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# Full scale test on a nailed wall in consolidated clay

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ABSTRACT: A field test on a 6 m high vertical soil retaining structure in consolidated clay is described. Numerous gauges were installed to measure deformations and nail forces due to dead load, applied uniform surface loads and creep properties of the soil. The wall was brought to failure. The results can serve as a basis for computational investigations, FE-analyses in particular.

## 1 INTRODUCTION

In 1975, the special contractor Bauer, Schrobenhausen, and the Institute of Soil Mechanics and Rock Mechanics of the University Karlsruhe started a five years research and development project "Bodenvernagelung" in joint venture. The project was supported partially by the German Federal Minister of Research and Technology. Using the literal translation from the German term "Bodenvernagelung", the method and the first results of the research program were then presented to the technical world at the end of the seventies (Stocker, Körber, Gässler, Gudehus 1979). The worldwide first nailed wall that had been tested scientifically is shown in Fig. 1.

The research program covered the following items:

(a) Theoretical stability analyses
(b) Model tests
(c) Execution of seven full scale tests on nailed walls in cohesive and non-cohesive soils

In addition, at the University of Karlsruhe intensive investigations were made to deduce partial safety factors for the design of nailed walls following the new statistic-probabilistical safety theory. This work took place from 1980 to 1983 and the results, firstly presented by Gässler and Gudehus (1983), are the basis of the modern German design of nailed walls in accordance to the Eurocode 7.

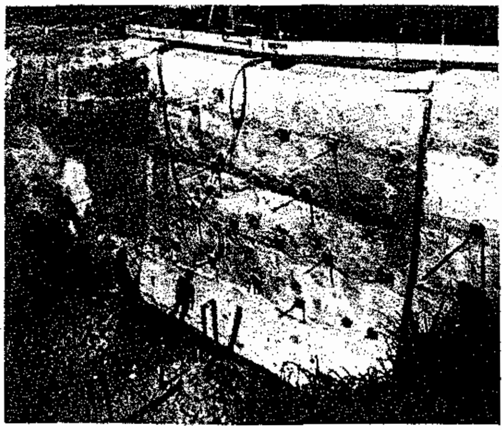

Fig. 1 First scientifically tested wall in the history of soil nailing 1976 (wall after failure)

Coming back to (a), the theoretical stability analyses as the supposition of practical design were presented briefly at the IS-Kyushu '88 (Gässler 1988), and in detail in the publications

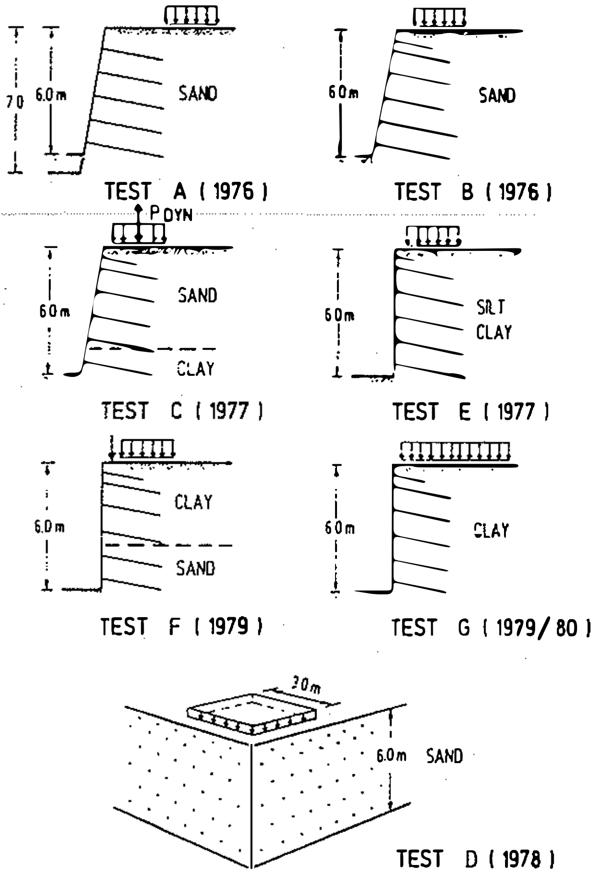

Fig. 2 Scope of the field test walls of the German research project "Soil Nailing"

of the Institute of Soil Mechanics and Rock Mechanics of the University of Karlsruhe (Gässler 1987).

A scope of all field tests in sand and clay is shown in Fig. 2. In each field test at least one cross-section of the wall was equipped with various gauges. All test walls were brought to failure. A series of technical reports given to the German Federal Minister of Research and Technology described the performance and the results of all seven field tests in detail (Körber, Gässler, Schwarz 1976-1980). As a representative example of the field tests in cohesive soils Test G (see Fig. 2) will be described in the following. The nailed wall of this field test yielded most interesting results especially due to the creep properties of the clay.

## 2. CONSTRUCTION AND INSTRUMENTATION OF TEST G IN CLAY

The test wall was constructed in the typical way for soil nailing: (1) excavation in stages of 1.1 m depth (2) shotcreting and (3) nailing.

The soil was part of the Meletta strata of the upper Rupel clay. Apart from the first excavation stage three undisturbed samples were taken in every stage. Table 1 presents the mean values and the standard deviations of the properties of all 12 samples. In general, the soil is to be described as a homogeneous clay of stiff to semi solid consistency with a high lime content (25 %). The clay is heavily overconsolidated. The mean value of the undrained cohesion $c_u$ was 125 kN/m². It was obtained from 8 undrained consolidated triaxial tests with a standard deviation of 10 kN/m².

Table 1: Soil properties of the test soil

| | $\gamma_d$ [kN/m³] | w [%] | $w_L$ [%] | $w_P$ [%] | $I_P$ [-] | $I_C$ [-] |
|---|---|---|---|---|---|---|
| mean value | 16.4 | 24.7 | 64.4 | 22.8 | 41.6 | 0.95 |
| standard deviation | 0.4 | 1.3 | 8.1 | 2.2 | 6.8 | 0.05 |

The cut of the test wall was vertical and 6.0 m deep. In the first excavation stage two nail rows were installed because of the surface load aligning the wall brim (Fig. 3). For the nail installation boreholes with 110 mm diameter were predrilled using augers without casing. One can state that for soil nailing dry drilling by means of augers is mostly used in clay soils and soft rocks today (Gässler 1990 a). The nails were set into the ground with 10 ° inclination to the horizontal and with 1.10 m vertical and 1.20 m horizontal spacing.

The tensile member of the nails consisted of a Gewi-steel bar with 22 mm diameter and 420 N/mm² yield stress. The nails were grouted

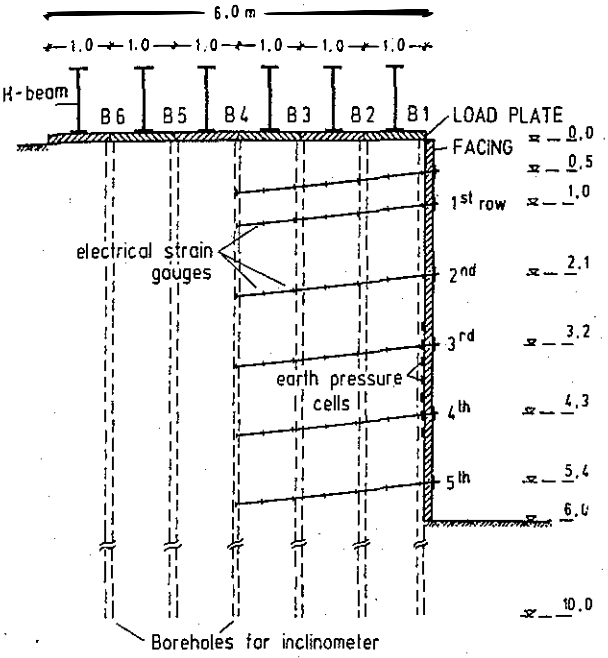

Fig. 3 Cross-section of the test wall with loading facility and instrumentation

under normal atmospheric pressure and fixed at the facing using a face plate and a nut. The shotcrete facing was 10 cm thick and reinforced by a wire mat at the earthside.

The width of the test wall was 6 m. A 10 cm thick and 6.5 m deep trench filled with bentonite suspension seperated the proper test wall section from the neighboured soil in order to approach plain strain conditions. Fig. 4 shows the test wall after completion with the loading facility.

The surcharge was applied using 6 reinforced concrete plates of 1 m width, 0.2 m thickness and nearly 6 m length (corresponding to the width of the test wall), which were pressed upon the upper ground surface by means of hydraulic jacks. Deep ground anchors served as abutments for the jacks.

The Test wall G in clay was one of the best instrumented walls shown in the summery of Fig. 2. It was equipped with various gauges, namely (Fig. 3):

- horizontal and vertical displacement gauges at the facing and on the ground surface
- electrical strain gauges from the upper to the lower end of the nails
- earth pressure cells behind the facing
- vertical boreholes for inclinometer measurements and settlement inside the reinforced soil.

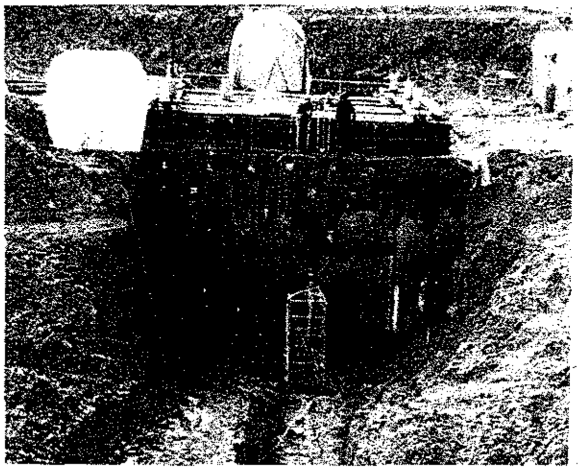

Fig. 4 View at the test wall G in clay with loading facility

## 3. TEST RESULTS

The test period took a total of 72 days. In Fig. 5 the test sequence is shown. Two weeks were needed for the construction of the wall, another two weeks for the mounting of the load facility. The dead weight of the load facility (concrete plates, H-beams) amounted to 6 kN/m². After a short period of 30 kN/m² load the creep behaviour of the wall under dead weight was observed for 624 h. The load was then raised up to 50 kN/m² and kept constant for 326 h (14 days). Additional short time loading up to 90 kN/m², 110 kN/m² and finally 130 kN/m² resulted horizontal displacement of more than 150 mm without any stabilization, so that the test had to be finished.

Fig. 6 shows the total displacement field in the cross-section of the wall after construction

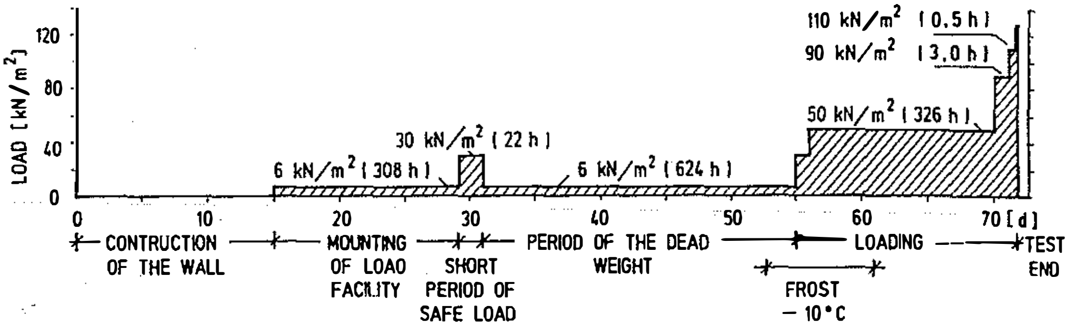

Fig. 5 Sequence of the field test

and mounting of the load facility. The arrows denote the resultant displacement vectors of the measured horizontal and vertical displacements of more than 40 points. The largest horizontal displacement at the top of the facing was 25 mm; this is about 1.75 times more than the displacements measured in the field tests A or B in sand (Gässler 1987). The ratio of the horizontal and the vertical displacements at the top is about 5:3. It is important to take notice of the fact that the horizontal displacement in 5 m distance from the facing (corresponding to 85 % of the wall height) was still 10 mm, which means 40 % of that measured at the facing.

Under surface loads the facing began to bulg with the largest displacement in the 2nd nail row, whilst the creep effects steadily increased with higher loads. For example, the total amount of the horizontal displacement of the facing in the 2nd row was 36 mm just after the 50 kN/m² surface load had been applied. The additional displacements measured during the following 326 hours (14 days) under 50 kN/m² constant load were plotted in a double-logarithmic diagram over the time (Fig. 7). The creep displacements during the constant loads 90 kN/m² and 110 kN/m² are also plotted in the same diagram. One can see, that the creep displacements s(t) follow a logarithmic law:

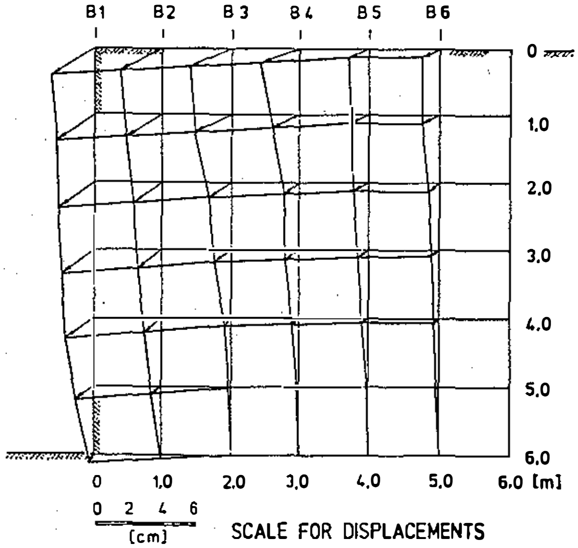

Fig. 6 Displacements after completion of the wall

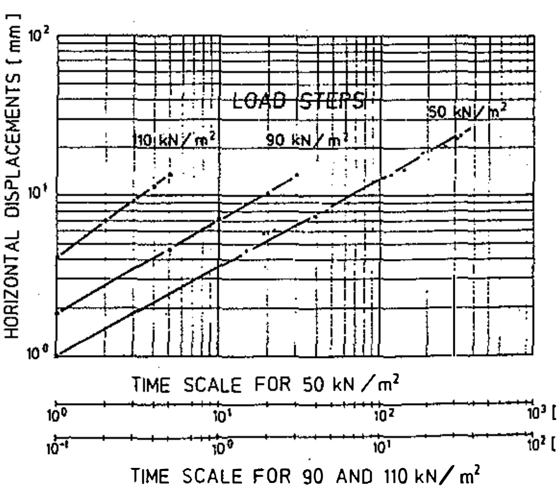

Fig. 7 Double-logarithmic plot of the creep displacements for constant loads 50, 90, 110 kN/m²

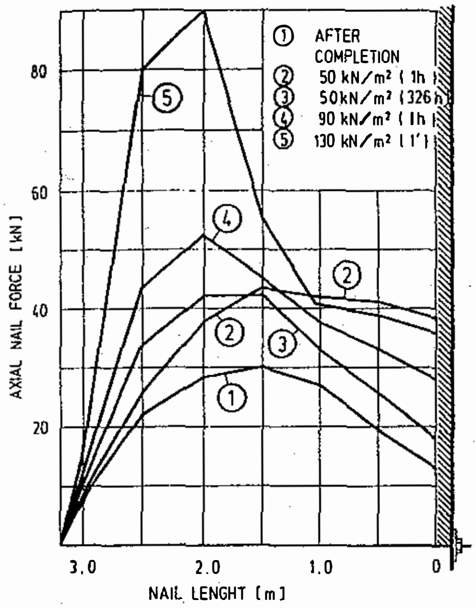

Fig. 8 Axial nail force distribution in the 2nd row

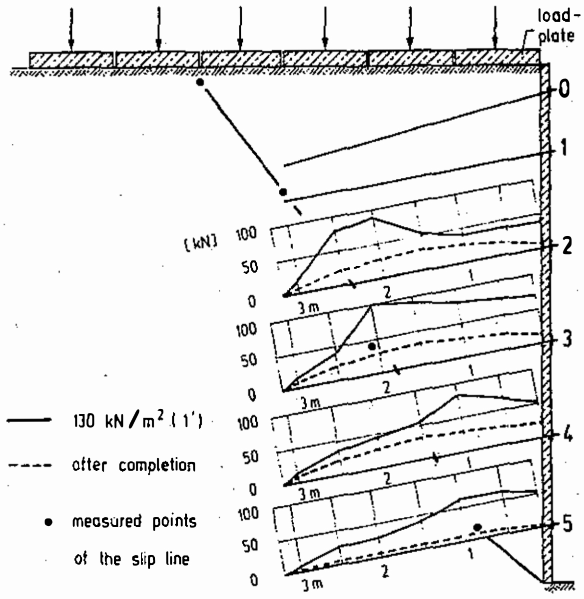

Fig. 9 Axial nail forces in the cross-section

$$s(t) = \exp(\ln s(o) + m * \ln t)$$

with $s(t)$ : displacement at time t

$s(o)$ : displacement at time $t = 1$ h

$m$ : gradient of the straight

During the test performance the displacements to be expected for the actual constant loads could be estimated. Supposing the validity of the law for very long periods, for the constant load of 50 kN/m$^2$ the following displacement would have occured af-ter $10^4$ hours (= 1 year plus 2 months): $s(t=10^4) = \exp(\ln 1 + 0.556 * \ln 10^4)$. The result is 167 mm, to which the preceeding 36 mm mentioned above have to be added. The total displacement is then about 200 mm, which means the servicebility of the wall is doubtful. The equivalent calculations with the higher loads show that failure in the sense of none-servicebility has to be defined definitely for loads higher than 50 kN/m$^2$.

Fig. 8 presents the axial force distribution of the instrumented nail in the 2nd row. Curve (1) shows the typical parabolic shape shortly after completion of the wall. Curve (2) represents the force distribution at the beginning of the 50 kN/m$^2$ load and curve (3) at the end of this load after 326 hours. The change of the distribution is obviously caused by creep effects: the peak of about 43 kN moved backwards and the force at the facing decreased to half its value. With increasing loads the peak value also increased markedly ( curves (4) and (5)). The frost period (Fig. 5) caused a large increase of the nail forces in all rows at the facing side. They increased rapidly by 50 % to 100 %, but decreased again nearly to the former values in the following thawing period.

In Fig. 9 the axial nail force distribution in the lower four rows is shown for the state shortly after completion and for the maximal load 130 kN/m$^2$ shortly before the end of the test. On the other hand with nails in non-cohesive soils a distinct slip plane was only observed after large horizontal displacements in the range of 150 mm. Fig. 10 shows the bulging facing of the test wall after failure. The slip plane was accompanied by a wide shear zone on both boundaries, so that the nails were not bent sharply. Consequently the dowel forces due to bending were of second order (cf. Gässler, 1990 b). For

Fig. 10 Test wall with bulging facing after failure

further information on the limit state the reader is referred to Gudehus (1982).

## 4. CONCLUSIONS

As a result from the test observations one should learn that the creep property of cohesive soils can play a major role in the behaviour of a nailed wall or nailed cut under dead load and dead load plus surface loads. From the measurements of the creep deformations or displacements a nailed wall seem to follow a double-logarathmic law. Quantitative predictions of creep deformations of nailed walls to be expected in clay soils are not yet possible. Maybe progress will be made using FE-analyses based on adequate visco-plastic material laws. The results of the test described in this paper may help to verify such computational trials.

## ACKNOWLEDGEMENT

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