STRAIN MONITORING IN THE SUBSOIL OF THE MUNICH SUBWAY

Christian Amstad  
Senior Research Engineer

Kalman Kovári  
Head of Rock Engineering Department

Swiss Federal Institute of Technology  
ISETH, ETH Hönggerberg, 8093 Zürich  
Switzerland

SYNOPSIS

To understand the mechanism of surface settlements and to control their development caused by tunnelling operations systematic strain monitoring of the subsoil using precision instruments has been performed in Munich (Federal Republic of Germany) since 1980. Such measurements allow observation of the effects of ground water control and the different stages of excavation upon settlements. The measuring technique applied yields a complete distribution of the axial strain along boreholes showing the ground response layer by layer. Back calculations of overall field material parameters provide a valuable feedback for forthcoming design and construction procedure. The instrument used is the Sliding Micrometer-ISETH. Its brief description is followed by the discussion of typical measuring results obtained at several sections of the Munich Subway.
1. INTRODUCTION

The most severe criteria for the design and construction of shallow tunnels in urban areas, e.g. for subway lines, emerges from the low values of the permitted differential or absolute surface settlements. The shape and size of the settlement trough is time dependent resulting from ground deformations caused by changes in pore water pressure (consolidation) and stress in the ground. Such changes must be considered in three dimensions with influences both in the direction of the tunnel axis and in the cross-sections. For example, the surface settlements generated in advance of the face by the compression of the material still to be excavated may account for 30% of the total displacements. Considering that the subsoil may consist of layers of different thickness with varying deformability it becomes clear that only advanced monitoring techniques are able to furnish an adequate understanding of the deformation mechanism. Based on the detailed knowledge of what is going on in the ground and at the surface as a result of the different constructional activities, proper measures can be taken to avoid excessive total or differential settlements and damage to adjacent surface structures and services respectively.

In the following the basic concept of a comparatively new deformation measuring technique using the portable borehole strain meter probe, the "Sliding Micrometer-ISETH", will be discussed. It was first applied (1) at the construction of the Republica-Station in Sao Paulo (Brazil) and subsequently at many other subway tunnels in Switzerland, Austria, Japan and Germany. The Sliding Micrometer has received its widest application at the construction of the Subway in Munich, which will comprise a total length of 80 km of the network when completed. Therefore, some typical results obtained in this case history in the period between 1980 - 84 will be discussed. Emphasis is placed on the practical implications of strain monitoring leading to higher safety and better economy. Furthermore, the careful data interpretation enhances our general understanding of patterns of behaviour of subway constructions as well.
2. THE CONCEPT OF LINEWISE OBSERVATION

The Sliding Micrometer-ISETH belongs to a family of instruments designed specifically to perform deformation measurements with the principle of "linewise observation" (2, 3). It involves the measuring of the distribution of a deformation quantity along a line. The line may be given by the axis of a borehole, by the intrados of a tunnel arch etc. The common feature in all measuring techniques developed at the Federal Institute of Technology in Zürich is that the line along which deformations are to be measured is transformed into a chain of well-defined reference points. The regular spacing between these points is constant and chosen according to both the nature of the problem to be solved and to the available instrument. Thus the continuous deformation measurement is reduced to that of observing the movements of the points in the measuring chain, usually the relative displacement of adjacent points.

In the case of the strain distribution measurement using the Sliding Micrometer-ISETH, first a hard PVC tube (Ø = 60 mm) containing ring-shaped measuring marks at regular intervals of 1.00 m is grouted into the borehole. These reference points, made of steel, serve on the one hand as coupling elements between two adjacent units of PVC tubes and on the other hand as a housing for stop fittings (Fig. 1). The latter have the function of holding the two heads of the portable device in position during the short time of a reading. The tube segments are screwed into the ring marks and the stop fittings are fixed in by bolting. All connections are such that the whole assembly is sufficiently robust for lowering into a deep borehole of any direction. On the other hand they are soft enough to avoid any "piling effect" along the measuring line. If the measuring marks displace relatively to each other due to the deformation of the surrounding subsoil, then the change in distance, i.e. the strain with the base length of 1.00 m, can be recorded as the difference between two readings. A set of measurements involves the following: beginning at the mouth of the tube, the probe is fixed between two measuring marks and a reading is taken. The probe is then traversed in a stepwise manner carrying out readings at each position. After reaching the end of the tube a repetition of the readings is made on retraction of the probe. The two sets of readings permit a valuable check of the actual field accuracy attained.
Fig. 1 Schematic view of the Sliding Micrometer-ISETH in Sliding- and Measuring Position

The main problem in the development of the Sliding Micrometer was to find a mechanically sound yet simple solution with regard to the placement of the instrument heads in the measuring marks. These requirements could be satisfied by means of a special design of the measuring marks and the instrument heads (1). If the measuring marks are in the form of a circular cone and the stops on the heads are spherical-shaped, the position of the centre of the sphere, with respect to the cone, is correctly defined. The accuracy of a setting expressed in terms of strain is within a few microstrains. The measuring marks and the stops on the heads are, of course, only parts of a cone and a sphere respectively, so that the instrument, after a rotation of 45 °, can be passed through the marks and moved along the borehole to any desired position.

The construction of the probe is shown schematically in Fig. 1. The two measuring heads are connected by an external spring-loaded protective tube which is stiff against torsion. The relative movement between the heads is transferred to a linear displacement transducer (LVDT). The joint connec-
tion of the installing rod is seen attached to the upper head. The electric cable transmitting the measured values is also brought out there. Since the distance between the measuring heads is smaller than that of the measuring marks, as the probe is set in the measuring position first of all the lower head contacts a measuring mark and after stretching the spring on the protective tube the upper head is pulled into the other measuring mark. It is thus ensured that when pulling on the rod both heads are pressed against the measuring marks.

Special features of the Sliding Micrometer:

The instrument is watertight up to 15 bar pressure. Temperature effects are largely eliminated by means of a self-compensating construction. However, to distinguish temperature induced strains in the concrete, rock or soil from those due to stresses or creep the instrument is fitted out with a temperature sensor. To control the correct functioning of the probe and the zero-point stability of the inductance transducer a portable calibration frame made out of invar steel is used. In the calibration frame there are two measuring marks, in which the probe is braced before and after every series of readings. It is worth mentioning, that the alternating operation of setting the probe and sliding it along the length of the casing is made extremely easy by means of an orientation blade in front of the instrument (Fig. 2). The forwards and backwards measurements along a 40 m stretch with 40 measuring points only requires about half an hour.

Fig. 2 Sliding Micrometer-ISETH equipment with probe and orientation blade, cable drum, read-out units and printer
The construction of the subway network in the city of Munich started 1965 and is scheduled to be completed in 1995 (4, 5).

At present (1984) already 41 km of the total 80 km length are in operation and a further length totalling 11 km is approaching its completion. Both cut-and-cover and tunnelling methods are applied, with increasing importance of the latter. In the period 1960 - 1975 only 25 % of the constructional work was carried out by tunnelling methods, whereas between 1975 - 1980 its portion increased to 75 %. The reason for this development is seen in the growing public sensitivity to large scale surface constructions in built-in urban areas but also in the steadily improved tunnelling technology resulting in lower costs. Using shotcrete as temporary lining has proved to be safe and economical (6) and its technical advantages have been dramatically improved by the simultaneous application of compressed air not exceeding 1.2 bar pressure (7).

The following discussions on deformation measurements mainly refer to the construction section no. 6 (Odeonsplatz) but also to that of no. 7 (Lehel) of the Linie 5/9. While about half of section no. 6 was excavated under atmospheric pressure conditions, section no. 7 was executed almost entirely using compressed air. Both single and double track tunnels were involved and also sections with varying spans and thin pillars left between the two tubes.

Figure 3 represents a typical geological section showing the two major formations, i.e. the quaternary deposits consisting of sandy gravel and
the tertiary marl, frequently referred to as "Flinzmergel", below it. The latter has a varying appearance consisting of stiff or even hard clays, clayey silts, marl, marlstones and fine to medium grained sand. The ground water in the quarternary formation is as a rule not connected with the water in the tertiary ones. There the pore water pressure can also be very different in adjacent sand lenses sometimes showing an artesian character. The clays and marls are nearly impermeable offering a reliable protection against the water in the quarternary formation providing the thickness of the marl layer above the tunnel roof is not less than 2 to 3 m. In the cases discussed below this condition was always fullfilled.

The method of excavation for a single track tunnel is the head and bench method (Fig. 4a). Emphasis is placed on shotcreting the invert very close to the head (2 to 4 m) and in a short time span of 1 - 2 days only. In this way a statically favourable action against ground deformations and surface settlement is produced immediately. The same principle is applied to the double track cross-section (Fig. 4b). Here, first half of the tunnel is excavated and supported as single-track tunnel. The enlargement to the full cross-section follows in a distance of approx. 15 m and again in head and bench operation. If water bearing sand layers are encountered special measures must be taken. They may involve decreasing of the piezometric head by drainage wells and also application of compressed air as an additional measure.
The tertiary sands are generally rather compact so that they are stable at the face providing that no excessive water pressure prevails.

If compressed air is applied the whole section is constructed using shotcrete as temporary support. After completion of the section atmospheric conditions are restored. The shotcrete lining resists the outside water pressure until the final reinforced concrete lining is constructed. This procedure has proved to be very successful being safe and having a reducing influence upon ground deformations.

4. DISCUSSION OF GROUND DEFORMATIONS

At the subway construction in Munich a strict methodical way in the monitoring of the behaviour of the different structural elements is imposed. Measurements are carried out in the tunnels, in the subsoil, on the ground surface and on structures subjected to subsidence (8). The instrumentation and the measuring programme is designed to give answers to specific questions. The results of the different observations should also allow some cross-checking and firm conclusions to be drawn. In the following selected examples of strain monitoring will be discussed with respect to:

- How changes in pore water pressure cause ground deformations?
- What deformations occur around two-track tunnels in the different phases of excavation?
- Are there observed deformations in one section comparable with those in another section under similar ground conditions?
- How the application of compressed air affects the strains in the subsoil in comparison with a construction under atmospheric condition?

These were some of the questions to be answered by Sliding Micrometer Measurements.
4.1 DEFORMATIONS OF THE SUBSOIL DUE TO CHANGES IN PORE WATER PRESSURE

Decrease of pore water pressure in soils increases the effective normal stress (Terzaghi) which in turn leads to compression of the material. This could be clearly observed in different sections of the subway line 5/9. In Fig. 5 the results of Sliding Micrometer measurements in two boreholes having a depth of 38 m are shown. The corresponding borehole logs show the start of the tertiary formation approximately at 8 m depth in both cases, whereas the stratification is different. The ground water in the quaternary formation was maintained at its original level. In the tertiary formation conventional and vacuum wells were operated and their effect observed by open standpipe water level recorders. In Fig. 5 the changes in piezometric heads are indicated by \( \Delta h_i \) for the different observation wells designated by \( w_i \). When interpreting

![Diagram showing strain distribution along two vertical measuring lines caused by partial dewatering of tertiary formation.](image)
the measured strain distribution one has to bear in mind that apart from the details of the geology of the area also the efficiency of the pumping operation is decisive. The accumulated strains along measuring line 1 resulted in a surface settlement of about 3 mm and those of the measuring line 2 yielded 4 mm. Such surface settlements occur before the tunnel construction. Therefore, one has to instrument the boreholes and to take readings well in advance.

4.2 DEFORMATIONS OF SUBSOIL DUE TO EXCAVATION UNDER ATMOSPHERIC CONDITIONS

In the measuring section MQ 21 of section 5/9-6 three boreholes, 40 m long each, were used for Sliding Micrometer measurements according to the arrangement in Fig. 6. The strain distribution along such lines in the vicinity of the two-track tunnel permitted a complete picture of the ground deformations to be obtained. In Fig. 7 the successive development of the strain resulting from the different phases of excavation can clearly be seen. The measuring line penetrating the cross-section (Fig. 7a) shows compression of the ground due to the approach of the head excavation 1 of the side drift. When crossing the measuring section due to the tunnel advance the casing of the borehole found in the cross-section is removed and readings are taken from the ground surface and, if required, also from the tunnel. The extension strains above the tunnel roof show an abrupt increase when the tunnel is enlarged to its full cross-section (3 + 4). Considering the strain distribution along boreholes to the left of the tunnel it is evident that deformations decrease quite quickly with increasing distance from the opening. All strains are compressive (Fig. 7c). A common feature of all three diagrams (Fig. 7a, b, c) is seen in the fact that after the enlargement of the profile (3 + 4) has been made, i.e. the shotcrete has been closed to a ring, no major deformations take place. In Fig. 7 the zones with vertical extension strain (E) and those exhibiting compressive strains (C) are tentatively indicated. It is obvious that a considerable portion of the surface
Fig. 7 Strain distribution along vertical measuring lines for selected stages of excavation
(E = zone with extension strain, C = compression strain)
Settlements are caused, in the case discussed here, by the compression of the ground in the vicinity of the opening.

4.3 Reproducibility of the Observed Results

The distribution of strain along vertical measuring lines passing through the axis of double-track tunnels were studied for four different situations having varying overburden, different depths of the quaternary layer and also different thicknesses of the tertiary formation above the tunnel roof (Fig. 8). Four different stages of excavation i.e. four different positions of the measuring lines relative to the position of the face of the heading are considered (Fig. 9). In Fig. 10a the compression of the ground in front of the face of the side drift is presented, whereas Fig. 10b shows the situation with the full face enlargement just having been completed. Fig. 10c confirms earlier findings on the negligible deformations occurring after the closing of the shotcrete to a ring. In Fig. 10d the total strains are shown resulting from the tunnel excavation. Considering the differences in the geometry of the geological profiles (Fig. 8) and in the location of the tunnel, but also
the inherent inhomogeneity of the tertiary marls, the scatter in the results as shown in Fig. 10 is surprisingly small. It is important to recognize that in the section GM 4 (on the left in Fig. 8) compressed air was applied during the excavation, so that the dotted line in Fig. 10 b indicates much less exten- 
tensional strain above the roof than the other curves resulting from atmos- 
pheric tunnelling operations. In the final stage (Fig. 10d) an increase of the strains at section GM 4 can be observed.

4.4 INTERACTION BETWEEN ADJACENT TUNNELS AND THE EFFECT OF COMPRESSED AIR

The interaction of adjacent tunnels and its effect on settlement is in- 
fluenced by various factors such as the shape, span and depth of the tunnels but also by the distance between them, the method of excavation, the rate of advance, the characteristics of the subsoil and finally the groundwater condi- 
tions. Obviously the prediction of ground settlements by computational methods has major shortcomings in such complex situations. If only a limited stretch of a subway line is subjected to severe restrictions on permissible settlements, different constructional measures can be tested before the critical area is reached by the tunnels. This was the case in Munich when undertunnelling old houses with low overburden near to "Odeonsplatz". The tunnel section between the starting shaft and the critical area was approx. 350 m offering a unique possibility for trial sections and an accompanying monitoring program. Along the trial stretch there were no buildings, services or major roads and there-
Fig. 10 Strain distribution along vertical measuring lines for the different stages of excavation, shown in Fig. 9. (......... compressed air tunnelling)
fore no severe limitations on permitted settlements. Two basically different constructional measures were tested with respect to their capability to reduce deformations. The first measure consisted of applying compressed air to control pore water pressure in the ground. The second proposal involved the excavation of the two-track tunnel in 5 different stages (Fig. 11c) instead of the commonly applied 4 stages (Fig. 11a, b). In order to assess the most effective method of construction and to establish the distribution and intensity of the ground settlements prior to the arrival of the tunnels at the critical area, three measuring sections were installed. From the results of the comprehensive measuring program only the Sliding Micrometer measurements will be discussed in this report. The diagrams shown in Fig. 11 reveal interesting details of the ground deformations caused by the construction of two parallel tunnels (I and II) using different excavation procedures under atmospheric and compressed air conditions. The distance between the three measuring sections was great enough to exclude interference but also small enough for the assumption of uniform ground conditions. The first section of the tunnel starting from the shaft was excavated in four steps under atmospheric conditions (Fig. 11a). Next, provisions were made for compressed air application using the same four stage excavation procedure (Fig. 11b). In the following section compressed air application was maintained but the method of excavation was made in five stages in the cross section (Fig. 11c). In this way the benefits resulting from a more sophisticated method of excavation and from compressed air application could clearly be assessed. From Fig. 11 it can be concluded that using compressed air results in markedly smaller ground deformations when compared with atmospheric conditions. On the other hand, no reduction in ground deformations can be observed due to the more sophisticated excavation method shown in Fig. 11c. Based on the unambiguous results from the trial construction sections a sound decision could be made regarding the method of construction to be applied when undertunnelling the critical city area. In fact, the compressed air application (Fig. 11b) was most successful throughout the whole construction section.

Two additional phenomena observed during the measuring campaign deserve to be mentioned. These are the "pillar effect", i.e. the compression of the ground between the two tunnels and the change of the pore water conditions due to the drop of compressed air pressure to atmospheric air pressure during
Fig. 11 Strain distribution caused by the excavation of tunnel I and II

a) Measuring section MQ 21, atmospheric conditions
b) Measuring section MQ 20, compressed air
c) Measuring section MQ 19, compressed air
24 hours. The "pillar effect" is clearly seen from all three cases a, b, and c in Fig. 11 whereas the effect of a drop of air overpressure from 0.8 bar to 0 bar is seen from the diagrams b and c.

5. CONCLUSIONS

Strain measurements along boreholes based on the principle of "linewise observations" using the Sliding Micrometer probe provide an adequate understanding of what is going on in the subsoil in the different stages of construction of subway tubes. Correct measuring arrangements and adequate interpretation of the readings may provide a firm basis for practical decisions to be made.

REFERENCES


(2) Kovári, K., Amstad, Ch.: Das Konzept der "Linienbeobachtung" bei Deformationsmessungen, Mitteilungen der Schweiz. Gesellschaft für Boden- und Felsmechanik, Nr. 102, 1981


Experience using Compressed-Air Drivage and Shotcreting during Construction of the Munich Underground, Proceedings of the STUVA Conference Nürnberg, 1983