Fault zones in Quaternary softrock in the Inn valley causing difficulties in dewatering ahead of a tunnel

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Abstract: The Vomp-Terfens tunnel of the Brenner Eisenbahn Gesellschaft is the first construction of a new railway line between Munich, Germany and Verona, Italy through the Tyrolean Inn Valley, Austria. This project was started in October 2003. With a total length of 7.7km it is the longest NATM tunnel used for this kind of infrastructure project. The three drives have to pass through a range of soft and hard rocks ranging from Quaternary sediments to Triassic dolomites and limestone of the northern Alps. There is a lot of interest in the construction of this tunnel because of its heterogeneous and locally very difficult geotechnical conditions. In the Pleistocene delta sediments, fault zones were well known before the investigation started. In the alluvial deposits of the Terfens Terrace, fault zones were not expected. It is notable that steeply dipping faults, which were filled with silt, occurred in the youngest soft rocks as moraine and gravel deposits in the project area. These fault zones, with offsets ranging from 1m up to 12m, dammed the groundwater so that the aquifer was divided into several 'pools' that could not be easily dewatered with drains drilled from the invert of the crown. It was therefore necessary to drill a row of wells from the surface. The synopsis of the face mappings and the drill logs led to the conclusion that the heading had been driven through a large inactive horst and rift structure at the edge of the valley of the River Inn. The range of approaches to groundwater management, which were used during the tunnel drive Vomp-Terfens in different geological settings, will be discussed in this paper.

Résumé: Le tunnel Vomp-Terfens est le premier profet pour l'extension de la route „München-Verona" sur le terrain de l'Autriche. En ce cas il s'agit d'un tunnel avec deux et trois voies d'une longitude environ de 7,7 kilomètres, qui est construit en façon de NATM. L'un des trois attaques traverse les rochers solides des Trias de alps calcaire. Les deux attaques, qui sont situé à l'ouest, s'entendent presque complètement dans les rochers desserrés quartaires de la terrasse de Gnadenwald. Dans la partie à l'ouest on a trouvé des matériaux de la moraine, gravier de terrasse et des dépôts de glaciation différrents. Il est remarquable, que les sédiments jeunes du Quartair ont été séparés par des discontinuités escarpés. Cettes discontinuités étaient efficaces pour retenir l'eau et elles divisaient l'aquifére dans des bassins isolés. Le dépouillement des dessins de géology de tunnel et des perçages d'exploration donne des remarques sur une rupture décalé dans les sédiments quartaires. Les particularités de la géologie ingénieur et les difficultés pendant qu'on draine la partie du tunnel, qui est située en devant, vont être expliquer.

Keywords: aquifers, discontinuities, soft rock, subsidence, tunnels, water wells

PROJECT OUTLINE

The Vomp-Terfens tunnel of the Brenner Eisenbahn Gesellschaft is the first construction of a new railway line between Munich, Germany and Verona, Italy through the Tyrolean Inn Valley, Austria. The three NATM drives of the 7,735 m long double track and triple track tunnel started in October 2003. The cross-sectional area of the double track tubes is 111-125 m^2. The cross-sectional area of the triple track tubes is 202 m^2. The 2,276 m long triple track tunnel is located in the hard rock section of the project. The works are planned to be finished in January 2007. Two of the three NATM-drives start at chainage km 52.110 from an adit tunnel in the gravel pit of Vomperbach. From here one drive is heading for chainage km 48.120 in the east. In the first 650 m, this tunnel crosses Pleistocene well-cemented gravel deposits of Vomperbach. In the remaining 3,342 m this drive crosses only hard rock. Another drive heads from km 52.110 to km 54.055 (1,945 m) in the west, crossing the delta sediments of Vomperbach and the soft rock of Terfens terrace. The third drive starts in the west near the village of Terfens at chainage km 55.755 heading east and also crosses the various soft rocks of the Terfens terrace. Chainage km 54.055 is the point at which the two soft rock drives break through.

In the years 1999-2001 an exploration tunnel was built from km 47.600 to km 53.160. The exploration tunnel is situated approximately 20 to 30m north of the main tunnel, on the uphill side, crossing the hard rock section, the Pleistocene delta sediments of the Vomperbach creek and the different terrace deposits. The exploration tunnel has recently become very important for the drainage of the groundwater in the hard rock section and in the section where the main tunnel crosses the Vomperbach stream. In the most western part of the main tunnel project there were only exploration drillings available. During the excavation period of this 2,500 m long section of the main tunnel in the years 2003-2005 it was possible to gather information about the faults in the Quaternary soft rocks.

GEOLOGY IN THE PROJECT AREA

The tunnel Vomp-Terfens is located at the southern margin of the calcareous Alps of the northern Tyrol (Karwendelgebirge). The tunnel crosses the eastern section of the ridge of Vomper Berg. This ridge consists of different hard rocks of the Walderjoch anticline and of the Vomperbach Schuppenzone. The rocks are: limestones, dolomites, sandstones, siltstones and evaporites of the Raibl formation, limestone and dolomite of Wetterstein formation and dolomites of Hauptdolomit formation.

The middle part of the tunnel line runs through the calcareous cemented gravel deposits of the Vomperbach delta sediments of Pleistocene age. These delta sediments are composed of rock material from the limestone Alps. The western part of the tunnel line is located in the different soft rocks of Terfens terrace and Gnadenwald terrace. The terraces consist of silt, sand and gravel which were deposited in the period between the Saale ice age and the Weichselian ice age, of widespread moraines (lodgement tills) of Weichselian ice age, of alluvial fan deposits and of postglacial gravel deposits.

Genesis

The genesis of the sequence is considered to be as follows. During the Quaternary age, the valley of the River Inn was blocked several times by delta deposits and fan deposits from the flanks of the valley so that the River Inn was dammed up. Therefore a complex aggradational sequence could develop. The bottom-sets consist of various fine bedded silt deposits with rhythmic stratification of dark grey silt, clay and fine grained sand (Poscher & Lelkes 1999). These bottom-set deposits interfinger with silt and sand of fore-set deposits from the marginal fans and deltas. The fore-set deposits overlie the bottom-set deposits. This sequence also interfingers with fluviatile top-set deposits or is covered by fluviatile top-set deposits. Some of the deposits were eroded by glaciers during the Weichselian ice age. The remaining sequence was covered by moraine material and lodgement till. In addition, different types of deposits near the margin of the glaciers built up complex and heterogeneous sequences of gravel, sand and silt. After the glaciers had disappeared and the permafrost had gone, the slopes of the terraces became unstable so that smaller landslides could occur. Therefore some parts of the older deposits were transported once more and resedimented as younger terraces. During the postglacial development of the Inn valley several events of erosion and sedimentation occurred (Patzelt 1987).

Sequence

The sequence of Quaternary soft rocks ranges from Pleistocene lake deposits to alluvial gravel deposits. Different types of deposits can be described as follows:

Postglacial (Weichselian ice age) gravel deposits (number 1 in Figure 1)

Brown to grey coloured sandy and silty gravel deposits with high compactness of packing, well bedded with interlayer of sand and silt. The postglacial deposits have a thickness of 10-30 m and result from fluviative transport and transport by landslides at the flanks of the valley. They consist of transported moraine material, and other older transported and resedimented gravel, sand and silt deposits of the Quaternary sequence. The gravel deposits interfinger with the alluvial fan deposits. The postglacial deposits are a main aquifer in the project area. Faults were not known in these deposits before but they were discovered during the tunnel drives.

Alluvial fan deposits (number 2 in Figure 1)

Light grey to light brown coloured sandy and silty gravel deposits with medium high compactness of packing, well bedded with interlayer of sandy silt and coarse-grained gravel and pebbles. The postglacial deposits are composed of rock material from the limestone Alps. In some places the fan deposits are slightly cemented by calcareous cement. The alluvial fan deposits have a thickness of 5-20 m and interfinger with the postglacial fluviatile gravel deposits. There is no ground water except some perched ground water in the fan deposits. Faults were not known in these deposits before but they were discovered during the tunnel drives.

Moraines and lodgement till of Weichselian ice age (number 3 in Figure 1)

Olive to bluish grey coloured gravelly silt and clay deposits with varying amounts of sand, gravel, stones and blocks. The non-bedded material is of high compactness of packing. The silt and clay matrix is stiff to firm. The moraine material is over consolidated because of the former overburden by glaciers. The primary components are crystalline rocks from the central Alps; some of the components consist of rock material from the limestone Alps. The moraine deposits have a varying thickness of 0.5-20 m. Except some small water filled lenses and layers of sand within the moraine material there is no groundwater in the moraine material. Faults were not known in these deposits before but they were discovered during the tunnel drives.

Gravel deposits of the Terfens terrace and of the Gnadenwald terrace (number 4 in Figure 1)

Grey to brown coloured sandy gravel deposits with high compactness of packing, well bedded with interlayers of sand and sometimes silt. The deposits result from fluviative transport by river Inn. They are supposed to be the top-set deposits of the sedimentation sequence between the Saale ice age and the Weichselian ice age. The material is highly consolidated because of the former overburden by glaciers of the Weichselian ice age. In some places the deposits are slightly cemented by calcareous cement. The gravel deposits have a thickness of approximately 10-50 m and interfinger with the delta sediments of Vomperbach. The terrace deposits are a main aquifer in the project area. Faults were not known in these deposits before but they were discovered during the tunnel drives.

Pleistocene delta sediments of Vomperbach (number 5 in Figure 1)

Light grey to light brown coloured sandy and silty gravel deposits with varying amounts of stones and blocks. The material is of high compactness of packing and well bedded with interlayers of sandy silt and coarse-grained gravel. The bedding dips 30° towards the southeast. The material is highly consolidated because of the former loading by glaciers of the Weichselian ice age. These deposits are supposed to be the fore-set deposits of the sedimentation sequence between the Saale ice age and the Weichselian ice age. The delta sediments are composed of rock material from the limestone Alps. The delta sediments are slightly to well cemented by calcareous cement. The delta sediments have a thickness of up to 200 m and interfinger with the gravel deposits of the terraces. The delta deposits are a main aquifer in the project area. Faults were well known in these deposits before and they were also encountered during the tunnel drives. The gravel pit of Vomperbach is located in these sediments, therefore the faults were well known before the investigation started in the year 1996.

Sand deposits of the Terfens terrace and of the Gnadenwald terrace (number 6 in Figure 1)

The sand deposits of the terrace underlie the gravel deposits of the terrace. The gravel deposits develop from the sand deposits. The sand deposits can be divided into two different bodies. The upper stratum consists of brown to reddish brown, coarse grained to medium grained sand with varying amounts of gravel (so called brown sand). The sand deposits are well bedded with interlayers of fine-grained gravel or silt. The components are mainly of crystalline rock material. The material is highly consolidated because of the former loading by glaciers of the Weichselian ice age and because of the overlying thickness of other sediments. The brown sand deposits have a thickness of approximately 10-30 m. These deposits are supposed to be the fore-set deposits of the sedimentation sequence between the Saale ice age and the Weichselian ice age. Underneath the stratum of brown sand lie fine grained, silty sand deposits of dark grey colour (so called grey sand). The grey sand deposits are well bedded with interlayers of stiff to firm silt. The material is highly consolidated because of the former loading by glaciers of the Weichselian ice age and because of the considerable thickness of overlying sediments. The grey sand deposits have a thickness of approximately 20-50 m.

The sand deposits of the terrace are a main aquifer in the project area. In the grey sand deposits, confined groundwater is well known with pressure up to 5 bars. Faults were not known in these deposits before but they were discovered during the tunnel drives.

Silt deposits of the Terfens terrace and of the Gnadenwald terrace (number 7 in Figure 1)

The silt deposits of the terrace underlie the sand deposits of the terrace. They develop from the grey sand deposits. The fine-bedded silt deposits consist of a rhythmic stratification of dark grey silt, clay and fine-grained sand. The firm material is highly consolidated because of the former loading by glaciers of the Weichselian ice age and because of the considerable thickness of overlying sediments. The thickness of the silt deposits is approximately 30-100 m. These deposits are supposed to be the lacustrine bottom-set deposits of the sedimentation sequence between the Saale ice age and the Weichselian ice age. With the exception of some lenses and layers of sand with confined groundwater, the silt deposits are free of groundwater. Faults were not known in these deposits before but they were discovered during the tunnel drives.

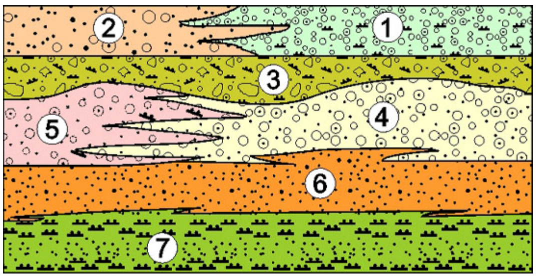

Figure 1. Sketch without scale showing the sequence of Quaternary soft rocks in the project area.

WELL KNOWN FAULTS IN THE DELTA SEDIMENTS

The gravel pit of Vomperbach is located in the delta sediments of Vomper Bach. Many faults and rifts can be studied in the steep walls of the gravel pit in the well-cemented delta sediments. Therefore the faults were well known before the investigation started in the year 1996. The exploration tunnel, which was built between 1999 and 2001, also encounterd faults in the delta sediments, as did the main tunnel.

Most of the steeply dipping faults are just closed discontinuities in the sediments without any aperture or filling. Most of the faults strike NE-SW and are steeply dipping. Other steeply dipping faults strike perpendicular to these faults NW-SE. The spacing of the faults is about 5-20 m. The displacement at the normal faults is up to several meters. In addition to these faults, steeply dipping rifts occur in the delta sediments. The aperture of the rifts ranges from 0.5 cm to 25 cm. The filling of the rifts consists of stiff to firm olive silts with varying amounts of fine-grained sand with mica. The silt is obviously floated material of uncertain origin (maybe moraine material). The rifts strike as the faults do; *i.e.* NW-SE and NE-SW. The spacing of the rifts is 10-40 m.

In the outcrop of the gravel pit, the Pleistocene delta sediments, where the faults appear, are covered by postglacial (Weichselian ice age) fan deposits, where no faults were detected. Therefore the age of the faults seemed to be younger than Pleistocene and older than the postglacial (Weichselian) fan deposits. Two theories about the origin of the faults were discussed by Tyrolean geologists but up to now there is no scientific publication of this topic available. One theory is that neotectonic processes are the reason for the faults. The other theory is that subsidence in the delta sediments and in the lacustrine sediments as a result of the former loading by glaciers of the Weichselian ice age is the origin of the faults. Some other possible theories will be discussed in this paper.

RECENTLY DISCOVERED FAULT ZONES

Faults were not known in the postglacial (Weichselian ice age) gravel deposits, in the alluvial fan deposits, in the moraine deposits, in the gravel deposits of the Terfens terrace, in the sand deposits of the Terfens terrace or in the silt deposits of the Terfens terrace until the driving of the main tunnel started in the western section of the project area. Sensational outcrops were uncovered in the tunnel driving.

Between the chainages km 52.8 and km 52.9 of driving, "West" faults in postglacial (Weichselian ice age) gravel deposits and in the alluvial fan deposits could be investigated. Most of these steeply dipping faults were just closed discontinuities in the sediments without any aperture or filling. Most of the faults had strikes NNE-SSW, sub parallel to the flanks of the Terfens terrace. The spacing of the faults was about 5-10 m. The measured displacement of the boundary between the postglacial gravel deposits and the alluvial fan deposits at normal faults was between 0.5 m and 10 m (observed in the cross-sectional area of the tunnel tubes). These faults are supposed to be younger than 15,000 years, because they affect postglacial (Weichselian age) deposits.

The driving "Terfens" crossed moraines and postglacial gravel deposits between chainages km 55.755 and km 55.525. Between chainage km 55.525 to chainage km 55.055, the heading crossed a lot of faults. These faults affected the whole range of quaternary sediments: the postglacial (Weichselian ice age) gravel deposits, the alluvial fan deposits, the moraine deposits, the gravel deposits of the Terfens terrace and the sand deposits of the Terfens terrace. The silt deposits of the Terfens terrace were not encountered during tunnelling. The faults had steep to moderate dips toward SE or NW with NE-SW strikes, which is sub parallel to the flanks of the Terfens terrace. Ancillary faults had strikes perpendicular or at obtuse angles to the main faults with medium steep to steep angle of dip. Figure 2 and Figure 3 show faults in the sand deposits of the terrace.

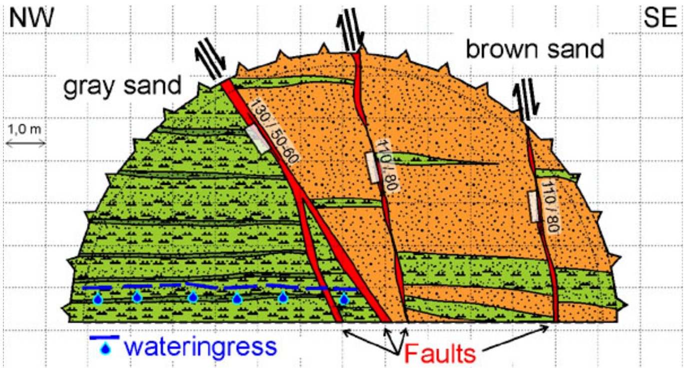

Figure 2. Faults between silty grey sand (left) and brown sand (right). The right hand side is displaced downward for more than 12 m. The faults are filled with silt. So the faults work as barriers to groundwater. Seepage occurs in the grey sand where the groundwater is dammed up.

The spacing of the main faults was 10-20 m. The spacing of the ancillary faults was about 5-10 m. Different from the faults discussed above, these faults had apertures ranging from 2 cm to 20 cm. The filling consisted of stiff to firm clayey silts or of stiff to firm silts with varying amounts of sand or gravel. The clayey fillings were of grey colour. The grey silt could be floated material. The sandy fillings were of brown colour. Often material of the faulted sediments was included in the brown fillings. Deflection of stratums could be observed close to the faults. The faults dammed up the ground water because they were filled with silt and clay and so they worked as upright barriers for water. Figure 3 shows seepage in the grey sand deposits of the terrace.

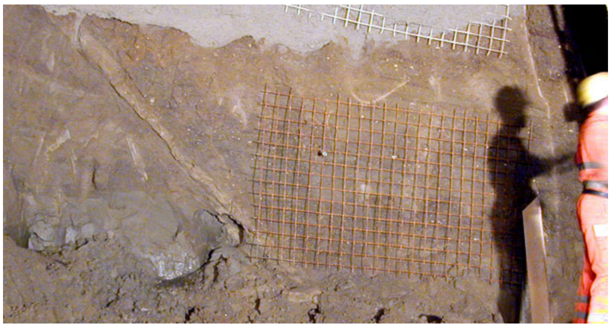

Figure 3. Fault between silty grey sand (left) and brown sand (right). The right hand side is displaced downward for more than 12 m. The fault is filled with silt. So the fault works as a barrier to groundwater. Seepage occurs in the silty grey sand where the groundwater is dammed up.

Besides the large faults with apertures of 2-20 cm a lot of very small faults with apertures of 1-5 mm and extension of less than 1 m could be detected during the geological investigation. These minor faults were filled with silty material just as the large faults were, so they also dammed up the groundwater. The displacement at these tiny discontinuities was about a few centimetres.

The measured displacement at normal faults was between 0.5 m and 12 m observed in the cross-sectional area of the tunnel tubes. The displacement by faults affected the whole Quaternary sequence so that faults became boundaries between the different members of the sequence: boundary between the gravel deposits of the Terfens terrace and moraine deposits, boundary between postglacial gravel deposits and moraine deposits, boundary between the brown sand deposits and the grey sand deposits as well as boundary between the grey sand deposits and postglacial gravel deposits and moraine deposits.

The direction of displacement by the normal faults was always downhill by reference to the flanks of the terrace. In some displaced blocks of soft rock the bedding was rotated antithetically.

The new detected faults are supposed to be younger than 15,000 years, because they affect postglacial (Weichselian age) deposits.

GEOLOGICAL MODEL AND THEORIES OF GENESIS

Geological model

The synopsis of the face mappings and the drill logs led to the conclusion that the heading was performed through a large inactive horst and rift structure at the edge of the valley of the River Inn.

The pattern of the faults and the offsets of stratums toward downhill by reference to the flanks of the terrace, are the arguments for a staged displacement system. Figure 4 shows a cross section of the staged displacement system at chainage 620 m in the driving “Terfens”. A cross section at chainage 620 m was also included in the tender documents showing a model of erosion and sedimentation without faults. The geological model of the tender document was based on exploration drillings, which were completed as piezometers for hydrological documentation. The model of erosion and sedimentation without faults was not implausible, given the geological sequence detected by the exploration drillings. However, the hydrological model of free groundwater in the different deposits did not fit very well to the staged water levels measured in the piezometers. The measured water levels could not be interpreted to represent a simple body of ground water. Therefore different bodies of ground water divided by water damming deposits were supposed in the tender documents.

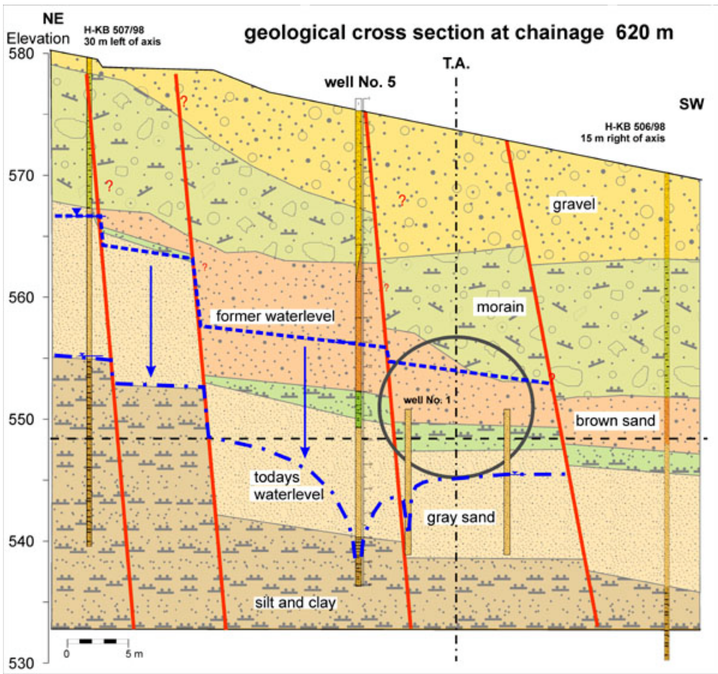

Figure 4. Cross-section showing the staged displacement system at chainage 620 m in the driving "Terfens". The Faults affect all deposits of the Quaternary sequence. The faults were filled with silt, so they dammed the groundwater. Therefore it was difficult to dewater ahead the tunnel drive.

It is absolutely conceivable that a local horst and rift structure can be developed in a staged displacement system. The tunnel driving detected clear evidence for a local horst and rift structure: The driving crossed deposits of different ages which were divided from each other by faults. The driving crossed a sequence as follows: postglacial deposits and moraine (of Weichselian ice age) – fault – terrace gravel deposits – fault – brown sand deposits of the terrace – fault – grey sand deposits of the terrace – fault – postglacial deposits and moraine (of Weichselian ice age).

In the encountered sequence the grey sand deposits are the oldest sediments. Therefore they represented the climax of the horst, whereas the postglacial gravel deposits and the moraine represent the youngest sediments the lowest block of the horst and rift structure.

Theories of genesis

The origin of the horst and rift structure within the staged displacement system is not known up to now, but different theories can be proposed as follows:

Weathering and dissolution of evaporites (salt, gypsum, anhydrite) in the hard rock basement of the Inn valley: Dissolving of evaporites causes loss of volume in rock mass, which gives rise to subsidence in the soft rock overburden. Dissolving of evaporites can also produce natural caverns in the remaining rock mass. If such solution caverns collapse, this can promote subsidence soft rock overburden. Anhydrite, gypsum or rock salt occur in Brixlegg, Fiecht and Hall close to the project area.

Recent tectonic processes cannot be excluded. The valley of River Inn is known to be an active zone - a noticeable number of earthquakes should be evidence enough. It is conceivable that pull-apart-basins could have developed recently. There are places in the valley of the River Inn, where the hard rock basement is detected at a depth of about 900 m, whereas in other places the hard rock basement is detected in a depth of less than 50 m. The cause of these zones of deep lying hard rock basement could be pull-apart-basins. The displacement of the hard rock basement could lead to subsidence in the soft rock overburden.

Subsidence in the soft rock filling of the Inn valley, particularly in lacustrine deposits is, in all probability the reason for the staged displacement system observed in the flanks of the valley. Supporting evidence for this theory comes from the observation that the faults only occur in areas where lacustrine sediments are detected underneath the soft rock sequence. During the postglacial era the valley of the River Inn was blocked several times by delta deposits and fan deposits from the flanks of the valley so that the River Inn was dammed up. If there had been a sudden outflow from a postglacial reservoir in the valley of River Inn as a result of breaching of the dam, massive erosion could have been caused. This erosion forms steep slopes, which leads to abrupt changes of stress in the steep slopes. After the glaciers had disappeared and the permafrost had gone the steep slopes of the terraces became unstable, and the sand started floating. The lacustrine sediments started to dewater and to consolidate. Subsidence could have occurred as a result of these processes.

Whichever theory is right, it is absolutely conceivable that the soft rock must have been frozen, for example in times of permafrost, when they were affected by faults, because the pattern of the faults and the appearance of the faults seems to be very similar to that of faults in hard rock.

In any event the processes that led to subsidence were probably not active in the last 100 years. This is evident because no damage to buildings as a result of subsidence has yet been detected or reported.

TUNNELLING IN FAULTED SOFT ROCK

The faults in soft rock caused three different kinds of major problems during tunnelling. The faults themselves presented one sort of difficulty. Though they occurred in soft rock, the faults worked as discontinuities in the rock mass where collapses of the face or parts of the face could originate. In some cases overbreaks occurred where faults appeared near the outline of the tunnel. To prevent this problem the face was opened in small parts of 2-4 m^3 and supported immediately with steel mesh and shotcrete. Another problem was the displacement of the rock stratums by faults. Therefore different types of soft rock occurred in the face next to each other. For example stiff to hard moraine material with firm rock behaviour occurred next to loose gravel deposits of the Terfens terrace with weak rock behaviour. So tunnelling had to deal with a kind of mixed face condition in soft rock. Therefore the support ahead the driving had to be adapted to the encountered rock condition. In moraine material fore polling was an effective method of support ahead of the driveage. In the loose gravel deposits pipe roof was the best method of support ahead the driving. In some sections, where changes of different material, e.g. moraine and gravel, appeared, fore polling in connection with grouting was the best way of support ahead of the driveage.

The major problem occurred because the faults were filled with silt so that they dammed the groundwater. Between km 55.755 and km 55.055 the driving Terfens crossed a body of groundwater in the different Quaternary sediments with water level about 2-3 m above the crown. Within the first 230 m the driving “Terfens” crossed moraine and gravel deposits without faults. In these deposits it was easy to dewater ahead of the driveage by systematically orientated drains in the invert of the crown, the invert of the bench and the base invert. The drains installed were simple pipe roof pipes, which were perforated with a few holes of 1 cm diameter and a fully opened mouth. Filter pipes were not necessary because a natural filter developed in the gravel and sand deposits during the dewatering process by transport and resedimentation of sand and fine-grained gravel.

In the faulted soft rock mass it was not possible to dewater ahead of the driveage by systematically orientated drains in the invert. The main faults, which have steep to moderate dips to the SE or NW, had strikes NE-SW, which is sub parallel to the flanks of the Terfens terrace. Ancillary faults had strikes perpendicular or at obtuse angles to the main faults with moderate to steep angles of dip. Therefore the aquifer was divided into separated ‘pools’ with different water levels. In this case it was necessary to orientate the drains referring to the mapped fault systems. In addition to this, the drillings were documented to get an idea of the ground condition ahead of the face. It was also necessary to stop the drillings at the estimated maximum inflow of water. The orientation of the drains was often in the shape of a fan ranging from parallel to the axis of the tunnel to perpendicular to the axis of the tunnel. The drains, which were orientated perpendicular to the axis, were necessary to dewater the groundwater bodies at the flanks of the tunnel tube because the major fault had a strike sub parallel to the axis of the tunnel and dammed up the water toward the hillside. So the danger of a higher groundwater level besides the tunnel tube could be executed. The used drains were simple pipe roof pipes, which were perforated with a few holes of 1 cm diameter, with a fully opened mouth and without filters. Special steel pipes with a mantle of plastics filter were used in the coarse-grained sand deposits of the terrace.

In the fine-grained sand deposits of the terrace it was not possible to dewater in that way, because the compound groundwater made the fine-grained sand flush out of the drains without developing a natural filter. For this reason special vacuum-drains were drilled from the invert and the crown of the tunnel. However, because the aquifer in the fine-grained sand was divided into separated ‘pools’ with different water levels, the influence of these small vacuum-drains was too weak for dewatering ahead the tunnel face. Up to 15 vacuum-drains with length of 9 to 12 m, oriented in the shape of an umbrella in the roof and in the invert were necessary to dewater a section of 3 to 6 m ahead of the face, while the process of drilling and effective dewatering of this section took several days to complete. Therefore this system of dewatering the fine-grained sand deposits was too expensive and not sufficiently effective. Several trials of dewatering the fine-grained sands ahead of the tunnel from the face failed. The only way to dewater the section, where the fine-grained sand occurred, was to drill wells from the surface. Because of the fault system that divided the aquifer into separated ‘pools’, it was necessary to drill wells in a distance of 2-3 m to the outline of the tunnel (see Figure 4). The distance between the wells was 5 m. The row of wells had a length of 60 m. The depth of the wells was 25 m. The wells were filtered in the elevation of the sand stratums. Vacuum was used in the wells to enlarge the potential of the wells. The drilling campaign lasted about one and a half months, but after the first four wells were completed and activated within two weeks, the heading could be started after a dewatering period of a few days. Using the vacuum-wells drilled from the surface, the heading crossed successfully the fine-grained sand deposits of the Terfens terrace within a month.

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