Soil Nailing in France: Research and Practice

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In 1986 a 4-year, $4 million research project named CLOUTERRE was initiated in France by the French Minister of Transport. The main objective was to develop recommendations on soil nailing for temporary and permanent nailed soil walls in excavation, with special emphasis on safety and durability. The results and the subsequent recommendations for seven selected important topics are presented. The behavior of a nailed soil wall during construction, in service, and near failure was studied on three full-scale experimental walls pushed to failure according to three modes of failure. A design method based on Schlosser's multicriterion is recommended to account for all possible modes of failure. The classical definition of the global factor of safety is abandoned, and a new procedure using partial safety factors and weighing factors is recommended. A new method is proposed to design the facing thickness as a function of the nail spacings. More than 450 in situ pullout tests were collected to create a unique data base allowing correlations between the nail and soil types and the soil-nail interface frictional resistance. Detailed recommendations are developed to calculate the extra thickness of steel required in permanent nailed soil structures depending on the characteristics of the soil. Limitations of soil nailing are clearly defined for different situations. CLOUTERRE recommendations are a major contribution to the status of knowledge on soil nailing in excavation. They will allow the increasing use of soil nailing for temporary and permanent structures.

Soil nailing is a technique that consists of reinforcing in-place soils with bars or structural members called nails, which can be either driven or installed and grouted in drilled holes. When used in excavation, the nails are horizontally placed and able to withstand primarily tensile forces, making possible the construction of nailed soil retaining walls. The construction procedure is simple; it consists of the following steps (Figure 1): (a) excavation of the in-place soil, (b) installation of the nails, and (c) construction or installation of the facing.

The first nailed soil retaining wall was built in France in 1972–1973 at Versailles to retain a cut for rail tracks (Figure 2). Since then, soil nailing has been used extensively in France and abroad for temporary retaining structures in excavation because of its many advantages. Compared with traditional techniques, soil nailing requires limited labor and only light construction equipment, and the wall can be finished while the soil is being excavated. In addition, this technique can be adapted to any type of site downtown or in the mountains and to most types of soil. This makes a time- and cost-effective technique, which explains the rapid worldwide success of soil nailing. However, because of this rapid success, the state of the practice was ahead of the state of knowledge. Moreover, until recently soil nailing was used primarily for temporary retaining structures because of the lack of knowledge about the longtime behavior of such structures. Therefore, in 1986 a 4-year, $4 million national research program, CLOUTERRE, was initiated by the French Minister of Transport. Twenty-one organizations, including private companies and public research laboratories, participated directly in the project.

The main objectives of CLOUTERRE were to promote soil nailing in France for temporary as well as permanent retaining structures in excavation by improving the current status of knowledge and developing recommendations for temporary and permanent nailed soil walls. The objective of this paper is to present the main results of the research and the subsequent recommendations for seven important topics: (a) behavior of a nailed soil wall during construction, in service, and near failure; (b) design methods; (c) safety considerations; (d) facing design; (e) pullout tests; (f) durability; and (g) limitations.

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BEHAVIOR OF A NAILED SOIL WALL

One of the major contributions of CLOUTERRE to the status of knowledge is the monitoring of three full-scale experimental walls from construction to failure through service by Plumelle and Schlosser (discussed in another paper in this Record). In the following section the main mechanisms involved in a nailed soil wall will be summarized and the design methods will be described.

Deformations

A nailed soil wall is constructed from the top to the bottom by alternating excavation with the installation of the nails and the facing. At each excavation step, the excavated soil remains exposed for some time before being nailed. This situation results in the vertical settlement and lateral decompression of the bottom soil, which generate horizontal and vertical outward displacements of the top of the wall. The top bends outward a bit more at each new excavation step (Figure 3) and ends up with vertical displacements of the same order as the horizontal displacements (Figure 4). All the measurements performed within CLOUTERRE (nine instrumented nailed soil walls) confirm that the ratio of horizontal displacement of the top of the wall (δ_H) over height of the wall (H) varies between 1/1,000 and 3/1,000 for walls built with a reasonable factor of safety (Figure 5). Moreover, the ratio of

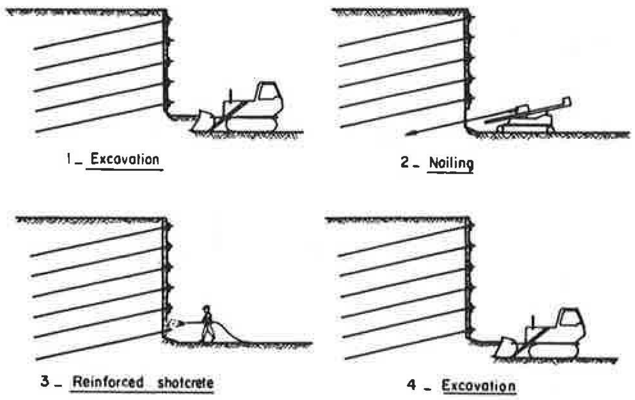

FIGURE 1 Steps in constructing nailed soil wall.

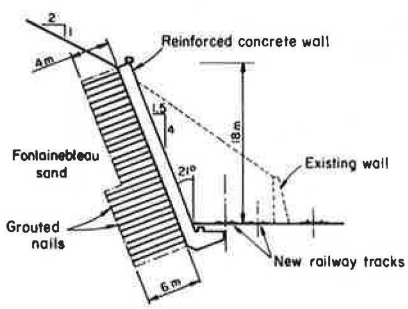

FIGURE 2 First nailed soil wall, in Versailles (*13*).

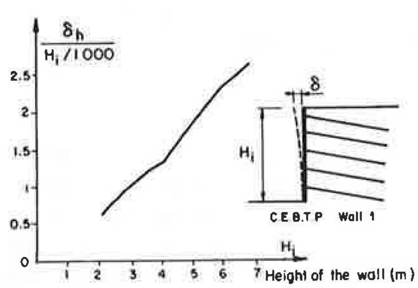

FIGURE 3 Evolution of horizontal displacements at top of nailed soil wall during construction.

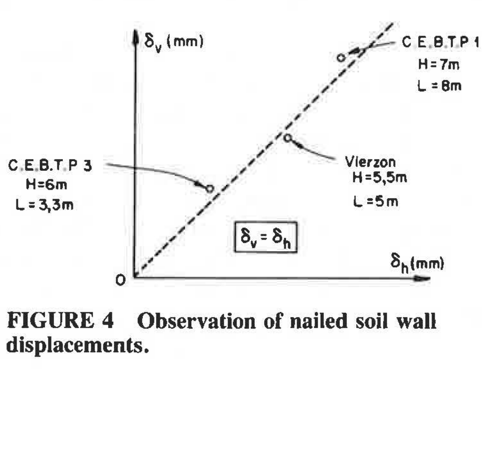

FIGURE 4 Observation of nailed soil wall displacements.

horizontal displacement at the surface right above the ends of the nails (δ_o) over H varies between 4/10,000 and 5/10,000 (Figure 6).

Soil-Nail Interaction

During construction, nails are loaded essentially in tension because of the lateral decompression of the soil. The transfer of stresses between the soil and the reinforcements involves a basic mechanism, namely, frictional resistance (*1*). The shear stress τ at the interface is limited in value by q_s, interface frictional resistance. In soil nailing where reinforcements are installed in in-place soils, the phenomenon of restrained dilatancy has been observed. This phenomenon, first described by Schlosser and Elias in 1978 (*2*) for reinforced earth, was observed for soil nailing by Cartier and Gigan (*3*) and confirmed by field and laboratory experiments in CLOUTERRE (*4*) (Figure 7). As a result, q_s is a function only of the soil, nail, and soil-nail interaction properties. Therefore, correlations have been developed between q_s and in situ testing measurements, typically the limit pressuremeter pressure, p_l (Figure 8). However, because of the high dispersion of such correlations, q_s is usually determined more precisely with pullout tests.

Distribution of Tension Forces in Nails

At each new excavation step, because of the horizontal lateral decompression of the soil, nails are activated essentially in

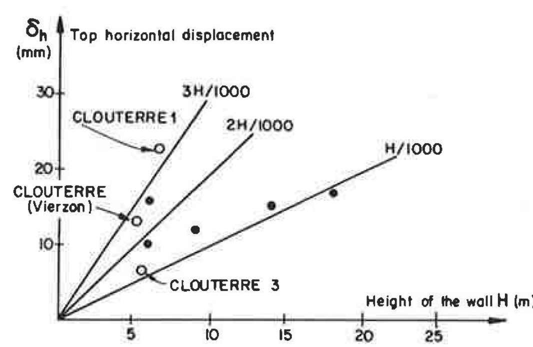

FIGURE 5 Horizontal displacements of nailed soil wall.

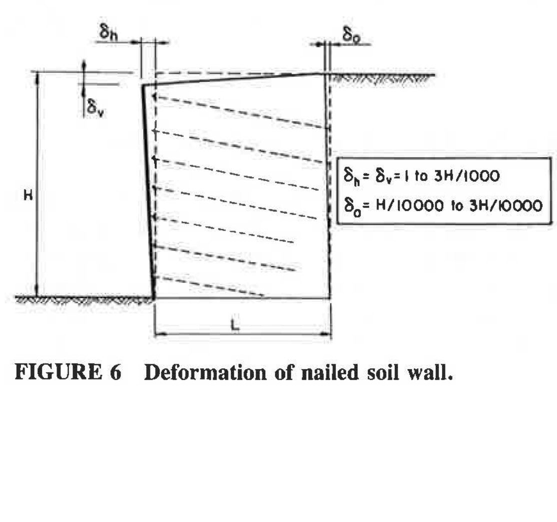

FIGURE 6 Deformation of nailed soil wall.

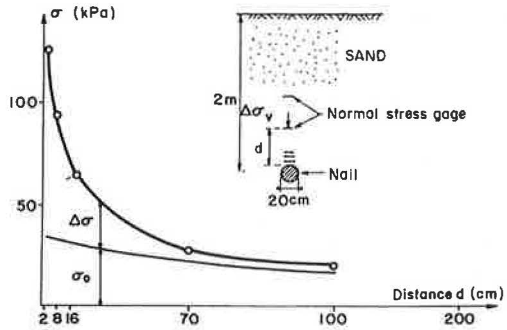

FIGURE 7 Increase in normal stress due to restrained dilatancy around nail.

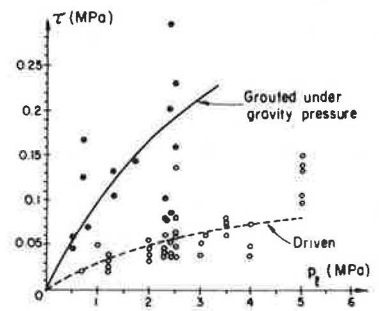

FIGURE 8 Correlations between limit frictional shear stress and limit pressure obtained from pressuremeter test (*12*).

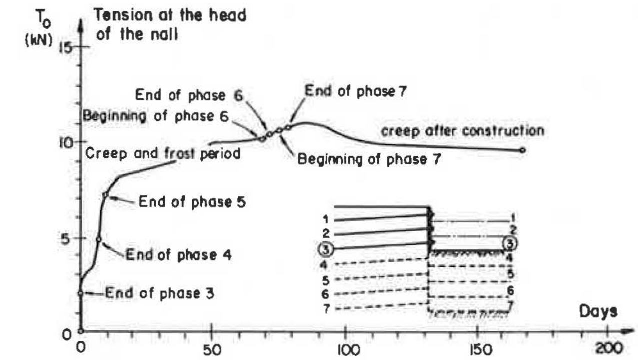

FIGURE 9 Variations of tension in nail head during excavation, Wall 1.

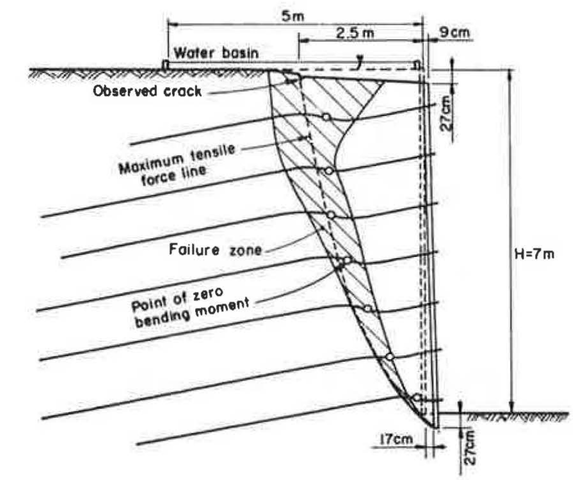

FIGURE 10 Failure zone developed in full-scale experiment on nailed soil wall.

tension. The progressive increase of nail tension was monitored in CLOUTERRE for several full-scale walls from construction to failure through service (Figure 9). The distribution of tension in the nails at the end of construction, that is, in service, is very similar in principle to the distributions that have been observed for other reinforcement techniques, such as reinforced earth. The maximum tension in the nails occurs at a certain distance from the facing and not at the facing. The locus of the points at which the tension T is maximum (T_{max}) defines a surface that divides the reinforced soil mass into two zones: the active zone and the passive zone. In the active zone, which is behind the facing, the shear stress acting on the nails is pointing outside the wall; in the passive zone it is pointing inside. At the top of a wall with a vertical facing and horizontal top, the locus of T_{max} is almost vertical; at the base it is inclined and goes through the toe of the wall (Figure 10).

Mobilization of Shear Force and Bending Moment

As far as the forces (tension or shear force) and moments (bending moment) that can be developed in a nail are concerned, a clear distinction among construction, service, and failure conditions must be made. During construction and in service, nails are essentially loaded in tension. Locally near the facing, small shear forces and bending moments may be generated during construction but only in extreme cases in which the facing is hanging on the nails. But near and at failure, significant shear forces and bending moments will appear along the failure surface. Concerning this point, the full-scale experimental wall—Wall 1—is of major interest. The 7-m-high nailed soil wall was pushed to failure as the sandy soil behind the facing was saturated. After failure, the deformed shape of the failed wall was investigated. Around the potential failure surface, represented by the locus of maximum tension, a wide zone of shear and distortion developed. Within this zone nails underwent distorsions of about 20 degrees (Figure 10). The importance of the shear force (T_c) compared with the tensile force (T_n) has been investigated by Marchal (*5*) with the direct shear box on soil samples reinforced with steel bars (Figures 11 and 12). The ratio T_c/T_n depends on the orientation of the reinforcing bar relative to the shear plane. However, for inclinations of about 70 to 90 degrees, the ratio T_c/T_n can be as high as 15 percent. Therefore, limit equilibrium design methods should be able to take into account this benefit of the shear forces and bending moment in the stability analysis. This is what will be developed in the next section with the multicriterion.

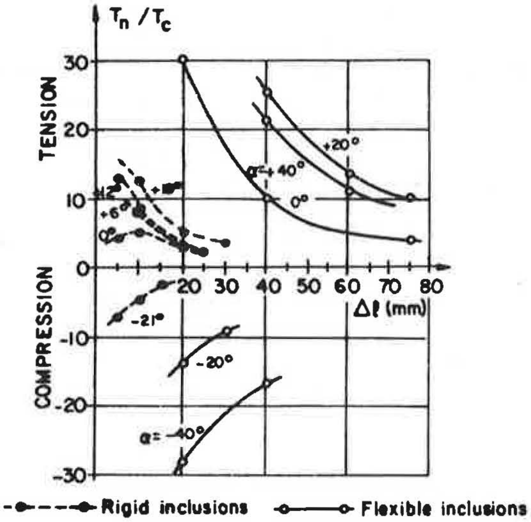

FIGURE 11 Evolution of ratio of tensile force to shear force as a function of displacement (α = inclination of bar with vertical) (5).

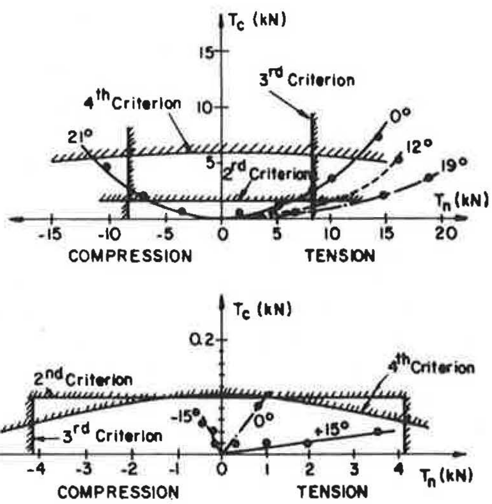

FIGURE 12 Evolution of limit values of tensile and shear forces: *top*, rigid inclusions (σ = 350 kPa); *bottom*, flexible inclusions (σ = 300 kPa) (5).

DESIGN METHOD

Until now, it has not been possible to develop effective design methods calculating both deformations and efforts in the nails in service. Only limit equilibrium design methods are available and used for design purposes. A suitable limit equilibrium design method should be able to (a) analyze the different failure modes—external, mixed, and internal—and (b) take into account the contribution (positive or negative) of the nail tension and compression for flexible nails; for nails with a sufficient bending stiffness, shear forces and bending moments should be taken into account as well.

Types of Failure

Three types of failure must be considered: external, mixed, and internal. In an external failure mode, the failure surface does not intersect the nailed soil mass, which is considered as a monolithic block. For this type of failure, classical limit equilibrium methods are sufficient for design purposes. A failure is said to be internal or mixed when the failure surface is totally or partially within the nailed soil volume. For the latter two failure modes, classical limit equilibrium methods are not sufficient. Internal failures of nailed soil walls are due to either the breakage of the nails or the lack of frictional resistance. Both types of internal failure have been realized on full-scale experimental walls (Walls 1 and 3, respectively).

Internal Failure by Breakage

In an internal failure by breakage, nails can break in tension or in tension and shear if the bending stiffness is high enough. The failure surface that develops in the wall from the toe to the top is very close to the locus of maximum tension. When nails have some bending stiffness, a shear zone rather than a clear failure surface develops around the locus of maximum tension. The rupture is less rapid and more progressive than it is with flexible nails because large shear deformations develop before the wall reaches complete failure. This point is important in the field because there is time to prevent a complete failure.

Failure by Pullout

In contrast to failure by breakage, failure by pullout is less common and had never really been studied before CLOUTERRE. This type of failure occurs when nails are not long enough or when the interface friction resistance is not sufficient to balance the maximum tension. Wall 3 of CLOUTERRE was induced to failure by reducing the length of the nails (Figure 13).

Multicriterion

It has been shown that the role of nails in the structure is quite complex and that different types of internal failure can occur. A suitable analysis should take into account all possible modes of failure and treat them in a simple way. This is what the multicriterion is all about. Limit equilibrium methods consider the equilibrium of a soil mass at a limit state. In the equations of equilibrium, only the tensions and compressions (T_n) and the shear forces (T_c) of the nails at the intersection with the potential failure surface play a role. For a given potential failure surface, (T_n, T_c) must be determined for each nail depending on the orientation of the nail with the failure surface and on the mode of failure that is most probable for the given surface. Four failure criteria must be considered to take into account all the possible failure conditions of a nail. Each criterion will be written in terms of (T_n, T_c), the values of the axial and shear forces in the nail at the point of intersection with the potential failure surface.

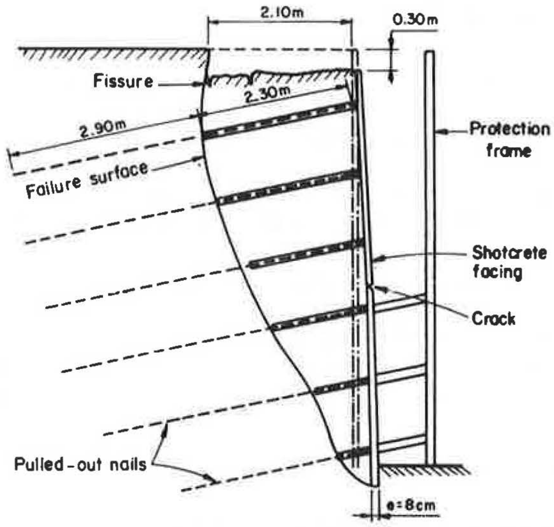

FIGURE 13 Postfailure investigation of Wall 3 (Fountainebleau sand, $\phi' = 38$ degrees, $c' = 9$ kPa).

1. The first criterion that corresponds to an internal failure by pullout depends on the interface frictional resistance q_s

$$T_n \leq q_s \pi DL_a \quad (1)$$

where

T_n = axial force,
q_s = interface frictional resistance,
D = diameter of nail, and
L_a = length of nail behind the failure surface.

2. The second criterion corresponds to the failure of the soil below a nail. The pressure of a nail on the soil below it is limited by the bearing capacity pressure p_u. The failure of the soil below a nail can be defined when p_u is reached at one point (the point of maximum shear force in the nail), which yields the following criterion:

$$T_c \leq l_o p_u D/2 \quad (2)$$

where l_o is the transfer length (elastic analysis).

3. The third criterion corresponds to the failure of the nail by breakage. The combination of (T_n, T_c) that occurs in a nail at failure can be represented by the following simple criterion proposed by Anthoine (*6*), which is somewhat more conservative than other proposed criteria (*7,8*):

$$(T_n/R_m)^2 + (T_c/R_c)^2 + |M/M_o| \leq 1 \quad (3)$$

where

T_c = shear force in a nail,
M = bending moment in a nail,
R_n = maximum tensile force,
R_c = maximum shear force, and
M_o = maximum bending moment in pure bending.

This third criterion is represented by an ellipse in the plane (T_c, T_n).

4. The nail can fail on two other points, however: the points of maximum moment. Those points are at a distance $l_s/2$ of the shear plane. The distance l_s can be considered as the width of the shear band that develops around the shear plane. At the present time, there is no available method to calculate l_s with reasonable precision. The only available information about l_s is that it is equal to $\pi l_o/2$ when the nail first starts to plastify at two points by bending moment (elastic analysis). After formation, the two plastic hinges move with the progressive plastification of the soil under the nail. In the absence of more practical information about l_s, a simple assumption can be made: l_s is constant and equal to its initial value $\pi l_o/2$. Assuming, then, that the two plastic hinges at the points of maximum moment are fixed, the following criterion (C_4) can be defined.

$$T_c \leq b\,(M_o/l_o)[1 - (T_n/R_n)^2] + cDl_o(p_u - p_o) \quad (4)$$

where b and c are constants and R_n is the maximum axial force in simple tension.

The envelope of these four criteria in the (T_c, T_n) plane defines a domain of stability that is convex and in which the point (T_c, T_n) can be placed anywhere a priori. Figure 14 shows such a stability domain that represents the combination, called the multicriterion, of all four failure criteria. It is very important to note here that, depending on the soil type and on the nail-bending stiffness, the first criterion may play no role because it is above the second criterion in the presented case. At failure, the point (T_c, T_n) is on the border of the stability domain but its position is unknown a priori. A rule must be chosen. Schlosser proposed in 1982 and 1983 to use the rule of maximum work (*9,10*) as a particular case of the "normality rule." The position of the point (T_c, T_n) on the border is chosen to maximize the work of the nail in the considered potential failure mechanism. Once the displacement of the nail point at the intersection with the failure surface is known, (T_c, T_n) can be determined to maximize the dissipated work.

Numerical simulations of the failure of Wall 1 have been performed using the multicriterion (*11*). The wall failed after saturation of the soil behind the facing to a height of 4 to 5 m from the bottom. Before saturation, the soil had an apparent cohesion of about 3 kPa in its unsaturated state. Because of saturation, this apparent cohesion was reduced to zero. Two limiting cases of the soil properties have been thus considered (Figure 15): (a) the soil keeps its initial 3-kPa cohesion everywhere, which gives an upper bound of the height of water at failure; and (b) the soil loses its 3-kPa cohesion only in the zone in which it is saturated; this gives a lower bound.

SAFETY CONSIDERATIONS

Traditionally, safety is calculated in slope stability analyses by considering the ratio τ/τ_{max}, where τ is the tangential component of external forces and τ_{max}, the shear strength that can be mobilized along a potential failure surface. This ratio, which is usually called the global safety factor, is supposed to take into account many factors, including variability of properties, uncertainties on measures of material strengths, scat-

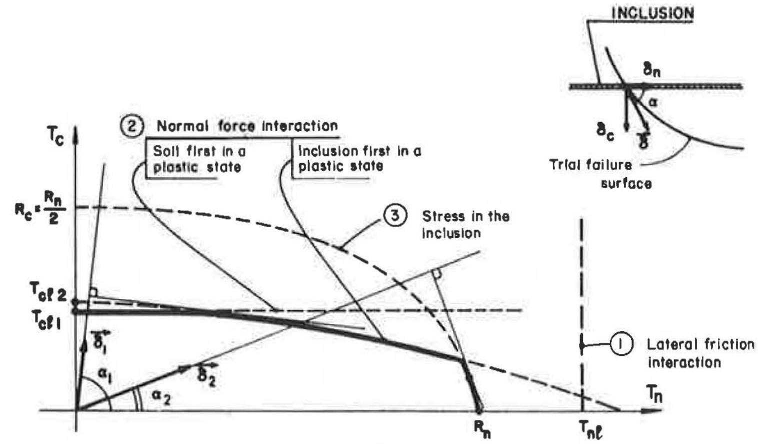

FIGURE 14 Various interaction mechanisms within normal force (T_n) and shear force (T_c) planes.

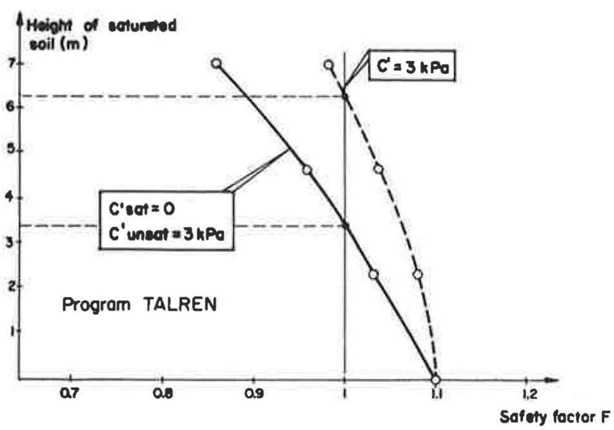

FIGURE 15 Evolution of safety factor in Wall 1.

tering of measures of material strengths, uncertainties on loading conditions, and errors inherent to the design method used. However, because all these factors are combined into one coefficient, they tend to be considered with equal importance. In the CLOUTERRE recommendations, a completely new formulation using different partial safety coefficients has been developed to separate clearly the factors described earlier.

The most probable values of the soil, nail, and soil-nail interaction parameters are determined by a geotechnician from the laboratory or in in situ testing with a sufficient number of samples. Then the variability and dispersion of these parameters are taken into account by defining characteristic values. These are calculated from the most probable values by using coefficients of scattering (*12*). Characteristic values of the material properties are then reduced with partial safety factors ($\Gamma_{m,c}$ = cohesion; $\Gamma_{m,\phi}$ = friction). On the other hand, actions will be multiplied by weighting factors (Γ_Q = loads; Γ_G = gravity) to obtain calculation values (Table 1). Once calculation values have been determined, limit equilibrium methods are used to determine the ratio τ_{max}/τ, which is required to be greater than Γ_{s3}, called the method coefficient.

$$\Gamma_{s3}\tau \leq \tau_{max} \qquad (5)$$

TABLE 1 EXAMPLE OF PARTIAL SAFETY FACTORS

FUNDAMENTAL	FUNDAMENTAL COMBINATION	ACCIDENTAL COMBINATION
SOIL		
$\tan \phi^*$	1.65	1
c^*	1.2	1
SOIL-NAIL INTERACTION		
q_s	1.6 (correlations) 1.3 (pull-out tests)	1.4 (correlations) 1.2 (pull-out tests)

This coefficient takes into account the errors inherent in the methods. For limit equilibrium methods using the multicriterion and searching circular potential failure surfaces, Γ_{s3} is chosen to be 1.125 for a fundamental combination and 1.0 for an accidental combination. A design will be acceptable according to the present status of knowledge if the inequality is respected.

FACING DESIGN

The facing may have several functions in a nailed soil structure: it provides a lateral confinement for the soil between the nails, and it carries external loads such as decorative panels. However, hereafter only the first function will be considered because it is the most important one. Locally between each nail, soil must be retained.

Two soil-nailing techniques exist in France. The first and oldest one, called "Hurpinoise" after its inventor, consists of short nails, with a length of about 0.5 to 0.7 H, that are driven with or without vibrations. Usually, it uses one or two nails per square meter. The second one uses grouted nails in drilled holes with a length of 0.8 to 1.2 H. The number of nails per unit surface is about 0.15 to 0.4, which is almost one order of magnitude smaller. Because of these different densities of the nails, the facing tends to be very thin for the first technique and much thicker for the second one.

The density of the nails is a major factor, but other factors, including the rigidity of the facing itself, play a role. The facing is in equilibrium by balancing the earth pressures and the forces applied by the nails. It is usual for design purposes to assume that these earth pressures are uniformly distributed. As a result, they are known as soon as the tension T_o is known. T_o is the tension in a nail at the facing when it is in a limit state while the rest of the structure (soil and nails) is in service. The ratio of T_o/T_{max}, T_{max} being the nail tension on the locus of maximum tensions, can be estimated from instrumented full-scale nailed soil walls. This ratio depends on many factors. However, as observed earlier, the nail spacing is the most important factor to the earth pressures, which are directly related to T_o. The ratio T_o/T_{max} can thus be estimated as a function of S_v and S_h, which are, respectively, the vertical and the horizontal spacing. On the basis of the experimental results, CLOUTERRE recommendations propose the following:

$$T_o/T_{max} = 0.5 + (S - 0.5)/S \quad \text{for } 1 \le S \le 3 \text{ m} \quad (6)$$

$$T_o/T_{max} = 0.6 \quad \text{for } S \le 1 \text{ m} \quad (7)$$

$$T_o/T_{max} = 1.0 \quad \text{for } S \ge 3 \text{ m} \quad (8)$$

where

S = $\max(S_v, S_h)$ (m),
S_v = vertical nail spacing, and
S_h = horizontal nail spacing.

Once the ratio T_o/T_{max} is known, one must estimate T_{max} to have T_o. A conservative approach is to calculate T_{max} from T_{lim}, maximum tension in the nails on the most critical failure surface, because the latter is a conservative value of T_{max}. Once the forces T_o and earth pressures acting on the facing are known, the facing can be designed like any similar concrete structure, typically, a floor carried by a great number of piles.

PULLOUT TESTS

One of the most important parameters in the design is q_s, the interface frictional resistance. For a given soil and nail type, q_s is independent of depth. Therefore, q_s can be calculated from the soil, nail, and soil-nail interface properties. Practically, q_s will be determined from the in situ testing measurements. Figure 8 shows such a correlation between q_s and p_l, the limit pressuremeter pressure. One can note the great amount of scatter in this figure, in which data on all types of soils are shown. One of the major contributions of CLOUTERRE has been to collect more than 450 results from pullout tests with the corresponding in situ pressuremeter test results. The processing of these data by type of soil and nail has allowed the development of correlation curves that will be useful for design. However, because of the great variability of q_s measurements, CLOUTERRE recommendations require that q_s be measured in the field in the soil and with the nails that will be used for construction using displacement-controlled pullout tests.

DURABILITY

Durability was of major concern in CLOUTERRE because one of the initial objectives was to promote soil nailing for permanent retaining structures. Most nailed soil structures are built with steel nails. Therefore, corrosion must be taken into account for structures with an expected service life of more than 18 months. Three types of provision can be taken to protect steel nails from corrosion: (a) increase of the nail sections, (b) protection with coatings, and (c) protection with barriers.

The most frequently used technique in soil nailing and in other reinforcement techniques such as reinforced earth is to use nails with thicker cross sections. This technique is efficient only if the type of steel used for the nails undergoes generalized corrosion and not punctual corrosion. The sections are calculated so that at the end of the expected service life the remaining noncorroded steel sections are thick enough. In the recommendations, a global index is defined to take into account the type of soil, its resistivity, its moisture content, and other parameters. Extra thicknesses of steel are then provided for each type of structure as a function of the global index (Table 2). Other techniques using special coatings, which may be painting or galvanization, can be used to slow steel corrosion. The last type of technique uses barriers that can be made with plastic to prevent corrosion. These barriers do not play any mechanical function. These types of techniques are used more and more because these types of nail are patented by the companies that develop and promote them.

LIMITATIONS OF SOIL NAILING

Despite its many advantages, the most important being its easy adaptation to any kind of site, soil nailing is a technique that has a few limitations. Most of them can be prevented by making construction or design provisions; however, these provisions may make soil nailing more expensive and thus less attractive. In nailed soil walls, displacements inherent to the technique occur. They are limited to about 0.003 the height of the wall, but this may still be too much for some urban sites. Different types of provisions can be chosen. One solution is to use bracings at the top of the nailed soil wall. Another solution is to install one or two rows of tiebacks in the upper part of the wall. This solution is often chosen especially for very high nailed soil walls (Figure 16). Because of the construction procedure for a nailed soil wall, it must be built above the water table level; it may be built below it only if the groundwater table can be lowered sufficiently for the construction duration. The last type of limitation concerns the in-place soils that can be nailed. Sandy soils without any apparent cohesion cannot be excavated over a sufficient depth

TABLE 2 EXTRA THICKNESSES RECOMMENDED FOR CORROSION PROTECTION

Class	Structures Expected Life ≤ 18 months	Structures Expected Life 1,5 to 30 years	Permanent Structures 30 to 100 years
IV	0	2 mm	4 mm
III	0	4 mm	8 mm
II	2 mm	8 mm	plastic barrier
I	Compulsory plastic barrier		

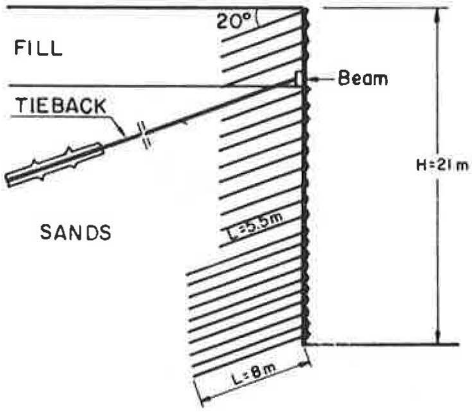

FIGURE 16 21-m-high nailed soil wall.

without protection. Clayey soils must be nailed with precautions; they may become saturated after construction and suffer a resulting significant decrease in the soil-nail interface frictional resistance.

CONCLUSIONS

CLOUTERRE, thanks to its 4 years of theoretical, numerical, and experimental research and its three full-scale experimental walls, has significantly increased the status of knowledge on soil nailing for temporary and permanent retaining structures in excavation.

The knowledge in seven topics has been improved: (a) behavior of nailed soil walls, (b) multicriterion design method, (c) partial safety coefficients, (d) design of the facing, (e) correlations for (q_s,p_l) based on 450 pullout tests, (f) corrosion provisions for steel nails, and (g) construction and design provisions.

CLOUTERRE recommendations will be a milestone in soil nailing because they will allow soil nailing to be used in more and more temporary and permanent structures. Every year new nailed soil walls are built in more difficult sites and with more difficult soils. The world record in height is 21 m. The limits of soil nailing have not yet been reached.

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