Nonlinear 3-D Analysis for NATM in Frankfurt Clay

Analyse 3-D Nonlinéaire pour NATM dans l'Argile

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SYNOPSIS Based on numerous laboratory test results a three dimensional nonlinear computation is carried out to analyse the critical zones in the overburden and the safety of tunnelling by NATM. This with regard to some breakdowns and damages that happened in the last time. Comparison with measured surface settlements indicates that the intermediate soil parameters used for the numerical step-by-step analysis deliver useful results. An arching effect above the tunnel face which is necessary for the stability of the excavation process could be pointed out by means of calculation.

INTRODUCTION

Before the New Austrian Tunnelling Method (NATM) was applied for the first time in urban tunnelling in Frankfurt/Main (West Germany), by means of two test tunnels was proved that NATM causes nearly the same total surface settlements as shield tunnelling and that the influence to the historical buildings remained within permissible limits (Breth/Chambosse 1975). With respect to these satisfactory experiences in the following years NATM was applied in several Frankfurt subway sites and also in other German cities because of the high flexibility and economy of this construction method. In the meantime even subway stations with an excavation area of more than 1oom^2 are driven by mining techniques and sometimes the tunnel route is planned so low beneath the ground surface that cover with stable soils is reduced to less than one tunnel radius. The experiences carried out by the previously completed test tunnels cannot be transferred to those conditions.

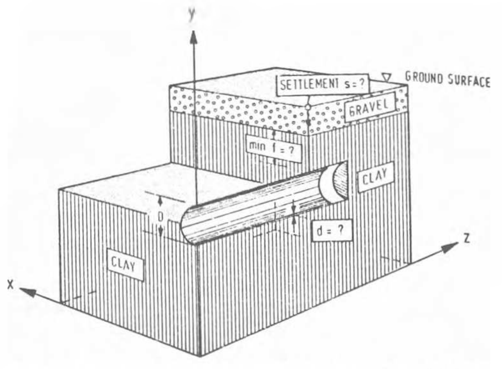

Fig.1 Questions on urban tunnelling

The questions on urban tunnelling (assessment of the settlements and dimensioning of the lining) are completed by another one: What's the minimum height of cover with stable soil (Fig.1)? This can only be answered if the three dimensional state of stress at the tunnel face is taken into consideration. From surface levelling we know that about 5o% of the total settlements occur before tunnel excavation reaches the observation section (Fig.2). These settlements are caused by

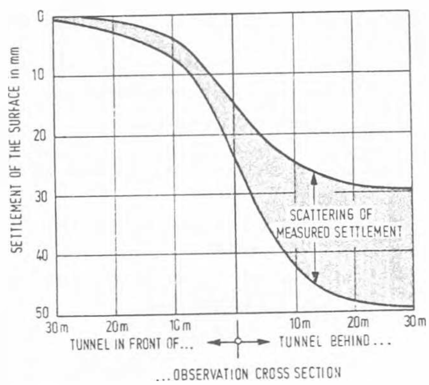

Fig.2 Measured surface settlement of an observation point during tunnel driving

the reduction of longitudinal stress and increasing vertical stress what indicates that there must be an arching effect above the tunnel face along tunnel axis. In a study for tunnelling in stiff plastic "Frankfurt clay" we analysed the three dimensional load-bearing arch to find out the critical states of excavation and the safety of unsealed surfaces.

SUBSOIL

Beneath a 7 m thick layer of quarternary gravel and sand occurs the clayey marl which is known as "Frankfurt clay". The clay is heavily overconsolidated, laminated and fissured (classification CH) (Breth et al. 197o). The tunnel sections driven by NATM are fully embedded in the clay, otherwise injection of the roof is necessary. During tunnelling the ground water table is lowered beneath the bottom of the tunnel.

Because of the fissures the clay is susceptible to disturbance during sampling and it is rather difficult to get satisfactory laboratory test

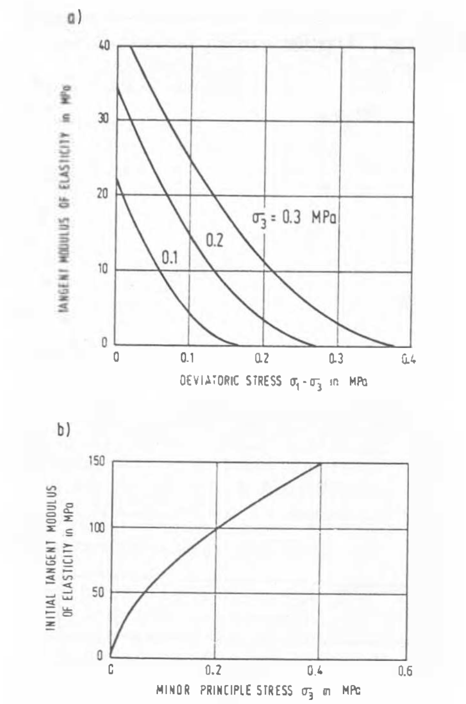

Fig.3 Nonlinear stress dependend stiffness of Frankfurt Clay

a) Modulus of elasticity for primary load

b) Modulus of elasticity for un- and reloading

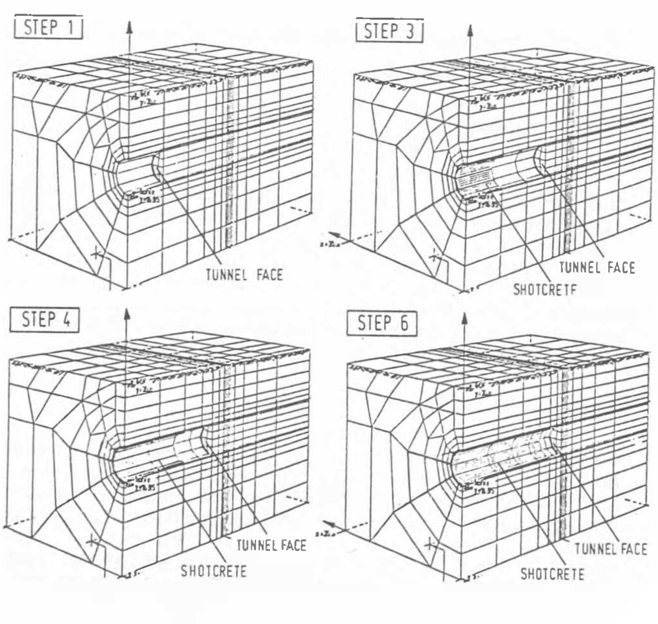

Fig.4 Numerical simulation of tunnel driving; example for 4 of altogether 15 excavation steps

results. With regard to this problems the stress strain behaviour of the clay is described by a rather simple nonlinear elastic constitutive law (Duncan et al. 197o). To use more refined constitutive laws in the case of prestressed fissured clay such as Frankfurt clay seems so long without any sense as we have not developed field tests and new sampling techniques to get a better feeling for the in situ state of stress of such soils and their deformation behaviour. Nevertheless, in connexion with deep excavations, foundation of multi-storey buildings and tunnelling in Frankfurt/Main a lot of specimen were tested at the Soil Mechanics Laboratory of the Technical University of Darmstadt. So we got a survey about the scattering of the strength and the stress-strain behaviour of the clay. For our analysis we used intermediate values for the stress-strain characteristics. The deformation behaviour depends on the actual state of stress and the stresspath. In the calculation procedure we distinguish between primary load and unloading (Fig.3) (Stroh/Breth 1976).

SIMULATION OF TUNNELLING

For the numerical analysis we subdivided a block of 59 m length, 35 m height and 35 m breadth into 99o finite elements with 6 and 8 nodes. This leads to an equation system of nearly 37oo unknowns with a front width of 3oo. As the analysis is executed for the middle part of the three dimensional structure there the mesh containes

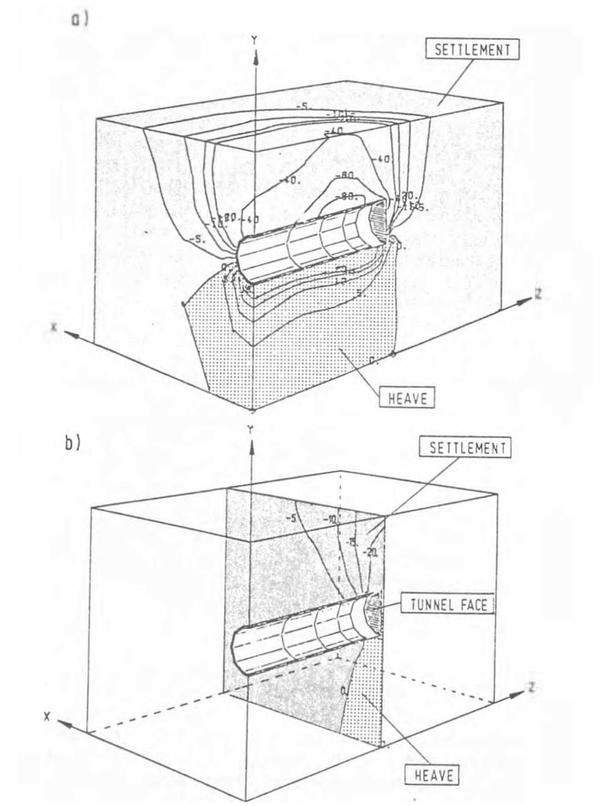

Fig.5 Iso-lines of computed total vertical displacements (in mm)

a) Survey (longitudinal area, ground surface, frontal area)

b) Cross section

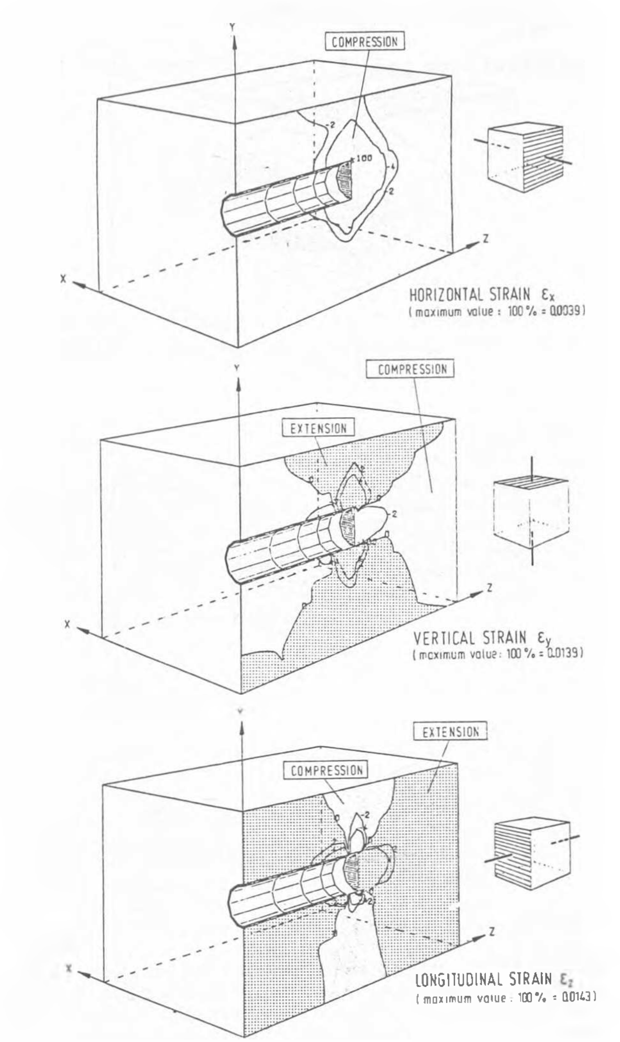

Fig.6 Iso-lines of strains (in percent of max. value) in the longitudinal section (caused by one excavation step)

many short slices to get enough calculation points for the stress transfer near tunnel face. The "dynamic" excavation process (Müller-Salzburg 1979) is simulated by a step-by-step analysis. In the first step the initial state of stress is computed: The vertical stress is equal to the weight of the overburden, the horizontal stress is computed by an at-rest coefficient K_o=o.8 for all horizontal directions. Then the numerical excavation process starts (Fig.4): In altogether 15 steps each simulating full face excavation of one slice the deformations and stresses are computed. An analysis with 3o steps (two steps per slice) delivered nearly the same results. By integration of the element stresses of those elements which shall be excavated equivalent nodal forces are computed and applied to the unsealed surface of the remaining structure. In this way the succeeding change of structure during tunnelling is part of the analysis. Lining with shotcrete is considered in that way that the elements which represent the lining are activated in that moment when the corresponding tunnel ring is installed. Any assumptions about the supporting effect of tunnel face, ring closure time or anchors are not necessary in the type of analysis described in this paper. More detailed information about numerical simulation techniques is given in the manual of the used program system (Czapla et al.1978).

RESULTS OF THE STUDY

In the following figures only a very small part of the altogether 3oo.ooo result data can be introduced. In Fig. 5 the total vertical displacements are plotted for a construction phase when the tunnel face is just in front of the middle cross section. The greatest surface settlement of about 4o mm occurs just as in reality more than one tunnel diameter behind the tunnel face. The area where heave can be observed is concentrated in the vicinity of the tunnel. Because of the stiffness of the clay at unloading heave of the bottom is smaller than roof settlements. Each excavation step causes in the center area (Fig. 6) vertical extension strains above and below the excavation area, in front of the tunnel face where one abutement of the three dimensional arch is situated the clay is vertically compressed. The longitudinal strains show just the opposite result: Horizontal compression above and below the actual excavation area, longitudinal extension in front of the tunnel caused by the loss of horizontal support at the tunnel face. By means of volumetric strain can be demonstrated that loosening zone extends to a height of o.75 diameter above the roof (Katzenbach/Breth 1981). Comparison of measured and computed surface settlements in cross

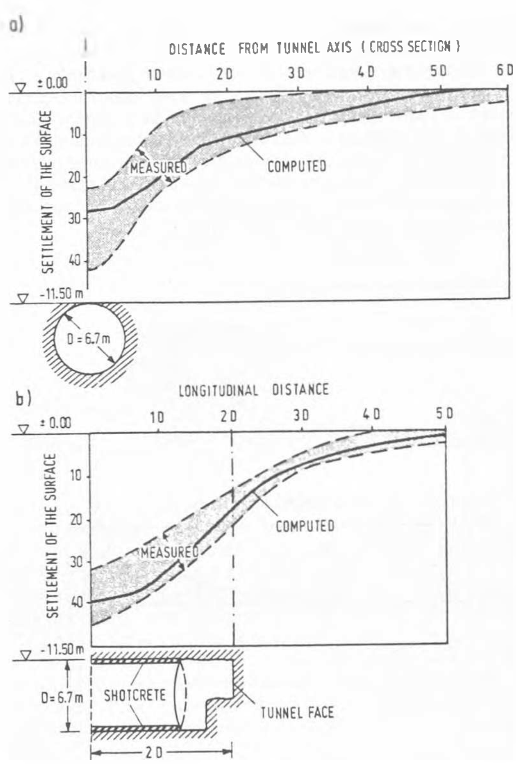

Fig.7 Measured and computed settlements of ground surface

a) Cross section

b) Longitudinal section

section and longitudinal section shows that the intermediate soil parameters and the above described calculation method deliver useful results. Fig. 8 demonstrates the arching effect along tunnel axis. In this figure the development of vertical stresses during several stages of construction is plotted. In the moment when the tunnel is 2o m in front of the element the vertical stress is yet equal to the in situ stress. But then with progressive tunnel driving the vertical stress increases so long, until the tunnel is 1.5 m in front of the element. At this state of excavation the vertical stress decreases rapidly because of the high longitudinal extension and the loss of horizontal support. The zigzag line in Fig. 8 is similar to the observations of Müller-Salzburg et al. (1978) who measured this effect of alternating stresses in model tests and tried to explain it by means of an undulatory stress distribution in the vicinity of the tunnel face.

CONCLUSIONS

The described analysis is a first step in the development of safety analysis for construction phases for tunnelling under low cover. The plot of stresslevel indicates that a high stressed zone surrounds the tunnel driven by NATM (Fig.9). Most critical is the roof area between the already closed ring and the face. This is typical for NATM and cannot be totally avoided. But it is possible to elevate the safety by an early ring closure. By means of the computed loosening zone and the dimension of the high stressed area above the roof an assessment of the minimum height of cover with stable soil is possible. In case of an actual practical problem it is necessary to carry out several calculations with different input data (height of overburden, excavation technique, change of diameter) to get reliable data about the safety of tunnel driving. The present study shows that the safety depends on the depth of the tunnel beneath the surface, tunnel diameter, distance between tunnel face and closed ring and last not least strength of the soil.

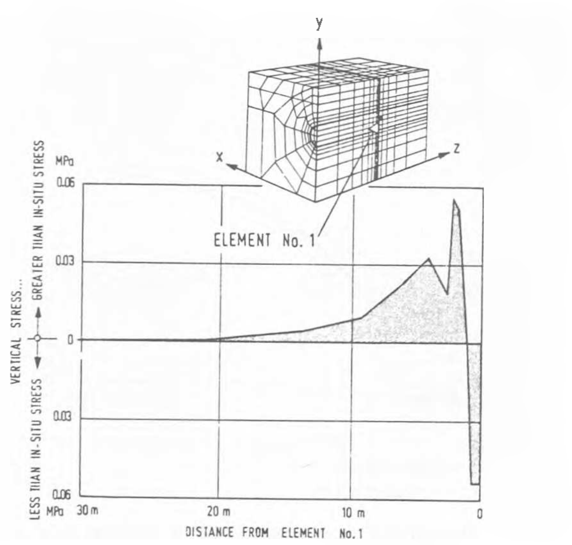

Fig.8 Arching along tunnel axis; development of vertical stress during tunnel driving in selected element No. 1

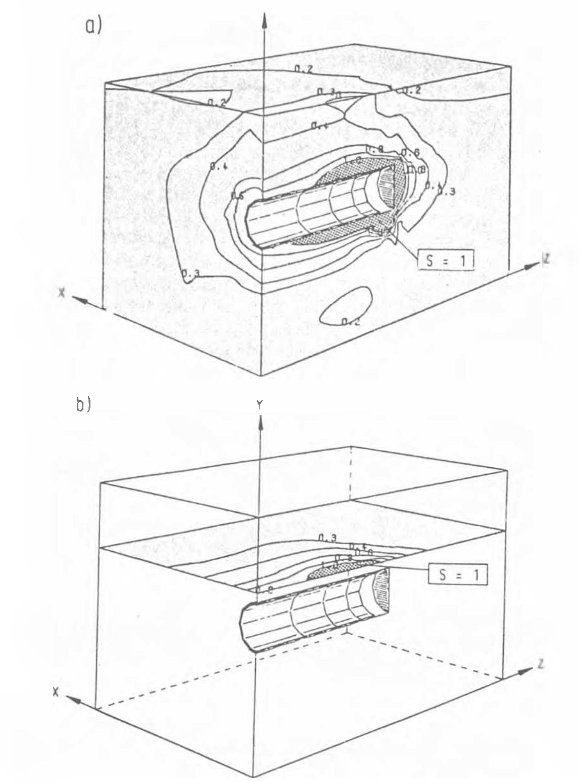

Fig.9 Stresslevel $S = tg\,\varphi_{mob}/tg\,\varphi$
a) Survey
b) Horizontal cross section 1.o m above the roof

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