Soft Ground Tunnelling under Buildings in Germany

Construction de Tunnels en Terrain Meuble sous Immeubles en Allemagne

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SYNOPSIS

In the last years it was frequently necessary to underpass buildings with subway tunnels in very unfavourable ground conditions and under low cover. The New Austrian Tunnelling Method was used to drive tunnels under big and ancient buildings. The influence of tunnelling to those buildings is described and especially the surface subsidence. The settlements above the tunnels always were so small that no damages of the buildings occurred.

INTRODUCTION

Driving subway tunnels in the heart of ancient cities presents special problems:

The buildings are often sensitive to settlements and situated close together, the roads are narrow and hardly ever follow a straight line. Beside: drawbacks like the great disturbance of traffic flow and city life in general, this is a major argument against the use of cut and cover tunnelling in these city districts. Subsoil tunnelling procedures allow much more freedom in tracing and the draw-backs mentioned above are avoided. In loose or soft soils tunnel construction by means of old conventional methods is unavoidably connected with large settlements and therefore with damage to the buildings above. This is partly true also for shield tunnelling. Exact measurements have shown that in shield tunnelling the settlements which previously have been considered to be neglectable, are in the order of 10 to 15cm, which is inacceptable in the case of small cover.

Surprisingly good results however have been obtained by application of the so called New Austrian Tunnelling Method. This method was originally developed for tunnelling in rock and was based on principles of rock mechanics. But later applications proved its usefulness in soft rock and even in soil of low cohesion and internal friction. Modification of the method to the special needs subway tunnelling have resulted in a reduction of settlements to approx. 40 mm on the ground surface. If necessary for specific reasons the subsidence can be further reduced by means of additional measures to as little as 10 or 20 mm. These special modification also resulted in a reduction in construction costs, so that the system can be competitive to the cut-and-cover-method and to shield tunnelling.

Some selected examples of subway tunnels in the German Federal Republik may demonstrate under which difficult soil conditions under-tunnelling of modern as well as historic buildings was possible without any damage to the buildings even at small cover.

EXAMPLES

In Francfort (Frankfurt/Main) twin tunnel tubes had to underpass the "RÖMER", a historic city-hall of the 15th century and a modern 8-story bank building, both founded in sand and gravel above stiff plastic clayey silt:

consistancy:	0.76	to	1.03
internal friction:	19°	to	25°
cohesion:	0.20	to	0.65 kp/cm²

with intercalations of hard limestone and sand. The groundwater level was above the

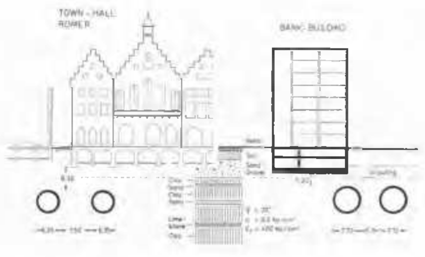

FIGURE 1:

Metro Francfort. Cross section through the Town Hall "RÖMER" and a bank building.

roof of the tunnel and had to be lowered by pumping below the invert of the tunnels. The limestones often were heavily fractured and water bearing. The vertical distance between the tunnel roof and the foundations was 6.2 m resp. 3.5 m only, (see figure 1). To avoid irregular settlements of the bank building the sand and gravel above the tunnel tubes were consolidated with cement and chemical grouting.

In Bochum a rapid traffic railway embankment and modern buildings have been situated on sand gravel and re-fill. The tunnel below had to be driven 3.5 m to 8.0 m below ground surface partly in silt, partly in soft and hard marl with properties as listed below:

Refill:

compressibility: 40 to 120 kp/cm^2
cohesion: 0 to 0.05 kp/cm^2
internal friction: 25° to 35°

Silt:

compressibility: 50 to 200 kp/cm^2
cohesion: 0.1 to 0.2 kp/cm^2
internal friction: 20° to 27.50°

Marl:

compressibility: 300 to 2500 kp/cm^2
cohesion: 0.2 to 0.5 kp/cm^2
internal friction: 20° to 25°

The line consists of twin tubes up to 11.6 m diameter (see figure 2), of single tubes, and of a subway station, where two tubes are connected together (see figure 6) The cover was between 3.0 and 8.0 m, partly the foundations of old buildings were met during the excavation of the tunnels. The groundwater level was lowered below the invert by means of pumping in boreholes.

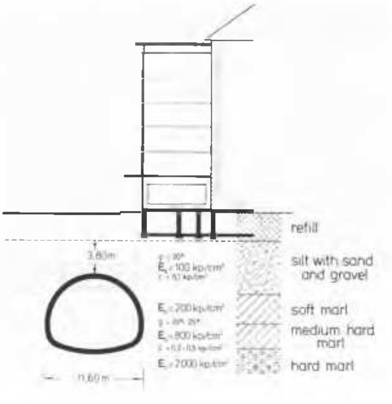

FIGURE 2: Metro Bochum.

Cross section twin tube below a building.

In the center of Nuremberg (Nürnberg) a similar subway station had to be driven recently in very soft clay-cemented sandstone

elasticity: 600 to 1,000 kp/cm^2
cohesion: 0.4 kp/cm^2
internal friction: 30°

with a cover of 3 m up to the foundation of two historic buildings, the famous St. LORENZ Cathedral of the 12th/13th century and the NASSAUER House of the 13th century (see figures 3 and 4).

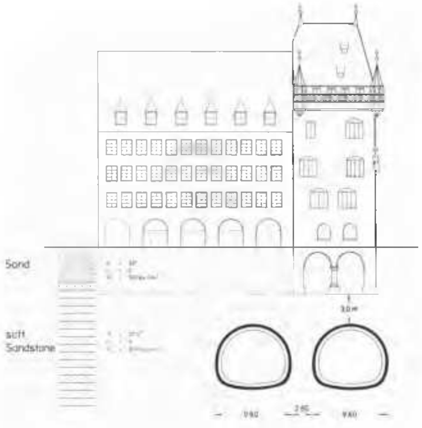

FIGURE 3:

Metro Nuremberg. Cross section NASSAUER House with underground station.

The whole station with a length of 110 m had to be driven either under buildings or roads with tramway traffic. Special problems arose from the fact that between the two tubes only 2.8 m of ground remained in which five cross passages had to be excavated.

The foundation of the tower of the St. LORENZ Cathedral was supported by single piles which were anchored to avoid horizontal movements as much as possible.

The NASSAUER House had to be crossed by the tunnels, whereas the tower of the St. LORENZ Cathedral is just 1 m beside the tunnel.

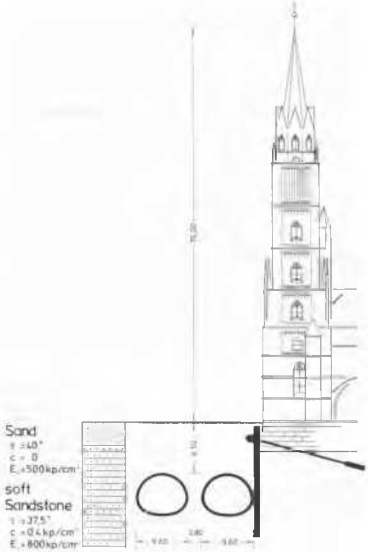

FIGURE 4:

Metro Nuremberg. Cross section St. LORENZ Cathedral with underground station and anchored piles.

SETTLEMENTS AND DEFORMATIONS

In all these cases the guideline of the design was to minimize subsidence and to guarantee that no damages to buildings would occur. Therefore it may be appropriate first to mention some of the major results regarding ground deformations and the settlements of the buildings before describing the methods of tunnelling used in these examples. The maximum settlement of the Francfort "RÖMER" foundation due to tunnelling was measured to be 42 mm, thereby the differential settlement only accounted for about half of this. Additional settlements of 44 mm due to lowering of the ground water level were of no importance because this movement did not create any differential settlements. At another subway tunnel in Francfort under old houses in the Bergerstrasse the subsidence due to tunnelling could be reduced to as much as 18 mm.

In Bochum a maximum settlement of the tracks on the railway embankment has been measured of 23 mm. Above the double tube station, where the road traffic was not interrupted during construction time, a maximal settlement of 30 mm was recorded. In a single case in the double track tube 72 mm subsidence occurred because of the calotta beeing driven too far ahead and the consequent delayed closing of the invert.

Excavation of the underground subway station of Nuremberg created a maximum settlement of the NASSAUER House of 9 mm, and only 2 mm of the settlement for the 75 m high church tower.

In all these cases the differential settlements were so small that neither cracks in the building have been observed nor did the doors and the windows get locked.

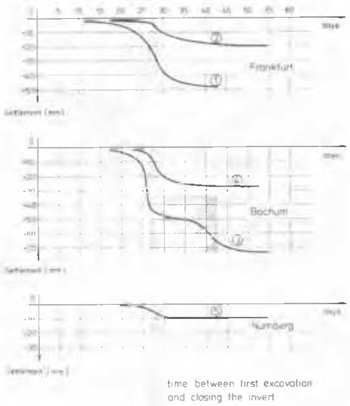

FIGURE 5:

Surface settlements during different tunnel excavations. Curves 1,3,and 5 show excavation with a vertical subdivided face and vertical steelribs; curves 2 and 4 show the influence of inclined steelribs; and curve 3 shows the effect of a late closing of the invert.

The deformation of the shotcrete lining never has been bigger than 20 mm. The settlements of the roof were 26 mm in maximum.

CONSTRUCTION METHOD

The design work of all these tunnels was governed not so much by static methods but mainly by the construction procedures, i. e. excavation work and primary (but not temporary) lining. Much effort was paid in specifying exact but at the same time flexible construction procedures, so that a short time after opening of the face quick stabilization of the whole system was achieved, whereby the static system consisted of both the thin shell of shotcrete and the surrounding ring of earth material. The essential elements of this tunnelling system are:

- a thin layer of shotcrete, sprayed immediately after excavation or within a strictly prescribed span of time, reinforced by wire mesh and light steel ribs,

- soil anchors prestressing the surrounding soil, so that a threedimensional state of stress is maintained around the tunnel tube,

- final lining, concreted continuously in the final construction stage.

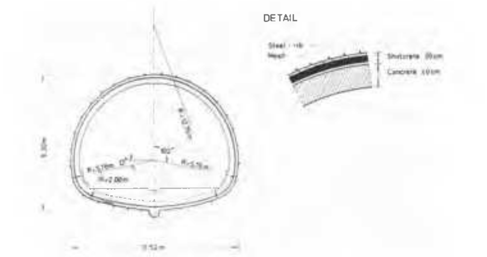

FIGURE 6:

Typical cross section through a twin tube tunnel.

A further essential element of this method is the control of the behaviour of the system by means of special instrumentation (see later).

Excavation was carried out by an excavator or a road header respectively. The sequence of operations is shown in figure 7. The quality of the ground always was so poor that a fullface excavation was impossible. Usually the excavation was split up in calotta, bench and invert. Each excavated part was supported as quickly as possible. For the opening of a short calotta, the benching, and the shotcreting procedures strict timing is required. This timing results from the evaluation of the daily measurements. The critical span of time is the interval between the first attack of the face and the closing of the invert and it is governed by the frequent change of ground conditions. Further parameters of influence are the length of attacks and the distance of steel ribs.

The distance of steel ribs was between 0.6 and 1.2 m. It could be proved that a reduction of the length of attacks of only 0.2 m could improve the stability of the ground above the tunnel and reduce the surface subsidence considerably.

The time between the first excavation in the calotta and the finishing of the support by placing shotcrete in the invert could be reduced to 10 hours only. The thickness of shotcrete varied between 15 cm in single rail tubes and 25 cm in enlarged double rail tunnels. In case of sand and gravel with very little cohesion fore-poling with steel plates was necessary.

The final lining consisted either of impermeable concrete or insulation and concrete.

In special situations where an extreme short time for closing of the invert was required, inclined steel ribs have been installed instead of the vertical ones usually used. In such cases the bench face also was excavated inclined (see figure 7). This was done e. g. in the Bergerstrasse in Francfort and under the railway embankment in Bochum with great success.

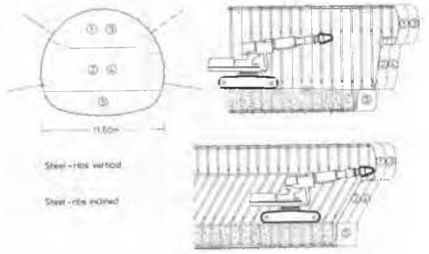

FIGURE 7:

Sequence of operations using the New Austrian Tunnelling Method.

In Bochum an underground station had to be built with only 0.8 m concrete between both tubes in soft marls under a road and between buildings. The method chosen, was to excavate at first one tube and support it with shotcrete, steel ribs, mesh, and anchors. Then the final lining was pourred in with a vertical wall toward the second tube interrupted by cross passages. The shotcrete support of the second tube was than based on this concrete wall. It is remarkable that the excavation of the second tube did not increase the surface subsidence which was finally only 30 mm above an excavated double tunnel of a span of 17.8 m under a cover of only 5.8 m.

A very important precondition for success is an experienced crew and a consequent application of the theoretical principles of the method.

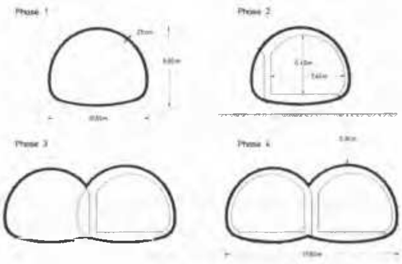

FIGURE 8.:

Metro Bochum. Construction of an underground station.

The daily progress when working in two shifts varied between two and six meters, depending on ground conditions, diameter, and possible length of attacks.

CONTROL MEASUREMENTS

Beside from conventional statical calculations in all projects finite element analysis was made which gave very good correspondence between the predicted and measured deformations and settlements.

Experience has shown that proper measurements of characteristic deformations are a significant index of the behaviour of the whole compound structure consisting of rock or soil, concrete and steel, and that its behaviour depends to a large degree on the quality of workmanship. Figure 9 shows a typical measuring section containing levelling points on the ground surface and at the tunnel roof, for convergence measurement bolts, multiple extensometers, chain deflectometers, and pressure cells measuring tangential stresses in the shotcrete shell and radial (contact) pressures between shotcrete and soil.

A large number of measurements had demonstrated that time is the most decisive parameter as regards the magnitude of the deformations of the compound system and the subsidence at the surface. This is demonstrated by the diagrams of figure 5, from which the influence of the invert closing time and the influence is obvious.

By a careful examination of all parameters which are influencing the tunnel works it is impossible to find the most safe and economic procedure of the sequence of operations and to avoid unnecessary safety measures as well as insufficient support conditions.

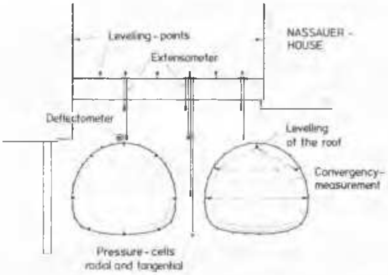

FIGURE 9:

Metro Nuremberg. Typical cross section with complete measuring equipment.

During all described tunnel works no heavy accidents of failures occurred and each project could be finished in the planned time schedule and costs.

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