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Aicha-Mauls on the Brenner Base Tunnel—status of the works and results

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ABSTRACT: The Brenner Base Tunnel is an indispensable element of the trans-border European priority scheme TEN Project No. 1 comprising a roughly 2,200 km long high-speed railway route between Berlin/Germany and Palermo/Italy. According to the latest planning the Brenner Base Tunnel will be 55 km long (fig. 1), including the directly following deviation tunnel of Innsbruck the entire tunnel construction will be 62,7 km long and hence the longest tunnel of the world. The concept of the tunnel comprises a maximum velocity of 250 km/h for the railway traffic. In the year 2007 the construction of the investigation tunnels Aicha and Mauls had begun; their construction is an integral part of the safety, maintenance and dewatering concept. The experience and results of their drivings and related monitoring of the rock and the rock mass behavior are crucial information for the latter design and construction of the main tunnels. Analogous to the system applied at the Gotthard Base Tunnel the Brenner Base Tunnel will consist of 2 single-tracked tunnels running parallel in a clearance of about 70 m. Between them runs a smaller exploration tunnel. Each 333 m rescue and service galleries will connect the main tunnel tubes (Figure 1).

1 PROJECT DESCRIPTION

The Brenner Base Tunnel is an essential link in the altogether 2,200 km high-speed rail route Berlin-Munich-Verona-Bologna-Palermo. The planned Brenner Base Tunnel is 55 km long, or including the underground line to bypass Innsbruck 62.7 km long. The tunnel is designed for rail traffic with a maximum speed of 250 km/h.

Work was started on the two investigation tunnels at Aicha and Mauls in Italy in 2007, the construction of these being an essential part of the rescue, maintenance and drainage concepts for the Brenner Base Tunnel as well as serving to investigate the geotechnical and tunnelling conditions of the future main tunnel. The Brenner Base Tunnel will consist of a system with two single-track tunnel bores (Figure 1), similarly to the Gotthard Base Tunnel. Beneath the two main tunnels, a smaller investigation tunnel is provided and pedestrian cross-passages will be constructed at regular intervals of 333 m between the two bores.

2 GEOLOGICAL AND TECTONIC OVERVIEW

The Aicha and Mauls tunnels will pass through the tectonic unit of the Brixener granite, which belongs to the South Alpine unit. This unit contains these lithologies: granite, granodiorite, aplitic and pegmatitic veins. The Brixener granite (Figure 2) is a non-metamorphic tectonic unit, strongly deformed during the Alpine orogeny. The result of this deformation was to form a multitude of brittle joints and faults. The northernmost part of the project area, where the intermediate starting cut at Mauls and the last kilometres of the Aicha investigation tunnel are situated, lies within the area of the Periadriatic Seam. The Periadriatic Seam represents geologically the northern border of the South Alpine unit and is a dominant, predominantly west-east striking fault system characterised by brittle fracture.

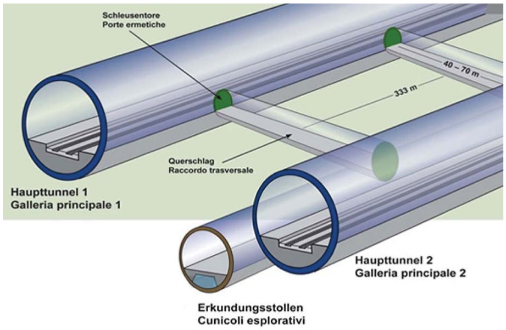

Figure 1. Concept of Brenner Base Tunnel.

Figure 2. Brixener granite with basalt vein.

3 MAULS ADIT

The Mauls adit will be used for material deliveries during the construction of the main bores of the base tunnel and after their completion will guarantee access for maintenance and rescue sorties. The 1,767 m long adit has a slope of 9% and an excavation cross-section of 92 m^2. On a second axis, the Mauls investigation tunnel ("Periadriat-ica" axis) will be constructed with a length of about 0.5 km toward the Aicha investigation tunnel and the dismantling chamber of the Aicha TBM drive will also be constructed. These tunnels were conventionally excavated in a single-stage with shotcrete lining. The tunnelling work in Mauls was completed at the end of October 2009 and the Periadriatic Seam section at the end of March 2010. The average advance rate was 5.85 and 5.21 m/d (net) respectively.

4 AICHA INVESTIGATION TUNNEL

Tunnelling work has been underway at Aicha since December 2007. The first 150 m were excavated by conventional drill and blast and then continued as planned with a tunnel boring machine (TBM) followed by segment lining to the intended end of the tunnel after 10.418 km. The excavated diameter of the double shield TBM is 6.3 m. The annular gap between segment and rock, which is specified with different type classes for the various structural loadings (overburden pressure, faults, water pressure), will be filled with gravel. The current net advance rate is about 16 m/d.

5 GEOTECHNICAL MEASUREMENT EQUIPMENT

Geotechnical measurement equipment is being installed a regular intervals in the mountain and in the form of measurement segments, from which the stress and strain alterations can be queried digitally over WLAN (Aicha Tunnel) or manually (Mauls Tunnel). The data is entered into the database (2doc) by the site supervision staff and evaluated with regard to the geological-tectonic situation at the face, the results of geophysical advance investigations of the measuring instruments installed in boreholes and the machine and the machine parameters. The data and the relevant graphical evaluations are available online at all times for the project parties. In addition, the site supervision staff produces daily, weekly and monthly geological-hydrogeological and geotechnical reports, in which the investigation results are displayed as a whole and evaluated with regard to the prognosis of rock behaviour and structural basics.

When fault zones or significant new discoveries regarding the rock/groundwater conditions are encountered, the site supervision, after discussion with the client, can order the installation of additional geotechnical measuring equipment. Table 1 shows the instrumentation installed in the two tunnels so far.

Near each of the portals at Aicha and Mauls, an inclinometer and a groundwater level gauge were installed. During the drives, surface levelling was carried out in these areas.

5.1 *Conventional advance*

During tunnelling work at the Mules intermediate starting point, the TBM dismantling chamber and the "Periadriatic Seam" section, the geotechnical measurement instrumentation was supplemented

Table 1. Overview of amount and kind of geotechnical and hydrological measurement devices.

Geotechnical-hydrogeological measurement equipment *Geotechnische-hydrogeologische messeinrichtung*	Number (as of 31/05/2010) *Anzahl (Stand 31.05.2010)* Aicha tunnel	Mauls adit	Periadriatic seam tunnel
Inclinometer *Inklinometer*	1	–	–
Groundwater quantity (portal) *Grundwassermessstelle (Portal)*	1	–	–
Surface leveling *Oberfldchennivellement*	1	1	–
Rock thermometer recording *Felsthermometrische Erhebung*	30	14	6
Magnetic extensometer *Magnetextensometer*	5	–	–
Five-point extensometer *Mehrfachstangenextensometer (5 fach)*	–	–	4
Measurement segment cross-section: (each 4 pairs of strain gauges/2 pairs of strain gauges) *Messtubbingquerschnitt (a 4 Paar Dehnungsmessgeber/a 2 Paar Dehnungsmessgeber)*	34/4	–	–
Measurement section, conventional excavation, with: Pair of strain gauges (CV) Pressure cell in rock (CP) Pressure cell in lining segment (CR) *Messquerschnitt konventioneller Vortrieb mit Dehnungsaufnehmerpaar (CV) Druckmessgeber im Gebirge (CP) Druckmessgeber im Ausbaubogen (CR)*	–	5X(5CV + 3CP) and 2X(3CV + 3CP + 5CR)	1X(5CV + 3CP)
Discharge measurement in tunnel/portal *Schiittungsmessung (im Tunnel/Portal)*	4/1	1/1	–
Piezometer in tunnel/portal *Piezometer (im Tunnel/Portal)*	7/1	1	–
Convergence survey section *Konvergenzmessquerschnitte*	46	63	16
Face deformation measurement (current/no longer current) *Ortsbrustverschiebungsmessungen (aktuell/nicht mehr aktuell)*	–	1/6	1/3

by the installation of thermometer and multiple extensometer and vibration measurements were carried out.

5.1.1 *Convergence measurement cross-sections*

Five surveying pins with removable reflex targets were installed at each survey cross-section. The survey pins were additionally equipped with protection against blasting in order to be able to perform a measurement soon after detonation. On average, convergence survey cross-sections were set up every 27.5 m; the targets were surveyed geodetically (3D). The maximum deformations (in this case convergences) were less than 4 mm for the entire period of measurement.

5.1.2 *Measurement of face deformation*

Whenever tunnelling was stopped for any length of time, nine reflex targets were installed in the face and surveyed geodetically (3D). The maximum horizontal deformation was less than 3 mm.

5.1.3 *Thermometer recording*

The rock temperature is monitored using altogether 14 resistance temperature sensors and three thermistors, which are each installed about 2 m deep in the rock. At the end of the drive toward the Periadriatic Seam, three thermistors were installed at depths of 0.5, 3 and 30 m. The rock temperature in the Mauls adit rises from 14 °C near the portal with 100 m overburden to 26 °C under an overburden of 1,210 m (Figure 3). In the Aicha Tunnel, the measured temperatures under overburden depths of 400 to about 1,200 m remain fairly constant at 20 to 22 °C.

5.1.4 *Strain gauges and pressure cells*

Main survey cross-sections were set up at 8 places along the Mauls adit. These cross-sections vary according to the type of layout and the number of instruments. A main survey cross-section normally consists of three pressure cells in the rock (crown, both spring lines) and five strain gauges

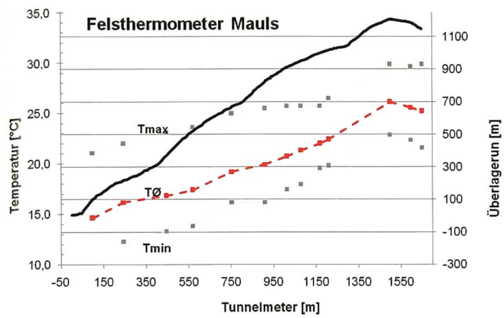

Figure 3. Results of the thermometer data at Mauls.

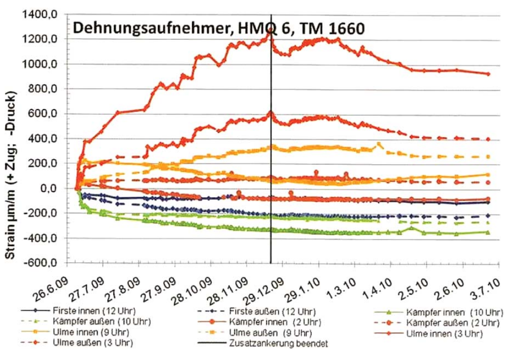

Figure 4. Graph of the strain measurements at main tunnel survey section 6, Mauls Tunnel Geological cross section.

(crown, both spring lines and both sides), which are installed in pairs in the shotcrete lining.

At the TBM dismantling chamber, the lining is additionally supported with steel arches. This is due to the greater cross-section required and the relatively short separation of the two later main tunnel bores. In this area, a main survey cross-section consists of three pressure cells in the rock (crown, left- and right-hand spring lines), six pressure pads on or in the steel arch and three strain gauges, which are installed in pairs in the shotcrete lining.

The measured data is not only recorded for the design of the planned main tunnel, but is also evaluated in the course of the tunnel advance with regard to the current stability of the tunnel and the lining. The main survey cross-section 6, which was installed at the start of July 2009, can serve as an example: a clear and continuous increase of the stresses (strains) was recorded in the right side of the shotcrete lining (Figure 4).

Neither the data from the convergence measurement cross-sections nor the evaluation of the geological conditions recorded during the advance could deliver any conclusions about the reasons for this increased stress. In the middle of October 2009, with the measured values continuing to rise, the first fine cracks were noticed in the shotcrete lining. Additional anchoring (12 Swellex, L = 5 m) only achieved a slowing ot the increasing strain, and only pattern bolting (1 m × 1 m) in a section of altogether 10 m long prevented a further increase of stress and stopped the progressive crack formation.

5.1.5 *Multiple extensometer*

At the end of the drive toward the Periadriatic Seam, the last main survey cross-section was set up near the face. The instrumentation included, in addition to the pressure cells and the strain gauges, four five-point extensometers. These measure the radial deformation at a distance of 1.5, 3.5, 4.5, 10.5 and 15 m from the side of the tunnel. In combination with the strain gauges and the pressure gauges in their immediate vicinity, these can be used to analyse deformations and stress transfers in the rock mass, above all in relation to further advance toward the Periadriatic Seam.

The survey cross-section installed at the end of the "Periadriatica" drive is equipped with a data logger, which records data from all the instrumentation installed at the section. The measured values are recorded and read out at fixed intervals.

5.2 *Mechanical advance*

Measurement segments, magnetic extensometers, rock thermometers and pore water pressure gauges were installed in the Aicha investigation tunnel. Four pairs of vibrating wire strain gauges are cast into the segments tan-gentially. Advance drilling, reflection seismic and geo-electrical measurements were undertaken to investigate ahead of the advance. The results were used to develop prognoses for the rock conditions ahead of the machine and risk management. The prognoses were compared and validated against the TBM parameters and the face images.

5.2.1 *Magnetic extensometer*

At four cross-sections, magnetic extensometers were installed with depths of up to 12 m and spacing between 0.8 and 2 m radially in the crown and spring line areas. These were installed using a radial drill behind the shield tail of the TBM so that stress transfers after excavation were taken into account. The maximum deformations measured were less than 1.5 mm/m.

5.2.2 *Measurement segments*

Instrumented segments are currently installed at 34 cross-sections. The eight strain gauges per measurement segment cross-section are each installed in pairs in the segments at the spring line and the crown.

The tangential arrangement of the strain gauges can measure positive and negative strains in the segment ring. These are read manually as long as the segment is within the TBM and after that by WLAN. The recorded values (us, Hz) are converted to stresses and provide useful information about the stress distribution and any relevant alterations in the stress distribution in the segment ring. At the same time, the client undertakes the back-calculation of the lining design for use for the planned main tunnel.

5.2.3 *Geodetic measurements*

In areas where significant strains were measured in the segments, removable reflex targets were installed and surveyed geodetically (3D) to check the deformation of the tunnel lining.

5.2.4 *WLAN query system*

The instrumentation (thermometer, measurement segments and piezometers) was equipped with a WLAN query system after leaving the backup. The measured values from each sensor were transmitted by radio to gateways.

The gateways are equipped with a data logger, which saves the received data at configurable times (twice a day). The data at the gateways can be read and further processed by special software at any time. In addition, it is possible using a radio-logger to control the sensors singly with a code at the location and read the data directly. At the moment, the gateways are connected with the glass fibre cables used to transmit all TBM data to the site management offices. This makes it possible to view and graphically process the data at and time.

5.2.5 *Hydrological measurements*

At locations with large water ingress, seven vibrating wire pore water pressure sensors were installed at a depth of 11 to 15 m in the tunnel side wall. The discharge is recorded at five positions in the tunnel with a measurement weir via data logger. The discharge at the portal is detected and recorded by a laser. The forecast short-term discharges were mostly not reached during the excavation.

At the moment, the discharge at the portal is about 55 1/s (forecast 200°1/s).The chosen arrangement of the various data loggers for discharge measurements in the tunnel and the measurement of the total discharge at the portal enable the observation of water ingress into the tunnel for individual sections. The maximum recorded water pressure in the tunnel is 2.1 bar.

5.2.6 *Rock behaviour*

To describe the variety of geological conditions, project-specific rock mass behaviour types based on the OGG guideline [1] were defined and assigned to each section [2] [3] [4]. During the tunnelling work, these forecasts were compared with the actually encountered rock classes (RMR according to Bieniawski) and the rock behaviour. After about 8,300 m had been driven, there was a good agreement with the forecast; the tendency is (excepting the problems described in the next section) slightly more favourable rock conditions (Table 2). In addition to the geological recording of the face, windows are provided in the segments for visual checking and recording of the rock in-situ.

6 FAILURE EVENT IN THE AICHA TUNNEL

After faults belonging to the Periadriatic Seam, running mostly across the direction of the tunnel, had been bored through as planned, a progressive failure of the segments occurred at the left side of the tunnel at 6.150 over a length of about 100 m, starting in the already lined tunnel and extending forward until the TBM was jammed (Figure 5).

Table 2. Comparison between the prognosis of rock classes and types of rock behaviour with the results of the investigation tunnel Aicha.

Prognosis				Actual	
Station (m) from, to	Rock type	Rock class (Bieniawski)	Rock behaviour type	Rock class (Bieniawski)	Rock behaviour type
0–70	GB-G-D-20 L	IV	undefined	III–IV	GVT1
70–2,340	GB-G-20 L	II–III	GVT2	I–III	GVT1
2,340–3,790	GB-G-19 L	III	GVT2	I–IV	GVT1
3,790–6,000	GB-G-19 K	II–III	GVT 2/5	I–V	GVT 1, seldom GVT 2
6,000–9,517	GB-G-181	II–III	GVT 2/5	I–IV	GVT 1, seldom GVT 2
9,517–10,408	GB-G-18H	II–III	undefined	not yet driven	not yet driven
Faults	GB-NE	I–V	GVT 3	III–V	GVT 2
Faults	GB-EW	I–V	GVT 3	III–V	GVT 2

Figure 5. Failure in the Aicha Tunnel, breakage of the left-hand shotcrete lining.

The failure occurred in an area, which had been defined as unfaulted or weakly faulted in both the advance investigations and the geological and rock mechanical face records. The geophysical process used was reflection seismic measurements performed every 150 m to investigate the geological-tectonic conditions in advance. This was supplemented with drillings ahead of the machine, which were however only undertaken when they fitted with construction logistics and during stoppages.

The data from the measurement segment installed at TM 6099 shows strain increases within 24 hours of (converted) up to 10 MPa (tension stress at inner strain gauge, compression at outer) in the left side wall (Figure 6).

After the failure, extensive additional investigation measures (radial core drilling, advance drilling) were carried out, and monitoring systems (automatic crack width sensors) were installed. Figure 7 shows the investigation measures and the installed measurement equipment.

The direct investigations carried out in the left-hand side and crown (20 m long core drillings) show that there is, an almost vertical fault zone running nearly parallel very close to the side of the tunnel (Figure 8). This could not be recognized from the tunnel itself.

For the determination of the structural loading, 3D-FE calculations were carried out (Figure 9), in which the measured deformations and stresses were back-calculated in parameter studies and limit state analysis and the appropriate combinations of values were determined [7] [8].

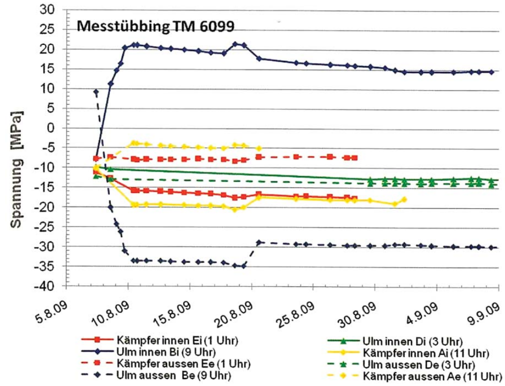

Figure 6. Data from the measurement segment at TM 6099.

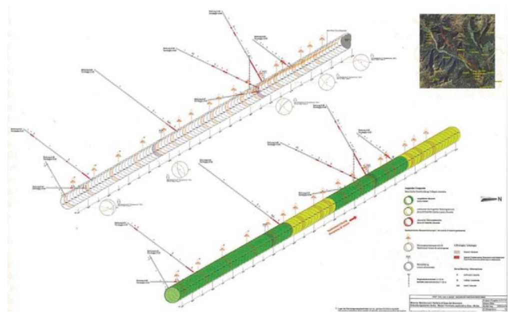

Figure 7. Overview of instrumentation and core drillings at TM 6150.

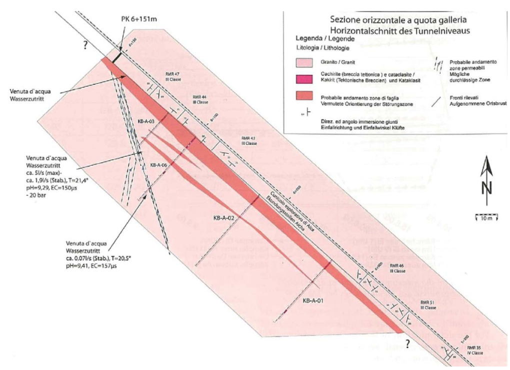

Figure 8. Plan of investigated fault zone and water ingress at TM 6000 to 6150.

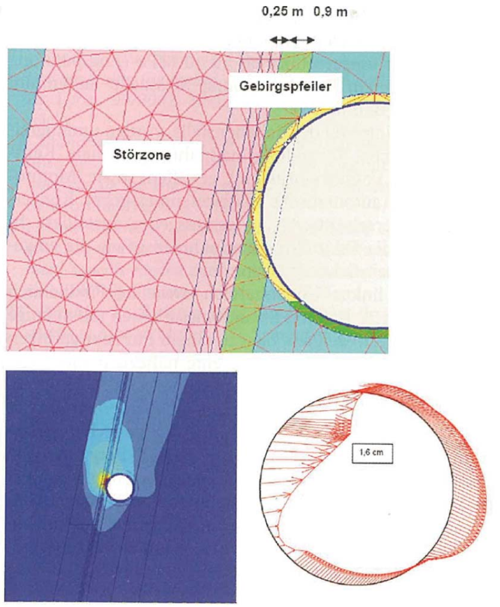

Figure 9. Calculation model and results of the 3D-FE calculations.

These were put into practice in further work on the verification of structural stability and the design of the lining.

The investigation works specified to clarify the cause and the subsequent repair caused a stoppage of one month. In parallel, an extended risk management scheme was produced to lay down fixed rules for the type and extent of measures and risk management functions for the remaining tunnelling work. The use of differently reinforced segments (types L to XXP) is also based on the experience gained in the tunnel and subsequent measurement data.

7 RISK MANAGEMENT

After the failure, the original procedure and extent of measures for risk management were widened. For the mechanical tunnel drive, at least two risk evaluations were undertaken every day by the site supervision.

The risk evaluation includes the assessment of the forecast and encountered geological situation (rock mechanics inventory of the face, interface properties, assignment of the rock class according to Bieniawski, description of hydrogeological indicators, analysis of the muck etc.) and the assessment and interpretation of the geo-technical data, the assessment and interpretation of the geophysical advance investigations and the current TBM parameters like penetration index, thrust force, revolution speed, torque, including control of the volume of annular gap filling.

Based on the risk evaluation, the previously fixed measures or packages of measures are applied. These include not only tunnelling measures but also decisions about lining and advance investigation:

- reduction of the advance rate,
- less thrust force,
- installation of segments of different thickness (Figure 10),
- use of additional strengthening measures (installation of steel ribs),
- installation of instrumentation (measurement segments),
- increasing the frequency of geological and rock mechanics investigations,
- drilling advance holes and recording of drilling parameters,
- geophysical down-hole investigations with radar.

In addition, hydrogeological evidence is kept and rock thermometers are installed according to risk class in addition t the planned instrumentation.

The penetration index (thrust force per mm penetration) has proved useful as an aid to risk evaluation (B). Particularly on account of the tendency to agree with the qualitative ups and downs of rock

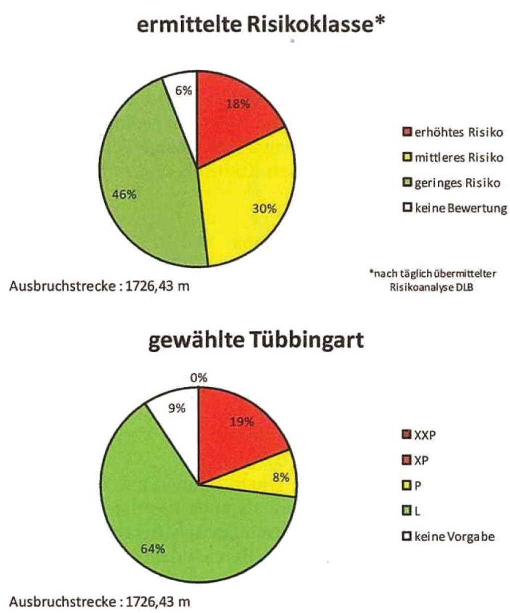

Figure 10. Risk class and segment types.

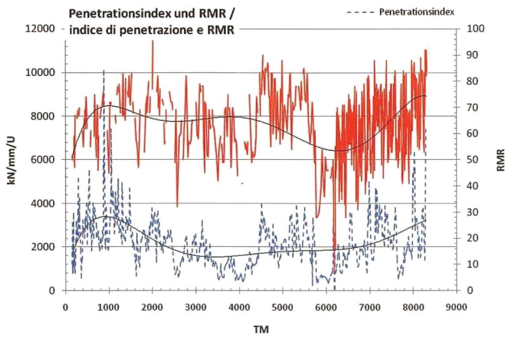

Figure 11. Penetration index as an aid to risk evaluation.

quality (measured by RMR values), the measures were selected and applied according to the risk management.

8 OUTLOOK

Tunnelling work in Aicha was completed in October 2010. The construction of the investigation tunnel by conventional and mechanical methods and the installed and interpreted instrumentation has provided valuable knowledge for the planning of the main tunnel bores.

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