Earth Reinforcement Practice, Ochiai, Hayashi & Otani (eds) © 1992 Balkema, Rotterdam. ISBN 90 5410 093 1

Failure of a full scale experimental soil nailed wall by reducing the nails lengths (French research project CLOUTERRE)

F. Schlosser
Ecole Nationale des Ponts et Chaussées, Paris & Terrasol, Tour Horizon, Puteaux, France

C. Plumelle
Centre Expérimental du Bâtiment et des Travaux Publics, Saint-Rémy-lès-Chevreuse, France

P. Unterreiner
Ecole Nationale des Ponts et Chaussées, Cermes, La Courtine, Noisy le Grand, France

J. Benoit
Department of Civil Engineering, University of New-Hampshire, Durham, N.H., USA

ABSTRACT : Within the national research project, Clouterre (1986-1991) on soil nailing performed in France, a full scale experiment on failure due to insufficient nails lengths had been carried out.
The soil nailed wall was constructed in a 6 meter high soil mass, artificially created in order to control precisely its characteristics. Telescopic nails were designed to simulate a pull-out failure of nails by progressively reducing their lengths step by step. The monitoring of this full scale experimental wall allowed to measure : displacements of the facing and inside of the soil mass and forces in the nails, at various stages during the experiment including construction and at failure.
The calculations using the multicriteria method (TALREN) at different stages of the construction and particularly at failure, give a good agreement with the experiment results.

1 INTRODUCTION

Soil nailing is a technique of in situ soil reinforcement based on using steel rods that interact with the soil. These last recently years, the important development of this technique, invented in France, which is the equivalent of reinforced earth for soils in cut (Schlosser 1982, 1983), has resulted in a french national research project called "CLOUTERRE".
Industrial laboratories, universities, consulting engineers, administrations, and major contractors, have contributed to work on this project. Its aim was to develop, after completion of a major test and study program, a code of practice for the building of temporary and permanent nailed soil walls. The code was published in December 1991.

Several job sites have been instrumented and monitored and three full scale experiments were conducted to study three types of failures.(Plumelle et Schlosser 1991).

. Failure of the nailed soil mass due to breakage of the bars
. Failure of the nailed soil mass during the excavation phases
. Failure of the nailed soil mass due to the lack of adhesion on the bars

This article describes the significant results of the third experiment.

2 SITE PREPARATIONS

This third experiment was conducted at the Centre Expérimental du Bâtiment et des Travaux Publics (C.E.B.T.P.) in Saint-Rémy-Lès-Chevreuse, near Paris.
The backfill sand had a uniform gradation, and is referred to as Fontainebleau sand. The density after compaction in 20 cm thick layers was 15.1 kN/m3 and is equivalent to a medium dense sand with a relative density of 60 %.
At this density the main characteristics of this sand are :

-the SPT results (Fig. 1) ranged from 8 blows per 0.3 m at 1 m depth to 15 blows per 0.3 m at a depth of 5 m,
- the limit pressure p_L and the modulus E_M measured using the Menard pressuremeter are given on Figure 1.

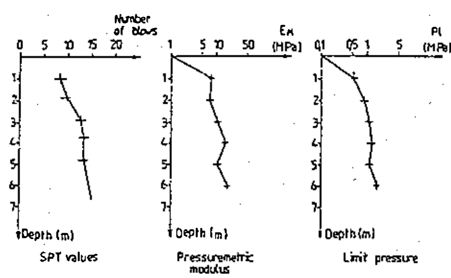

Fig.1 Results from SPT and Pressuremeter Tests

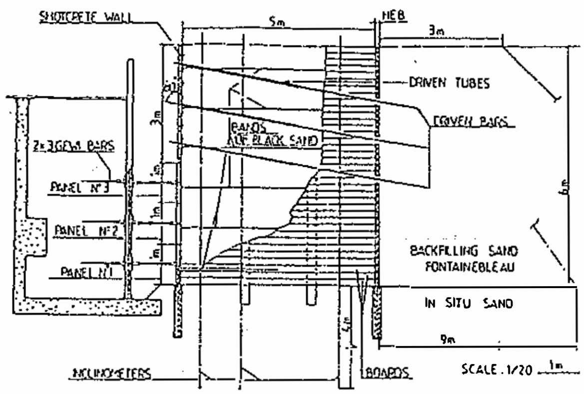

Fig. 2 Experiment layout at the end of the third stage

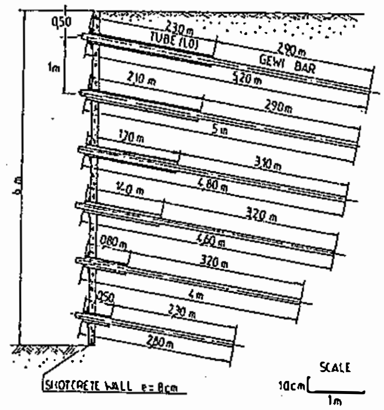

Fig 3 Scheme of the nailed wall at the end of the construction

- The shear strength characteristics of this sand established in laboratory are $\phi' = 38°$ and $c' = 3$ kPa .

3 CHARACTERISTICS OF THE EXPERIMENTAL WALL AND LATERAL WALLS.

The sand mass to be used for the experiment, 6 m high and 2 m wide, was reconstructed inside two walls made of boards. The boards were constrained by two lateral walls made of formworks, which were anchored by bolted rods on channel beam embedded in the soil.(Fig. 2).

During backfilling, the sand mass was butressed by metallic panels braced on a frame made of two twin H-Beam. Starting from the bottom, there were six removable panels 1 m high. The sand was placed simultaneously on all the sides of the board walls to create an experimental sand mass and two lateral walls. The inside face of the board walls were covered with a greased double plastic layer to prevent friction on the sidewalls and to ensure plane strain conditions.(Fig.2).

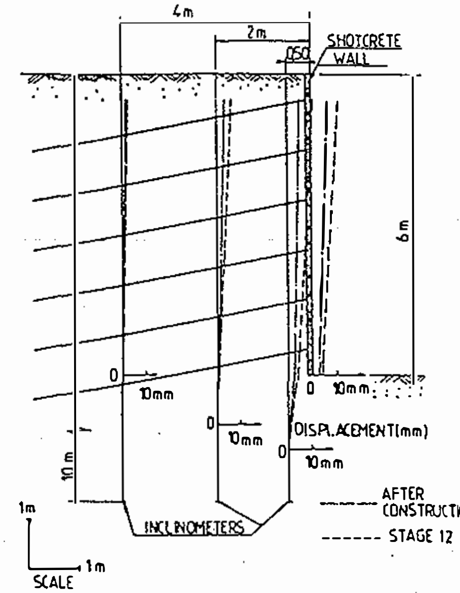

Fig 4 Measures of the horizontal displacements

4 CONSTRUCTION OF THE NAILED WALL.

The wall was nailed from the top down using a system of telescopic nails driven in the sand, made of bars (50 mm diameter) inside tubes (71 mm diameter) as shown on Figure 3.

5 DISPLACEMENTS OF THE NAILED MASS

Displacements plotted on Figure 4 were measured at the end of the construction of the nailed wall and at the twelfth stage (four stages before failure) of shortening the nails, for which nails of the first layer were 2.3 m long, those of the second layer 2.1 m and the four others at 1.8 m. These displacements are displacements of the sand, just behind the facing, measured during excavation by inclinometers, and displacements of the facing after its construction. These measurements complete those carried out during execution of the nailed wall 1, where only displacements of the facing were recorded.

For this nailed wall, it is to be noticed that the horizontal displacemements at the end of the construction, is 0.12 % of total height of the nailed wall. Otherwise significant displacements of mass of sand beneath the foot of facing were recorded.(Fig.4).

6 FORCES IN NAILS

Forces in nails, at the end of the nailed wall construction, are small but comparable with those recorded during the experimentation of nailed wall 1. The maximum forces, 9 kN, were recorded on nails located near the middle of the wall.

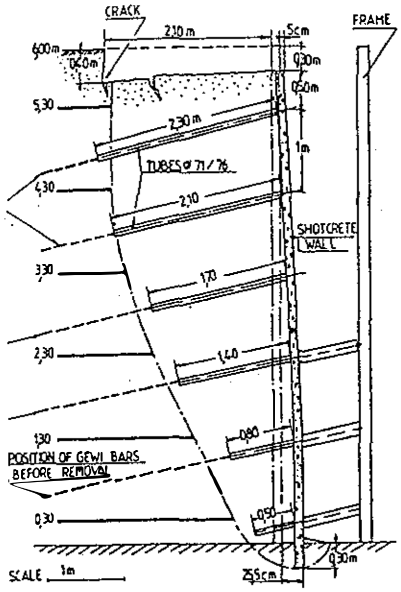

Fig. 5 Scheme after failure

The distribution of forces do not follow any particular trend with depth.

7 FAILURE OF THE NAILED WALL BY SHORTENING OF NAILS

Initial lengths of nails provided substantial stability of this nailed mass at the beginning. During the process of shortening nails, with a same length of 2.4 m for the nails, stability was still maintained. Failure of the sand mass, reinforced with the tubes of decreasing length with depth, occurred not because of lack of adhesion, but due to sliding of a block limited by the facing and along a rupture surface situated behind the ends of the nails. This block dropped 0.4 m, and the facing subsided 0.3 m beneath its previous level. (Fig.5).

8 DESIGN METHOD : MULTICRITERIA THEORY

The Multicriteria method, implemented in the TALREN method, was used for design.

The TALREN program considers the equilibrium of a soil mass at a limit state, taking into account the tensile resistance (T_n) and the shear forces (T_c) of the nails at the intersections with the potential failure surface.

For a given potential failure surface, (T_n, T_c) have to be determined for each nail depending on the orientation of the nail with respect to failure surface and depending on the mode of failure which is the most probable for the given surface. Four failure criteria have to be considered to take into account all the possible failure conditions of a nail. Each

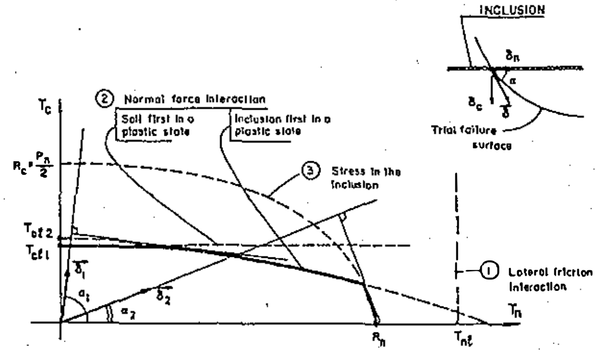

Fig 6 Representation of the Various Interaction Mechanisms Within the Normal Force (T_n),and the Shear Force (T_c) Plane

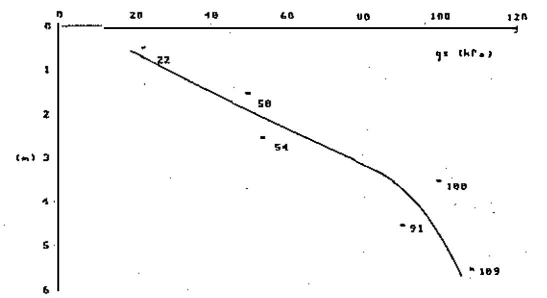

Fig 7 Interface frictional resistance q_s versus depth.

criterium is written in terms of (T_n, T_c) - Fig.6 -.T_n and T_c are the values of the axial and shear forces in the nail at the point of intersection with the potential failure surface. (Schlosser 1982, Schlosser et Unterreiner 1991).

The Multicriteria method (program TALREN) uses either circular or non circular potential failure surfaces. In accordance with the "Recommendations CLOUTERRE 1991" partial safety factors are introduced in the limit equilibrium design method. But in order to perform calculations and to compare them with test results, all the partial safety factors, except the coefficient method, were taken equal to 1. Calculations yield the coefficient method equal to τ_{max}/τ. Formally, this ratio is the classical global factor of safety. Three calculations had been conducted to study the different stages of the experiment :

1) at the end of construction (Figure 3),
2) when all the nails had a same length of 2,7 m,
3) just before failure of the soil nailed wall, (at this stage, only tubes remained).

- The following parameters of the soil were used :

. ϕ' = 38 ° et c' = 3 kPa
. p_l=1 MPa EM = 10 Mpa

γ = 16,6 kN/m3

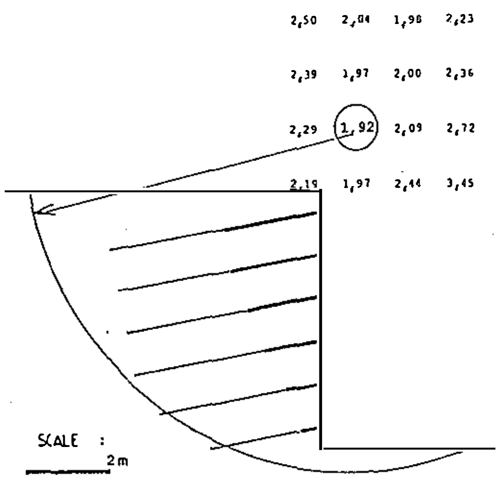

Fig 8 Factor of safety at the end of the construction

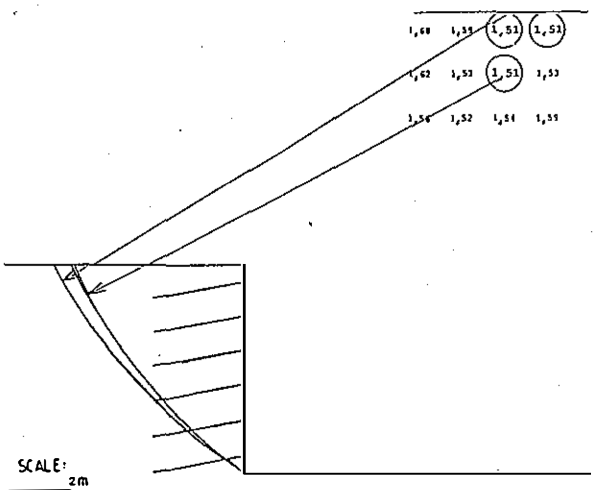

Fig 9 Factor of safety with shortened nails
(l = 2.7 m)

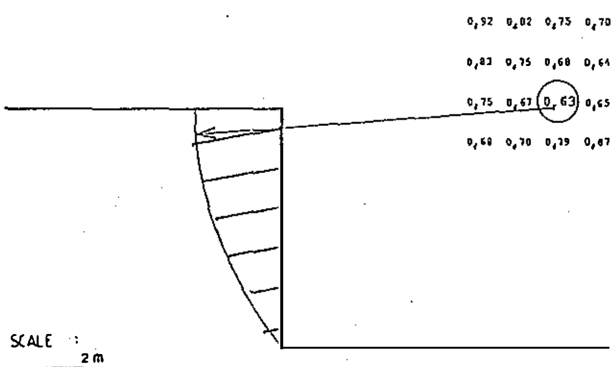

Fig 10 Factor of safety just before failure
(circular failure surface)

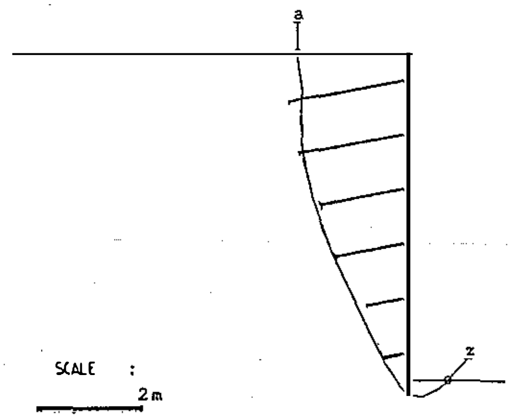

Fig 11 Factor of safety just before failure
(actual non circular failure surface)

The interface frictional resistance q_s - measured for each row of nails (Figure 7) were used in the calculations.

i) At the end of the construction, the ratio τ_{max}/τ was 1.87 taking account only of the tensile resistance of the steel bars.

When the shear and bending resistance was added, it became 1.92.(Fig.8). It should be noticed that horizontal displacements at the end of the construction with these safety factors, are only 0.12 % of the total height of the nailed wall.

ii) When all the nails had been shortened to the same length of 2.7 m , the ratio τ_{max}/τ was 1.39 when only taking into account the tensile resistance. When the shear and bending resistance was added, it increased up to 1.51.(Fig.9).
At this stage, the displacement of the top of the wall was 11 mm, which represents 0.18 % of the total height of the nailed wall.

iii) Just before failure of the nailed wall.

With the assumption of a cohesion of 3 KPa, the ratio τ/τ_{max} is 0.63 for the most critical potential circular failure surface going through the toe of the wall. (Fig.10).

With the actual non circular surface, measured after failure (Fig.11) on the field which goes under the toe of the wall, the ratio increases up to 0.76.
The cohesion which is taken into account in the stability calculations is an apparent cohesion, i.e., due to the fine content of the sand. Because of the partial saturation, the sand was observed to have a cohesion ranging from 3 to 10 kPa. Backcalculations indicate a value of 7.5 KPa to yield a factor of safety of 1.

9 CONCLUSION

The french national project CLOUTERRE and the recommendations CLOUTERRE 1991 are a major contribution to the state of knowledge of soil nailing. Lessons which can be drawn from the full scale experimental soil nailed wall pushed to failure presented above are following

- The range of the horizontal and vertical displacements, at the top of the facing, is 0.1 % to 0.3 % of the total height of the wall. These displacements depend on the global safety factor, they decrease as the global safety factor increases.

- Comparisons with the experimental results show that the multicriteria design method (implemented in the TALREN program) is capable of accurately predicting the behaviour of soil nailed wall, taken to failure, either with circular surface or with non circular surface.

- The analysis of stability is highly sensitive to the value of the cohesion. Most in situ soils have a small apparent cohesion due to their fine content and partial saturation. This cohesion of a few kPa is very difficult to estimate.

REFERENCES

Plumelle C ; Schlosser F, "Three full-scale experiments of the French project on soil nailing : CLOUTERRE" 70th Transportation Research Board Annual Meeting, Washington D.C, U.S.A. Jan. 13-17 1991.

Schlosser F "Behaviour and Design of Soil Nailing" Symposium on Soil and Rock Improvement Techniques including Geotextile, Reinforced Earth and Modern Piling Methods, Bangkok, 1982.

Schlosser F "Analogie et différences dans le comportement et le calcul des ouvrages de soutènement en Terre Armée et par clouage des sols" Annales de l'ITBTP, N° 418, pp 8-23, oct.1983.

Schlosser F and Unterreiner P "Soil Nailing in France : Research and Practice" 70th Transportation Research Board Annual Meeting, Washington D.C, U.S.A., Jan. 13-17 1991.