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SOIL NAILING: THE SECOND DECADE

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Soil nailing is a geotechnical engineering process of insitu earth reinforcement with over 15 years of successful application. It has particular value in stabilizing cut slopes and deep foundation excavations in soils. The paper highlights the major features of the technique--the development, application, design, construction and performance--with special reference to projects executed in Europe and North America.

1. INTRODUCTION

Since 1972, engineers in Europe and North America have been exploiting the special advantages of the technique of soil nailing. This geotechnical engineering process comprises the insitu reinforcement of soils and has a wide range of applications for stabilizing excavations and slopes, such as are associated with deep foundations or cut and cover tunnelling schemes. It has been researched with large budgets since 1975 by collaborations of Contractors, Universities and Government organizations. It has been the subject of International Conferences, Symposia and Seminars since 1979, and has given rise to a rapidly expanding literature of technical papers and articles. There are abundant successful case histories to cite in a wide variety of ground conditions and applications.

However, it would seem that, so far, engineers in Britain have either ignored these developments or have remained unaware of the pedigree the technique has established over the years. This paper has been produced following a worldwide state of the art review (Bruce and Jewell, 1986/1987; Jewell and Bruce, 1987), but highlights the recent developments in soil nailing concepts and practice. Detailed appreciations of the subject and, in particular, design methods, are to be found in Jewell and Bruce (1987), and in the NCHRP 24-2 study, soon to be published in the USA.

2. CHARACTERISTIC FEATURES

Soil nailing is a practical and proven technique used in constructing excavations and stabilizing slopes by reinforcing the ground insitu with relatively short, fully bonded inclusions, usually steel bars. These are introduced into the soil mass as staged excavation proceeds and act to produce a zone of reinforced ground. This zone then performs as a homogeneous and resistant unit to support the unreinforced ground behind, in a manner similar to a conventional gravity retaining wall (Figure 1).

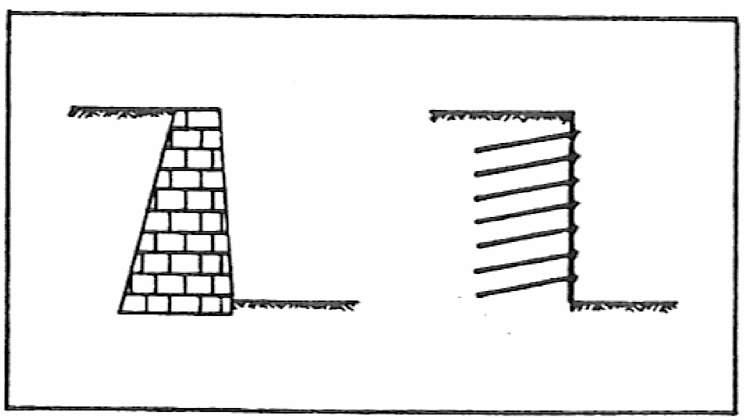


Fig. 1 - The Analogy Between a Gravity Wall and a Soil Nailed Structure (Stocker et al., 1979).

The design of a nailed structure must therefore address its resistance to external forces and its internal stability.

2.1 Piling and Insitu Reinforcement Techniques

It is important to differentiate between piles--inclusions placed or formed in the ground to support external loads applied directly to them, and insitu reinforcement--inclusions to maintain equilibrium under the soil self weight loading, and surcharge loading on the soil. Insitu reinforcement may be further subdivided into three categories, with respect to slope and excavation stabilization:

(a) Soil nailing refers to reinforcement installed horizontally or subhorizontally so that it improves the shearing resistance of the soil by acting in tension (Figure 2a). Elements are most commonly steel bars or pipes fully grouted into drilled or jetted boreholes. However, in France especially, one may find "driven" nails which consist of angle iron percussed or vibrated directly into the soil (Hurpinoise Method). Such installations have different characteristics from the grouted type, as discussed below, but generally perform in the same way.

(b) Reticulated micro piles are steeply inclined in the soil at various angles both perpendicular and parallel to the wall face (Figure 2b). The overall aim is similar to soil nailing, namely to provide a stable block of reinforced soil to act like a gravity retaining structure. In this technique, the soil is held together by the multiplicity of reinforcement members acting to resist bending and shearing forces. The interested reader is referred to publications by Lizzi (1982) and Nicholson and Boley (1985).

(c) Soil dowelling is applied to reduce or halt downslope movements on well defined shear surfaces (Figure 2c). The slopes treated by dowelling are typically much flatter than those in soil nailing or reticulated micro pile applications. Gudehus (1983) showed that the most efficient way to improve the shearing resistance on a weakened shear surface through the soil is to use relatively large diameter piles which combine a large surface area with high bending stiffness. The diameter of a soil dowel is, therefore, far greater than that of a soil nail or micro pile, which is typically less than 150mm.

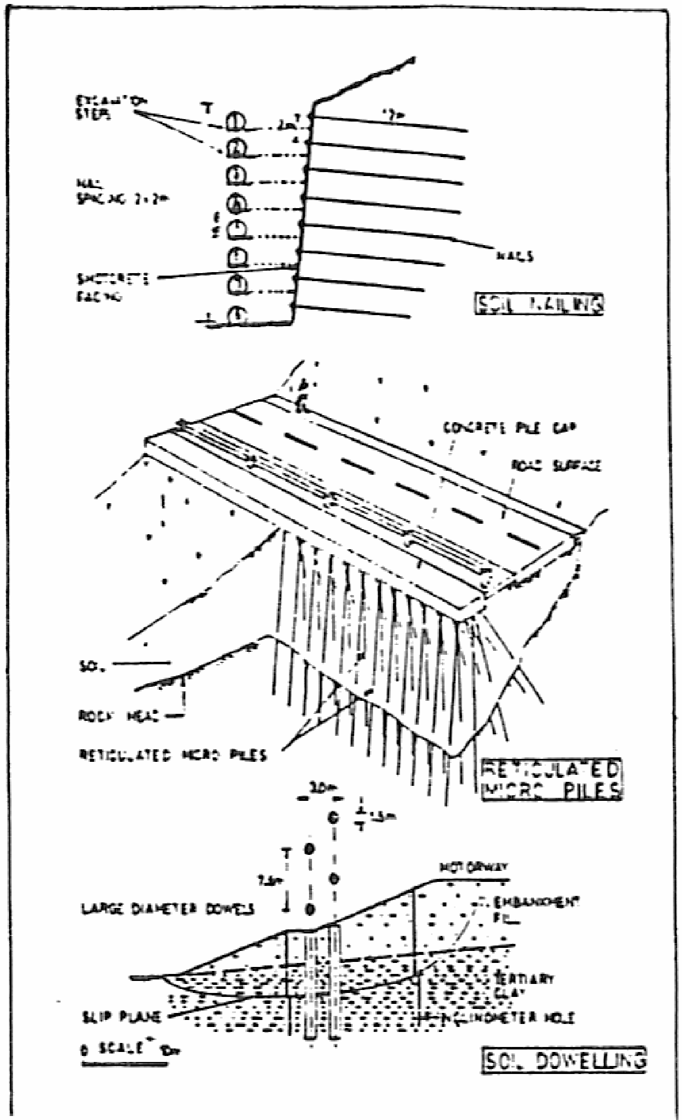


Fig. 2 - The Family of Insitu Soil Reinforcement Techniques: (a) Soil Nailing (after Schlosser, 1982), (b) Reticulated Micropiles (after Boley and Crayne, 1985) and (c) Soil Dowelling (after Gudehus and Schwarz, 1984)

2.2 Selecting the Insitu Reinforcement Method

There are fundamental differences in the mechanical action of these three insitu reinforcement techniques, and there may be circumstances where more than one may be considered as potential solutions for slope stabilization. The following general points may be concluded from practical, economic and theoretical (Jewell, 1980) viewpoints;

- where a steep face is to be excavated in a homogeneous granular soil, it is most efficient to place the reinforcement through the face in a direction close to horizontal (i.e., by soil nailing).

- in marginally stable granular or scree slopes requiring reinforcement, but where excavation is not necessary or forseen, then soil nailing or reticulated micropiling are valid choices, with price often being the decisive factor. Where access requirements prevent excavation and nailing equipment being placed on the actual slope, then the latter solution is clearly preferable.

- soil dowelling is restricted to the conditions described above. If access is problemmatical, then again, reticulated micropiling will have to be considered, despite the high likelihood of increased cost.

2.3 Comparison With Prestressed Ground Anchorages

Superficially, there would appear to be a number of similarities between nails and prestressed ground anchorages when used for slope or excavation stability. Indeed it is tempting to regard nails merely as "passive" small scale anchorages. However, there are major functional distinctions to be made, which will favour the choice of one over the other. The following comparisons and contrasts may be drawn:

- Ground anchorages are stressed after installation so that in service they ideally prevent any structural movement occurring. In contrast, soil nails are not prestressed, [as noted later, a small prestress is commonly applied to "drilled and grouted" nails--however, this is done to provide proper seating of the nail/shotcrete/soil structural interface], and require a finite (albeit very small) soil deformation to cause them work.

- Nails are in contact with the ground over most of their length (typically 3-10m), whereas ground anchorages transfer load only along the distal, fixed anchorage length. A direct consequence of this is that the distribution of stresses in the retained mass is different for each type.

- Since nails are installed at a higher density (typically 1 per 0.5 to 5m^2 of face) the consequences of a one unit failure are not necessarily so severe. In addition, the constructional tolerances of installation need not be so high, given their overall, interactive mode of operation.

- As high loads have to be applied to anchorages, appropriate bearing facilities must be provided at the head to eliminate the possibility of "punching" through the face of the retained structure. Substantial head bearing arrangements are not necessary with nails whose low individual head loadings are easily accommodated on small steel bearing plates placed on the shotcreted surface.

- Individual anchorages tend to be longer (say 15-45m) and so may necessitate larger scale installation equipment. Also an anchorage system is often provided to stablilize a substantial retaining structure, such as a diaphragm wall or bored pile wall which will itself necessitate large scale construction equipment.

- In general, if the overall stability calculations show the problem to be deep seated, then ground anchorages will most probably be required.

Conversely, for vertical excavations, soil nailing has frequently proved preferable to other methods of lateral support incorporating prestressed ground anchorages (such as Berlin or diaphragm walls).

2.4 Comparison With Reinforced Earth Walls

Although soil nailing shares certain features with the older and more widely known technique of reinforced earth for retaining wall construction (Vidal, 1966), there are also some fundamental differences which are important to note (Schlosser, 1982).

The main similarities are:

- The reinforcement is placed in the soil unstressed; the reinforcement forces are mobilized by subsequent deformation of soil.

- The reinforcement forces are sustained by frictional bond between the soil and the reinforcing element. The reinforced zone is stable and resists the thrust from the unreinforced soil it supports.

- The facing of the retained structure is thin - prefabricated elements in the case of reinforced earth, and usually shotcrete in soil nailing - and does not play a major role in the overall structural stability.

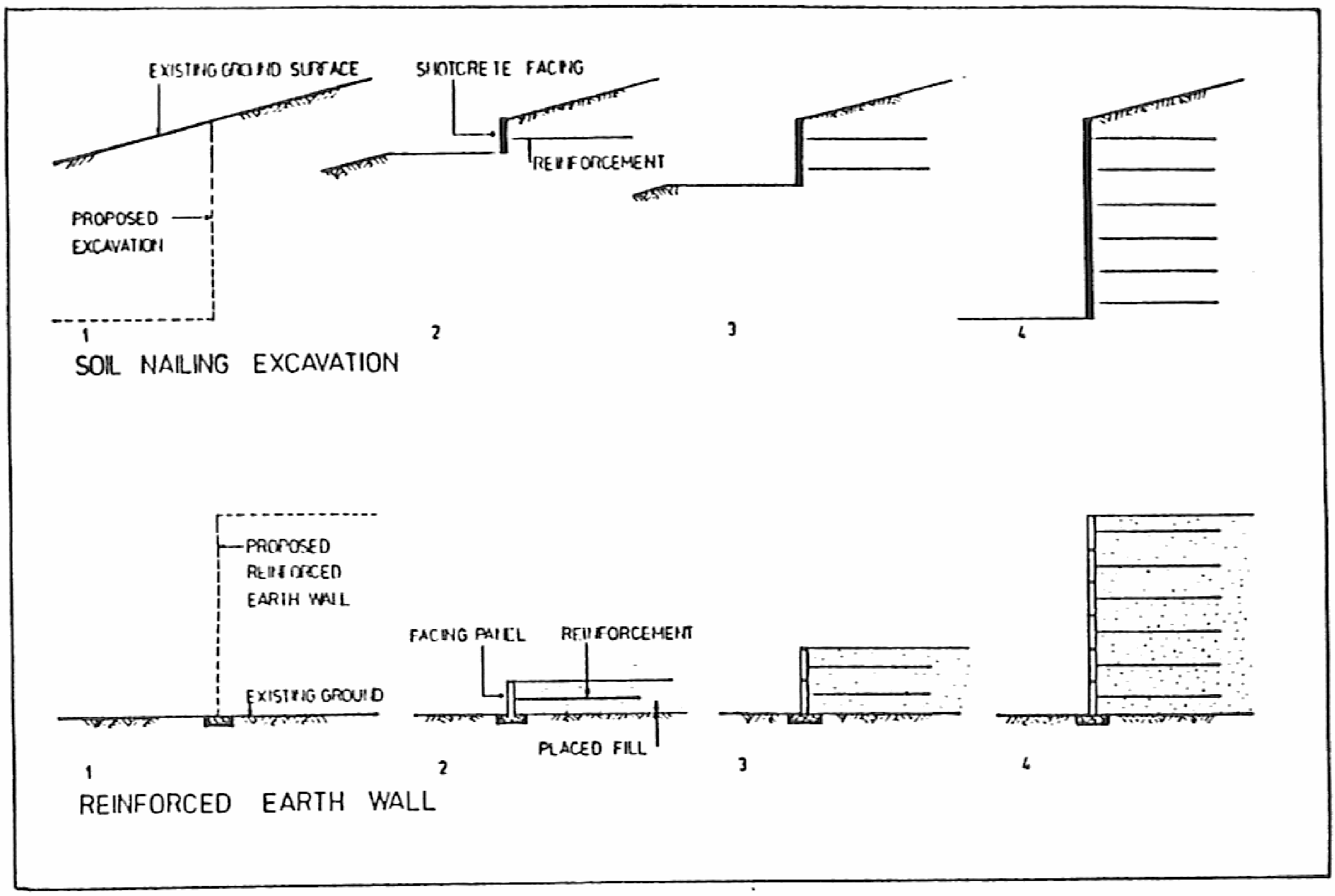


Fig. 3 - Contrasting Construction Sequences for Soil Nailing ("top down") and Reinforced Earth ("bottom up")

The main dissimilarities are:

- Although at the end of construction the two structures may look similar, the construction sequence is radically different. Soil nailing is constructed by staged excavations from "top down" while reinforced earth is constructed "bottom up" (Figure 3). This has an important influence on the distribution of the forces which develop in the reinforcement, particularly during the construction period.

- Soil nailing is an insitu reinforcement technique exploiting natural ground, the properties of which cannot be preselected and controlled as they are for reinforced earth fills.

- Grouting techniques are usually employed to bond the reinforcement to the surrounding ground: load is transferred along the grout to soil interface. In reinforced earth, friction is generated directly along the strip to soil interface.

2.5 Benefits and Limitations of Soil Nailing

Several factors have contributed to the growing popularity of soil nailing as a construction technique, and these include;

- Economic Advantage - based on discussions with specialists in Europe, it would seem that the cost saving for excavations of the order of 10m deep is 10% to 30% relative to an anchored diaphragm or

Berlin wall alternative. This is supported by a claimed saving of 30% on an early soil nailed excavation in Portland, Oregon (ENR, 1976).

- Construction Equipment - drilling rigs for reinforcement installation and guns for shotcrete application are relatively small scale, mobile and quiet. This is highly advantageous in urban environments, where noise, vibration or access may pose problems. Equally in remote rural areas it may prove impractical to deploy large scale equipment for piling or diaphragm walling.
- Construction Flexibility - soil nailing can proceed rapidly and the excavation can be shaped easily. It is a flexible technique, readily accommodating variations in soil conditions and work programmes as excavation progresses.
- Performance - field measurements indicate that the overall movements required to mobilize the reinforcement forces are surprisingly small, as quantified below. Furthermore, nailing is applied at the earliest possible time after excavation, and in intimate contact with the cut soil surface. This minimizes the disturbance to the ground and so the possibility of damage being caused to adjacent structures. This "early support" also allows the natural undisturbed properties of the soil to be exploited to advantage.

Naturally, this technique has certain practical limitations to its application, and these are primarily as follows:

- Soil nail construction requires the formation of cuts generally 1-2m high in the soil. These must then be capable of standing up unsupported for at least a few hours, prior to shotcreting and nailing. The soil must, therefore, have some natural degree of "cohesion" or cementing. Otherwise, a pretreatment such as grouting may be necessary to stabilize the ground immediately behind the face, but this will add both complication and cost.
- A dewatered face in the excavation is desirable for soil nailing. If the groundwater tries to percolate through the face, the unreinforced soil will slump locally on initial excavation making it impossible to establish a satisfactory shotcrete skin.
- Excavations in soft clay are also unsuited to stabilization by soil nailing. The low frictional resistance of soft clay would require a very high density of insitu reinforcement of considerable length to ensure adequate levels of stability. Bored or jet grouted piles, or diaphragm walls, with anchorages are more suited to these conditions.

3. EVOLUTION

"Ancrages passifs" had been widely used in mines and rock slope stabilizations (Figure 4) before their incorporation as a key feature in soft ground support in the New Austrian Tunnelling Method (Rabcewicz, 1964/1965). This principle of applying "shotcrete and bolts" to newly exposed soil faces proved its worth in the metro tunnel applications in West Germany and elsewhere in the 60's and early 70's.

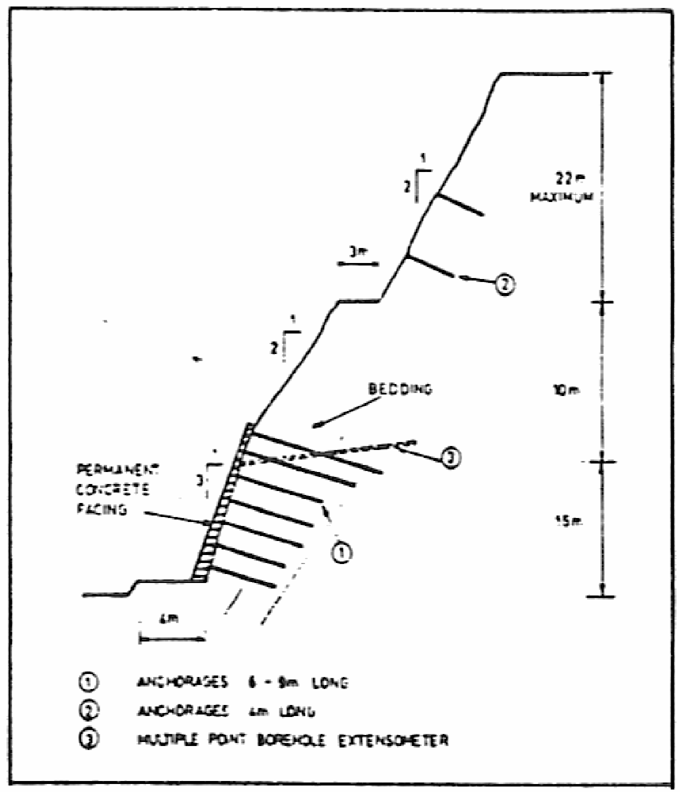


Fig. 4 - Retaining Wall Construction, A9 Autoroute, France (Bonazzi and Colombet, 1984)

The French contractor Bouygues had gained experience with the method in France, and began to consider its application in above ground structures. In 1972, together with Soletanche Entreprise, they commenced work on a 70° cut slope, in heavily cemented Fountainbleu sand for a railway widening scheme near Versailles (Figure 5). This first and very successful application was well publicized and encouraged further development in France. By the mid 70's, similar systems were being tested and installed in West Germany and North

America, although it appears that engineers in these three main areas proceeded largely independently until the 1979 Paris Conference provided an international forum for the exchange of information.

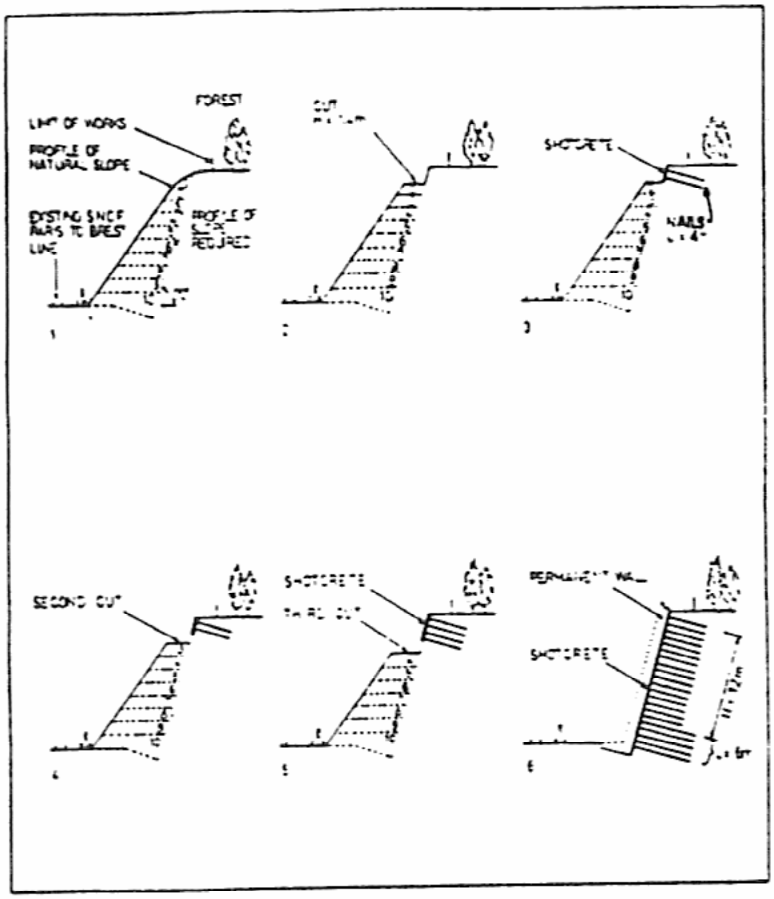


Fig. 5 - Cut Slope Stabilisation Construction. Sequence, Versailles, France (Hovart and Rami, 1975)

In each of the three leading countries, a major feature has been the active and productive research and development liaisons between groupings of industry, adacemia and government, and the names of the engineers from each category, who have championed the cause of soil nailing, stand equally credited.

With respect to "market size," the authors' estimate in each of the major countries is as follows:

- France: perhaps 50 projects per year with 5 permanent. Average contract size 1000 to 2000m^2, with some several times that scale.
- West Germany: activity level currently perhaps 25%-50% that of France, but with the potential to reach the same level.
- USA: until 1986 probably about the same as West Germany, but with far greater potential as the attractions of soil nailing become more widely known. Considerable activity in the San Francisco area since 1980, and in the eastern States since 1982.

Elsewhere in the world, several applications were reported (ENR, 1976) in Western Canada in the early 1970's (but not independently verifiable by the current authors), while Banyai (1984) records 10 examples in Hungary prior to 1984. In Britain, only three small contracts are suspected to have been executed. It is a matter of conjecture as to why the soil nailing technique has not "caught on" in certain countries. However, factors must include lack of applications, unsuitable soils, lack of engineering knowledge or awareness, and deliberate protectionism of alternative technologies by vested interests.

4. APPLICATIONS, AND DETAILS FROM PUBLISHED CASE HISTORIES

Soil nailing has been used successfully in temporary and permanent applications, in new and remedial construction, in rural and urban settings, and in a wide variety of soils.

The following categories of applications can be identified:

A. NEW CONSTRUCTION

1. Slope Stabilization - for cuts required for new or widened railway lines or roads (Figure 5).
2. Retaining Walls - for excavations associated with foundations of buildings, underground car parks and cut and cover constructions for transportation systems (Figure 6).
3. Stabilizing Tunnel Portals - to provide excavation stability to tunnel portals and adjacent slopes (Figure 7).

B. REMEDIAL WORKS

1. Repair of Reinforced Earth Walls - to replace the effect of the reinforcing strips or fasteners damaged by overloading or corrosion (Figure 8).

2. Repair of Masonry Gravity Retaining Walls - after or just before failure caused by long-term decay of wall, or movements behind (Figure 9).

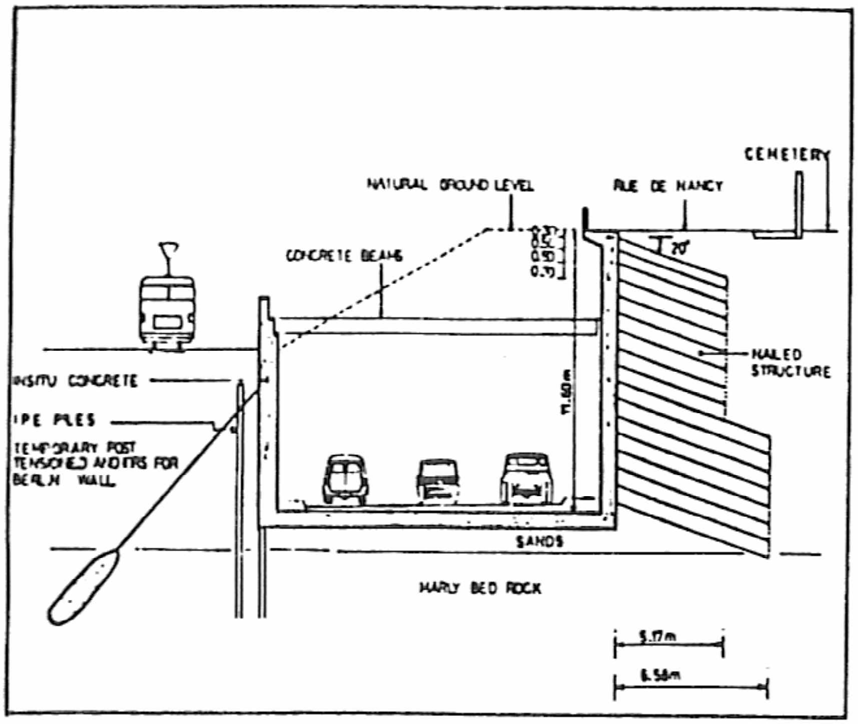


Fig. 6 - Cross Section of the Nogent-sur-Marne A86 Excavation (after Goulesco and Medio, 1981)

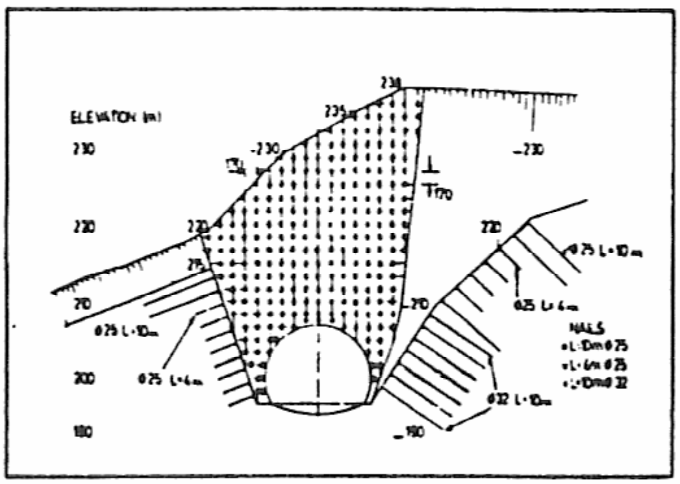


Fig. 7 - Stabilisation of Tunnel Portals and Adjacent Cut Slopes (after Louis, 1981)

3. Stabilization of Failed Soil Slopes - after collapse of slope due to failure or inadequacy of preexisting support methods, or catastrophic movements due to hydrogeological reasons (Figure 10).

4. Repair of Anchored Walls - after failure of the prestressed rock anchorages by structural overloading or by corrosion of tendons (Figure 11).

Details extracted from published case histories are summarized in Table I differentiating between ground classifications and nail types. In addition, four derived ratios are tabulated which provide a basis for comparing design and performance parameters:

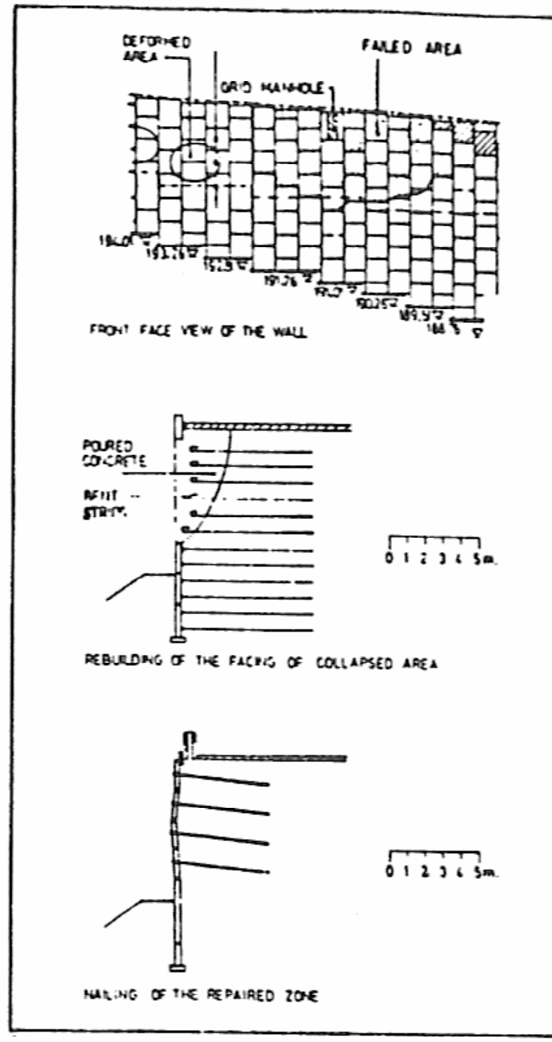


Fig. 8 - Repair of Reinforced Earth Wall, Frejus, France (after Long et al., 1981)

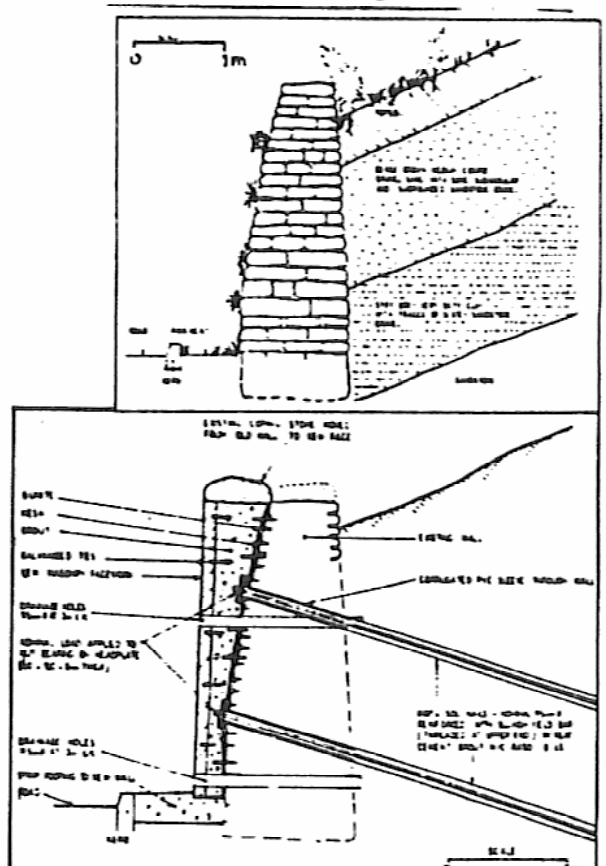


Fig. 9 - Repair of a Masonry Gravity Retaining Wall near Bradford, UK

• GRANULAR SOILS

PROJECT NAME Description and Scale	DATE	GROUND CONDITIONS Cohesion/Friction/- Unit Weight (kN/m2/degrees/kN/m3)	SLOPE ANGLE degrees	HEIGHT (m)	NAIL LENGTH (m)	NAIL LENGTH Diameter (mm)	NAIL HOLE Diameter (mm)	NAIL SPACING Horizontal/ Vertical/Area (m/m/1 per m2)	NAIL ANGLE below horz. deg.
DRILLED AND GROUTED									
VERSAILLES-CHANTIERS railway cutting 70 degree cutting stabilization over 12,400 m2 facing, up to 21.6 m deep.	1972	Cemented Fontainebleau Sand 20 32 20	70	11.3 21.6	4.0 6.0	14.1 14.1 (eq)	100 100	0.70 0.70 0.49 0.70 0.70 0.49	20 20
GOOD SAMARITAN HOSPITAL, Portland, Oregon Vertical Foundation Excavation over 2140 m2 facing, up to 13.7 m deep.	1976	Silty Fine Sand 0 34 16.2	90	11.3 11.3	8.5 7.0	38.1 38.1	100 100	1.83 1.53 2.80 1.22 1.53 1.87	15 15
FREJUS WALL, France Repair to 60 m2 of facing of a reinforced earth wall damaged by frost action.	1981	Compact Granular Fill	90	6.0 repaired	5.0	25.0	100 (as)	1.50 1.50 2.25	10
CODRS D'HERBOUVILLE, Lyon, France slope 35 m high collapsed July 1977, nailing provided temporary stability for the repair works in 10 m cuts.	1982	Silty Boulder Clay 0 25 18 Cemented Basal Beds 50 35 20	75 overall	10.0 repair steps	10.0	30.0	100 (as)	3.00 2.50 7.50 (est)	10
HDB DE FERRIERES-SOI-ARIEGE, France 80 degree cutting up to 19 m deep in weathered Schists	1982	Weathered Schists 0 45 20	80	16.5	9.0	32.0	56	2.00 1.00 2.00	10
PPG BUILDING, Pittsburgh, Pennsylvania Vertical foundation excavation up to 9.1 m deep, adjacent to sensitive buildings.	1982	Alluvial Silt, Sand & Gravel 0 25-35 15.4	90	9.1	7.0	30.0 (est)	127	1.22 1.22 1.49	15
CUMBERLAND GAP, Kentucky 75 degree cutting stabilization over 900 m2 facing up to 12 m deep.	1985	Weathered Shales & Siltstones 0 38 16.4	75	12.3	9.0	30.0 (est)	114	1.52 1.52 2.31	15
DENHOLME CLOUGH, Bradford, UK Repair to 120 m collapsing drystone wall supporting 3 m cut in sloping terrain	1985	Weathered Material Over Completely Weathered Sandstone	80	3.0	5.0	16.0	115	1.50 1.50 2.25	15
DRIVEN NAILS									
LES INVALIDES METRO, Paris Vertical excavation over 1000 m2, up to 12 m deep.	1974	Fill 0 25 * Alluvium 0 30 * Sand 0 35 *	90	12.0	6.0	28.0 (eq)	49	0.70 0.70 0.49	20
PARKING BOULEVARD VICTOR, Paris Vertical excavation over 12000 m2, up to 11 m deep, with top 4 m Berlin wall.	1978	Fill 0 25 * Sand 0 33 * Clay 60 0 *	90	11.0	6.0	25.2 (eq)	64 (eq)	0.70 0.70 0.49 (assumed)	*
AUTOROUT A86, Nogent-sur-Marne Vertical excavation over 900 m2, up to 11.6 m deep, for cut and cover road.	1980	Fine Sand 0 33 20	90	5.6 11.6	5.5 7.0	25.2 30.3 (eq)	64 76 (eq)	0.70 0.70 0.49 0.70 0.70 0.49	20 20
PARKING DE MAISONS LAFITTE, Paris Vertical excavation over 2500 m2, up to 12 m deep, facing used in permanent works.	1981	Sand * * * Marls * * *	90	12.0	6.0	25.2	64	0.70 0.70 0.49 (assumed)	*

• OVERCONSOLIDATED CLAYS & MIXED SOILS

DRILLED AND GROUTED									
LA CLUSAZ, France Steep excavation up to 14 m deep over 1000 m2 facing in very compact Morraine.	1980	Compact Morraine with High Friction 0 35-35 22	80	14.0	11.0	25.0	100 (as)	3.00 2.00 6.00	10
DRAGUIGNAN, France Steep excavation up to 11 m deep over 750 m2 facing in Marl/Limestone deposits.	1983	Interbedded Marl and Limestone 20 35 *	80	11.0	11.0	32.0	100 (as)	3.00 2.00 6.00	15
GRAND PARC DE CIMIEZ, NICE, France Steep excavation over 400 m2 facing up to 11 m deep, in mixed Marls.	1983	Sandy Marls 10 35 *	80	11.0	8.0	28.0	100 (as)	2.50 2.00 5.00	10
Marl Slope Stabilization, West Germany Steep excavation up to 16 m deep in red Keuper Marl.	*	Keuper Marl	80 (est)	16.0	8.0	*	*	* * *	10 (est)
ELYSIAN PALACE, Nashville, TN Permanent vertical excavation over 170 m2 facing up to 8.2 m deep, in firm clay.	1985	Firm Silty Clay * * *	90	8.2	4.3 average	25.4	102	1.50 1.60 2.40	15
DRIVEN NAILS									
PARAVALANCHE DE CHAMONIX, France Permanent vertical excavation 8 m deep over 1500 m2 in compact Morraine.	1983	Compact Morraine with boulders 10 40 *	80 overall	8.0	8.0	30.3 (Angle 60 x 60 x 6)	76 (Angle 60 x 60 x 6)	1.10 0.60 0.66	20

NOTES:

1. (as) = assumed
2. (est) = estimated
3. (eq) = equivalent
4. deg = degrees

Conversion factors for Europinoise steel angle: Angle (B x B x t)
Equivalent bar diameter (d) bar = (8Bt/pi) 0.5
Equivalent hole diameter (d) hole = 4B/pi)

Table 1 Details from Soil Nailing Case Histories Published with Construction Details
(NB references for each case history appear in Bruce & Jewell 1987)

*GRANULAR SOILS

PROJECT NAME Description and Scale	DATE	CUT STEPS (m)	FACING (mm)	MEASURED MOVEMENT (at crest) (mm)	NOTES	OVERALL L/H	DERIVED PARAMETERS BOND (d*hole.L spacing)	STRENGTH (d/bar)² spacing	MEASURED MOVEMENT movement/height
DRILLED AND GROUTED									
VERSAILLES-CHANTIER railway cutting 70 degree cutting stabilisation over 12,000 m2 facing, up to 21.6 m deep	1972	1.4 1.4	80 80		First recorded application of nailing for temporary slope stabilisation.	0.35 0.28	0.82 1.33	4.06E-04 4.06E-04	
GOOD SAMARITAN HOSPITAL, Portland, Oregon Vertical Foundation Excavation over 2140 m2 facing, up to 13.7 m deep.	1976	1.5 1.5	100 100	33	First published USA project. One wall section adjacent to a four story building.	0.75 0.62	0.30 0.38	5.18E-04 7.78E-04	0.00293
FREJUS WALL, France Repair to 60 m2 of facing of a reinforced earth wall damaged by frost action.	1981	-			Collapsed facing replaced and existing panels were nailed in damaged area.	0.83	0.22	3.48E-04	
COURS D'HERBOUVILLE, Lyon, France slope 35 m high collapsed July 1977. Nailing provided temporary stability for the repair works in 10 m cuts.	1982	2.5	150		Nailing used to stabilise 10 m vertical cuts. Permanent support by anchorages and abutments.	1.00	0.13	1.20E-04	
HOF DE FERRIERES-SUR-ARIEGE, France 80 degree cutting up to 19 m deep in weathered Schists.	1982	2.0	100	34 (max)		0.55	0.25	5.12E-04	0.00145
PPG BUILDING, Pittsburgh, Pennsylvania Vertical foundation excavation up to 9.1 m deep, adjacent to sensitive buildings.	1982	1.2	200	3.2 (max)	First combinded nailing with face stabilization by preinjected grout columns.	0.77	0.60	6.05E-04	0.00035
CUMBERLAND GAP, Kentucky 75 degree cutting stabilisation over 900 m2 facing up to 12 m deep.	1985	1.5	150	10 (max)	Use of fabric drains placed immediately behind the shotcrete facing.	0.72	0.44	3.80E-04	0.00081
DENHOLME CLOUGH, Bradford, UK Repair to 120 m collapsing drystone wall supporting 3 m cut in sloping terrain	1985	-	50 on drystone wall		Probably first soil nailing repair in the UK. Existing wall stabilised by nails.	1.67	0.26	1.14E-04	
DRIVEN NAILS									
LES INVALIDES METRO, Paris Vertical excavation over 1000 m2, up to 12 m deep.	1974	1.4	*		First application with nails driven directly into the ground.	0.50	0.60	1.60E-03	
PARKING BOULEVARD VICTOR, Paris Vertical excavation over 12000 m2, up to 13 m deep, with top 4 m Berlin wall.	1978	*	*		First "Hurpinoise" wall with driven angle iron reinforcement.	0.55	0.78	1.30E-03	
AUTOROUTE A86, Nogent-sur-Marne Vertical excavation over 900 m2, up to 11.6 m deep, for cut and cover road.	1980	1.4 1.4	50 - 100 50 - 100		First "Hurpinoise" wall to be fully monitored and with experimental sections.	0.98 0.60	0.72 1.09	1.30E-03 1.87E-03	
PARKING DE MAISONS LAFITTE, Paris Vertical excavation over 2500 m2, up to 12 m deep, facing used in permanent works.	1981	*	250		Shotcrete facing used as part of the permanent works finish.	0.50	0.78	1.30E-03	

*OVERCONSOLIDATED CLAYS & MIXED SOILS

PROJECT NAME Description and Scale	DATE	CUT STEPS (m)	FACING (mm)	MEASURED MOVEMENT (at crest) (mm)	NOTES	OVERALL L/H	DERIVED PARAMETERS BOND (d*hole.L spacing)	STRENGTH (d/bar)² spacing	MEASURED MOVEMENT movement/height
DRILLED AND GROUTED									
LA CLUSAZ, France Steep excavation up to 14 m deep over 1000 m2 facing in very compact Morraine.	1980	2 (est)	150	15 (10 - 20)	Nailing replaced a section of Berlin wall. Movements & forces recorded in winter.	0.79	0.18	1.04E-04	0.00107
DRAGUIGNAN, France Steep excavation up to 11 m deep over 750 m2 facing in Marl/Limestone deposits.	1981	2 (est)	Metal Facing			1.00	0.18	1.71E-04	
GRAND PARC DE CIMIEZ, NICE, France Steep excavation over 400 m2 facing up to 21 m deep, in mixed Marls.	1983	2 (est)	100-200			0.?3	0.16	1.57E-04	
Marl Slope Stabilization, West Germany Steep excavation up to 16 m deep in red Keuper Marl.	*	*	*	24 (max)	Almost no creep detected. Three levels of nails instrumented.	0.50			0.0015
ELYSIAN PALACE, Nashville, TN Permanent vertical excavation over 170-m2 facing up to 8.2 m deep, in firm clay.	1985	1.5	150		Permanent excavation with good performance reported.	0.50	0.17	2.69E-04	
DRIVEN NAILS									
PARAVALANCHE DE CHAMONIX, France Permanent vertical excavation 8 m deep over 1500 m2 in compact Morraine.	1983	1.2 (av)	*		First permanent "Hurpinoise" structure (note some nails were drilled & grouted).	1.00	0.93	1.39E-03	

Table 1 continued from previous page

1 Length Ratio = $\frac{\text{Maximum nail length}}{\text{Excavation height}}$ i.e. $\frac{L}{H}$

This reflects the overall geometry of the system

2 Bond Ratio = $\frac{\text{Hole diameter x nail length}}{\text{Nail spacing}}$ i.e. $\frac{(d_{hole})L}{S}$

This reflects the nail surface area bonding with the soil

3 Strength Ratio = $\frac{(\text{Bar diameter})^2}{\text{Nail spacing}}$ i.e. $\frac{d^2(bar)}{S}$

This reflects the strength of the nail

4 Performance Ratio = $\frac{\text{Outward movement at top of excavation}}{\text{Excavation height}}$

i.e. $\frac{\delta_{horiz}}{H}$

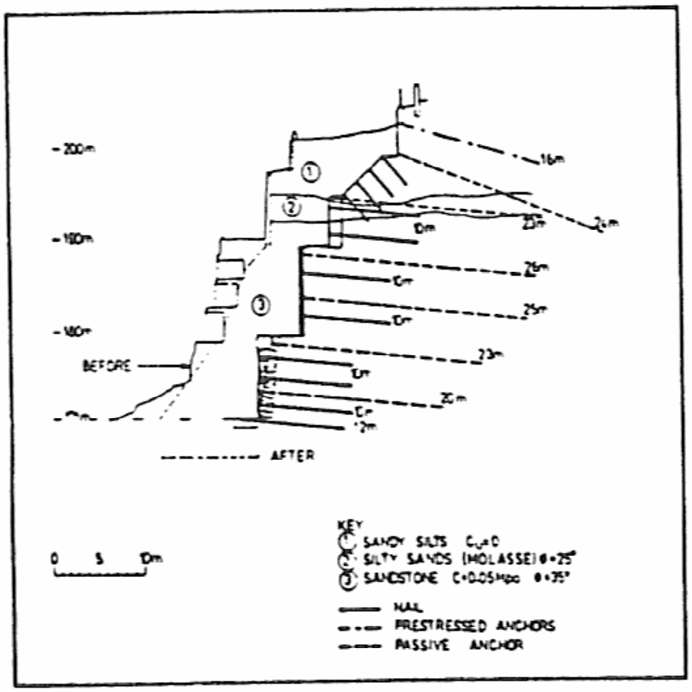


Fig. 10 - Repair of a Failed Soil Slope at Herbouville, Lyons, France (after Gausset, 1985)

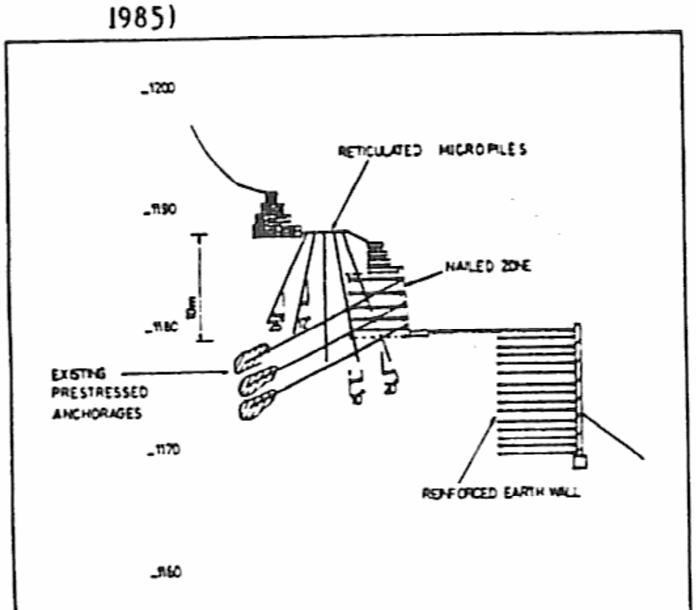


Fig. 11 - Repair of an Anchored Wall at Frejus, France (after Corte and Garnier, 1984)

The following general observations may be made:

- Steep granular slopes - for steep slope (80° or more) projects in granular soils, there is a reasonable correlation of the derived parameters as shown in Table 2.

	NAIL INSTALLATION METHOD	
	DRILLED and GROUTED	DRIVEN
Length Ratio	0.5 - 0.8	0.5 - 0.6
Bond Ratio	0.3 - 0.6	0.6 - 1.1
Strength Ratio (10^{-3})	0.4 - 0.8	1.3 - 1.9
Performance Ratio	001 - 003	no data

TABLE 2 - Summary of Derived Parameters for Nailing of Steep Granular Slopes

Overall the driven nails are shorter than those which have been drilled and grouted. Probably to compensate for the relatively smooth surface of driven nails, about twice as much surface area is provided for bonding with the soil than is the case with the drilled and grouted nails.

The most striking difference, however, is in the strength ratio which shows that about three times as much cross sectional area of steel is used with driven nails compared to drilled and grouted nails. At least part of this, however, must be caused by providing more surface area for bonding with the driven nails.

The performance ratio for drilled and grouted nails shows consistently an outward movement of up to 0.3% of the excavation depth. Similar excellent performance would be expected for the driven nails although no measurements were reported on the commercial projects.

- Comparisons Between Projects in Granular Soils and Stiff Clays - For drilled and grouted nail projects less bond and less strength are provided for the excavation in Morraine or Marl than for the excavations in granular soil. The results are shown in Table 3. Although the length ratio is similar for projects in the two types of soil, about 2 or 3 times less surface area for bonding is provided in the Morraine and Marl projects. The cross sectional area of steel used to stabilize the Morraine and Marl excavations is about 4 times less than was the case for granular soils.

	SOIL TYPE	
	GRANULAR	MORRAINE & MARLS
Length Ratio	0.5 - 0.8	0.5 - 1.0
Bond Ratio	0.3 - 0.5	0.15 - 0.20
Strength Ratio (10^{-3})	0.4 - 0.8	0.1 - 0.2

TABLE 3 - Summary of Derived Parameters for Nailing in Different Ground Conditions (Drilled and Grouted Types Only)

In comparison, the one project in Morraine using driven nails (Paravalanche de Chamonix) had a similar bond ratio and strength ratio to the typical values for driven nails in granular soil.

o <u>Comments on Reported Failures</u> - Two contracts which involved reported failures and subsequent remedial works are summarized in <u>Table 4</u>. The failure at Les Eparris is well documented and the slip was due to lack of available bond between the reinforcement and the clay. This is reflected in the repair cross section where the bond ratio was increased by a factor of three but the strength ratio was little changed.

Much less information is available for the Gare du Nord failure, but both the bond ratio and the strength ratio were increased in the repair cross section by a factor of two to three.

5. ASPECTS OF CONSTRUCTION

Good practice in soil nail construction is described in detail by Bruce & Jewell (1987). The following points focus on the more novel and innovative aspects, likely to become standard practice in the next few years.

5.1 <u>Excavation and Facing</u>

Nicholson and Wycliffe-Jones (1984) described the pretreatment of cohesionless deposits, prior to excavation, by vertical, closely spaced grout columns.
This process prevented materials from running into the excavation during cutting, and so further safeguarded adjacent overlying structures against potentially damaging settlements.

The use of silica fume, and fiber reinforced shotcrete is likewise becoming more widespread, bringing the advantages of higher, earlier strength and superior performance, often with a reduction in the volume of shotcrete required and associated shorter spraying times. For permanent structures where an exposed shotcrete surface is acceptable, the appearance can be made more attractive or more sympathetic to the natural environment by the addition of special pigments or aggregates to the final layer, as appropriate.

5.2 <u>Drainage</u>

The use of shallow face drains (e.g., 100mm diameter pvc tubes about 300mm long) or deeper soil drains into and beyond the retained mass is standard practice. An interesting alternative was used recently at Cumberland Gap, Kentucky (Nicholson, 1986) where vertical geotextile band drains were fixed to the face at regular horizontal distances prior to shotcreting. As each successive cut was made, each drain was connected downwards, so that by the final cut, the slope was being drained by full height continuous band drains, feeding ultimately into a base collector. As in all such face drainage systems, the intensity

PROJECT NAME Description and Scale / DRILLED AND GROUTED	DATE	MAIN REFERENCES	GROUND CONDITIONS Cohesion/Friction/ Unit Weight (kN/m2/-/kN/m3)	SLOPE ANGLE degrees	HEIGHT (m)	NAIL LENGTH	NAIL Diameter (mm)	NAIL HOLE Diameter (mm)	NAIL SPACING Horizontal/ Vertical/Area (m/m/1 per m2)	NAIL ANGLE (below Hor) degrees
FAILURE A41 LES EPARRIS, France 70 degree clay cutting 4.2m high in ground sloping at 15 degrees	1981	Schlosser, 1982 Gigan, 1986	Plastic Clay (18>PI>15) 0 28 20	70	4.2	4.5	28.0	100 (approx)	3.00 1.40 4.20	20
REPAIR Repaired to a 60 degrees slope 5.2 m high	1982	Schlosser, 1986 Gigan, 1986	0 28 20	60	5.2	10.0	26.0	105	2.00 1.73 3.46	30
FAILURE PARIS GARE DU NORD, France Excavation of 10 m overall in Marls	1979	Gigan, 1986	Fill Overlying 0 30 * Heterogeneous Marls 50 20 *	75 overall	10.0 overall	6.5	32.0	100 (est)	2.50 1.60 4.00	20 overall
REPAIR Repaired as a vertical wall 8.5 m high	1979	Gigan, 1986	Assumed Strength 0 25 *	90	8.5	10.0	32.0	100	1.50 1.25 1.88	15

Table 4 - Details from Soil Nailing Case Histories Relating to Failures

of such drainage must be chosen to reflect the threat of damage by frost or ice action, as well as the usual hydraulic considerations.

5.3 Installation

Apart from simple "driven nails" pioneered by Bouygues, all other installations are the "drilled and grouted type. Thus, good practice should reflect the procedures of ground anchorage construction, for example, and in this context, the recommendations of DD81 (1982) would apply to works conducted in the UK. The most recent and radical developments have been reported by Louis (1986) who has patented systems featuring the simultaneous driving and cement grouting (at pressures of over $20M_{pa}$) of steel bars (Figure 12). These "jet bolts" can give very high rates of production, in appropriate conditions, arising from the lubricating and jetting effect of the cement grout, and the elimination of temporary borehole support systems such as casings. The author claims that such rigorous grouting techniques not only enhance grout-soil grout (Figure 13) but cause an improvement in the performance of the ground between the nails. It is understood that commercial application of this method is now underway in France, following good experiences in field trials in the Rhone alluvials. A further advantage of the jet

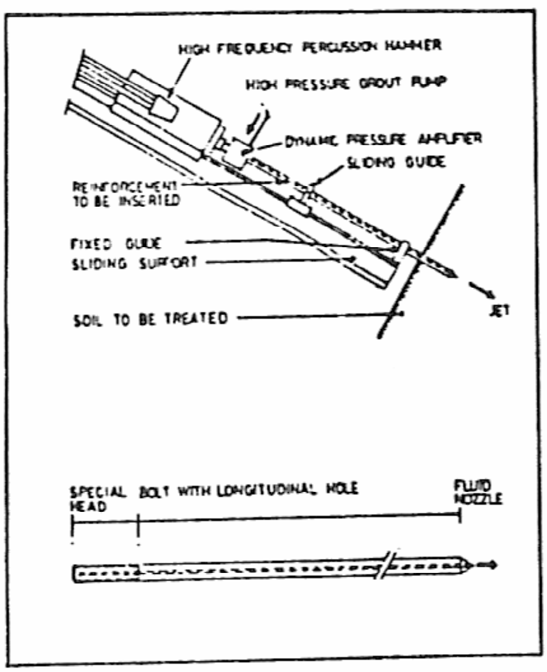
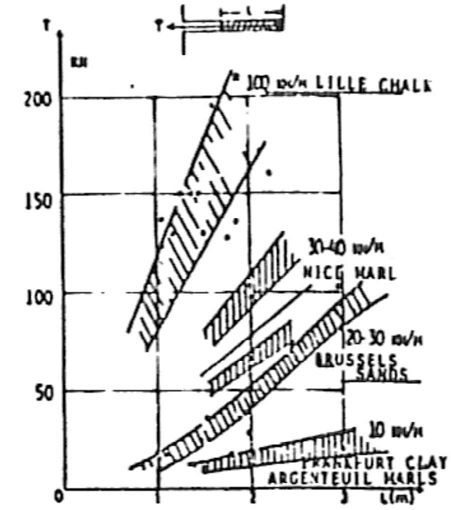


Fig. 12 - The "Jet Nailing" Technique for Soil Nail Installation Which Combines Vibropercussion and High Pressure Grout Jetting at the Nail Tip (Louis, 1986)



Nail Pull-Out Resistance in 50mm (2") Dia. Drill Holes for Different Soils

τ_{max} (10^5Pa)	DRIVEN without grouting	GROUTED Nails (auger/cased)	JET NAILING
clayey silt *	0.4 - 0.8	0.4 - 0.9	---
colluvium *	0.4 - 0.8	0.6 - 1.0	---
sand	1	2	4
sand - gravel	2	4	10
overburden :	no influence	influence	large influence

INFLUENCE OF THE NAILING PROCEDURE

Tests in sand and gravel (Lyon) Driven Bars

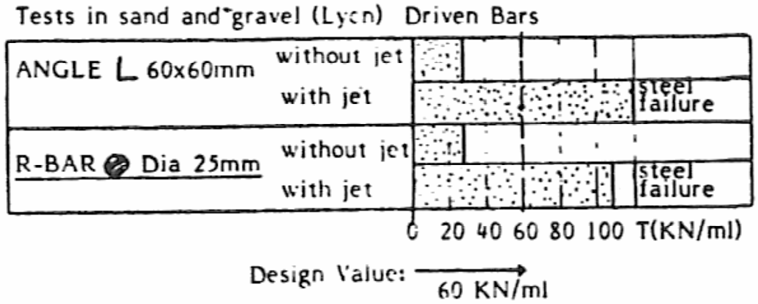


Fig. 13 - Nail Pullout Test Data, Showing Benefit of Jet Nailing (Louis, 1986)

bolting principle is that it permits nails to be installed with equal facility in an upwards inclination--often the most favourable orientation in terms of efficiency of load transfer (see Section 2.2 above).

5.4 Reinforcement and Corrosion Protection

Most nailing applications to date have been temporary, and in any event have been geographically far removed from particularly aggressive conditions such as marine environments. Thus, corrosion protection systems have been basic--relying on the bonding grout as a protection, often supplemented, as in the USA, by epoxy coating to the bar surface. In the case of driven reinforcements of the Hurpinoise system, there is not even that level of protection--the angle iron is in direct contact with the ground--but no corrosion-related problems have been reported. However, there is an increasing number of permanent applications and there is concern in certain circles regarding the corrosion-related failures of certain Reinforced Earth applications. In light of the findings of recent reports (e.g., FHA, 1985) and FIP State of the Art Review, "Corrosion and Corrosion Protection of Prestressed Ground Anchorages, 1986, led by Professor Littlejohn), it would be logical to presume that increased attention will be paid to this question for soil nails. Thus one should expect to see at least one layer of sheathing provided to the bar, as is the case for permanent nails in Germany (Figure 14).

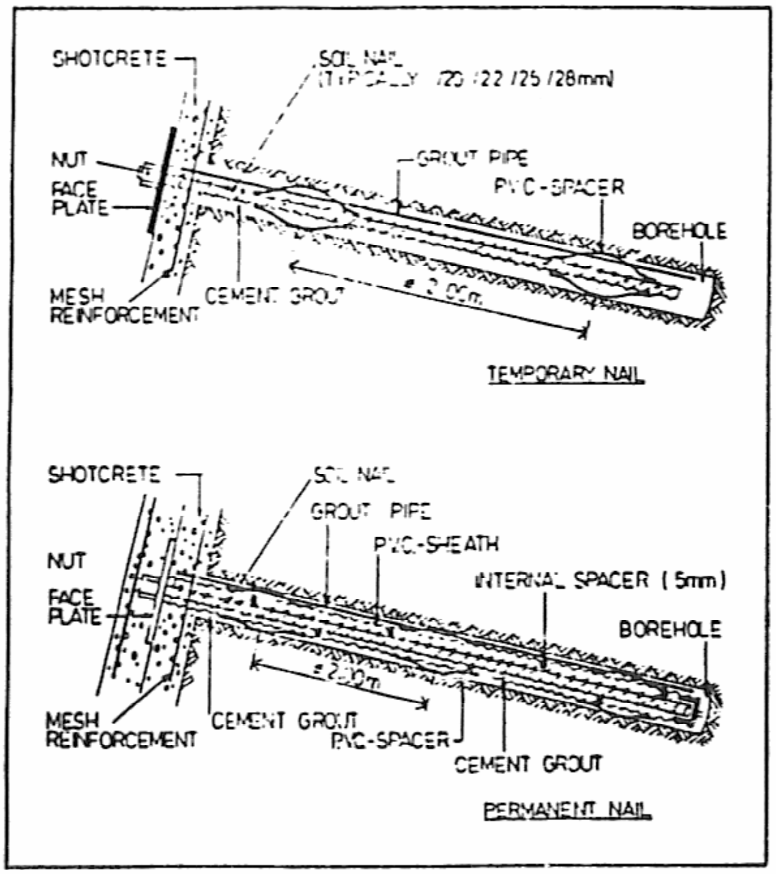


Fig. 14 - Examples of Good Practice for Drilled and Grouted Nail Installation (a) for temporary applications and (b) for permanent applications (Based on West German experience, reproduced with permission of Bauer).

5.5 Face Claddings

Soil nailing is finding increasing permanent applications in situations where a shotcrete is finding increasing permanent application in situations where a shotcrete finish--no matter how carefully integrated or disguised--is not visually acceptable. Slope stabilization in scenic areas of the French Riviera or Western California is a typical example. In such circumstances precast element facings are proving an excellent choice, permitting the landscape or architect free reign (Louis, 1986). Thus elements are being used which incorporate vegetation troughs, or which provide particularly good durability or noise absorption properties. Such precast claddings may be placed directly in contact with the slope face during construction, or may be used as a last stage in construction to front the standard shotcrete slope. It should be noted that whereas soil nailing as a technique is not patented, certain aspects of the construction such as jet bolting, or the natures of certain precast claddings, are so protected.

6. RESEARCH AND DEVELOPMENT

As indicated in Section 3, the technique of soil nailing has attracted the attentions of leading groups of researchers in the three countries where constructional activity is highest:

- France - CERMES, the research group at the Ecole National des Ponts et Chaussées under the direction of Professor Schlosser has carried out model tests and finite elements analyses of soil nailing, supervised by Dr. Juran, now at Louisiana State University. In addition, Centre d'Etudes et des Recherches du Bâtiment et des Travaux Publics (CEBTP) built and tested to failure a 7m high experimental wall during 1984/1985 under the direction of M. Plumelle. Overall, research is being continued under the nationally organized project "Programme Clouterre." There is also a very strong postgraduate research element at various universities, but especially under Dr. Louis at Ecole Nationale des Travaux Publics de État (ENTPE), Lyon.

• West Germany - Developments have been led by the specialist contractor Karl Bauer AG in association with the Institut fur Bodenmechanik und Felsmechanik (IBF) of the University of Karlsruhe, with financial support by the Federal Ministry of Research and Technology (Stocker, 1976). In a four-year programme commencing in 1975, eight carefully instrumented large scale field trials were conducted and analyzed (Stocker et al., 1979). Model testing and theoretical research into soil nailing is also conducted at IBF, University of Karlsruhe, under Professor Gudehus.

• USA - An early phase of research was conducted by Professor Shen's team at the University of California at Davis. They monitored the Portland contract in 1976, and thereafter conducted centrifuge model testing, an instrumented full scale trial, and finite element analyses. The research was funded principally by the National Science Foundation, and the final report published in 1981 (Shen et al.). The most recent phase has been triggered by the upsurge in construction activity dating from the time of the PPG contract (1982). One product of this has been the National Cooperative Highway Research Program NCHRP Project 24-2 Report sponsored by the Transportation Research Board and the Academy of Science, due to be published shortly. This is a very comprehensive review of insitu reinforcement. On the experimental side, FHWA research contracts were let in 1985 for fundamental laboratory and field tests, leading to the issue of a formal Manual of Practice for Soil Nailing in late 1988. Mr. Elias is the Principal Investigator.

Obviously much of the earlier fundamental experimental data have been published, especially those from West Germany (e.g., Stocker et al., 1979; Gassler & Gudehus, 1981). In addition, much valuable field information has also been made available from closely instrumented commercial projects (e.g., Goulesco & Medio, 1981; Cartier & Gigan, 1983). Data have been recorded both during construction and in service, and are generated by (Figure 15).

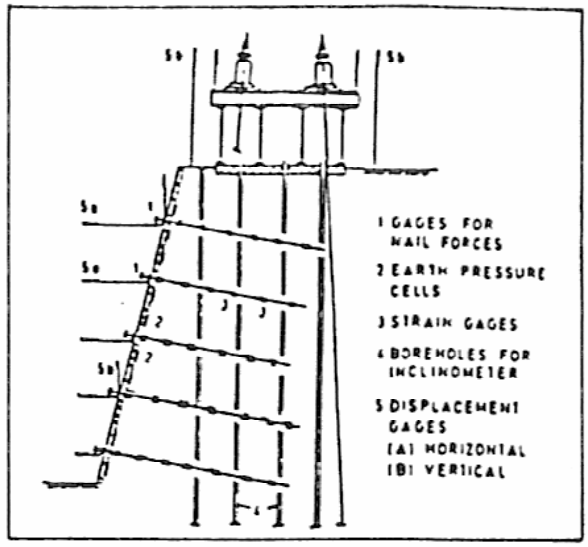


Fig. 15 - Range of Instrumentation Used for Monitoring Performance of Soil Nails, and Structure (Gassler and Gudehus, 1981)

(1) Load cells: placed under nail heads to monitor nail loads.
(2) Earth pressure cells: placed under the facing to monitor earth pressures transmitted to the facing.
(3) Strain gauges: to measure the magnitude, distribution and development of bar stresses.
(4) Borehole inclinometers: to illustrate the displacements in the supported ground (e.g., Figure 16).
(5) Displacement gauges: to permit survey of the face.

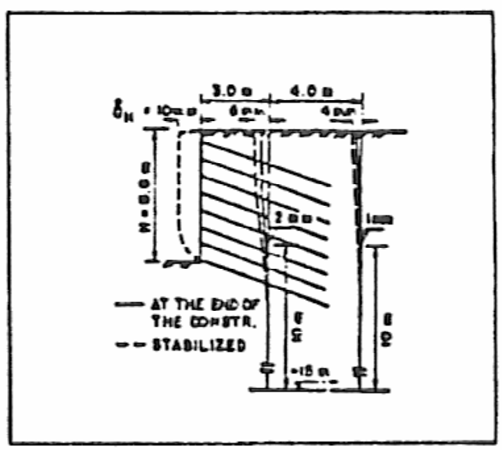


Fig. 16 - Horizontal Displacements Inside and Behind a Nailed Soil Wall (Cartier and Gigan, 1983)

In addition, as pullout tests on individual bars are an essential prerequisite to the start of full-scale production works on every site, much data of this type exists for synthesis (e.g., Figure 13).

Thus there already exists a substantial volume of information the designer can exploit to safely and economically dimension the various elements of soil nailing construction, and to predict its performance. Nevertheless, certain design concepts remain open to debate and further data from all sources are essential to improve understanding.

7. CLOSING REMARKS

Soil nailing is a technique of great potential and proven cost effectiveness, for the stabilization of excavations and slopes in soil. It is, therefore, worthy of attention and consideration by all engineers and constructors involved in such projects. Although so far barely acknowledged in Britain, it is regarded as a regular construction technique in continental Western Europe and North America. The authors look forward therefore to its similar exploitation under appropriate conditions in the United Kingdom as well.

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