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Geotechnical measurements in swelling rock – instrumentation of exploratory headings, results, conclusions

Christian Kitzler

Herbert Walter

Christian Kitzler, Dipl-Ing.
IGT Geotechnik und Tunnelbau ZT GmbH
Mauracherstr. 9
A-5020 Salzburg
e-mail: c.kitzler@igt.co.at
homepage: www.igt.co.at

Herbert Walter, Dipl-Ing. Dr.
IGT Geotechnik und Tunnelbau ZT GmbH
Mauracherstr. 9
A-5020 Salzburg
e-mail: h.walter@igt.co.at
homepage: www.igt.co.at

Abstract: Driving tunnels through rock containing expansive argillaceous components requires special provisions for the design and the construction of the tunnel. Quantification of the swelling potential beforehand is essential in order to be able to develop a design and construction technique which is both, safe and economical. As an example, experiences gathered during the preliminary stages of an Alpine 3-lane road tunnel project are reported. The tunnel runs mainly through tertiary sediments of the Lower Freshwater Molasse. Measurements during construction of the pilot drift as well as damage to the shotcrete side wall and considerable heave of the invert segment showed the swelling potential of the rock. In order to gain more insight into the swelling behaviour the pilot tunnel was enlarged to the size of the top heading of the road tunnel over a length of 25 m. Additional measuring equipment and an irrigation system were installed. The irrigation caused increasing invert heave resulting in subsequent failure of the shotcrete.
The experiences with the pilot drift and the enlargement resulted in a design of the main road tunnel with a deep invert arch, consisting of a 40 cm shotcrete lining and a cast concrete invert arch with a maximum thickness of 260 cm. A maximum interval of 6 months between the start of excavation and ring closure of the secondary lining has been specified.
A number of recommendations for exploratory tunnels of future tunnels in swelling rock finish the paper. These contain requirements for laboratory tests, types and frequency of measurements, the shape of enlargement sections and collection of water during construction.

1 Introduction

Driving tunnels through rock containing expansive argillaceous components requires extraordinary care and – depending on the expected swelling potential – special provisions for the design and the construction of the tunnel. Costly measures like massive invert construction and/or anchoring in the invert may or may not be required. Quantification of the swelling potential beforehand is essential in order to be able to develop a design and construction technique which is both, safe and economical.
Among other aspects, the swelling potential of the minerals at the alignment of the Achraintunnel near Dornbirn, Vorarlberg, was an important factor which lead to the decision to excavate a pilot drift ahead of the construction of the main three-lane road tunnel. The tunnel is about 3 km long and runs mainly through alternating sequences of marl and sandstone of the Weissach-formation, tertiary sediments of the Lower Freshwater Molasse. The sandstone-layers are water bearing whereas the marl-layers are practically impermeable and contain clay minerals with swelling potential. The overburden amounts to approximately 200 m.

2 Laboratory swelling tests, comparison with other projects

Specimens taken from the exploratory borings contained between about 32 % and 62 % of phyllosilicates [1]. The content of clay minerals with swelling potential (montmorillonite-group, smectite) was in the range of 35 to 60 % of the clay minerals with a grain size < 2 µ [1]. The value for the content of smectite with grain size < 2 µ was in the range of up to 11 % of the total mineral mass [2]. Obviously it was difficult to win specimens from the cores in sufficient quality for swelling tests. As a consequence, only 5 free swelling tests resulting in swelling strains between 0 and 1.0 % were successful. Additional information was gained by powder swelling tests according to Thuro [3], which yielded swelling strains between 12 % and 22 % [2]. (In this type of test the swelling potential is overestimated, in general, because the calcitic skeleton which reduces swelling is destroyed.) Estimates of the swelling pressures to be expected were gained by an empirical relation based on the mineral content [1] and were in the range between 70 and 410 kPa.
The cores – from which the specimens for the free swelling tests were taken – were drilled by water-flushed boring. It can be concluded that a part of the swelling process had already taken place before the experiments started. A higher amount of swelling strains can therefore be expected.

The swelling potential according to the laboratory tests is comparable with (and tendentially somewhat lower than) that of other tunnels running through similar geologic formations:
One similar project is the Sieberg-Tunnel [9], a 2-track railway tunnel near St. Valentin in Lower Austria. Part of it runs through tertiary marine sediments of the Oligocene with swelling potential (there called Oligozänschlier). The Oligozänschlier contains water bearing joints and gravel layers. The mineralogical composition consisted of 40 to 90 % clay minerals, of which up to 60 % (one value of 90 %) belonged to the smectite-group. (What percentage was in the size below 2 µ has not been identified in the reports.) In laboratory tests axial swelling stresses with a mean value of 260 kN/m² (12 specimens) and a maximum of 505 kN/m2 were determined. The radial swelling strains reached a maximum of 11.1 % and a mean value of 5.7 % (out of 10 specimens).
The overburden amounts to 10 to 60 m above crown.
A design with a deep invert arch was chosen where primary and secondary lining together should be able to bear swelling pressures up to the maximum overburden (1200 kN/m²). The lining thickness of the primary lining is 50 cm in the invert and 40 cm in the arch; the inner lining has a thickness of up to 2.80 m in the invert and of 40 cm in the arch (see figure 1). Practically no swelling effects were observed during construction of the tunnel; swelling pressures of up to 300 kN/m² (one value 800 kN/m²) were observed by help of pressure cells. Probably the stiff primary support prevented any visible swelling displacements.

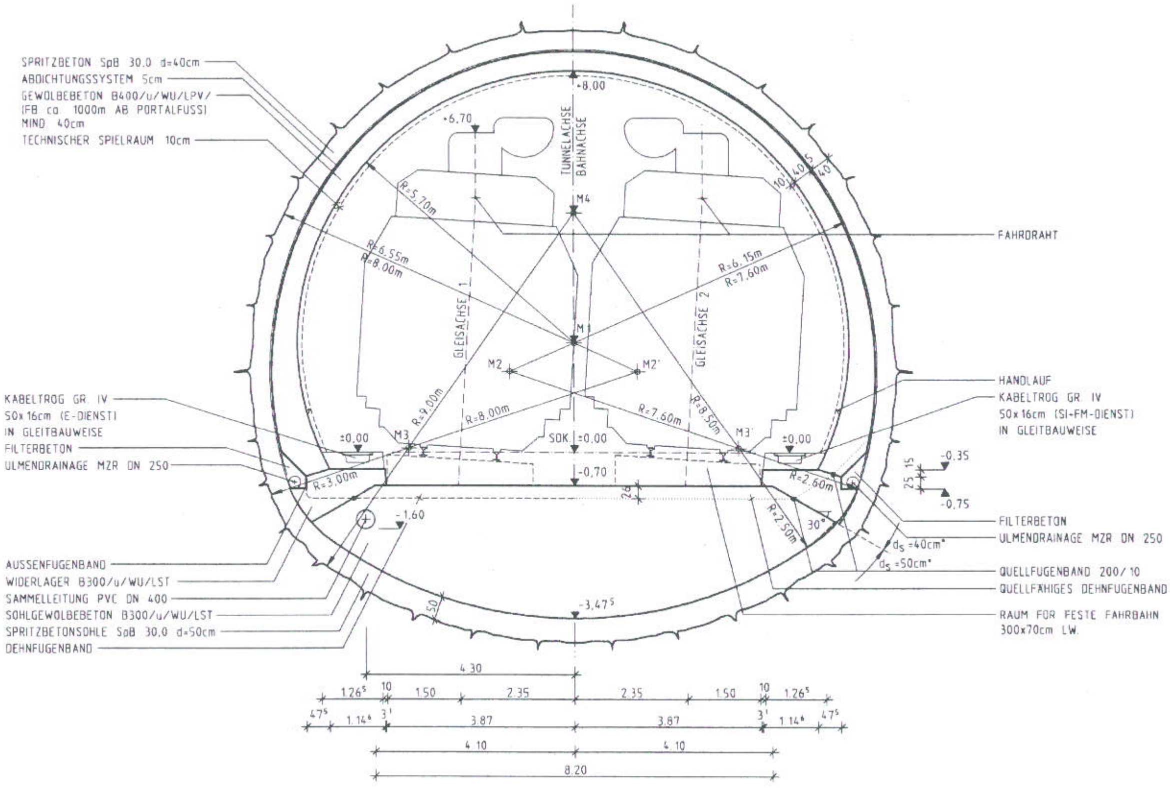

Figure 1 – Regular cross section of the Sieberg-Tunnel in Oligozänschlier [9]

Another tunnel project, located only about 10 km from the construction site, is the Pfändertunnel. The tunnel runs mainly through sediments of the Upper Freshwater Molasse and Upper Marine Molasse. Mineralogical investigations there showed 10 to 70 % phyllosilicates of the total mass and up to 80 % montmorillonite-content of the clay minerals with sizes < 2 µ [4]. Swelling strains of up to 15 % (mean value 5 %) were measured in laboratory tests and swelling pressures of up to 35 MPa (mean value 1.3 MPa) at full confinement were measured by Madsen [4] and confirmed essentially by other laboratories

[4, 5]. The swelling of the marl resulted in considerable damage to the tunnel and expensive refurbishment measures [6].

3 Exploratory drift

The pilot drift, which will be reused as an escape tunnel after construction of the full cross section of the road tunnel, has a diameter of 3.9 m. It has been driven with the help of an open TBM. The lining design consisted of an invert segment with a maximum thickness of 25 cm and a fibre-reinforced shotcrete lining with a nominal thickness of 5 cm (Fig. 2). The invert segments contain a drainage ditch in the centre and form the track way for the tail of the TBM and the mucking train.

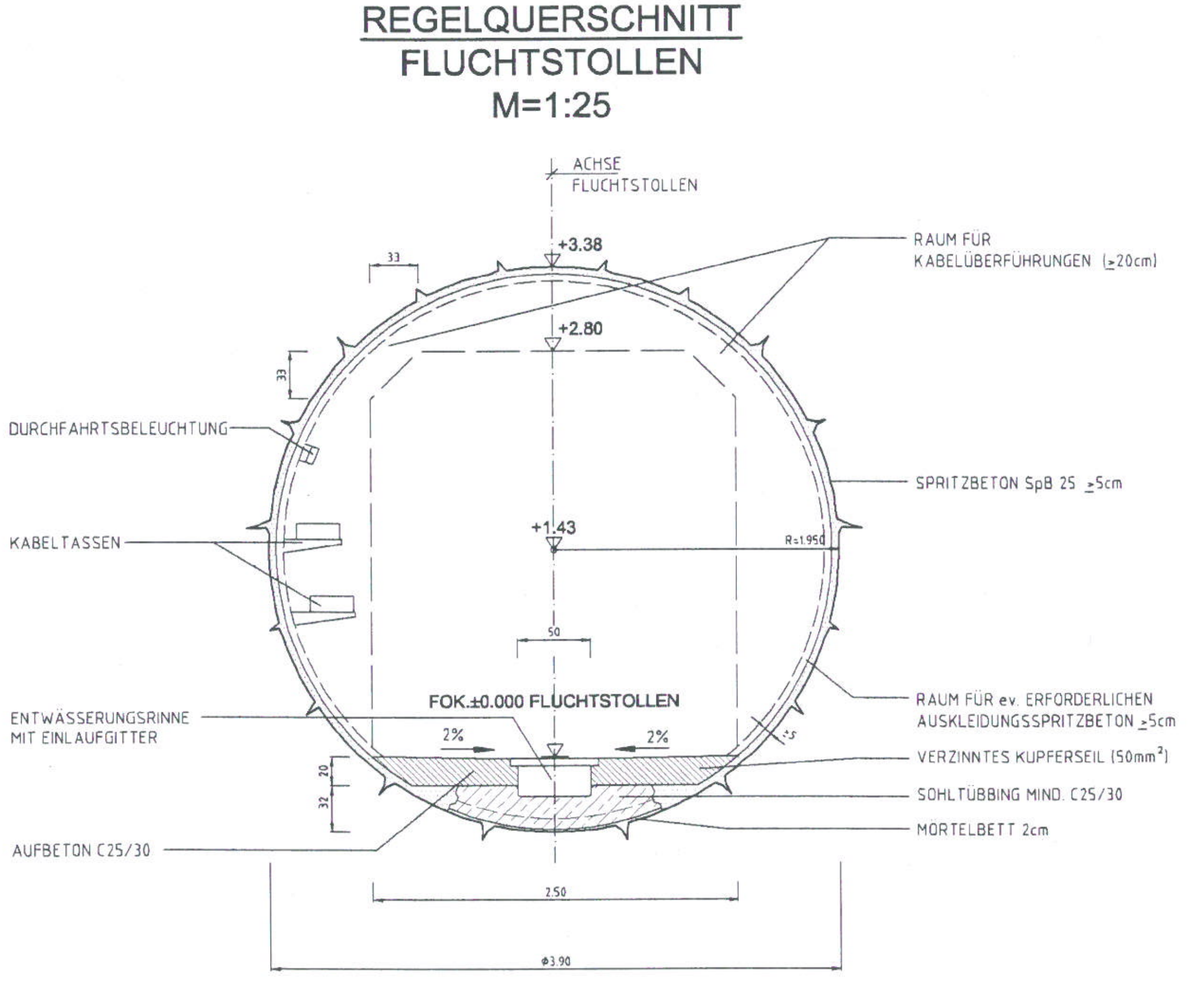

Figure 2 – Regular cross section of the pilot tunnel.

The following equipment was used in order to observe the behaviour of the pilot drift:

- Convergence measurements every 20 to 30 m
- levelling with the help of plug gauges, both in the crown and the invert
- extensometers (4 cross sections with 4 triple extensometers).

Later on, before the construction of the enlargement section (see below), additional equipment for geodetic measurements was installed near the enlargement section (5 points per cross section).

The measurements during construction of the pilot tunnel showed the following results:

- convergence measurements: no or hardly measurable horizontal convergences
- levelling: very little displacements of the crown (up to 2 mm)
  invert heave up to about 20 cm with large variations along the unnel length (see fig. 3)
- extensometers: confirm the size of the invert heave measured by levelling

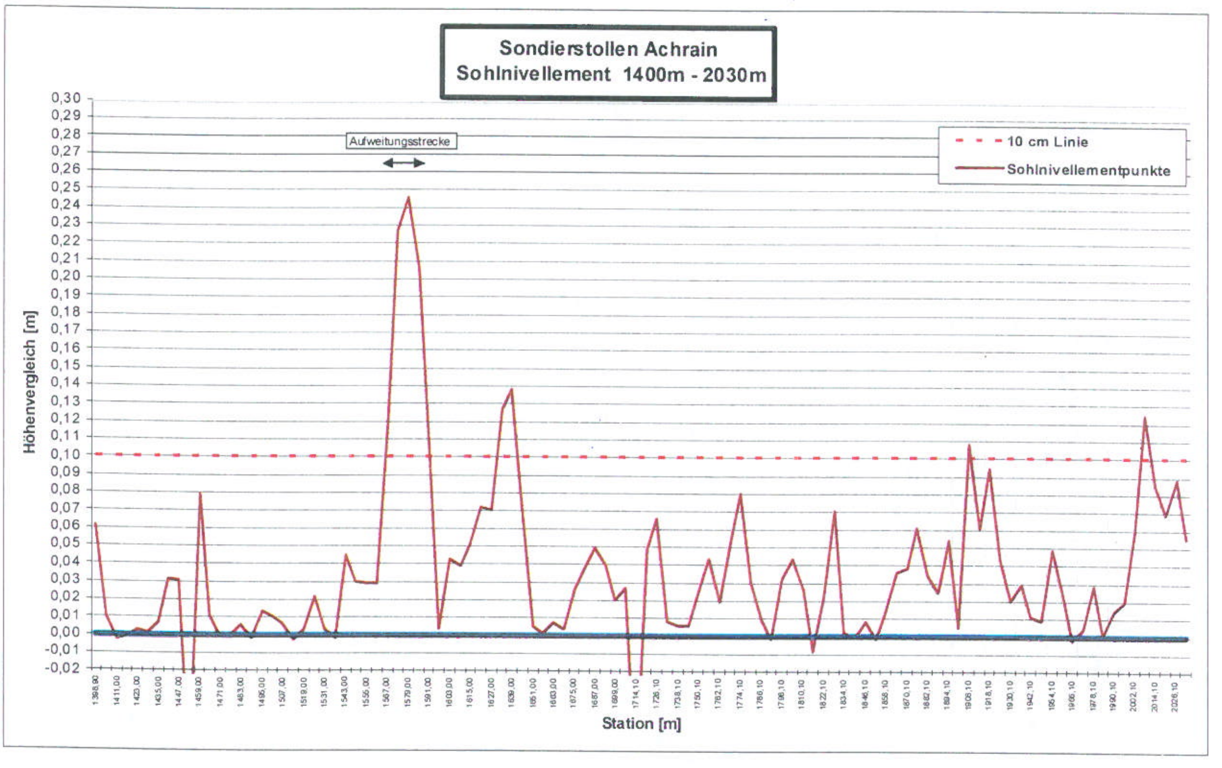

Figure 3 – Invert heaves in the pilot tunnel between 1400 m and 2030 m

The invert heave started a few weeks after excavation with monotonically increasing tendency. It resulted in damage to the lining: Most of the damage occurred to the shotcrete lining in the lower part of the side walls. Shear failure was a common observation, see fig. 4, and occurred on about 1 km of the tunnel length. At various locations, altogether over a length of 30 m, the heave of the invert segments was so large that the segments had to be replaced. The uplift exceeded 10 cm and the segments were both, displaced and rotated. Fig. 5 illustrates that at some locations the movements of the segments differed considerably from one segment (length 3 m) to the next. These differential movements indicate that the swelling potential and / or the amount of water available for triggering the swelling process varied considerably within short range.

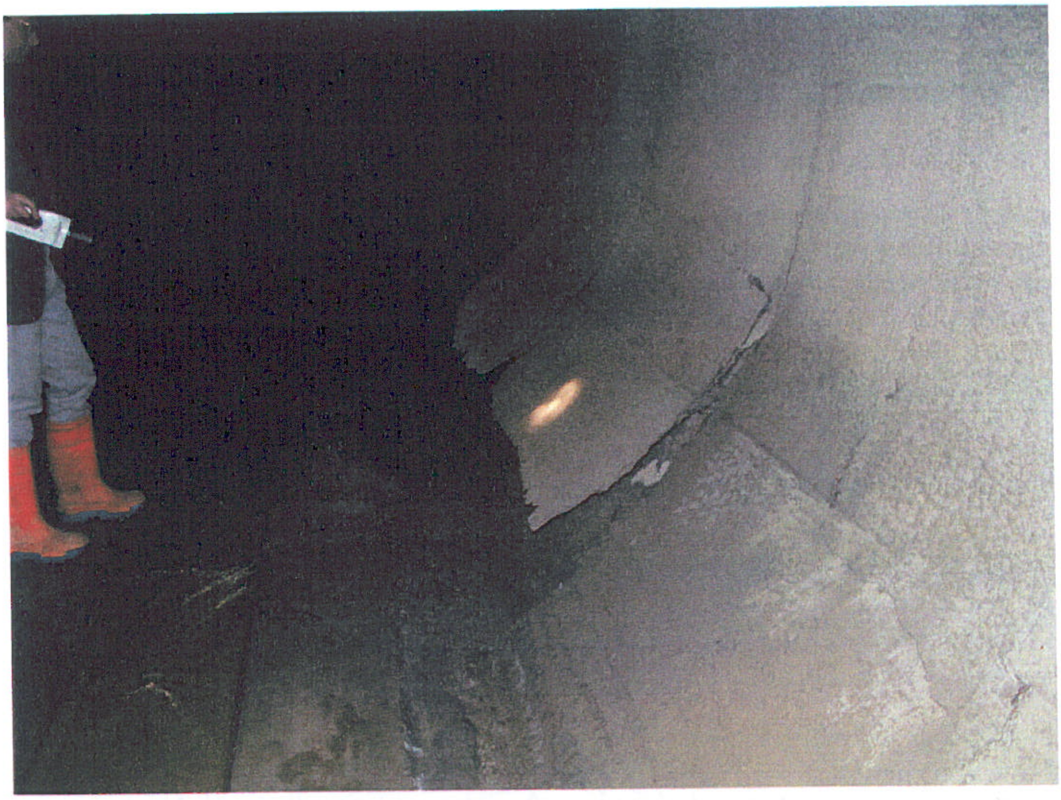

Figure 4 – Shear failure of the shotcrete lining of the pilot tunnel

Figure 5 – Variation of the invert heaves from one segment to the next

The invert heave was observed mainly in the middle part of the tunnel where it runs through the Weissach-formation. Further, the amount of invert heave was obviously related to areas with visible wetting of the marl.

First refurbishing measures and strengthening the lining of the tunnel stretch still under construction (increasing the thickness of the shotcrete lining, addition of mesh reinforcement, adding of steel girders, see fig. 6) could not stop the swelling process (fig. 7). The reuse of the pilot drift as an escape tunnel requires further strengthening of the sections where the swelling process has not come to a stand-still.

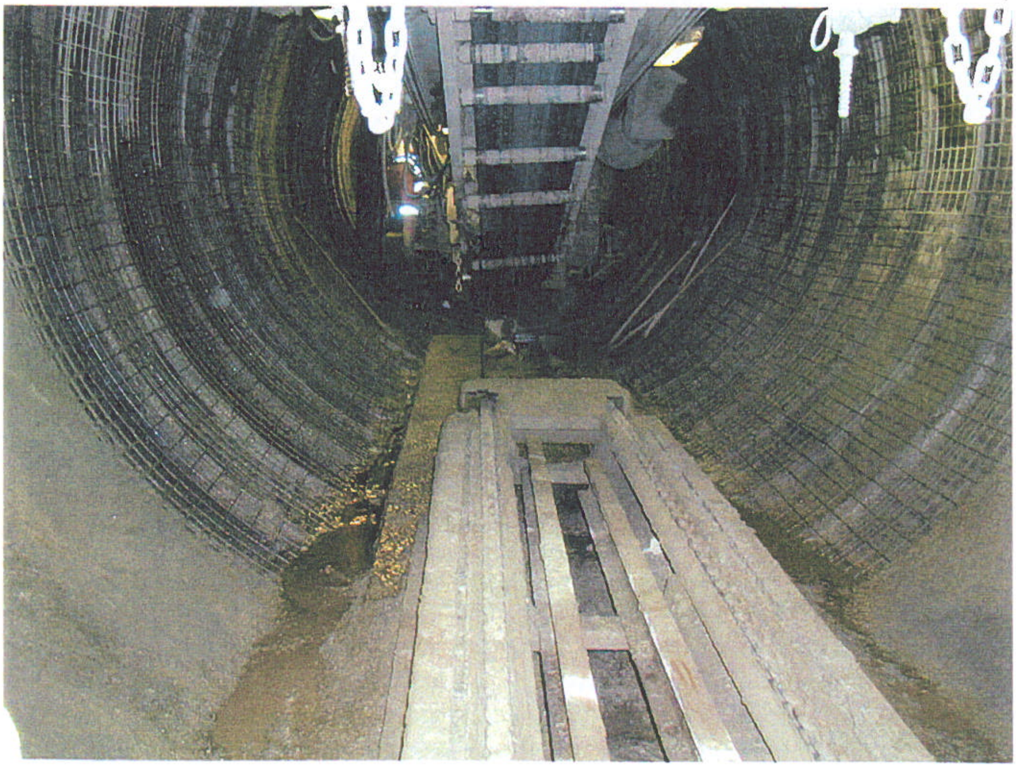

Figure 6 – Strengthened support of the pilot tunnel

Figure 7 – Kinking of the reinforcement of the shotcrete lining due to swelling

4 Enlargement section

In order to gain more insight into the swelling behaviour it was decided to enlarge the pilot tunnel to the size of the top heading of the road tunnel over a length of 25 m. The height of the enlarged section measures 5 m, the span 12 m.
This enlargement was sealed with a stronger lining, consisting of 30 cm shotcrete in the arch with two layers of mesh reinforcement and of 20 cm shotcrete with an outer layer of mesh reinforcement in the invert which was built with a radius of 15 m (Fig. 8).

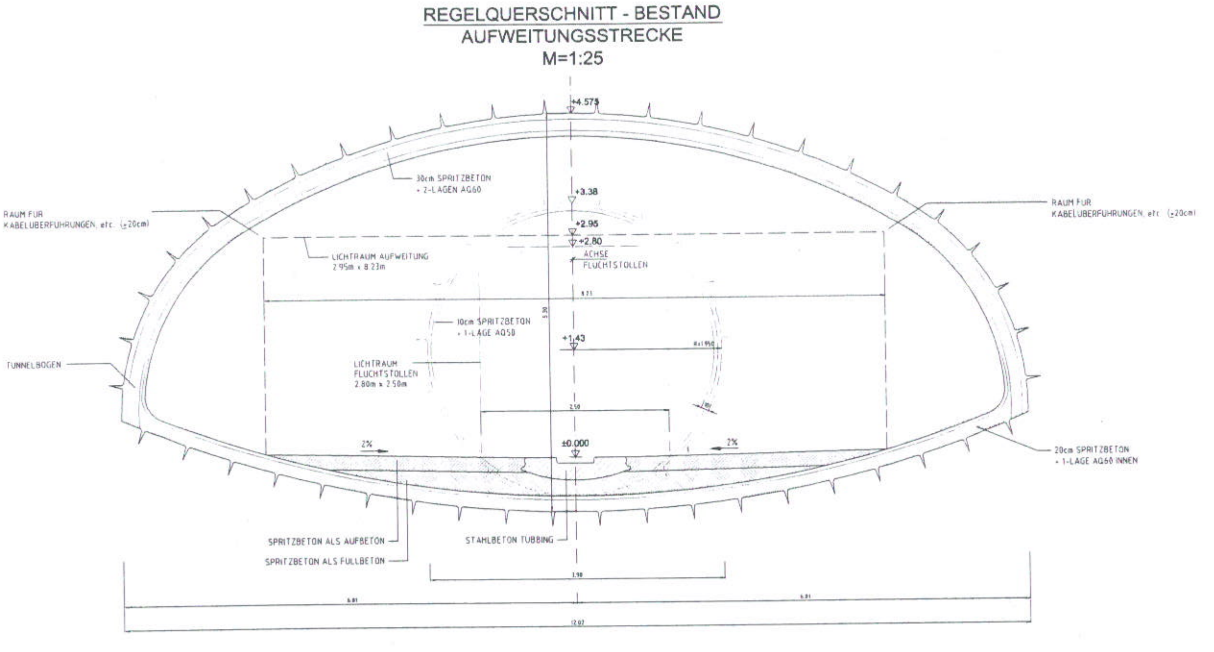

Figure 8 – Cross section of the enlargement section

Additional measuring equipment was installed, both in the enlargement and in the pilot drift in the vicinity of the enlargement (equipment for geodetic measurements, one cross section with 4 triple extensometers, pressure cells in circumferential direction in the shotcrete lining). Further on, 6 m of the invert of the enlargement were equipped with an irrigation system (consisting of napped foil and perforated hoses lagged with fleece) prior to application of the shotcrete lining.
During excavation of the enlargement section at the face a roughly circular area of decompaction with a thickness of about 1.5 m around the pilot tunnel was clearly visible (loosening, opening of joints), see fig. 9. A trial shaft below the invert in a damaged zone of the pilot tunnel matches these observations: The marl was completely loosened up to a depth of 1.1 m. The deteriorated rock there did not appear wet, but only earth-moist. It could be removed easily by help of an excavator shovel.

Figure 9 – Face of the enlargement section

The effects of the irrigation (every other day over a period of one month) were closely monitored. As expected, the irrigation caused monotonously increasing invert heave. After a period of about 7 months the swelling pressure became strong enough to cause failure of the shotcrete lining of the invert. The missing resistance of the lining lead to an acceleration of the heave, which had summed up to about 6 cm until then. After a period of approximately one year the lining of the invert was completely broken into pieces. The measurements indicated an uplift of 25 cm and more.
The last measurements available indicate a continuation of the swelling process without clear decrease at some regions of the tunnel, see fig. 10.

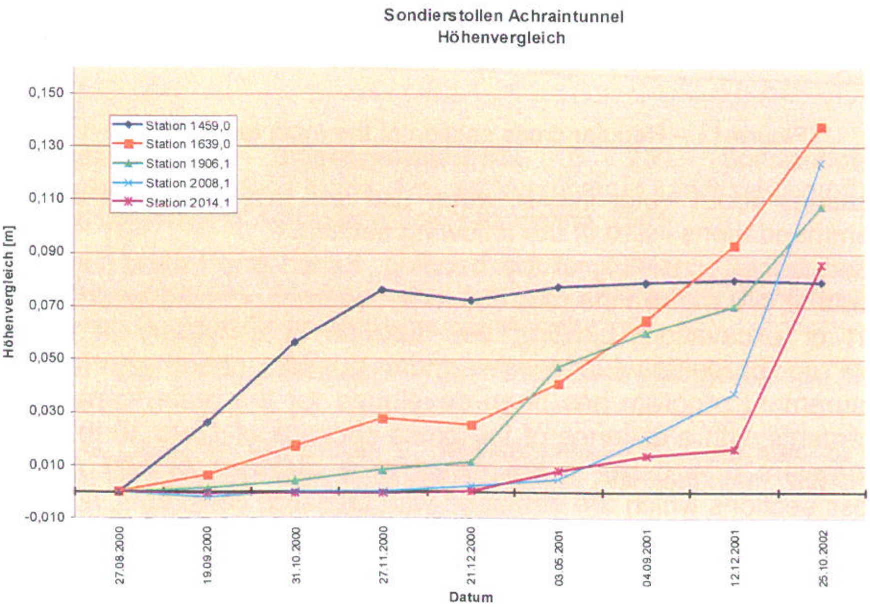

Figure 10 – Development of swelling with time at some points of the enlargement section

5 Effects on the design of the main tunnel

The experiences with the pilot drift and the enlargement resulted in a design of the main road tunnel with a deep invert arch, consisting of a 40 cm shotcrete lining and a cast concrete invert arch with a maximum thickness of 260 cm (fig. 11). The design specifications for the construction contain, for example, a maximum interval of 6 months between the start of excavation and ring closure of the secondary lining. Provisions for additional application of anchors in the invert have been made if unacceptable displacements should occur.

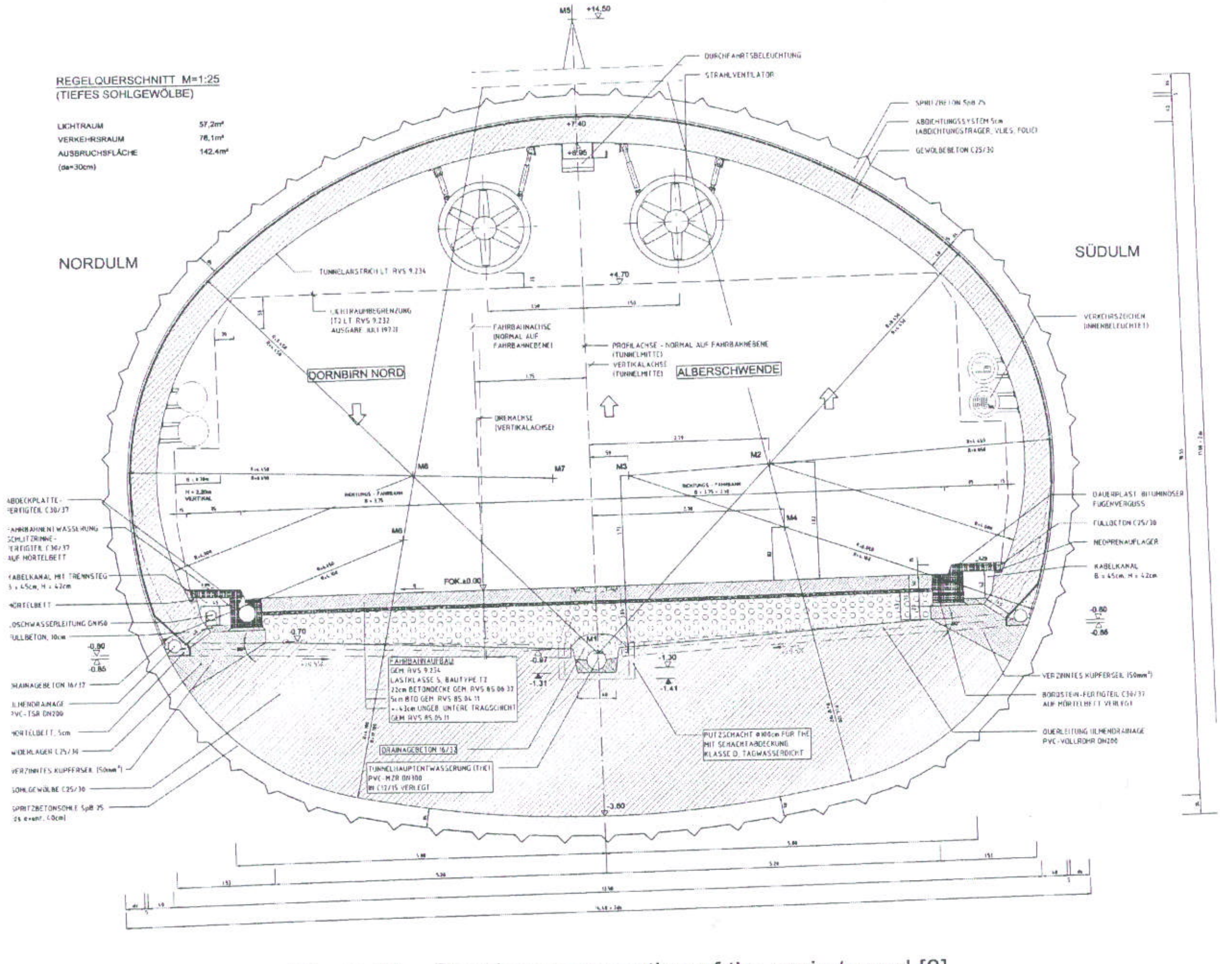

Figure 11 – Regular cross section of the main tunnel [8]

Stringent specifications about water intake, water use and drainage have been prescribed following the recommendations listed in the following section.

The excavation sequence, consisting of top heading, bench and invert, has to be finished with ring closure within 170 m from the face (20 m between bench and invert) and within two month after start of excavation. Limiting the duration is obligatory in order to avoid deterioration of the rock properties due to water and/or humidity near the surface.

A thorough measurement program has been developed for the main tunnel. It consists of geodetic measurements with a distance of the cross sections of 10 to 30 m, cross sections with two extensometers (l = 6 m) in the invert at a distance of 100 m, and 6 main measurement cross sections which are equipped with pressure cells, both in the primary and secondary lining, and extensometers of different lengths at seven points of the cross section. The invert arch will be equipped with levelling studs, and the extensometers in the invert will be equipped with remote sensing, in order to allow monitoring deformations during operation of the tunnel.

6 Recommendations for future exploratory headings and measurements

The experiences gathered from the pilot drift and the enlargement section of the Achrain tunnel have lead to the following recommendations for exploratory tunnels (with enlargement sections, if possible) of future tunnels in swelling rock:

- Samples for laboratory swelling tests should be taken not only by water-flushed boring in order to be able to eliminate the effect of the method of winning specimens on the measured swelling potential.
- Laboratory tests following the ISRM-recommendations [7] should be conducted. Information about the orientation of the specimens in respect to foliation and test setup is required. Mineralogical investigations should contain results both for the total mineral content and for grain sizes less than 2 µ.
- If a pilot drift has been built, excavation of an enlargement section with an irrigation system is recommended.
- The shape of the invert of the enlargement (which usually has about the height of the top heading of the main tunnel) should be as close as possible to the envisaged geometry of the invert of the main tunnel. This holds for the thickness of the primary lining of the invert as well.
- Measurements should start as early as possible, the frequency should be adapted to the displacement rate, and monitoring should continue until the displacements have stabilized.
- The use of extensometers allows the monitoring of invert heaves even in case of damage to the lining in the invert.
- Wet drilling is only permitted for blast holes, but not for holes for rock bolts or anchors.
- Careful collection of construction water and mountain water in closed pipes is important during all stages of the project. Water drainage in open ditches has to be avoided. At the face, the water has to be collected in a pump sump and drained in a closed pipe. Wet rock areas should be drained with the help of nap foils and hoses which are directly connected to the drainage pipe.
- In case a road header shall be used water cannot be applied to limit formation of dust.
- Immediate sealing of excavated areas with shotcrete is essential even in case of stable rock.

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