and nail walls were used to retain cuts in more competent weathered limestone rock and to retain pier excavations at viaduct pier columns. Top photo shows a typical cross-section for the highway cutslope permanent nail walls. Bottom photo shows cross-section for some of the viaduct pier footing excavations and foundations. (Photos courtesy Scetauroute)

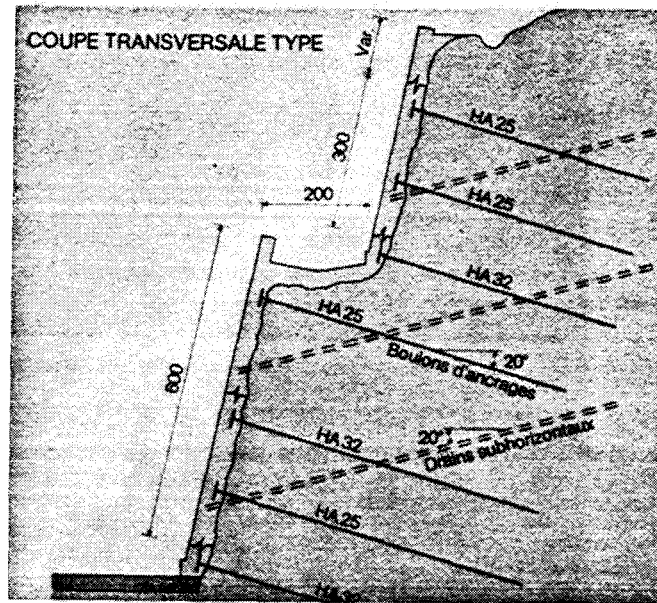


Photo 26

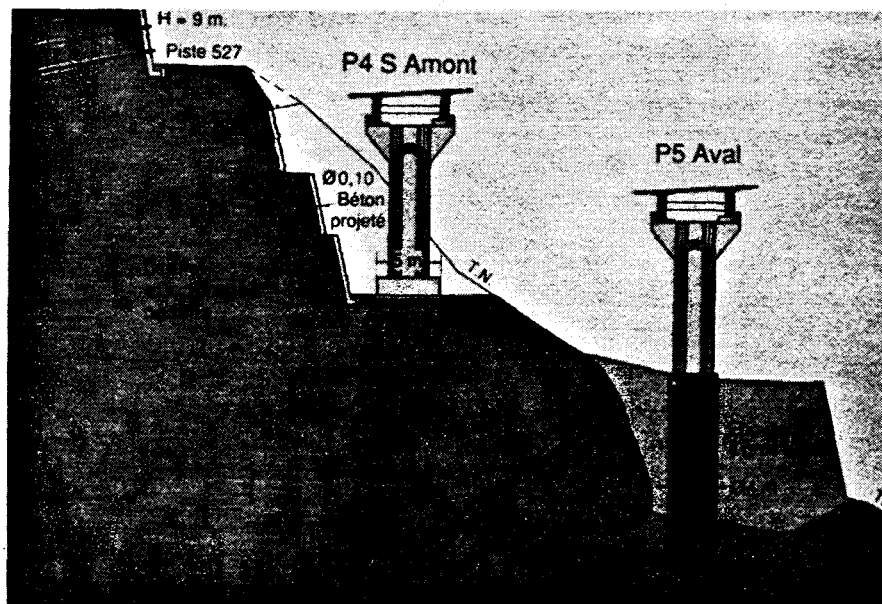


Photo 27

Project: A-40 Highway, Nantua Valley, Southern France (cont'd.)

Description: Top photo shows both temporary nail walls used along portions of viaduct construction access road and permanent nail walls used at pier footing excavations. The permanent nail walls used at pier column excavations had a permanent Cast-in-Place facing placed over the shotcrete. Bottom photo shows the Cast-in-Place facing with architectural treatment used on the permanent soil nail walls used along the highway. Construction cost of the nail walls was reported at \$400/m² (\$40/ft²) and the anchored walls at \$1,200/m² (\$120/ft²). (Photos courtesy Scetauroute and J. Walkinshaw)



Photo 28



Photo 29

Project: "Bodenvernagelung" Research Project, Germany (1975-1980)

Description: The German research project was the first major European soil nailing research project and included extensive model tests and load testing of seven full-scale test walls. Photo below shows one of the failed model test walls. The figure shows cross-sections of the seven full-scale test walls. The German research project was a cooperative effort between Specialty Contractor Bauer, the University of Karlsruhe, and the German Department of Transport. (Photo courtesy Dr. Gässler, University of Stuttgart).

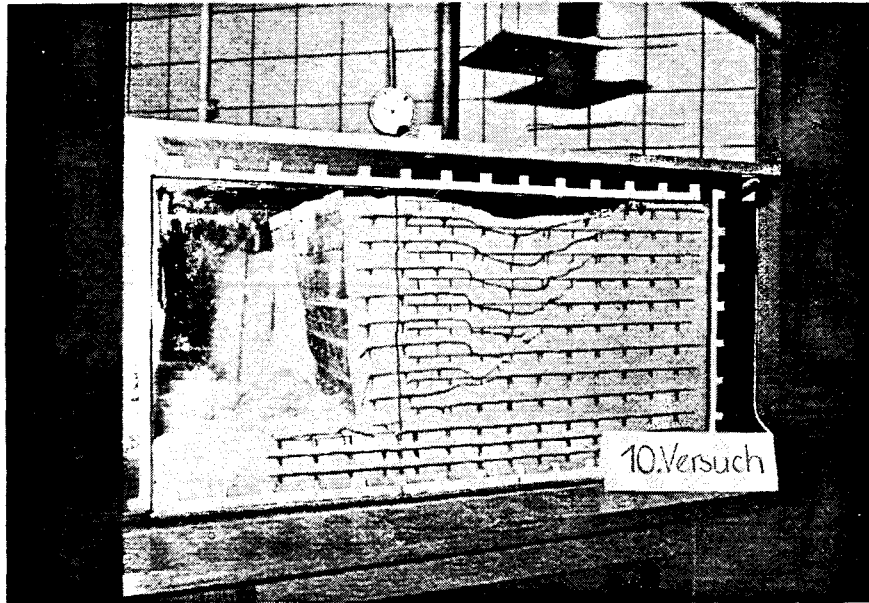
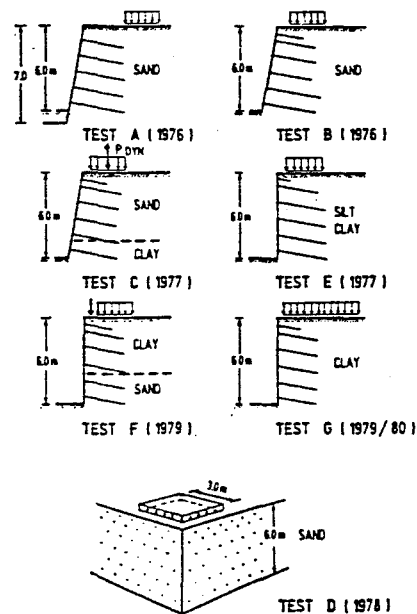


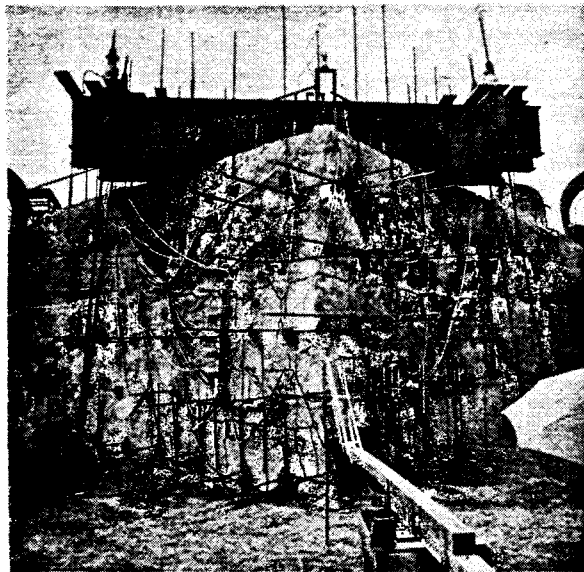
Photo 30



Scope of the field test walls of the German Research Project "Bodenvernagelung" (1975-1980).

Project: "Bodenvernagelung" Research Project, Germany (1975-1980) (cont'd.)

Description: Photos below show one of the German full-scale test walls before and after failure. The test walls were "failed" by applying a progressively increasing surcharge load through the use of jacks and a reaction system anchored to tiedowns. The test walls were extensively instrumented. It is significant to note that complete collapse could not be induced in any of the seven full-scale test walls. "Failure" was in the form of large deformations. In the test wall shown below, even the wall shotcrete facing remained intact and relatively distress free, except for the vertical crack (see bottom photo) which formed where the shotcrete wire mesh reinforcement was intentionally left unlapped. (Photos courtesy Bauer)



Maximum loading of a projecting retaining wall corner (sandy soil). 340 kN/m².
height: 6 m

Photo 31

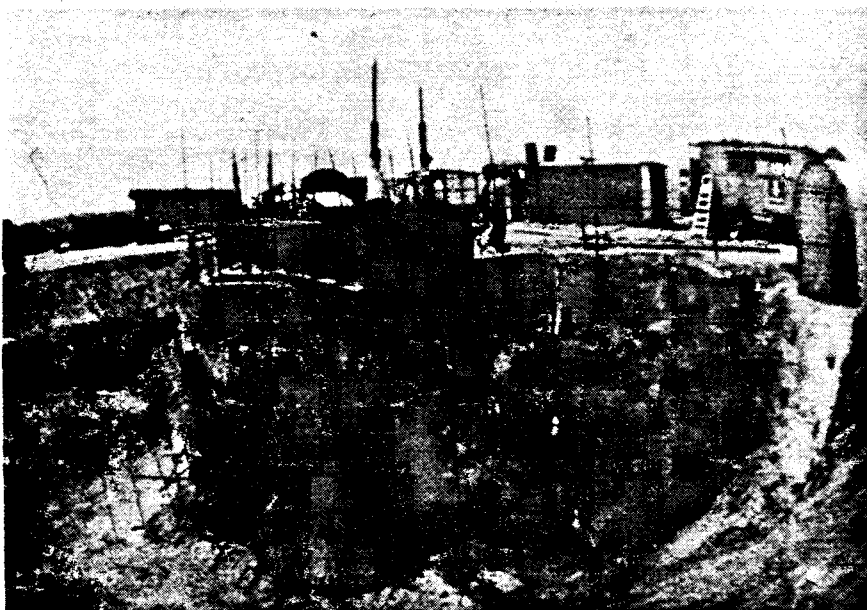


Photo 32

Project: First German Permanent Soil Nail Wall, Stuttgart, Germany

Description: First commercial use of a permanent soil nail wall constructed in 1979 in Stuttgart, Germany by Specialty Contractor Bauer. The wall is 14 m (46 feet) high and nail holes were constructed using augers drilling open holes. The wall facing is dry-mix shotcrete left in the "gun" finish. Wall movements were monitored over a 10-year period and all movements ceased after 5 years. The maximum wall deflection was less than 0.3 percent of the wall height. *(Photo courtesy Bauer)*

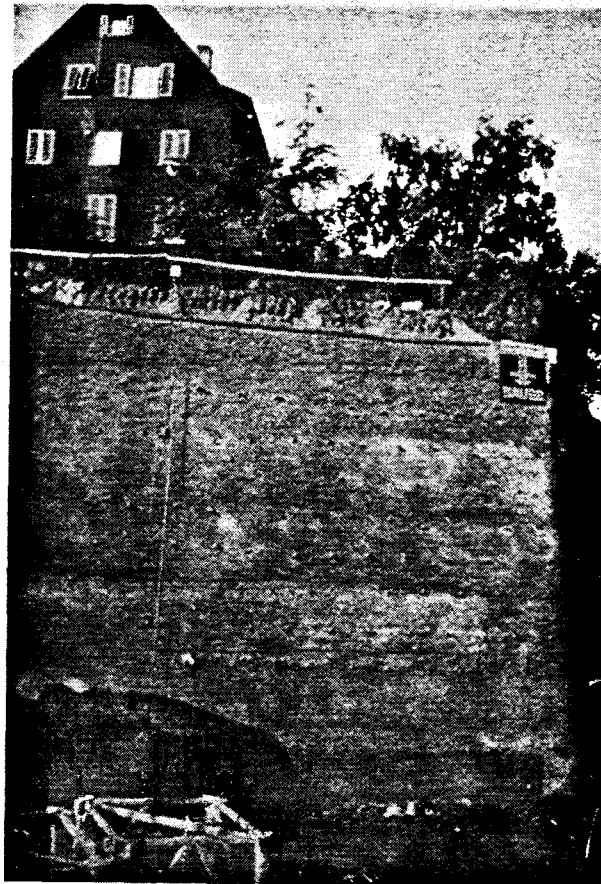


Photo 33

Project: Soil Nail "Greening" Walls, Germany

Description: Two highway permanent soil nail walls in Germany. Called "greening" nail walls, these walls (built top-down) are terraced to provide planter benches. Results in a pleasing appearance. Facing of both walls shown below is dry-mix shotcrete left in the gun finish. The wall in the top photo also has weep holes through the face (vertical white stain marks). *(Photos courtesy of Bauer)*

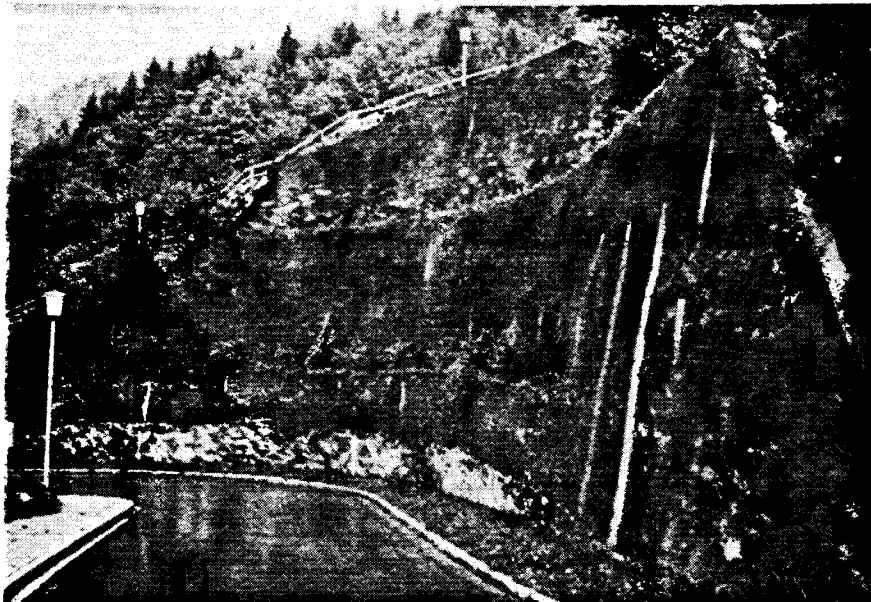


Photo 34



Photo 35

Project: Soil nail wall with prefabricated facing elements, Sindelfingen, Germany

Description: 8 m (26 feet) high permanent soil nail wall with prefabricated concrete facing elements. Constructed for Daimler Benz AG at Sindelfingen, Germany (near Stuttgart) in 1988. Provides terracing to allow for plantings. Nails are drilled and installed through blockout holes cast along the bottom of the precast elements. One of the German engineers gave the following cautions relative to use of larger size prefab face elements such as used on this project. These are: 1) the flexibility of the soil nailing technique, especially the ability of accommodating irregular cut slopes, cannot be retained in large prefab elements; 2) difficult in some ground to perform accurate plane cuts for large precast elements, and; 3) heavy face elements give a considerable load to the next excavation cut and local face stability may be difficult to maintain. *(Photos courtesy Dr. Hermann Lohmiller)*

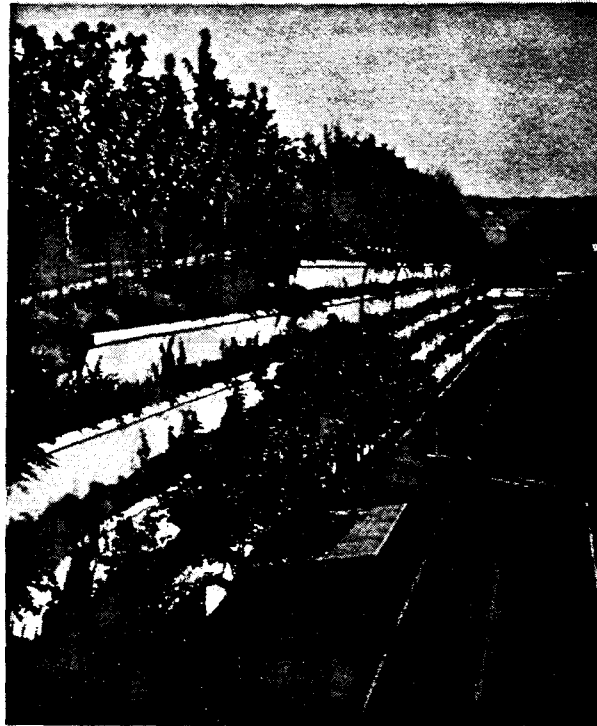


Photo 36

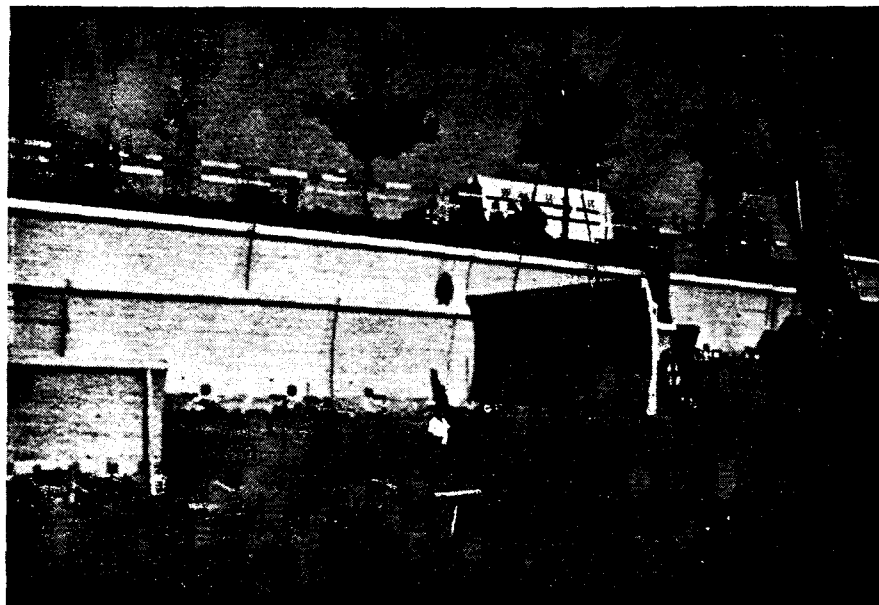


Photo 37

Project: Health Spa Center, Stuttgart, Germany (1992)

Description: This project included a permanent soil nail wall up to 14 m (46 feet) high. Boulders were encountered in the wall excavation face and the project architect requested that the larger boulders encountered be left exposed through the wall face (top photo). Bottom photo also illustrates an advantage of soil nail walls, i.e. the ability to easily contour the wall to fit existing site geometry -- e.g. note where soil nail wall ties in against an older existing wall which was tiedback and will remain in place. Also note the "buttonheads" on the wall face where additional shotcrete was placed to cover the nail heads and bearing plates both for aesthetic reasons and to provide long-term corrosion protection. The wall was installed on a slight batter. One layer of mesh and shotcrete was used, except at the nail head, where two layers ("buttonheads") were used. The nails were installed in open drill holes and tremie-grouted. The nail test results were questionable, since they showed absolutely no movement. There may not have been an unbonded length provided, even though it was required by specifications. *(Photos courtesy R. Chassie and J. Walkinshaw)*

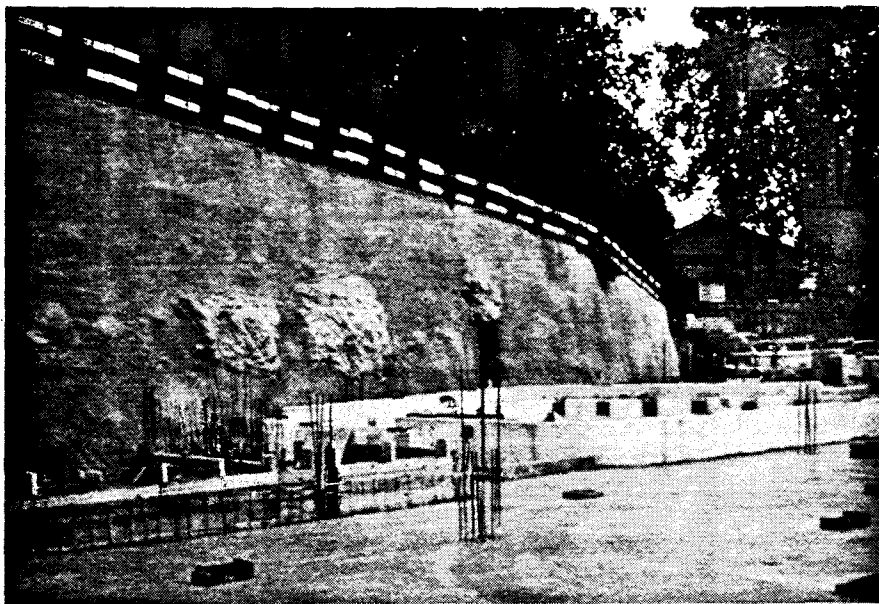


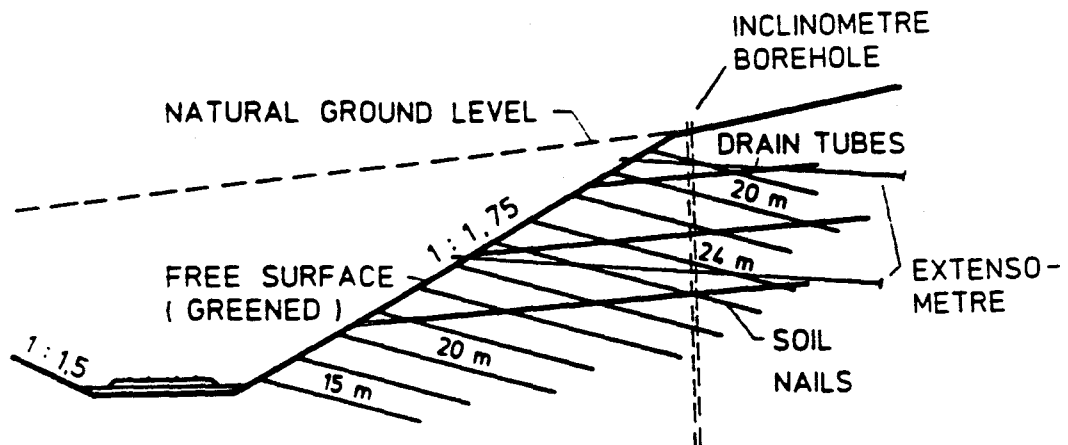
Photo 38



Photo 39

Project: Nailed slope stabilization on high speed rail line, Germany

Description: Cross-section of unstable cutslope on the high speed Mannheim-Stuttgart railway line (Southwest Germany) stabilized in 1987 using soil nails. (Courtesy Dr. Günter Gässler)



Project: Equipment and materials innovations, Germany

Description: Robotic drill rig (top photo) developed and manufactured by specialty contractor Bauer, Schrobenuhausen, Germany. Rig has "gatling gun" revolving magazine that holds five 6 m (19.7 feet) long sections of drill casing. Once the magazine is loaded, operator can drill a 30 m (100 feet) deep tieback or nail drillhole without touching the drill rod. *(Photo courtesy Bauer)*

"Dywidur" fiberglass bar developed by Dywidag, Munich, Germany. Has been used in mine and tunnel applications, particularly in places where the temporary reinforcement bars later have to be excavated through, such as at tunnel portal areas or along tunnel headings. This is an interesting innovation in that use of fiberglass would eliminate long-term corrosion concern inherent with steel bars, however, the fiberglass bars are "brittle" and can not take much bending, so should be used very cautiously in applications where may be subjected to bending. *(Photo courtesy Dywidag)*

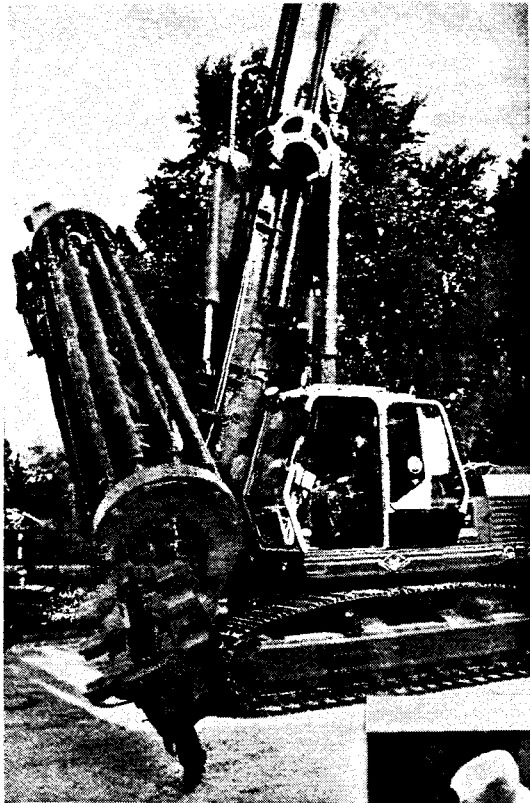


Photo 40

Photo 41



**DYWIDUR® -
the first glassfibre bar
with formed threads**



Please send us more
information concerning
DYWIDUR®-glassfibre bars

SCANNING TEAM (in York, England)

Left to Right: John Walkinshaw, Jim Keeley, Claus Ludwig, Al Dimillio, Ken Jackura, John Byrne, Pete Nicholson, Ron Chassie.



Photo 42

SCANNING TEAM WITH GERMAN HOSTS (Stuttgart, Germany)

Ron Chapman (third from left) and Don Bruce (third from right).

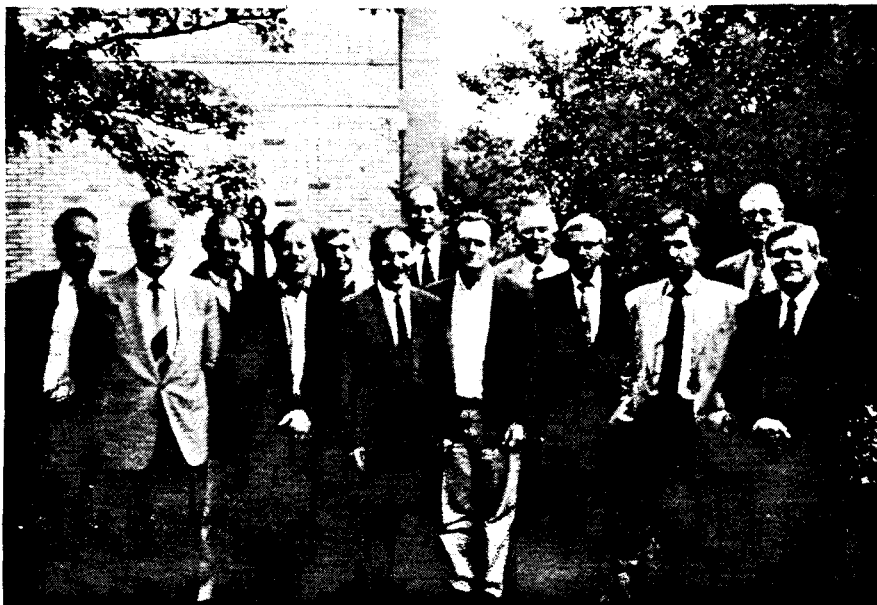


Photo 43

Back Cover Photograph: Pictured is the East Portal of "Pissicart Ouest" Tunnel on France's A8 toll road in the vicinity of Nice on the Mediterranean coast. This view is facing the traffic exiting the tunnel. This picture illustrates the broad diversity of the possible applications of soil nailing and its adaptability to the steep terrain. Taken by John L. Walkinshaw, July 11, 1986.

The slope was first stabilized with permanent soil nails and conventional wire mesh reinforced shotcrete. Some of this work can still be seen above the planter boxes in the top left of the photograph. In Europe, a troweled shotcrete finish is often the accepted permanent facing.

At this site, precast concrete panels, some with planter boxes, were erected from the bottom up, against the battered shotcrete facing and with special connections to the nail heads. More frequently in common practice, designers use cast-in-place concrete facing when deemed necessary for aesthetic or structural reasons.

The masonry wall in the left foreground, channels the water collected in a "V" ditch at the top of the wall down to a culvert. Climbing vines had recently been planted at the base of the wall in the "planter box" created by the concrete barrier.

