Underground Construction in Soft Ground, Fujita & Kusakabe (eds) © 1995 Balkema, Rotterdam. ISBN 90 5410 536 4

German national report on tunnelling in soft ground

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SYNOPSIS: In this national report, a brief description is given on the tunneling technology in soft ground which is currently applied in Germany. After a brief statistical survey on current German tunneling construction, the paper covers heading and support techniques, computational methods for the determination of lining loads and surface settlements, and monitoring methods.

A SURVEY OF THE TUNNELLING PROJECTS IN THE FEDERAL REPUBLIC OF GERMANY

According to the statistics of the Society for Underground Traffic Systems - STUVA -, at the turn of the year 1990/91 tunnels of a total length of about 134 km were under construction in Germany. These tunnelling projects were essentially divided into the following usages:

- metropolitan railways - 54.5 km
- long distance railways - 4.6 km
- roads - 29.4 km
- supply - 10.1 km
- sewage - 35.1 km

Regarding the supply and the disposal tunnels, only tunnels with a diameter d › 1 m were taken into consideration, in the case of the sewage tunnels furthermore only the main sewers.

For further tunnels of a total length of about 121 km construction is to start very soon. Those statistics, of course, contain all tunnels independent of the ground conditions. Corresponding to the large proportion of metro as well as supply and disposal tunnels, which are mainly driven in large developed areas, it can be estimated that the tunnels driven in soil constitute more then 50 % of the total length mentioned above.

CONSTRUCTION METHODS

In the following a report is given on the heading techniques used and on the different supports that were employed.

Heading

At first one has to distinguish between the cut and cover method and the underground construction method.

Figure 1 provides a survey of the share of the cut and cover method in metro tunnels (figure 1a) and of the total traffic tunnel construction (figure 1b). The reasons which lead to a decision in favour of the open construction method have to be looked for less in the particular ground conditions than in the location of the tunnel gradient, in the boundary conditions set by neighbouring development and in the resulting economic aspects.

The large share of shotcrete vs. shield tunnelling (figure 1a) can be put down to the fact that this statistic also contains the tunnels driven in rock.

Concerning the supply and disposal tunnels which are not included in the statistics shown in figure 1, a tendency to the more frequent use of underground construction methods, especially tube headings, can be observed, since this construction method leads to the least restrictions on the innercity traffic.

In recent years metro tunnels were increasingly driven using the shotcrete method. The combination of this method with compressed air support at the working face below the ground water table has proved efficient in low permeability subsoil conditions too in terms of minimizing surface settlements. In Munich, numerous sections of subway tunnels were driven this way in

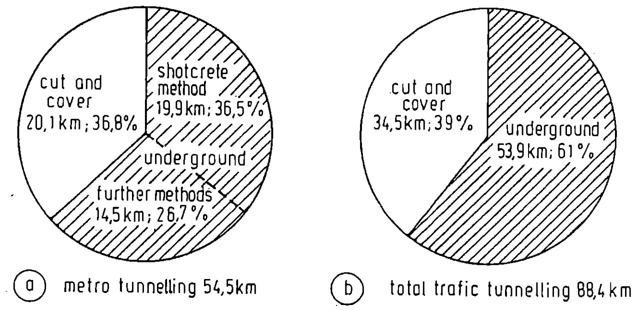


Figure 1 Shares of construction methods in German traffic tunneling, end of 1990, HAACK (1991)

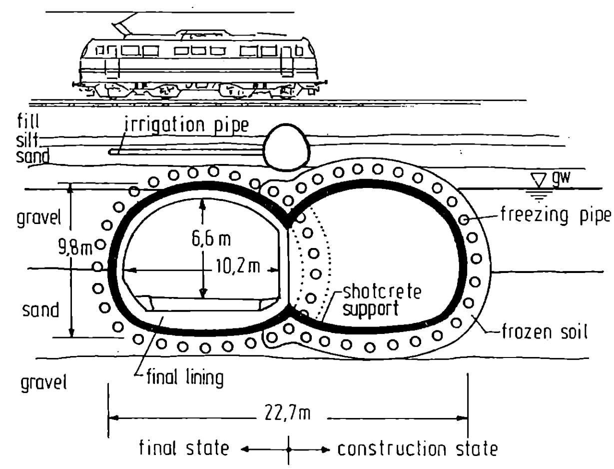
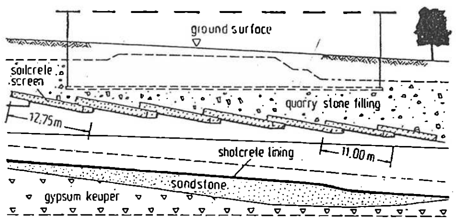


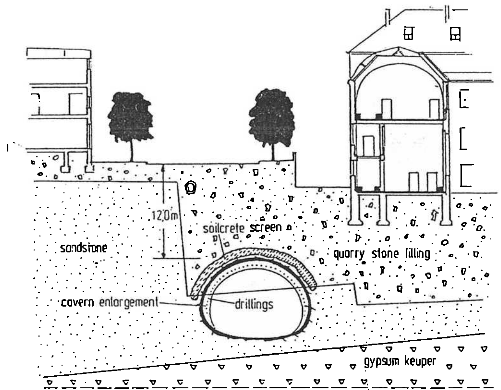
Figure 2 Fahrlach tunnel, Mannheim, tunneling with frozen soil support, DUSCH, MAYER (1989)

tertiary sand and silt, in Essen in silt, sand and marlstone. To some extend the shotcrete method is also combined with freezing measures, if the tunnels are located in heavily water-bearing layers of sand. Examples for this are tunnel sections of the metro lines in Hannover and Düsseldorf as well as a road tunnel in Mannheim (see figure 2). The frozen soil areas are used to seal off the excavation cross-section against the ground water as well as to create a closed load-carrying ring in the unstable soil, under the protection of which the tunnel can be driven.

Grouting and the soilcrete technique were also combined with the shotcrete method. As example serves the so-called Expo tunnel of the Stuttgart metro (fig. 3).



a) longitudinal section



b) cross section

Figure 3 Expo tunnel, Stuttgart, tunneling with an advancing soilcrete screen, BEICHE et al. (1992)

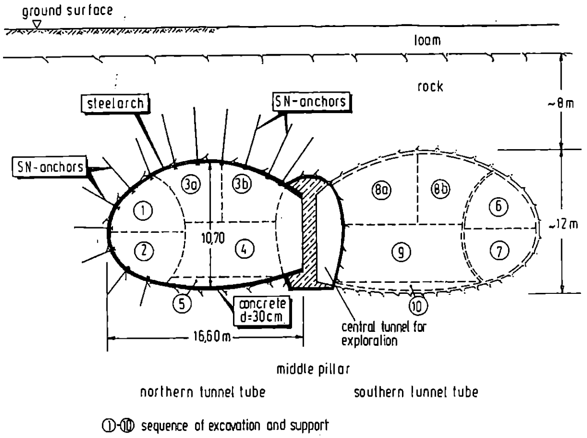


Figure 4 Road tunnel, Wuppertal, driving of a large cross section in partial headings, MODEMANN, WITTKE (1987)

The subdivision of the cross-section into partial headings should be mentioned as well, which is often performed for large cross-sections in difficult ground conditions. This technique is depicted in fig. 4 for the example of a road tunnel.

Shield tunnelling constitutes the third large group of the tunnelling methods in soil. Apart from cutter shields, which are only occasionally used for the driving of horseshoe-shaped tunnel cross-sections, compressed air and soil pressure shields as well as shields with a liquid-supported working face and mix shields are employed. Probably the most frequently used shields are those with a liquid-supported working face. For this hydro and thix shields are being employed. An example of the ground conditions during construction of a sewer in Hamburg using a thix shield is shown in figure 5.

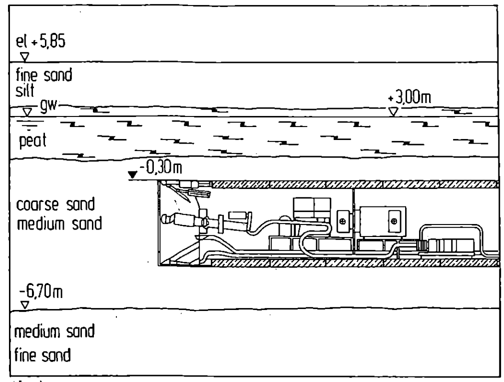


Figure 5 Tube heading of a sewer in Hamburg, STADT HAMBURG (1988) (slightly changed)

The use of the different shield systems depends on the respective ground and other boundary conditions. For this two examples are briefly mentioned.

Figure 6 illustrates the greatly varying ground conditions of contract section 32/33 of the metro tunnel in Essen. The tunnel alignment runs alternately through organic mud sediments and jointed marlstone. In this case an earth pressure shield in combination with the extru-concrete method was a suitable solution.

When building a tunnel for a remote heating pipe line underneath the Kiel inlet (Kieler Förde), though, the decision was in favour of a mere compressed air shield (see fig. 7). Finally, a tunnel shall be mentioned which is constructed for the industry railway of the Ruhr Coal Co. (Ruhrkohle AG). It is founded on soft soil and will be finally covered by 80 m of surcharge (fig. 8a and b).

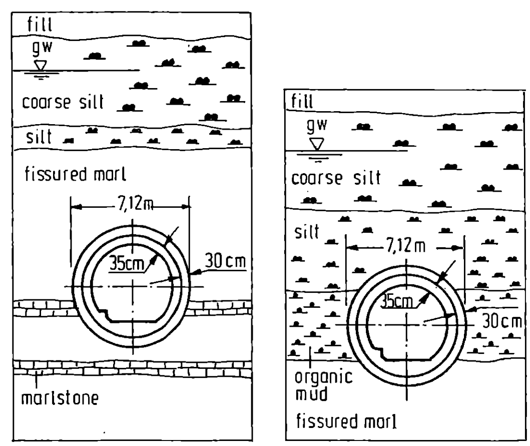


Figure 6 Metro Essen, use of an earth pressure shield in varying geological conditions, HOCHTIEF (1988)

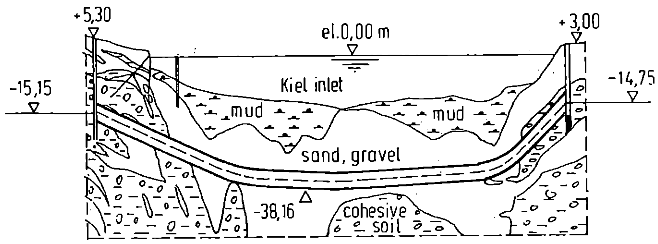
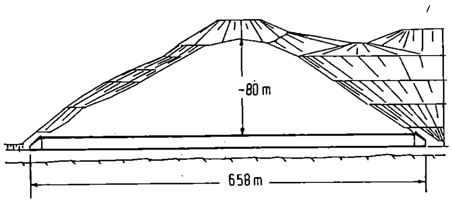
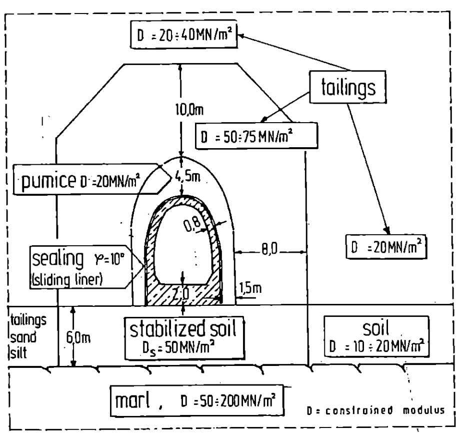


Figure 7 Use of a compressed air shield under the Kiel inlet (Kieler Förde). Geological cross section, BARG, THIEMANN (1990)



a) longitudinal section, final state



b) cross section

Figure 8 Industry railway of the Ruhr Coal Co. (Ruhrkohle AG), tunnel to be covered in the course of tailings piling, WITTKE (1988)

Excavation Support

Corresponding to the great number of different heading techniques, various methods for excavation support are applied as well. They range from shotcrete to extru-concrete and from steel and steel reinforced concrete tubbings to pipe heading.

As already shown in the beginning, in Germany the shotcrete method is used more and more frequently as well in soil. Recent developments pass from the conventional double lining to a single lining shotcrete method (see figure 9). In this context the use of steel fibre shotcrete is currently tested. With the double liner method, the outer lining is generally taken into account as a temporary support, without a load carrying and sealing function. The single lining shotcrete method still consists of two layers, which are applied in two operations. The aim, however, is to achieve a supporting action of the first shotcrete membrane as a permanent function and to be able to take it into account in numerical analyses. The first test sections with a lining of this type were constructed for metro projects in Dortmund and Bielefeld. Recent

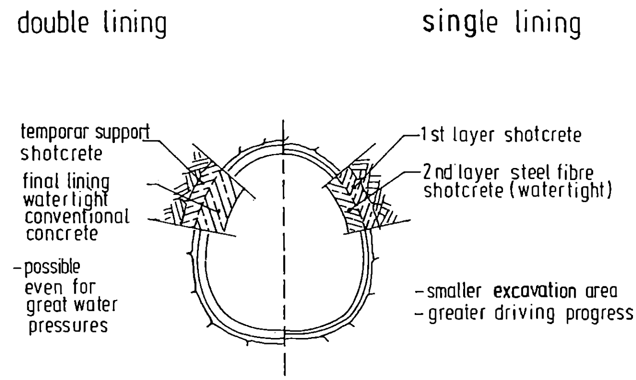


Figure 9 Shotcrete support, comparison of single and double lining, MAIDL, KOENNING (1989)

developments include the use of gypsum - reduced or gypsum - free cement for ground water protection reasons. Thus, accelerators shall be dispensed with and a lower final void ratio of the shotcrete be achieved.

In shield tunneling mainly tubbing linings are constructed. The use of cast-iron and steel tubbings takes second place to the use of reinforced concrete tubbings. Today tunnel lining with tubbings occurres single lined as well. Therefore the lining has to have a load carrying capacity and to be waterproof immediately after its installation in the shield tail.

Apart from the tubbing lining prefabricated tubular segments are being used, especially in pipe line construction. The shield advancement is effected by tube heading using jacks in the starting shaft or, with longer heading distances, using intermediate jack stations. With this method it is quite possible to drive relatively large cross sections. In this way the already mentioned sewer in Hamburg was driven as a tube heading with reinforced concrete tubes made of B 45. With an inside diameter of d = 3.5 m and a length of l = 3.5 m, the tube segments have a wall thickness of 33 cm. The heading distance was 500 m.

Great expectations, particularly with regard to tunneling with little settlements, are placed in tunnel lining with extru-concrete. In Germany, e.g. the above mentioned tunnel section of the Essen metro was driven using this construction method (fig. 10). The liquid concrete completely fills the annular gap between lining and subsoil, so that ideally heading almost free of settlements is achieved.

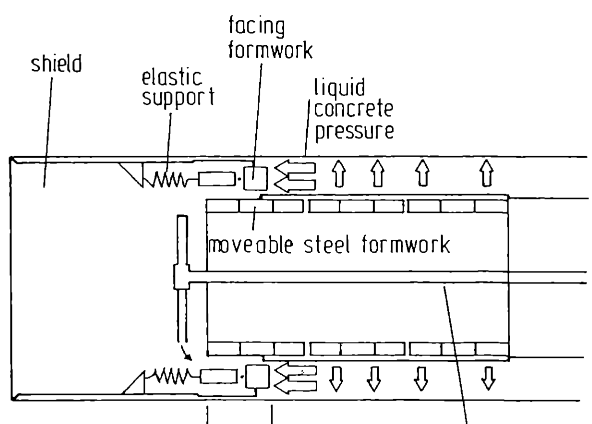


Figure 10 Metro Essen, earth pressure shield with extru-concrete support, WITTKE (1989)

ANALYSIS METHODS

There are no specific codes for tunnel analysis in Germany. The most important information from the respective recommendations of the German Society for Soil Mechanics and Foundation Engineering (Deutsche Gesellschaft für Erd- und Grundbau, DGEG) as well as from other guidelines, e.g. by German Rail, are summarized in the following.

Tunnel Lining Design

For tunnels, safety has to be proved for the following cases:

- non-structural failure (watertightness)
- exceeding deformations
- local failure of the lining
- total failure

Safety against these items has to be proved with the help of structural analyses. The results of model tests or of direct measurements on already existing tunnels are only used in combination with comparative structural analyses for the design of tunnel linings.

At present, usually only the final state after tunnel construction is analysed in two-dimensional structural analysis models. But the use of the finite element method for tunnel analysis has increased continuously in the recent years, so that the sequence of construction for partial headings and also the effect of stress relief in the subsoil before the installation of the final tunnel support and in the area of the working face is increasingly analysed computationally. Two- and three-dimensional models are used for this purpose.

Two-dimensional calculation models are often still based on the Winkler model. Apart from charts for circular cylinder linings on a Winkler bedding, practically always calculation models for connected beam sections on a Winkler bedding are used with the rising spread of PCs. These have the advantage of not only being able to analyze circular but any kind of cross sections.

For the assumption of a supporting action in the subsoil, depending on the depth, the two cases reprensented in figure 11 are distinguished.

The loadings are derived from the in-situ stresses. Usually the loadings are assumed equal to the in-situ-stresses. In these calculation models, the effect of stress redistributions due to tunneling on the loading can only be taken into consideration via empirical parameters.

The soil-lining-interaction can only be realistically simulated with the help of continuum mechanics models according to the finite element method. With the obligation for more and more economical construction and with computing capacities being available to more and more favourable conditions, the use of this method increases. In figure 12 the finite element mesh for the analysis of a tunnel cross section of the road tunnel Stuttgart-Heslach is presented exemplarily.

The soil parameters used in these computational models are determined from the standard soil mechanics laboratory tests, the oedometer test on undisturbed soil samples. To a certain extent field tests, e.g. pressiometer tests,

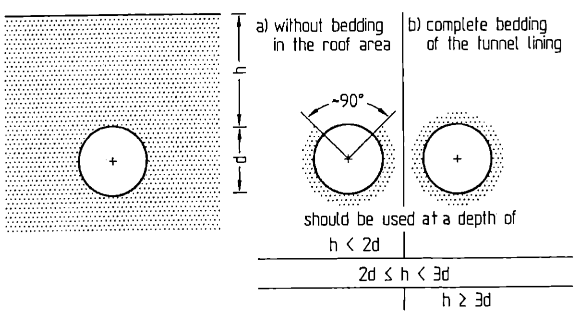


Figure 11 Assumptions for soil-lining-interaction, AK 10 (1980)

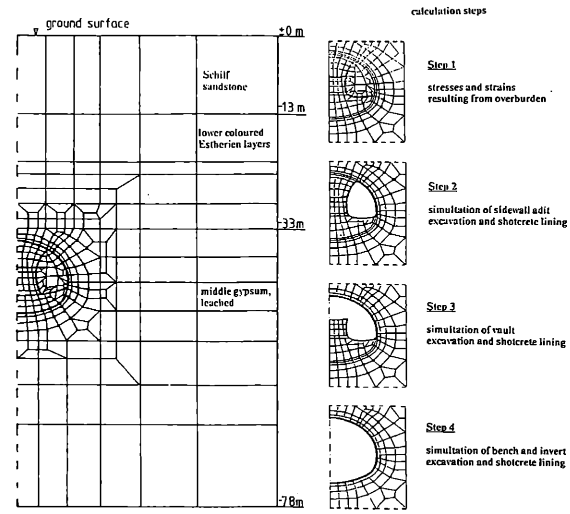


Figure 12 Road tunnel Stuttgart-Heslach II, FE mesh, WITTKE (1987)

are carried out as well. If measuring values of e.g. neighbouring or test headings are available, the soil parameters are calibrated by back-calculation of the measuring values in numerical models. The parameters for the numerical analyses are chosen based on the engineer's evaluation of all these test data.

For calculations taking into account the non-linear stress-strain behaviour of the soil, further parameters have to be determined according to the used constitutive law. Usually these additional parameters can also be determined from the tests and calibration methods mentioned above.

For tunnel lining design usually no partial safety factors are applied to the soil parameters and loadings. The safety against failure is expressed in terms of permissible values of working stresses and deformations.

Calculation of Surface Settlements

The amount and distribution of surface settlements are estimated beforehand not only from calculation results. With three dimensional FE-calculations it is possible to simulate the areas in front of and behind the working face and the heading in its individual construction stages, but this great a computational expense is at present only incurred in few cases. Moreover all computations can only be as precise as the assumed soil parameters and loadings. Therefore for the estimation of surface settlements in the course of shallow tunnel heading, additional information from experience and measurements are included from earlier projects.

In recent years, with interactive measuring and grouting techniques, new methods for monitoring and compensation of surface settlements caused by tunneling have been investigated. These are presented, amongst other things, in the following passages.

MONITORING

Measurements During Construction

Measurements accompanying the construction process are now carried out for practically every tunnelling project in Germany. The extent of the measuring program, however, clearly varies according to the respective boundary conditions and aims. The following measuring problems are distinguished:

- securing of evidence
- verification of analysis results
- effects of tunnel heading and of individual auxiliary construction measures on the surrounding area

- back-calculation of soil parameters regarding future projects under comparable ground conditions
- a general understanding of the structure's behaviour

In the course of securing evidence, usually prior to beginning and after completion of the project stock-taking measures through close inspection and several levelings are carried out.

To verify the analysis results, mainly the deformations and stresses in tunnel lining are measured. The deformations are recorded through convergence measurements and levelings. For the stress measurements pressure cells or strain gauges distributed over the lining thickness are made use of. Apart from the stresses in the tunnel lining soil and water pressures are measured as well. Especially the stress measurements are exposed to interferences and damages due to construction operations, because the sensitive measuring instruments are installed parallel to the heading. Therefore stress measurements, in contrast to deformation measurements, are used to a lesser extent. Their importance for the meaningfulness of a measuring program becomes obvious by the results of stress measurements available to the author, which to some extent show that effects of the construction method, e.g. squeezing due to the installment of tubbings, constitute a considerable share of the loading on the tunnel lining.

In innercity traffic tunnelling, deformation measurements are carried out today to a great extent as a routine for the monitoring of the tunnel heading in order to keep off the maximum permissible amount of subsidence resp. heave of neighbouring structures. In contrast to measurements which mainly serve for the verification and the further development of calculation models and the verification of the parameters used in them, these deformation measurements are more largely accepted by clients and construction companies. Next to the already mentioned measuring techniques, surface levelings, extensometer or sliding micrometer and inclinometer measurements are used.

An example for an extensive surface leveling is the undercrossing of a 60-m-wide railroad trackage already presented in fig. 2 above. For the monitoring of the trackage alone about 300 leveling points were installed.

Figure 13 exemplarily shows a measuring cross section of the metro construction in Munich. The cross section is equipped with two sliding micrometers. The results of the sliding micrometer measurements show the development of strains in the subsoil with time. Both tunnel tubes were driven at the same time, the heading of tube 1 ahead of the heading of tube 2.

During metro construction in Essen an extensive measuring instrumentation was coupled with grouting equipment at the undercrossing of an industrial

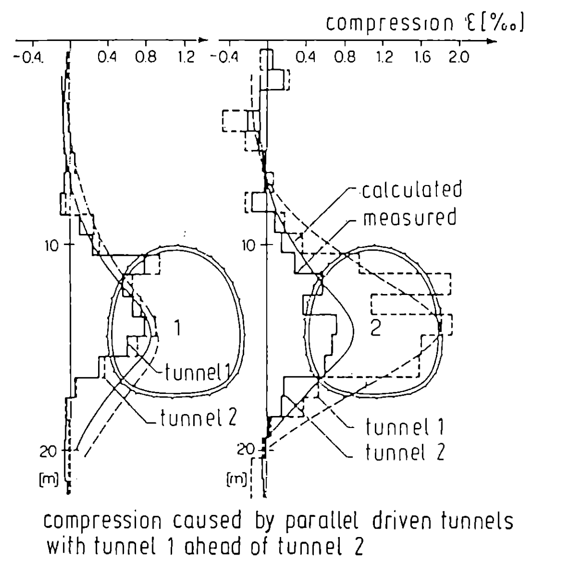


Figure 13 Metro Munich, staggered parallel heading of two tunnels, measured vs. computed subsoil compression, KOVARI, AMSTAD (1987)

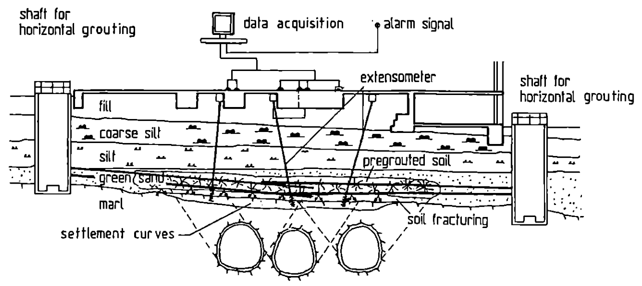


Figure 14 Metro Essen, undercrossing of an industrial building, measuring and grouting scheme, STADT ESSEN (1987)

building to compensate the settlements by grouting. In figure 14 the instrumentation and the arrangement of the grouting drillings are schematically represented in a cross section.

The measuring values of the extensometers as well as of the settlement and inclination gauges at the building's foundations were continuously recorded and analysed with a computer. The grouting in the areas affected by settlements was controlled by the same computer, according to the measurement results. In this way it was possible, in this critical area, to carry out the tunnel heading without interrupting or impairing the production operations in the industrial building.

Monitoring During The Operational Period of The Tunnel

For monitoring during the operational period of a tunnel mainly simple deformation as well as convergence measurements and levelings are carried out. In individual cases the measuring cross sections with e.g. extensometers installed for the construction period continue to be operated.

Apart from these customary measurements, methods for the so called non-destructive tunnel inspection are used more and more frequently. In this method the complete surface of the tunnel lining is examined for defects such as cavities and wet areas with the help of three dimensional photographic and thermographic or radar imaging.

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