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Slurry penetration into coarse grained soils and settlements from a large slurry shield tunnel

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ABSTRACT: During the construction of the 5.5 km long mined section of the Grauholz tunnel in Switzerland through heterogeneous glacial soils and tertiary bedrock with a mix-shield of 11.6 metres outside diameter observations on slurry penetration into coarse-grained soils could be carried out. Also settlement observations of this large diameter tunnel were made for different ground conditions. The construction of lateral niches required stabilisation of the ground by grouting. The grout take with cement and silicates varied with distance from the lining of the main tunnel and was a function of the slurry density utilised for the main tunnel drive. This indicates that the penetration of slurry from the shield was a function of its quality, primarily sand content. Surface settlements were of concern only in particular spots. A road was undercrossed with 6.5 meters cover and settlements of 25 mm corresponding to a loss of ground of 0.4% were observed. Even lower settlements were observed at the end of the tunnel.

1 INTRODUCTION

The construction of the Grauholz tunnel near Bern, Switzerland provided some unique opportunities for observation of slurry penetration into coarse grained ground, fluvioglacial gravel. The penetration of the slurry was a function of its sand content.

The tunnel crossed essentially under the free field, thus settlements were of lesser concern. Settlements were monitored below major roads and below pipelines. The results of these settlement observations for a large diameter tunnel (11.6 m) are of general interest.

2 GROUND CONDITIONS

A geologic section along the Grauholz tunnel is shown on Fig. 1. The tunnel crosses quarternary glacial soils with and without ground water and enters in its central part into tertiary bedrock. As the tunnel was driven from east to west ground conditions are described in the same direction. More details on the experience during construction are described elsewhere (Steiner & Becker, 1991; Steiner, 1993; Scheidegger et al. 1993; Jancsecz & Steiner, 1994). The tunnel first crosses glacial soils with ground water several metres above the crown, excavated in the slurry mode of the Mix-shield. For 400 meters dense silts and sands are crossed. About 100 metres after starting, there is state road T1, the former main east-west highway (Bern-Zurich) before the construction of motorways in Switzerland. Following is a depression with glacial tills and gravel. Then the tunnel enters into bedrock with small rock cover. This section also includes a depression in the surface of bedrock with mixed-face conditions, excavated in the slurry mode. With sufficient rock cover excavation was in the TBM mode. Then bedrock with large cover was excavated in the open TBM mode. The tunnel then entered into the fluvioglacial gravel from km 7.85 to 6.5. From exploratory drilling the gravel was considered to have a silt content from 7 to 35 % with an average of 18% (Steiner, 1993; Scheidegger et al. 1993). During excavation of the tunnel the grain-size distribution indicated less silt content, only 6% on the average. During construction of the lateral caverns samples could be taken which showed clean well graded gravel (Fig. 2) without fines and little sand (10%). Also nearly clean fine to medium sands were encountered but are of limited extent. The last section from km 6.5 to 5.8 was in ice-marginal deposits encompassing nearly all grain-sizes. The transition around km 6.3 is, however, characterised by interfingering of gravel strata with fine-grained deposits.

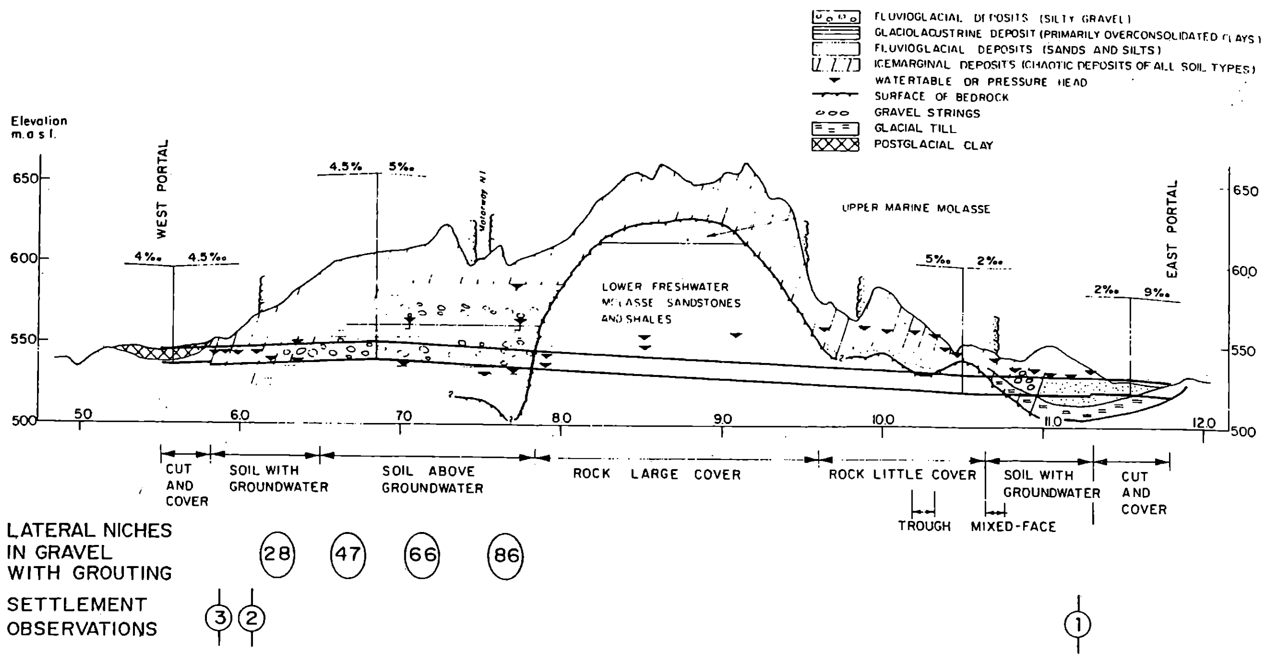

Fig. 1 Geologic Section along Grauholz tunnel with observation points of slurry penetration an settlements

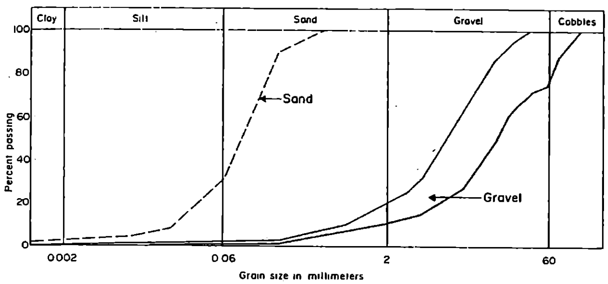

Fig. 2 Grainsize distributions, km 6.5 to 7.8

3 OBSERVATION OF SLURRY PENETRATION

3.1 *Method of observation*

For housing technical equipment of the safety and the communications systems lateral chambers were constructed every 500 metres along the main tunnel. The Grauholz tunnel is lined with a single shell segmental lining of 400 mm thickness. Each ring has a length of 1.8 meters and is formed by six elements and a keystone. Form and size of the entrance to the cavern (niche) were adapted to the ring width. The entrance to each cavern was limited to 1.5 meter width in order that the cavern opening partly intersected only two rings. Thus, it became possible to carry the structural lining loads in the remaining section of the segments. No segment was thus completely cut. The length of the cavern was adapted to provide the necessary space for the equipment and varied from 7 to 9 meters. Ground conditions varied along the alignment and different construction procedures were used. In the east, silt below the ground water table was stabilised by ground freezing. In bedrock conventional excavation with shotcrete support was used. In the western section with fluvioglacial gravel the experience gained during driving of the main tunnel with the mix-shield in the slurry mode led to the necessity to use grouting in the crown and at the sides of the lateral caverns to stabilise the clean gravel above the ground water table. The untreated ground was judged to lead to running ground conditions. Stabilisation by means of multistage grouting with cement and silicates was carried out from sleeve packer pipes that were placed along the circumference of the excavation for the caverns. Grouting was terminated when either a pre-set pressure was exceeded or a limit quantity was reached.

During execution of the grouting it became apparent that grouting varied with distance from the lining of the main tunnel. The operational procedure of the slurry shield, the quality of the slurry, had changed along the main tunnel drive (Steiner, 1993). It became apparent that the content of fines, characterised by the density of the slurry, had a major influence on the penetration of the slurry, this presumes that the gravel does not change its gradation significantly which was confirmed by the samples excavated. The location of the four pairs of lateral chambers where such observations could be performed are shown on Fig. 1.

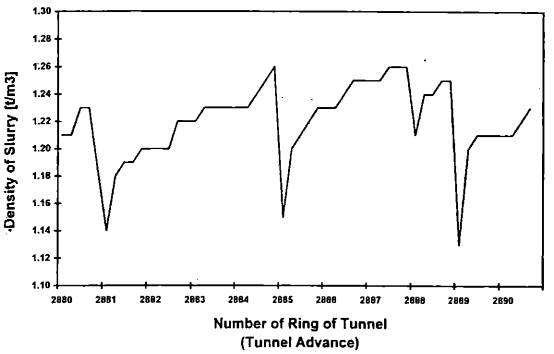

Fig. 3 Slurry density close to cavern 28 (west end)

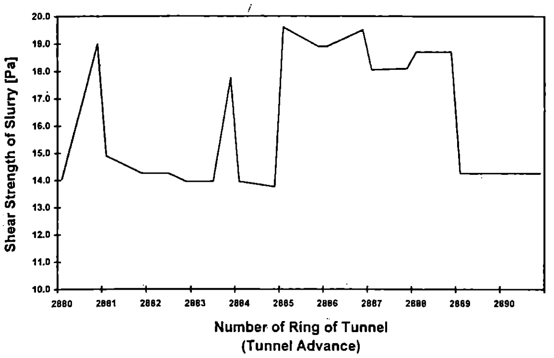

Fig. 4 Shear strength of slurry near cavern 28

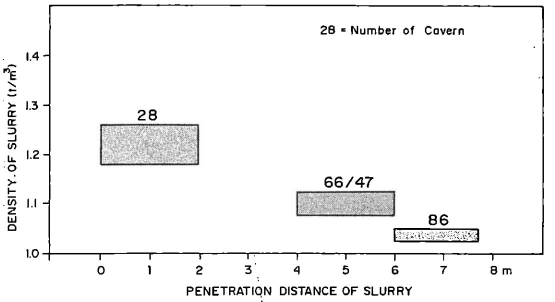

Fig. 5 Slurry Penetration as a function of density

3.2 *Results of observations*

The tunnel cross section was located completely in gravel with the exception for chamber 28 where fine-grained lacustrine deposits were present in the invert. For the tunnel section from km 7.85 to km 7.66 where chamber 86 is located, the slurry in the circuit contained little fines. The recirculated slurry had a density of 1.03 to 1.05 t/m^3 which essentially corresponds to the density of pure bentonite slurry. At station km 7.66 during compressed air support a sudden loss of support pressure occurred, this resulted in a face collapse (Steiner, 1993). After stabilisation works of several month the tunnel advance could resume. Tunnelling procedures had been modified. In particular, in addition to bentonite (50 kg/m^3) also polymers (1 kg/m^3) were used and the separation plant was modified such that more sand and fines remained suspended in the bentonite. The density of the recirculated slurry varied from 1.08 to 1.12 t/m^3. These changes led to much less problems with face stability during tunnel driving and to high advance rates (Scheidegger et al., 1993; Steiner, 1993). West of km 6.47 the tunnel encountered fine-grained lacustrine deposits in the invert. These were silty and sandy layers together with low plasticity clays. Once excavated these soils were mixed with the slurry and remained suspended in the slurry. The slurry density varied during advance from 1.14 to 1.24 t/m^3 (Fig. 3). The low density was achieved when new bentonite slurry was added to the slurry circuit. The density increased over four rings or 7.2 meters of tunnel advance and the slurry had then to be refreshed. In addition to the density also the shear strength of the slurry was monitored (Fig. 4) which showed less fluctuations. Similar values of shear strength were observed in the other section of the tunnel with gravel.

During the grouting operations for the stabilisation of the ground around the lateral caverns grout takes and grouting pressures were observed and evaluated.

This evaluation indicated that bentonite slurry must have penetrated ground to different degrees and distances from the main tunnel. In cavern 86 the bentonite must have penetrated 6 to 8 meters, practically over the total length of the lateral cavern, since cement grouting was impossible over this distance. Also during excavation of the cavern it was possible to identify thickened bentonite slurry in the voids of coarser parts of the gravel. Silicate grouting was, however, possible and achieved the stabilisation of the ground.

For caverns 66 and 47 where slurry with a higher sand (density γ = 1.08 to 1.12 t/m^3) content was used. The penetration distance was smaller, 4 to 6 meters from the circumference of the main tunnel. The same result was obtained for cavern 66 which was grouted with normal cement and for cavern 47 where micro-fine cement was used.

For cavern 28 the slurry penetration was none to two meters due to the higher slurry density and the corresponding higher content of suspended fines. The observed slurry penetration versus density of the slurry for bentonite tunnelling is presented on Fig. 5.

3.3 *Conclusions on slurry penetration*

Excessive slurry penetration leads to an excessive use of bentonite with supplemental costs to the tunnelling operation. In addition penetrating slurry reduces the effectiveness of slurry support, no sufficient gradient can develop that stabilises the

Undercrossing State Road T1

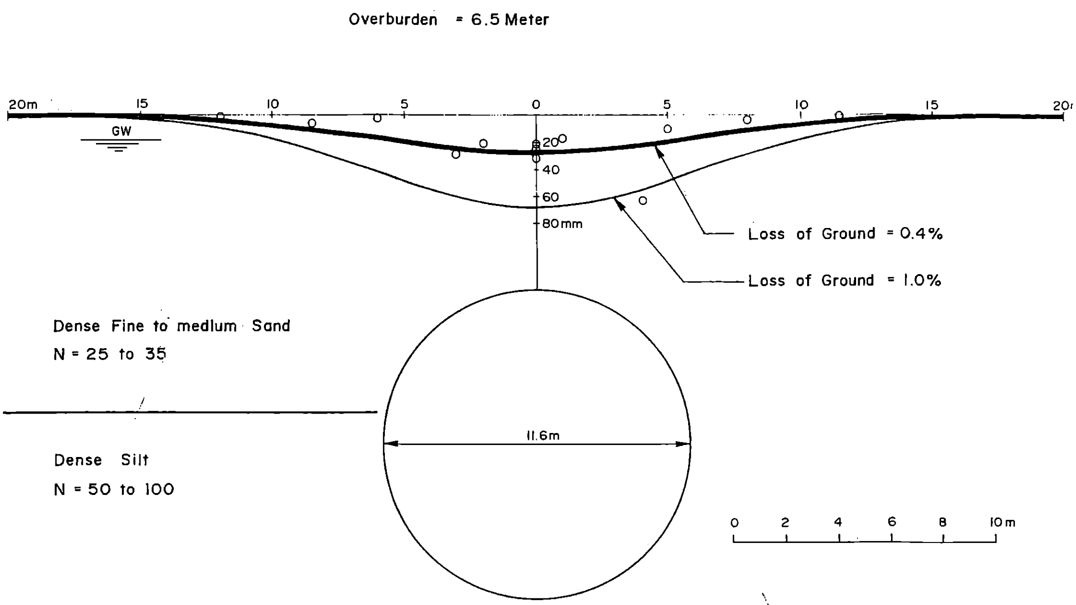

Fig. 6 Observed Settlements induced by tunnelling below State Road T1.

face of the tunnel. This was confirmed by the difficulties encountered when driving the section km 7.85 - 7.66 and the reduction of these difficulties in the following sections (Steiner, 1993). This experience demonstrates that slurry penetration can be controlled through the sand content in the slurry, The suspended solids clog the pore channels and reduce the penetration of the slurry thus a positive face support can be achieved. In this case sand was present in the ground and had to be kept in the slurry circuit, otherwise it would have to be added to the slurry.

4 SETTLEMENTS OBSERVED

The Grauholz tunnel crossed mostly under the free field, mostly agricultural land and forest. Surface settlements were therefore of minor interest. Several major roads and a feeder pipeline to a petrol storage were crossed with varying overburden. The major east-west motorway N1 in Switzerland was crossed through soil with 60 meters overburden. The motorway was not diverted when the tunnel was excavated beneath it.

However, only slurry mode excavation was permitted. If an entry into the working chamber would have been necessary, the ground above the face would have been grouted from the rear section of the shield. The shallower roads, both near the portals, were diverted when the tunnel was crossing below the original alignment and afterwards traffic was moved back to the original alignment.

Approximately 100 meters after initiating the tunnel drive, state road T1, the former major highway between Bern and Zurich, together with a main co-axial telephone cable was crossed with 6.5 meter cover (Fig. 6; section 1 of Fig. 1). The road was temporarily diverted. The telephone cable in an opened trench was suspended on a truss with 20 meters span over the tunnel. No major incident happened. The monitored settlement are shown in Fig. 6. The settlement at the axis was 22 to 32 millimetres. These settlements developed within a few days, practically in parallel to the tunnel advance. Most data points plot close to a curve corresponding to a loss of ground = 0.4% according to Schmidt (1969). There is one exception of a point with 70 mm to the right, this settlement is most likely related to excavation for the trench for suspending the telephone cable.

On the eastern side no other settlement observations were performed.

Settlements were observed along the Grauholz road and motorway N1, both with 60 meter overburden. No settlement was detected. Between these two roads a delayed collapse (Steiner, 1993) to the surface occurred. However, settlement measurements did not provide any signs of forewarning.

Near the west portal, section 2, an empty pipeline to a petrol storage depot was crossed with 20 meters overburden. Settlements at the surface were monitored but none were detected

Similar at section 3 a road and a gas pipeline, which was temporarily suspended on a truss, were undercrossed with 8 meters cover. The monitoring of the settlement did not indicate any surface settlements. This is attributed to the probably better grouting procedures of the tail void and the dense ice marginal deposits. The silts and low plasticity clays have had a superior stand-up time for grouting the tail void.

4.1 *Conclusions on settlements*

Relatively small surface settlements induced by regular tunnelling were observed from a large (11.6m) diameter slurry shield. The observed loss of ground was 0.4% or less. The observation with 0.4% loss of ground was shortly after starting the tunnel advance with 6.5 meter overburden. Near the end of tunnelling no surface settlements could be observed. This may either be due to the improved construction procedures (learning effect) towards the end of construction or the slightly better ground conditions or a combination of both. It is important to control face support during tunnel driving and to control and monitor grouting procedures of the tail void.

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