Encl. No. 2

Anisotropic swelling behaviour of diagenetic consolidated claystone

Enlarged summary:

Since the last century invert heave in tunnelling in swelling rock with nearly horizontal bedding ist known. The swelling behaviour causes damage of the tunnel lining. v. Rabciewicz reports about side wall deformations in swelling rock with a dipping of 45° resp. 90°. It seems that swelling normal to the bedding is larger than parallel to the bedding and that the curvature of the invert and the construction method are not the most important influences to explain the invert heave.

Swelling of claystone is caused by an annexation of water and exchange of ions in resp. on the clay minerals. Clay minerals are very flat; therefore the anisotropy of swelling depends on the degree of mineral adjustment. Many factors with influence to the swelling mechanism are discussed to explain the mathematical model and the facts in tunnelling. On the basis of the structure and the orientation of the clay minerals you can expect an anisotropic swelling behaviour.

The methods to test the potential swellability are to divide in the group with quantitative results and the group with index results. Mineralogical tests like DTA, TG, specific inner surface, X-ray and the soil and rock mechanics standard tests like plasticity, water capability and free swelling belong to the index value group. During the most tests the inner structure and the water content will be disturbed. A correlation of the index values is a quantitative swelling of claystone is not sufficient. The determination of the swelling in anisotropy is not possible.

The direct orientated test of the swelling behaviour is necessary. Therefore unconfined swelling tests and oedometer tests, sometimes with the measurement of the confining pressure were carried out.

The unconfined swelling deformations are normal to the bedding planes up to 15 times larger than parallel to the bedding planes; the mean value is about 6. Different rock types of various locations had been tested.

The tests to determine the swelling pressure depending on the orientation (fig. 2) had been done with cylindrical, lateral confined specimens. The testing unit (fig. 1) is developped and constructed by the Lehrstuhl für Felsmechanik at the Univerity of Karlsruhe. The testing procedure includes a cycle of loading, deloading and reloading of the specimen before the cell will be flooded with water on a high stress level. The specimen will be deloaded stepwisely while the time depending swelling deformations will be measured on each stress level (fig. 3). The maximum pressure with swelling deformation is called the maximum possible swelling pressure, a different value as the maximum swelling pressure under constant volume.

The total axial deformation (fig. 3) is to divide in the terms of elastic deformations and swell deformations. Between the swell deformations and the logartithm of the axial pressure exists a linear correlation. As a result of the orientated tests you can see that the maximum possible swelling pressure normal to the bedding planes is about hundred percents larger than the responding value parallel to the bedding. The ratio of the swelling pressure normal to the bedding to parallel to the bedding depends on the swelling deformations and the stress level. The lower the stress level the larger is the anisotropy of the swelling pressure. The mean value of the anisotropy of the swelling pressure is about 30 under an axial pressure of

-0,01 MPa (compression: negative).

A comparison of the test results shows that the swelling pressure anisotropy on low stress level correlates with increasing of the unconfined swelling deformations.

The deformation about the unconfined swelling deformations and the maximum possible swelling pressure is not enough. You need the complete dependence of the swelling deformations on the stress levels. As the schematic diagram in fig. 4 shows the swelling pressure of a stiff rock is higher than the value of a soft rock if the swelling pressure is developing under constant volume. The higher the stress level at the beginning of the swelling the swelling pressure under cnstant volume will increase. A swelling process under constant volume means that the volume increase caused by the swelling is equal to the elastic compression caused by the increase of the pressure. Therefore, you can say that the swelling behaviour depends on the deformation parameters of the rock. A pressure increase parallel to the bedding planes is caused by a high swelling pressure normal to the bedding planes. Therefore the anisotropy of the swelling pressure will decrease if the stress level increases and the Poisson ratio is high.

The test results of the anisotropic swelling and the theoretical deducations (e.g. by Fecker and Mühlhaus) lead to a material law as a reduced material model which desribes the orthotropic swelling behaviour superposed on an elastic material behaviour.

$$\varepsilon_{ij}^{ges} = \left(\frac{1}{2G} \cdot \sigma_{ij} + \frac{2G - 3K}{18\, K \cdot G} \sigma_{kk}\delta_{ij}\right) + \beta n_i n_j f\ (\sigma_n)$$

$$\sigma_n = \sigma_{ij} n_i n_j$$

$$f(\sigma_n) =: \ln \frac{\sigma_n}{\sigma_{n0}} \text{ für } \sigma_n \leq \sigma_{n0}$$

$$f(\sigma_n) =: 0 \text{ für } \sigma_n > \sigma_{n0}$$

σ_{n0} : maximum possible swelling pressure

β : swelling coefficient

This model is implementated in a finite element program. This mathematical model describes the finished swelling process and has no information about the time dependence. While the material behaviour is hyperlinear the initial strain method is assumed.

Different models are calculated with this FE-program. In the following few examples are explained. Fig. 5 shows the displacements of the top and the side wall depending on the swelling deformation capacity on low stress level. The displacements of the top/invert are about ten times larger than the displacements of the side wall. If the overburden pressure increases the top/invert displacements decrease (fig. 6) without change of the swelling parameters. The horizontal wall distance will be enlarged if the overburden surcharge increases. The top/ invert displacements decrease and the horizontal convergence increases if the ratio of the horizontal to the vertical stress increases (fig. 7). The calculations of fig. 5 to fig. 7 describe a tunnel without lining and fixed boundary conditions. The total section of the rock mass is swelling.

To estimate the influence of the swelling behaviour in tunnelling the following basic questions are to be answered:

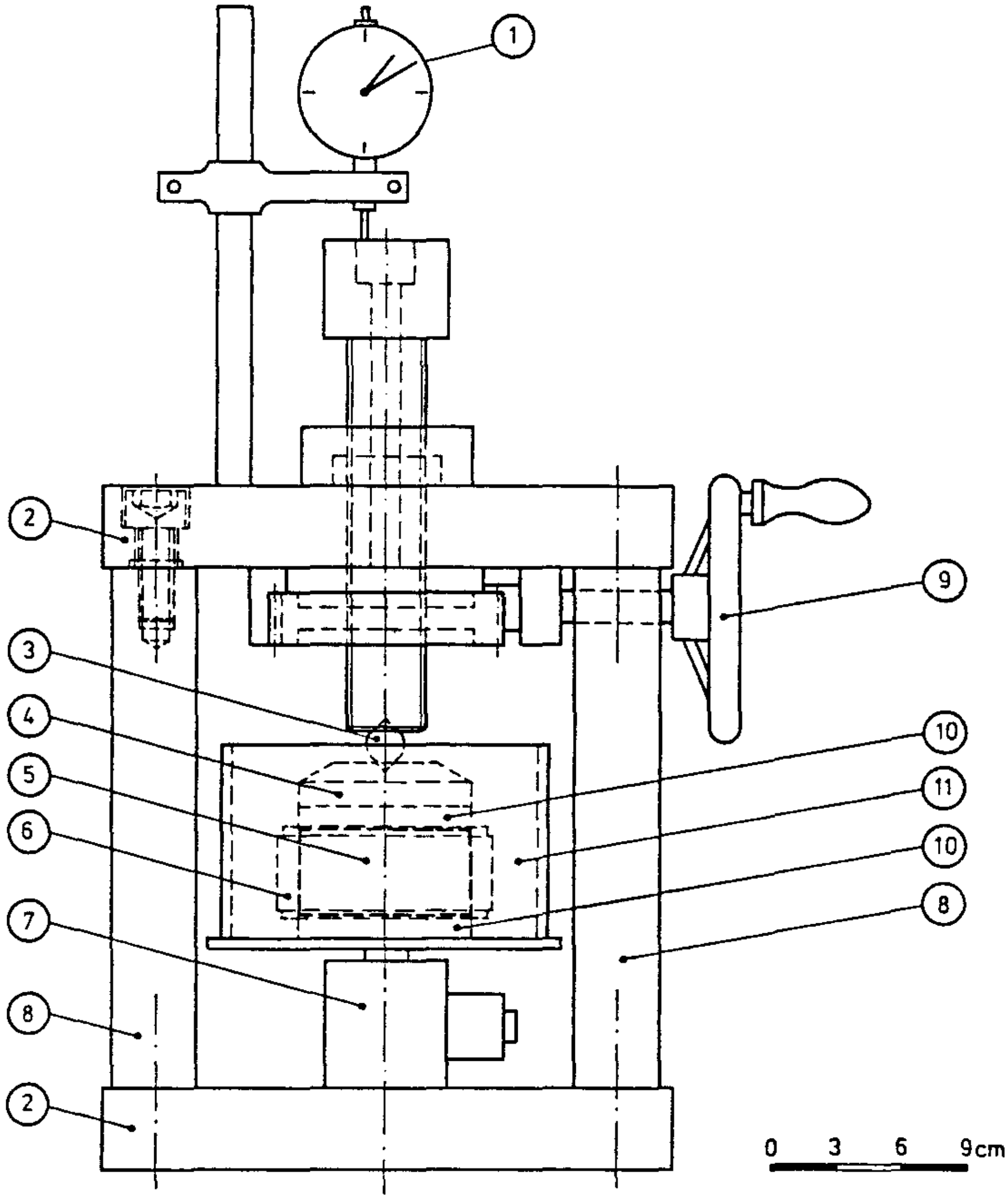
- Which section of the rock mass is swellable?

- Which section of the rock mass will be influenced by tunnelling?

- How much has the rock mass swelled before tunnelling starts?

To study the influence of the extent of the swelling rock section around a tunnel, a tunnel model with a flat invert and an overburden of 110 m is calculated (fig. 8). If the extent of an annular swelling rock section increases up to a thickness of about 1,5 diameter the vertical convergence increases (fig. 9). The complete rock mass over the tunnel will be heaved (fig. 10). The magnitude of the displacements of the tunnel and the surrounding rock depends on the stiffness of the non swelling rock.A heaving of the surface can be observed in situ. Although the swelling rock section is annular around the tunnel (see fig. 8) the vertical convergence is extremely higher than the horizontal convergence (fig. 11). The distance of the side walls can enlarge.

To estimate the pressure on a tunnel lining the vertical load deformation line of a concrete tube is compared with the vertical tunnel convergence of the calculations of the FE-model of fig. 8 (fig. 12). The vertical tunnel convergence is calculated for different extent of the annular swelling rock section and for different internal tunnel pressures. The vertical convergence of the concrete tube is calculated with a radial pressure p depending on the angle of the circumference (fig. 13) and considering the forces caused by the modulus of subgrade on the side wall. The effective pressure to the tunnel lining (- 1,788 MPa) is significantly lower than the maximum possible swelling pressure (σ_{no} = - 10,0 MPa) - see fig. 12. If the thickness of the concrete lining increases the moment forces in the lining increase. The described tests and calculations show that the swelling behaviour of claystone is extensively anisotropic. The anisotropy of the swelling is the most important cause for the characteristic of the measured displacements in tunnelling. The finite element model gives the possibility for the first time to calculate the influence of the anisotropic swelling behaviour.



(1) mechanical strain gauge

(2) endplates of the frame

(3) center ball for loading

(4) plate for load distribution

(5) oriented rock sample

(6) brass ring for lateral deformation restriction of the rock sample

(7) electrical load cell

(8) four columns of the frame

(9) spindle feed unit

(10) porous filter disc

(11) container for the rock specimen and water

Fig. 1: Swelling pressure apparatus

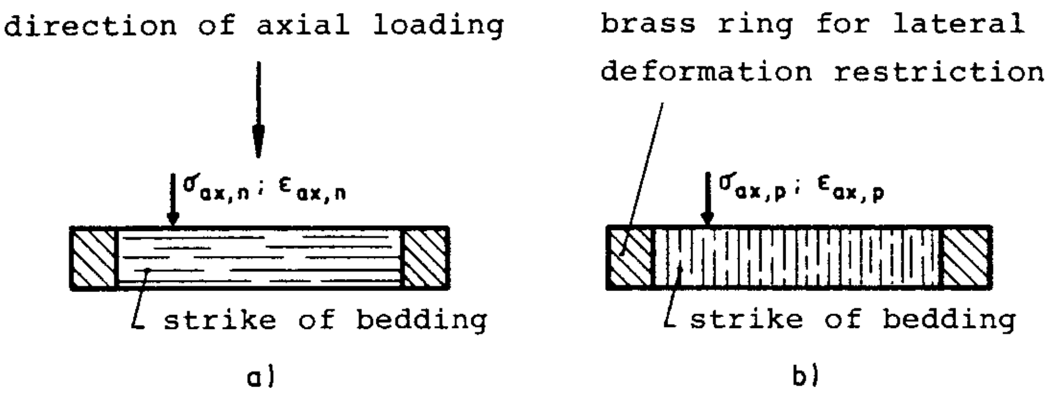


Fig. 2: Oriented rock sample in the test ring

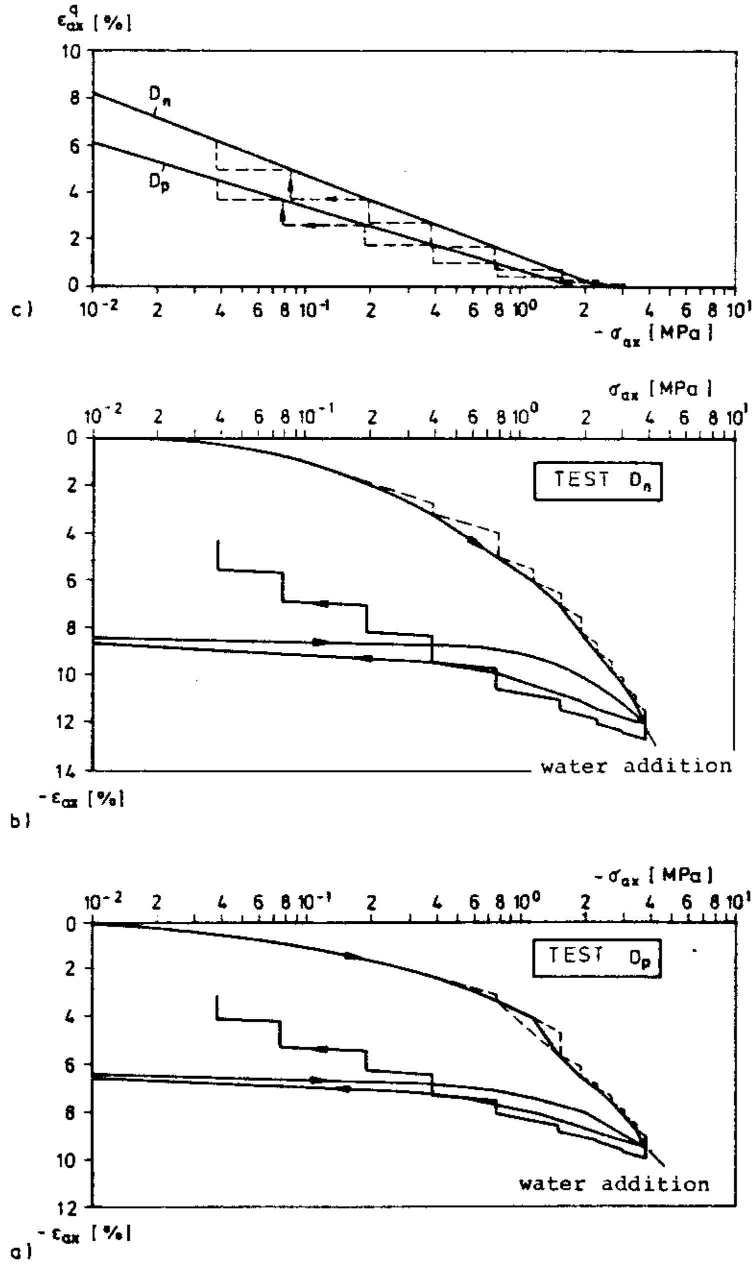


Fig. 3: Results of a swelling-pressure test

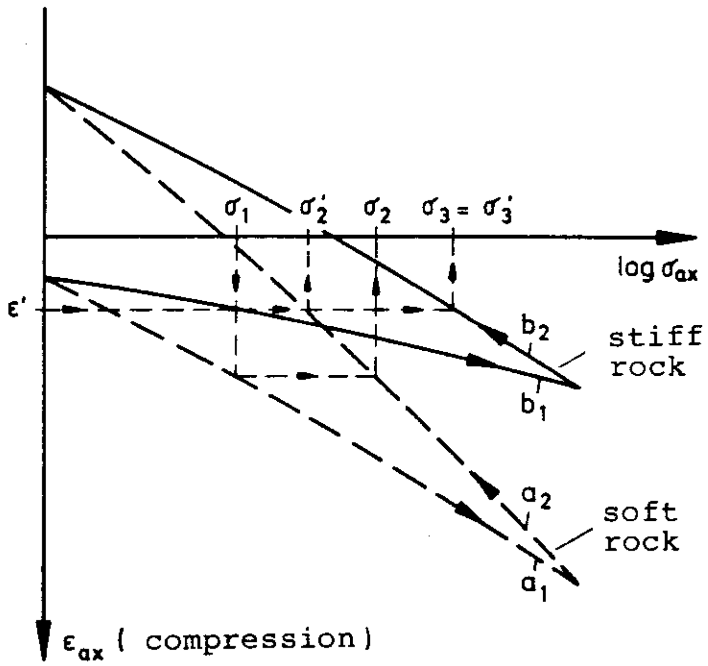


Fig. 4: Swelling pressure depending on the stiffness of the rock/rock mass

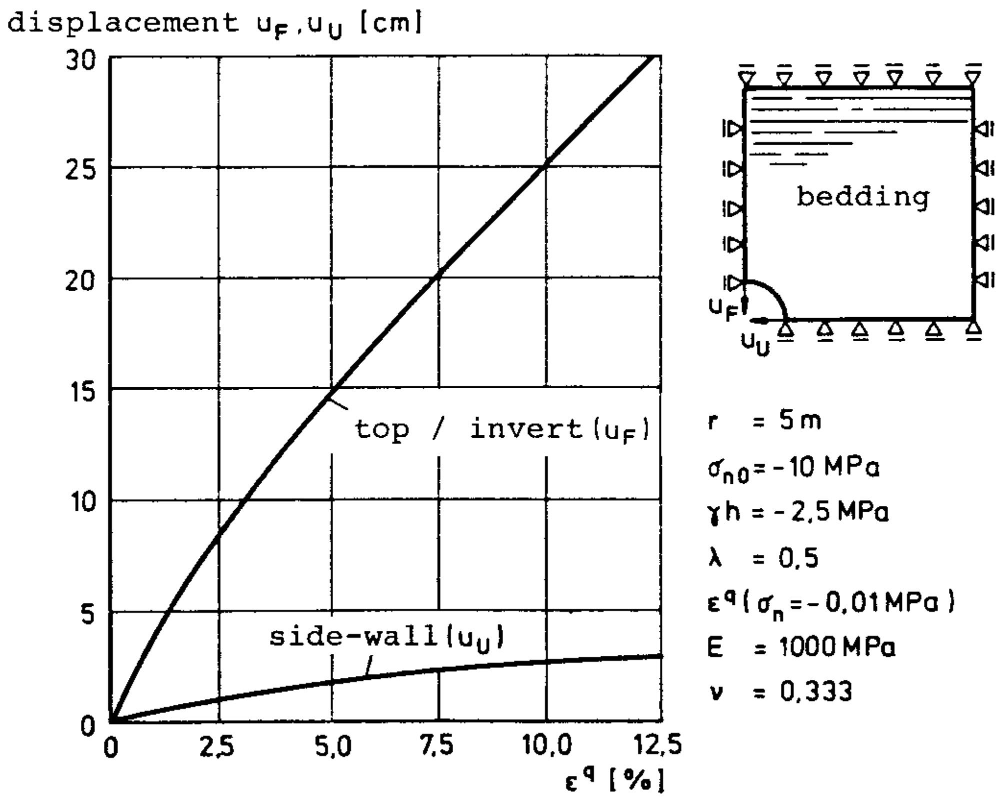


Fig. 5: Displacement of the top/invert and the side-wall depending on the swelling deformation capacity ε_q (σ_n = - 0,01 MPa)

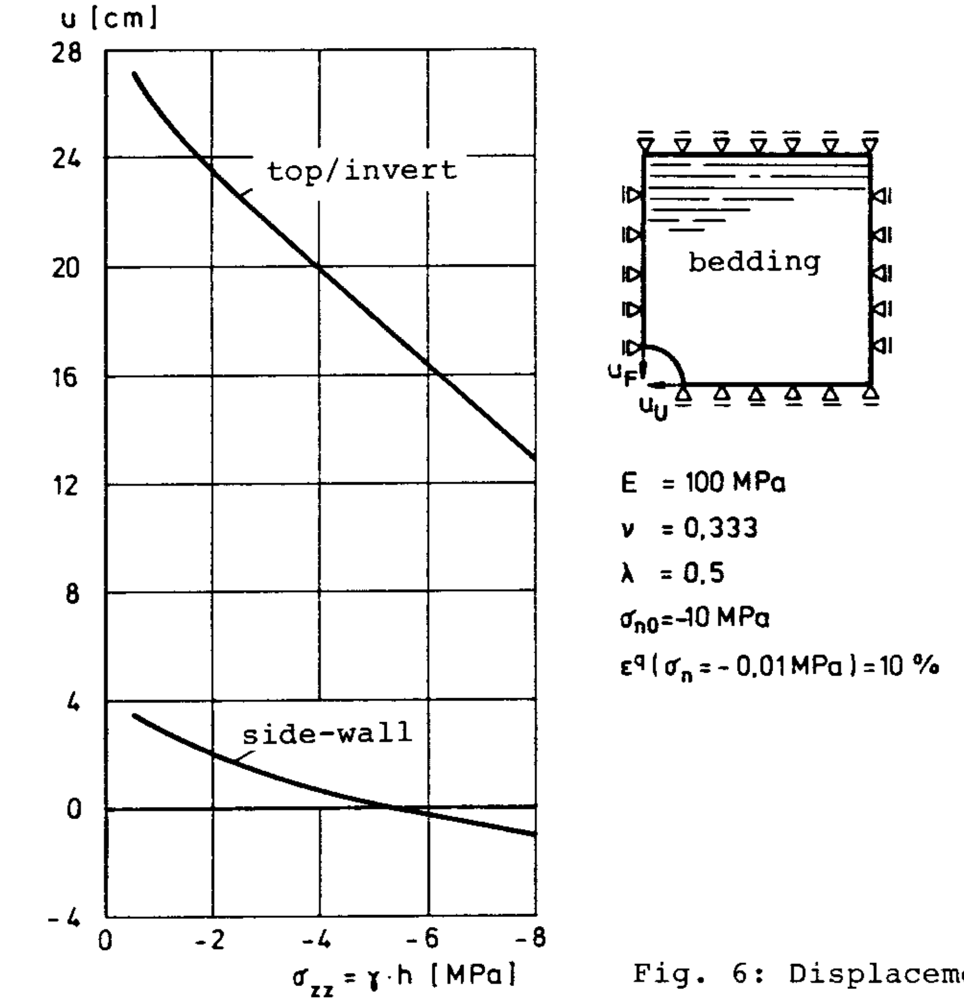


Fig. 6: Displacements of the top/invert and the side-wall depending on the overburden pressure

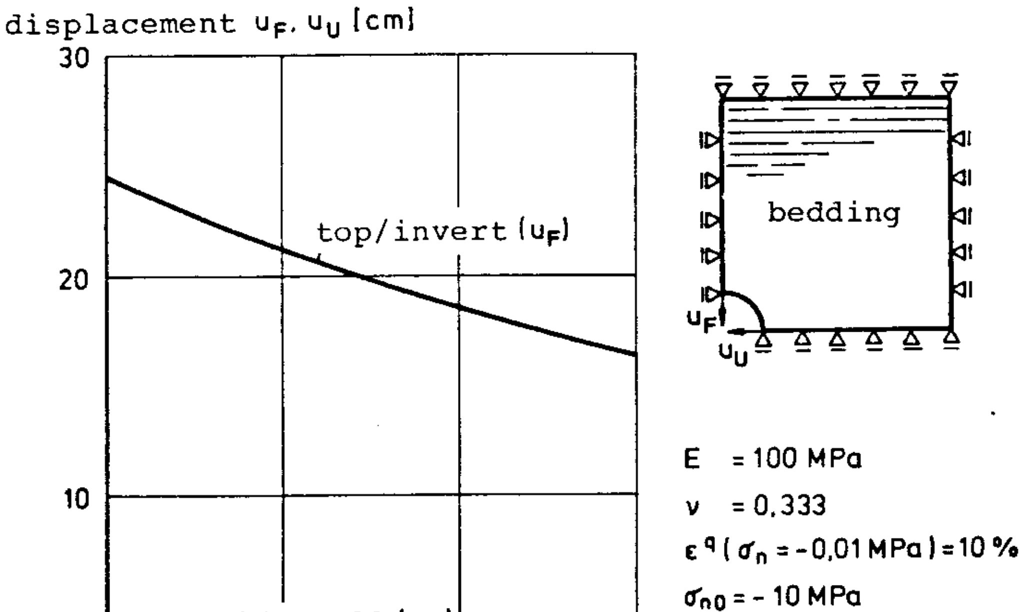


Fig. 7: Displacement of the top/invert and the side-wall depending on the ratio λ (λ = horiz. stress/ vertic. stress)

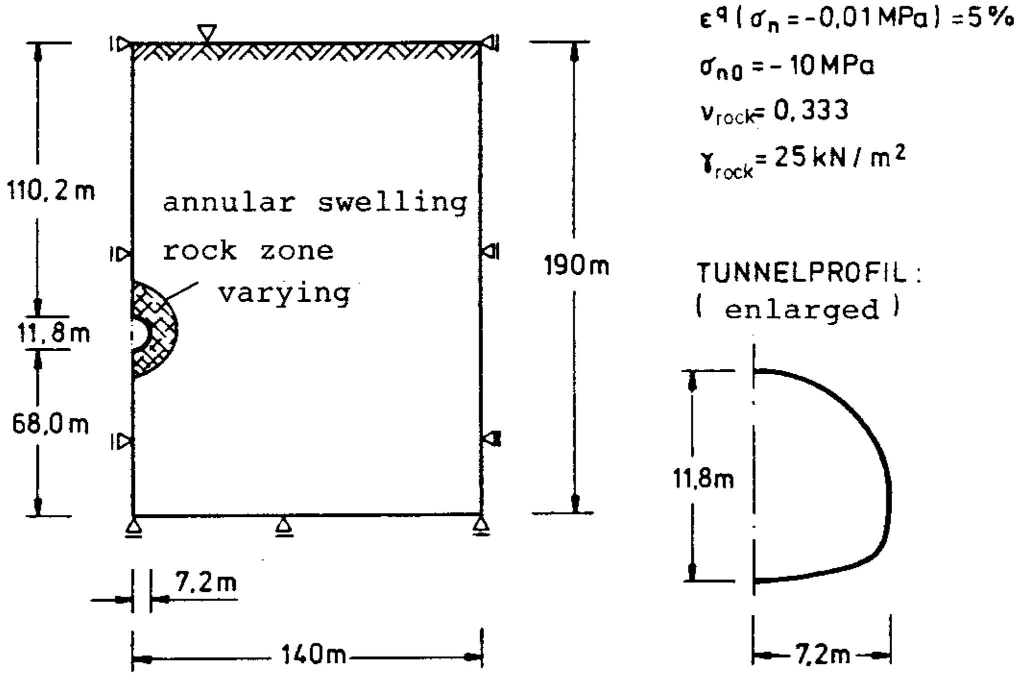


Fig. 8: Rock mass section with tunnel profil
swelling rock mass : E-Modul : E_i
non-swelling rock mass : E-Modul : E_a

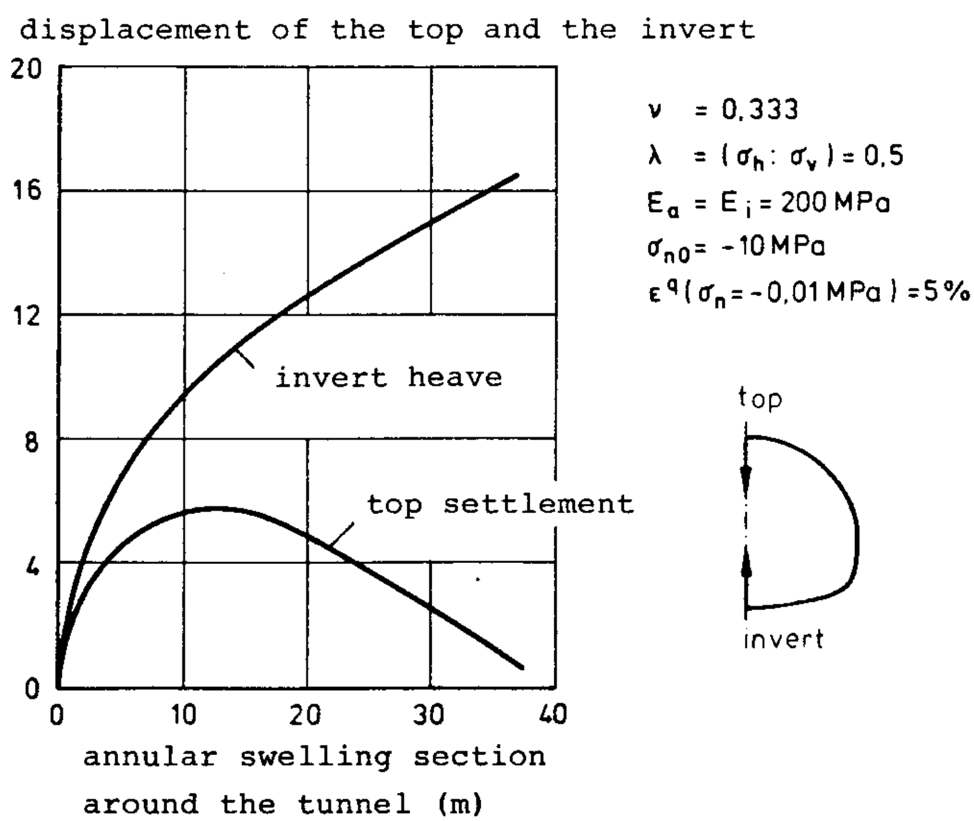


Fig. 9 : Top settlement and invert heave depending on the extention af the annular swelling section around the tunnel

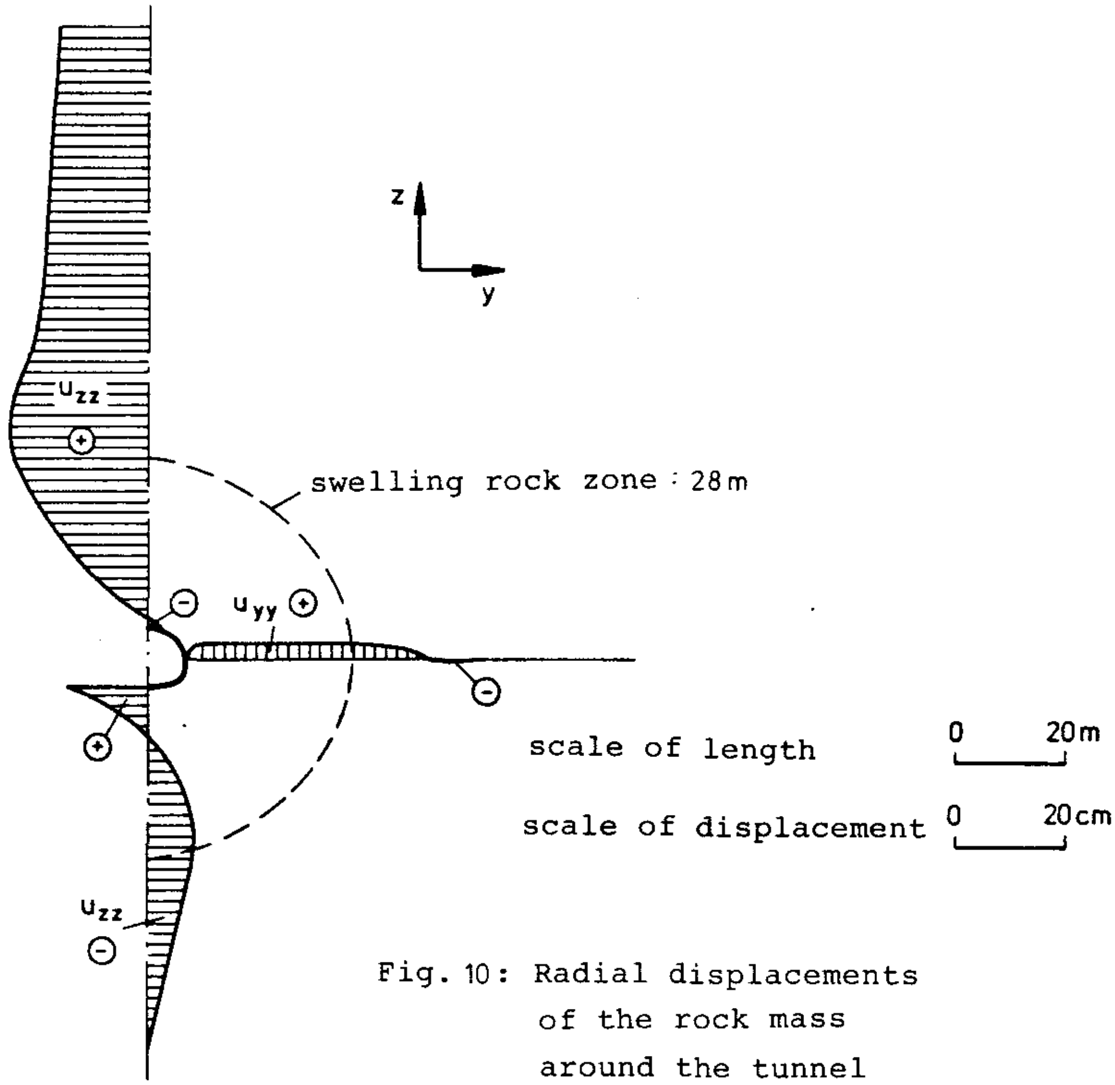


Fig. 10: Radial displacements of the rock mass around the tunnel

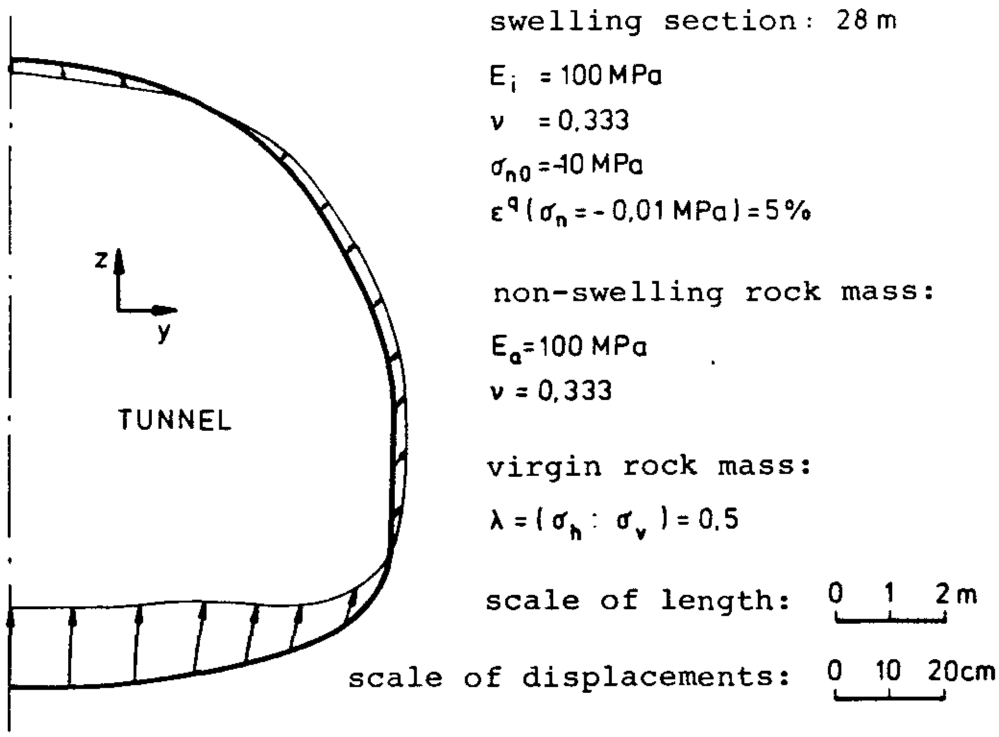


Fig. 11 : Displacement of the tunnel cross-section

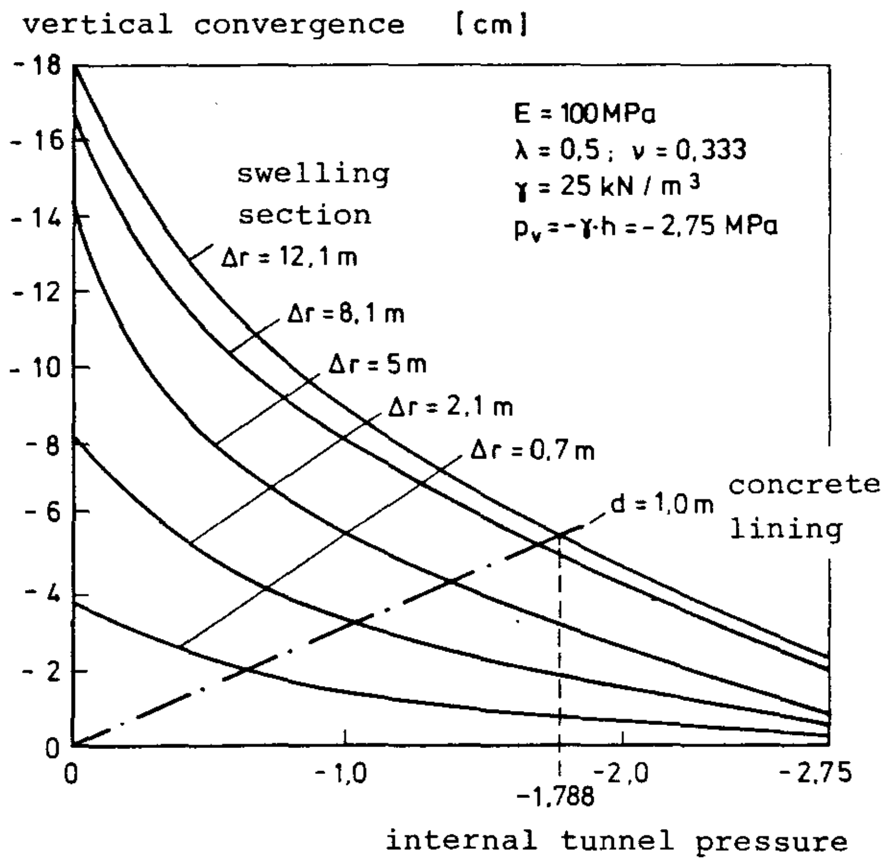


Fig. 12: Vertical tunnel convergence depending on the internal tunnel pressure (as a reference for the vertical pressure)

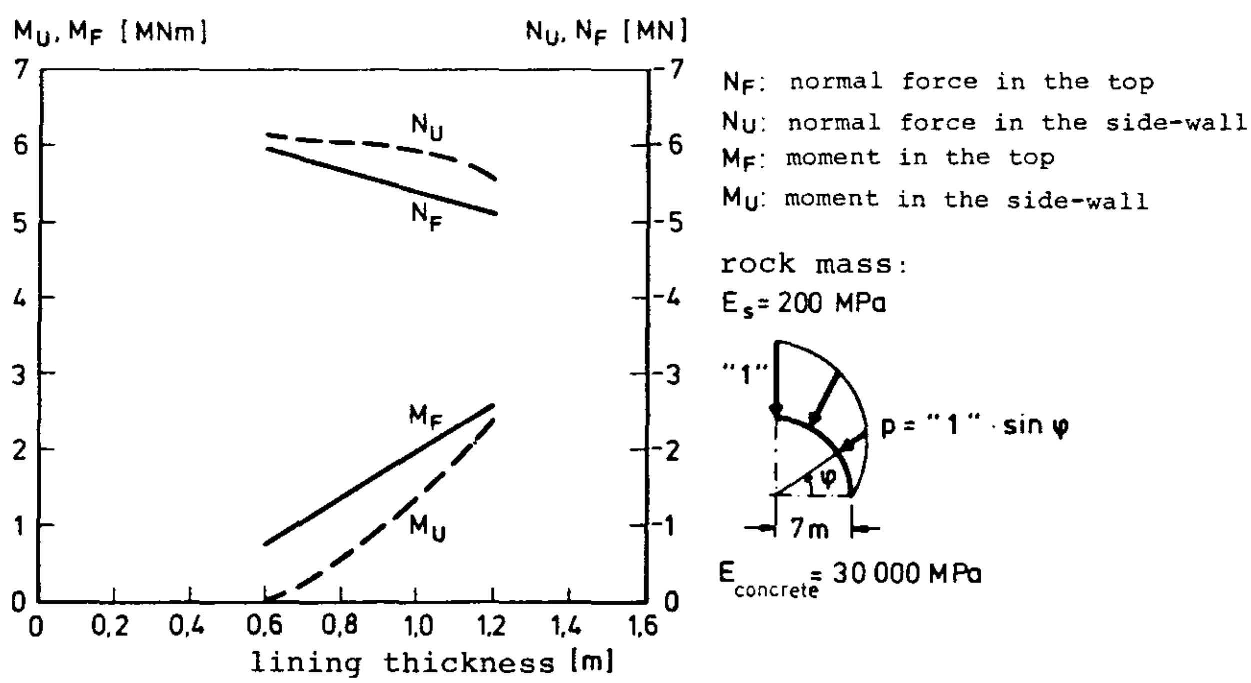


Fig. 13: Moments and normal forces in the top and the side-wall of an annular concrete tube depending on the thickness of the lining (radial loading p = "1" · $\sin \phi$)