

# Three Full-Scale Experiments of French Project on Soil Nailing: CLOUTERRE

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CLOUTERRE, a national research project on soil nailing, was performed in France during 1986–1990 to study the behavior of nailed soil retaining walls, develop design methods, and publish a French code of practice for building temporary and permanent nailed soil walls. Three full-scale experiments are described: a nailed soil wall pushed to failure, a wall built to study its stability during the excavation stages, and a simulation of failure due to the lack of adhesion on the bars. The nails, soil, and wall facing were instrumented to measure the displacements, forces, and stresses generated in the soil and reinforcements.

Soil nailing, invented in France, is a technique of in situ soil reinforcement using steel rods that interact with the soil. It is equivalent to reinforced earth for soils in a cut (1). Recent important developments in the soil-nailing technique have resulted in a research project called CLOUTERRE. Industrial laboratories, universities, consulting engineers, and major contractors participated in this project; their aim was to complete a major test and study program and propose a code of practice for building temporary and permanent nailed soil walls. The code was to be published in 1991.

Several job sites were instrumented and monitored, and three full-scale experiments were conducted to study the three types of failure shown in Figures 1–3. This paper describes the significant results of these three experiments.

## SITE PREPARATION

The experiments were conducted at the Centre Expérimental du Bâtiment et des Travaux Publics (CEBTP) in Saint-Rémy-Les-Chevreuse, near Paris.

The backfill sand was of uniform gradation; it is referred to as Fontainebleau sand. The minimum and maximum densities of this sand were 1.31 kN/m<sup>3</sup> and 1.69 kN/m<sup>3</sup>, respectively. The density after compaction in 20-cm-thick layers was 1.51 kN/m<sup>3</sup>, equivalent to a medium-dense sand with an index density of 0.6. At this relative density, the sand had a dilatant behavior. The static pressure transducer (SPT) results (Figure 4) ranged from 8 blows per 0.3 m at a depth of 1 m to 15 blows per 0.3 m at a depth of 5 m; the limit pressure ( $p_l$ ) and the modulus ( $E_m$ ) measured by the Menard pressuremeter are also given in Figure 4. The sand's strength characteristics established in the laboratory were  $\phi' = 38$  degrees and  $c' =$

$3$  kPa. In comparison,  $\phi' = 34$  degrees and  $c' = 0$  were obtained by a phycometer (2) at a depth of 1.5 m.

## WALL 1: FAILURE BY BREAKAGE OF BARS

Before construction of the nailed wall, a soil mass 7 m high was created. The soil was excavated and the wall built in layers, meter by meter. The vertical distance between the nails was 1 m, and the horizontal spacing was 1.15 m (Figure 5).

The characteristics of the nails were chosen so that the nails would fail by breakage or large deformations and not by pull-out (3). These characteristics required a design safety factor of 1.1 against the breakage of the bars.

The nailed sand mass was instrumented to follow the movements of the facing and the soil and to determine the strengths at the head and along the nails during construction of the nailed wall and during collapse.

Figure 6 indicates that the ratio  $T_o/T_{max}$  between the tensile force at the head (at the facing) and the maximum tensile force decreased as construction progressed. At the beginning of construction the ratio was about 1 and at the end it was about 0.7.

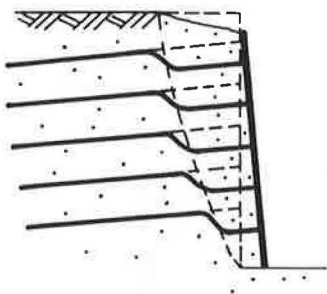
When the wall was finished, the nailed soil mass was progressively flooded with water from the top to increase its density and decrease its cohesion. This kind of failure was chosen to simulate the stresses that develop during a flood, major precipitation, or snowmelt in northern countries or mountains.

The flooding did not completely destroy the structure. The nailed wall, however, subsided 27 cm from its previous level. It advanced 8 cm at the top and 19 cm at the foot (3,4). During construction, knowledge of inclinometer displacements and the maximum tensile force line allowed the prediction of the failure zone (Figure 7). This conclusion is important because it shows that the failure design methods of TALREN (5,6) type are correct; thus, they will be adopted by the code of practice.

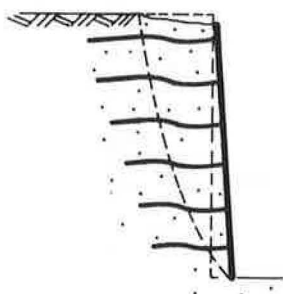
After failure, the nailed soil zone was excavated. The nails had suffered large bending deformations, and some of them were broken. Measured positions of the bands of black sand permitted reconstruction of the failure zone (Figure 8). One can note that the maximum tensile force line lies within the failure zone (Figure 9).

During construction, the tensile force in the nail was the first resisting force to be mobilized. However, before failure and under large deformations, the bending stiffness of the nails was also mobilized (Figure 10).

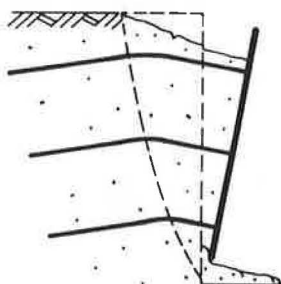
C. Plumelle, Centre Expérimental du Bâtiment et des Travaux Publics, Domaine de St Paul, 78470 St-Rémy-Les-Chevreuse, France. F. Schlosser, TERRASOL, Tour Horizon, 52 quai de Dion Bouton, 92806 Puteaux Cédex, France.



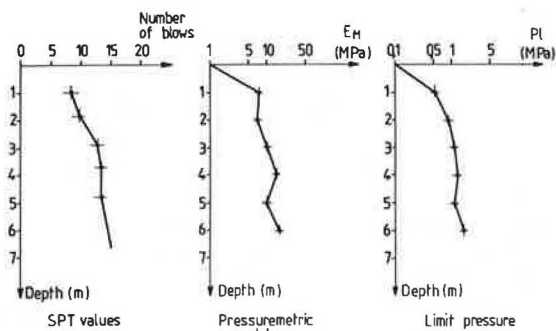
**FIGURE 1** Failure of nailed soil mass due to breakage of bars.



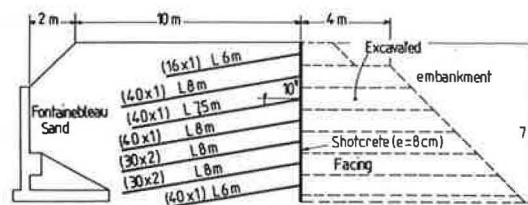
**FIGURE 2** Failure of nailed soil mass during excavation.



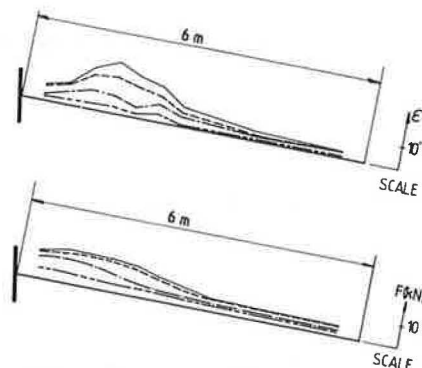
**FIGURE 3** Failure of nailed soil mass due to lack of adhesion on bars.



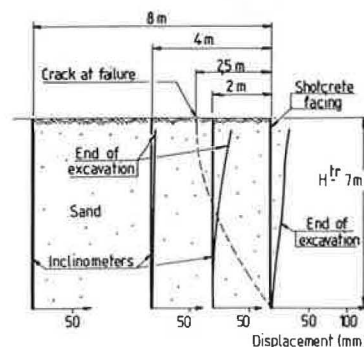
**FIGURE 4** Results from SPT and pressuremeter tests.



**FIGURE 5** Layout of full-scale experiment, Wall 1.



**FIGURE 6** Distributions of strains and strengths, Nail 3, Phases 4 to 7.



**FIGURE 7** Horizontal displacements and failure zone, Wall 1.

## WALL 2: FAILURE DURING EXCAVATION

### Description of Experimental and Lateral Walls

The sand mass, 6 m high and 2 m wide, was constructed inside two walls made of boards. The boards were constrained by two lateral walls made of formworks and anchored by bolted rods on UAP embedded in the soil (Figure 11).

During backfilling, the sand mass was buttressed by metallic panels braced on a frame made of twin HEBs. Starting from the bottom, there were three removable panels 1 m high (Panels 1, 2, and 3) and a fixed panel that was to be nailed 3 m high (Panel 4). The sand was put on both sides of the board walls simultaneously to create an experimental sand

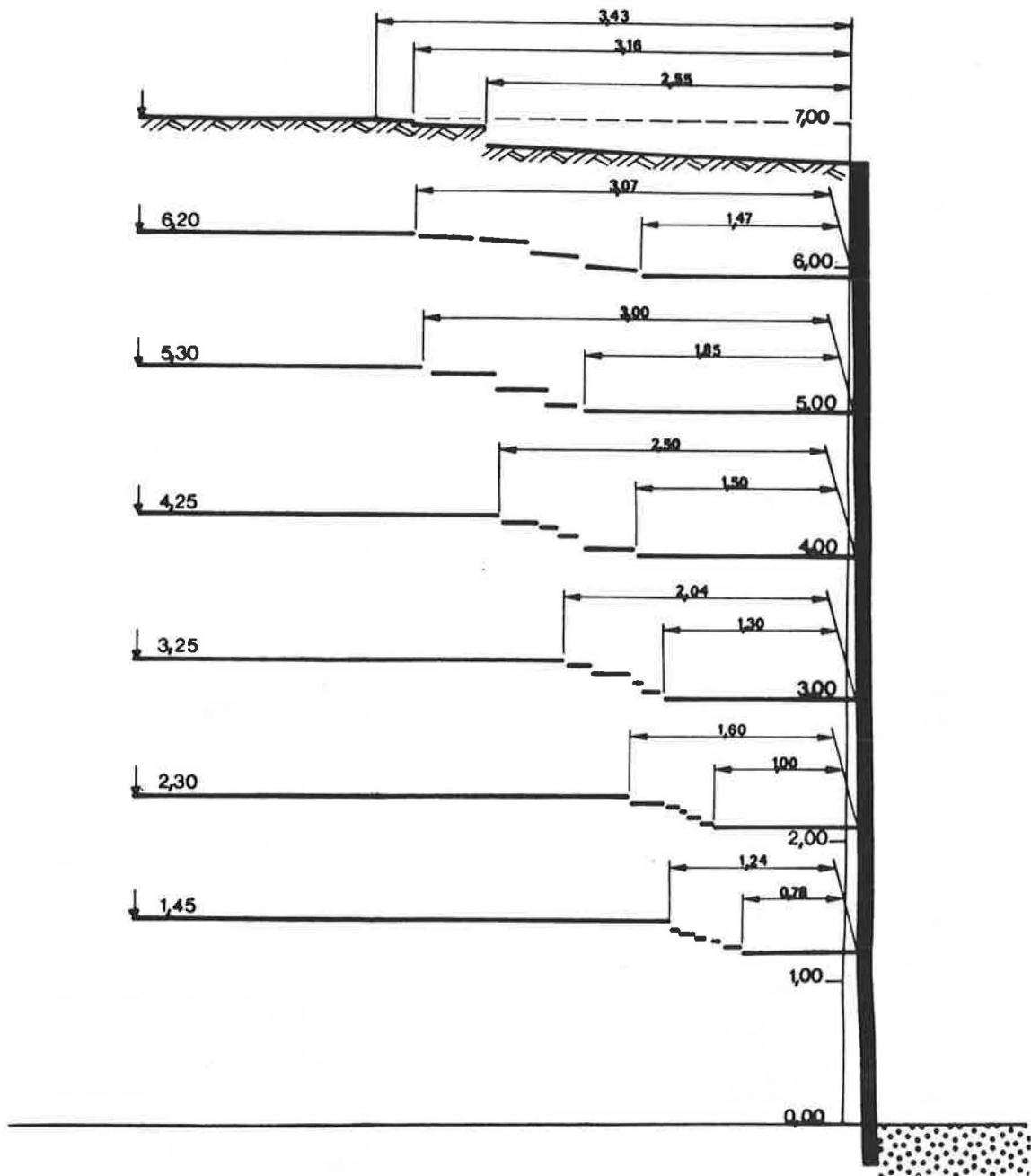


FIGURE 8 Displacements of bands of black sand after failure of nailed mass.

mass and two lateral walls. The board walls were covered inside with a greased double layer of plastic to prevent friction on the sides and to enforce plane strain conditions (Figure 11).

#### Nailing of Fixed Panel

Panel 4 was nailed with six nails made of aluminum tube (40-mm diameter, 1-mm wall thickness) and sealed with liquid cement in a 63-mm-diameter borehole. Each nail was 6 m long (Figure 11).

#### Instrumentation of Facing and Nailed Mass

At each phase the horizontal and vertical movements of the shotcrete facing were followed by microtriangulation.

The six nails were equipped with an electrical dynamometer to measure strengths at the head, and one nail per layer was instrumented with seven pairs of strain gages. The calibration of one identical nail under tensile force during the experiment on Wall 1 allowed the forces to be taken from the strains. Finally, during the construction of the sand mass, a horizontal band of black sand was placed at every meter along the axis of the wall.

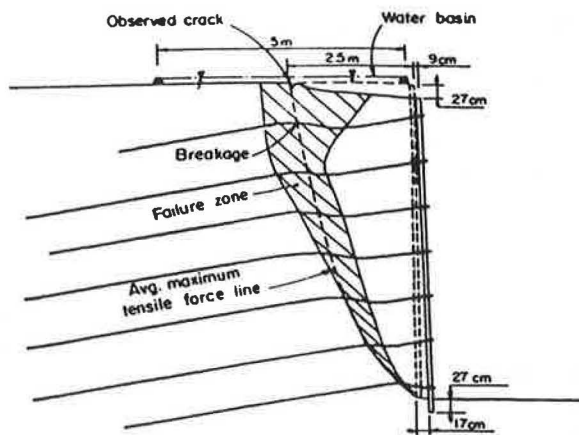


FIGURE 9 Failure zone developed in nailed soil wall.

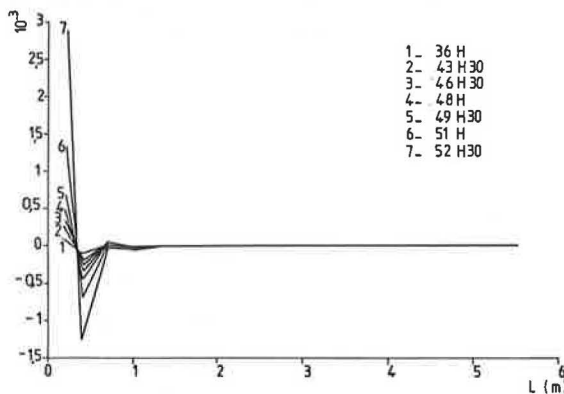


FIGURE 10 Bending moment strains just before failure.

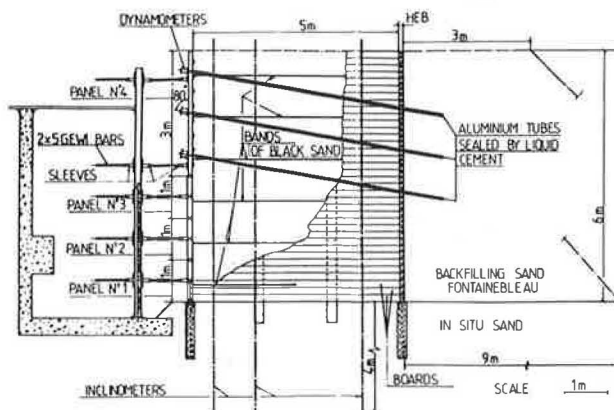


FIGURE 11 Layout of full-scale experiment, Wall 2.

## Execution of Experiment

### Aims

The aim of the experiment was to find, as the depth of excavation increases, the development of

- Stable excavation,
- Local instability, and
- Global instability.

In this study Panel 4 simulated a nailed wall that would be 3 m high, and Panels 3, 2, and 1 simulated excavation phases of 1, 2, and 3 m, respectively. During the experimental phases the behavior of the nailed mass was recorded as the displacements of Panel 4 and the strengths at the head and along the nails were measured.

### Removal of Panel 4

To remove Panel 4 from its bars, the sleeves were unscrewed, putting the six nails under tensile stress.

### Removal of Panel 3

To remove Panel 3 from the frame (Figure 12), two jacks were fixed on two HEBs of the frame and the sleeves that overtightened it were unscrewed simultaneously. The soil was intact and showed no cracks.

### Removal of Panel 2

Panel 2 was removed in the same manner as Panel 3. When this panel was removed, a crack appeared under Panel 4. This crack grew until the sand fell and created a soil arch (Figure 13). This arch remained stable during the 24 hr preceding the last phase.

### Removal of Panel 1

In the beginning of the last phase, the arch began to crack. The failure occurred for a 45-mm removal of the panel. When

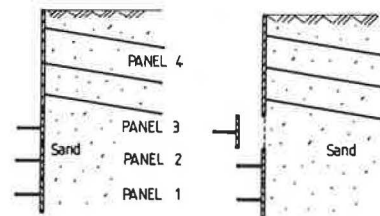


FIGURE 12 Test layout.

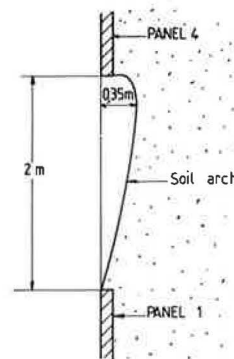


FIGURE 13 Cross section of soil arch.

the arch cracked, it induced a global instability in a few seconds. The nailed panel subsided 1.4 m but remained attached to the six nails, which did not break (Figure 14).

The excavation of the nailed sand mass allowed the discovery of the nail deformations and the reconstruction of the profile of the sand zone that had slipped.

## MEASUREMENT RESULTS

### Displacements of Panel 4

The displacements of the panel were in the same range as Wall 1, which had a 3-mm horizontal displacement of the facing in the third phase.

### Evolution of Strength at Head

Figure 15 shows the evolution of the force at the head of the nails during each phase. Notice during Phase 1 of panel removal that mainly the first layer of nails was under stress; the bottom of the nailed panel was lying on Panel 3.

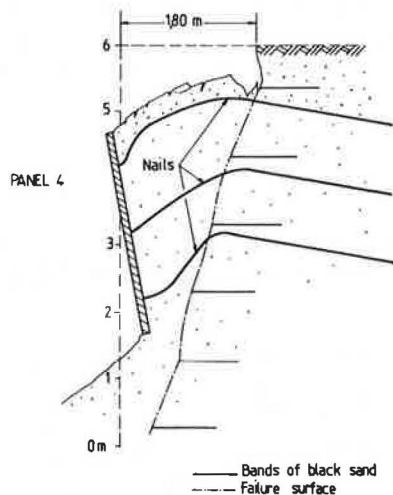


FIGURE 14 Cross section of failure.

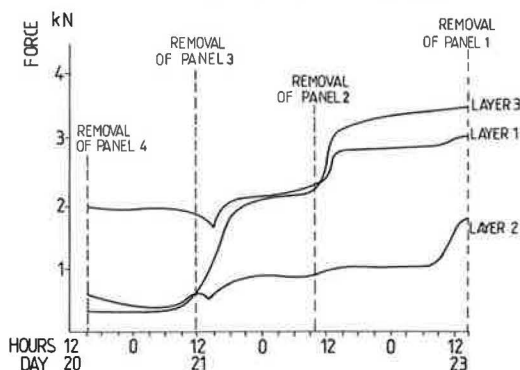


FIGURE 15 Evolution of strength at head for each phase.

During Phase 2, which simulated 1-m-deep excavation, forces on the first layer of nails did not significantly increase, but the nails of the third layer were rapidly put under stress.

The creation of the arch during Phase 3 with a 2-m-deep excavation insignificantly increased forces, but forces did increase in the third layer as it responded to the arch pressure.

### Distribution of Forces Along Nails

Figures 16–18 synthesize the evolution of the tensile forces along the nails of the three layers versus phases. The third phase represents the last stage before failure. Note that the creation of the arch involved an increase of the tensile force only in the first layer.

The maximum tensile force points were the same as they were in the first nailed wall. They were located in the back of the facing; before the failure they were 2 m from the facing for the first layer and 0.7 m for the last layer.

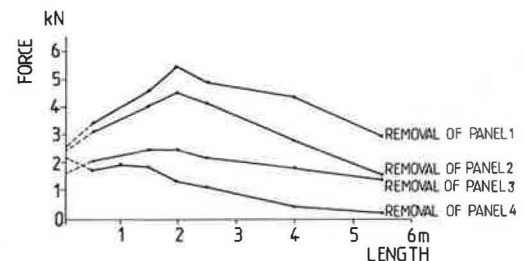


FIGURE 16 Load distribution along Nail 1 for each phase.

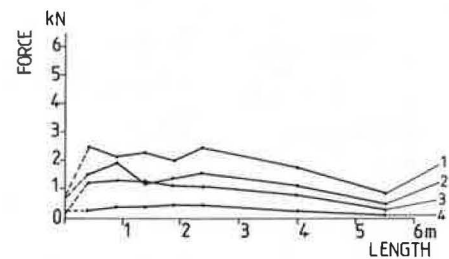


FIGURE 17 Load distribution along Nail 3 for each phase.

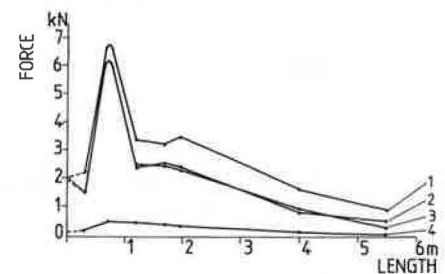


FIGURE 18 Load distribution along Nail 5 for each phase.

### WALL 3: FAILURE FROM LACK OF ADHESION ON BARS

#### Description of Experimental and Lateral Walls

Construction of the sand mass backfilling, 6 m high and 2 m wide, was similar to that of Wall 2. Starting from the bottom, there were six removable panels 1 m high (Figure 19).

#### Construction of Nailed Wall

The wall was nailed by telescopic nails made of bars (50-mm diameter) inside tubes (71-mm diameter) driven into the sand, as shown in Figure 20.

#### Displacements of Nailed Mass

Displacements plotted on Figure 21 were measured at the end of the construction of the nailed wall and at the 12th stage of shortening of nails (4 stages before failure), for which nails

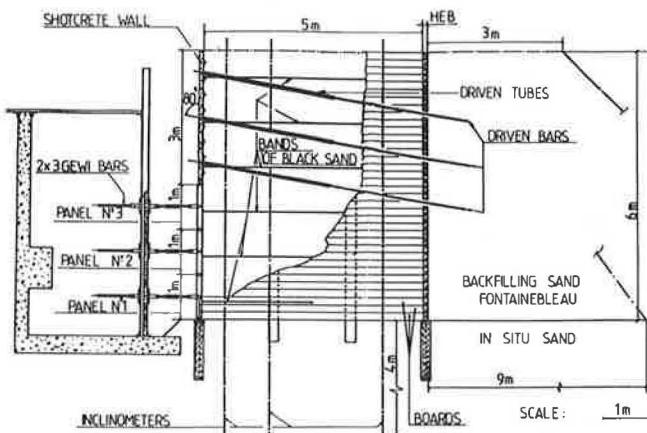


FIGURE 19 Layout of Wall 2 at end of Phase 3.

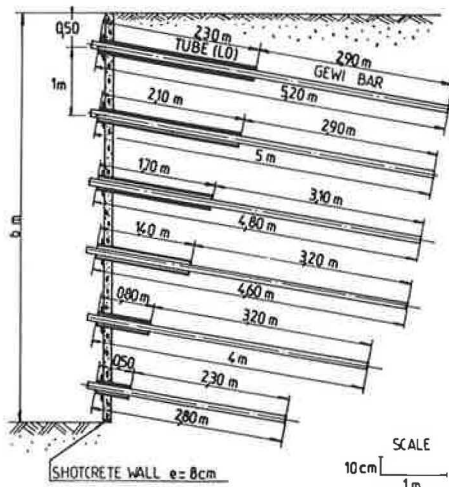


FIGURE 20 Scheme of Wall 3 at end of construction.

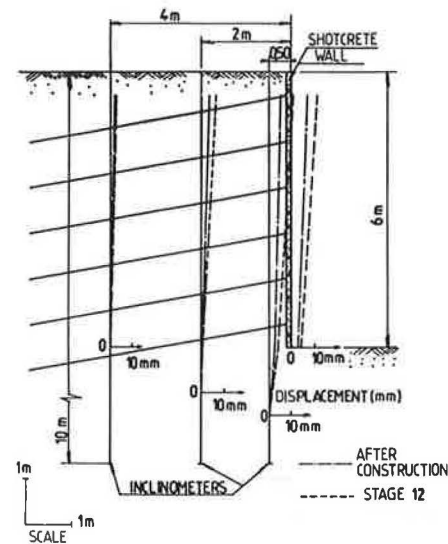


FIGURE 21 Measurements of horizontal displacements.

of the first layer were 2.3 m long; those of the second layer, 2.1 m; and those of four others, 1.8 m. These displacements were displacements of sand just behind the facing measured during excavation by inclinometers and displacements of facing after its construction. These measurements complete those carried out during execution of the Wall 1, during which only displacements of facing had been recorded.

For Wall 3, it should be noted that a horizontal displacement at the end of the construction, with a safety factor larger than 3, was 0.12 percent of total height of the nailed wall. Otherwise, significant displacements of mass of the sand beneath the foot of the facing were recorded.

#### Forces in Nails

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

#### FAILURE BY SHORTENING NAILS

The initial length of the nails gave great stability to this nailed mass in the beginning. During the experiment in which the nails were shortened, with the same length of 2.4 m, stability was still maintained. Failure of the sand mass reinforced with tubes of decreasing length with depth occurred not because of the lack of adhesion, but because of the sliding of a block limited by the facing and a 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 (Figure 22).

#### CONCLUSIONS

The three full-scale experiments performed by CEBTP focused on failure due to breakage of the bars, failure during

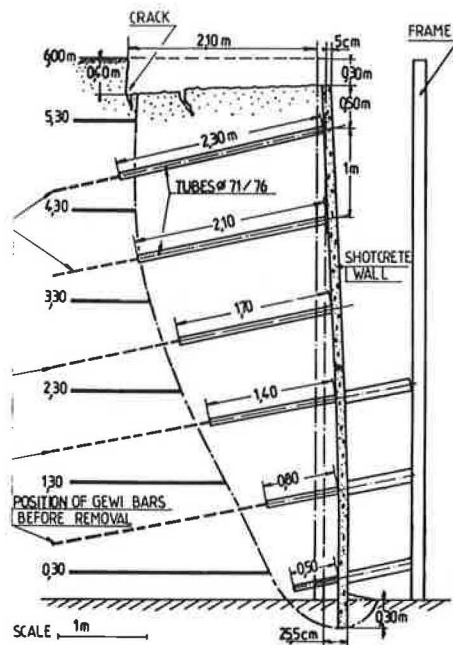


FIGURE 22 Scheme of failure for Wall 3.

a deep excavation phase, and failure due to shortening of the nails. The main conclusions from these tests are

- The maximum tensile force is not located at the front of the wall but at some distance from the facing; the ratio  $T_0/T_{max}$  decreases as the excavation progresses.
- The line of maximum tensile forces lies within the failure zone.
- The first resisting force to be mobilized is the tensile force in the nail. Before failure the bending stiffness gives an additional safety factor and prevents a sudden collapse.
- These results demonstrate that the TALREN method (5) is capable of accurately predicting the behavior of a nailed soil wall taken to failure.

- The excavation phases are difficult stages during the construction. If the depth of the cut is too great, a soil arch develops and the displacements of the soil above remain small. For a deeper excavation the soil arch becomes unstable and a sudden failure occurs.

- The horizontal and vertical displacements are the same at the head of the facing. The range is between 0.1 and 0.3 percent of the total height of the wall. The displacements depend on the safety factor, and they decrease as the safety factor increases.

- Significant displacements appear beneath the foot of the facing as the excavation progresses.

- Nails having great inertia give stability to the soil mass. In this case the slip surface for shortened nails occurred behind the nails.

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