A Fault Zone Management for Deep Seated Tunnels

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1. INTRODUCTION

Geological uncertainties and the ensuing risks in the construction of long tunnels at great depth has been described in the ITA Report no. 4 - Long tunnels at great depth (ITA) [1]: "*.... the deeper the tunnel, the larger the uncertainties; the higher the probability of encountering adverse or unforeseen conditions for tunnelling, the greater the effort and the cost for site investigations to reduce the uncertainties*".

Among the identified hazard sources, faults play a dominant role, due to their squeezing potential, swelling and creep, possible inflow of water (and/or gases) and debris, or eventual displacements along active shear zones.

Tunnelling through fault zones may therefore lead to critical events for both the construction process and the safety of the personnel. In order to minimise the risk, to be prepared in the case of an event or to overcome fault zones efficiently, a Fault Zone Management Plan has been developed. This Fault Zone Management Plan provides a systematic process developed for the cross-border BBT (Brenner Base Tunnel) railway tunnel at great depth between Italy and Austria (Bergmeister [2]).

Information from other base tunnels, the existing BBT geomechanical project and the knowledge from currently driven BBT exploratory and main tunnels will be taken into account in order to optimise the fault zone management process.

2. SPECIFICS FOR A TUNNEL AT GREAT DEPTH

2.1. General

Examining the design projects of tunnels at great depth, the experience gained from the first BBT exploration tunnels crossing different fault zones and from international tunnel projects served to define several specifics for tunnels at great depth. These specifics have to be considered in the fault zone management plan.

Experience in the BBT project include the following:

- Perpendicular main fault in granite crossed by the Aica-Mules exploration tunnel with a instationary inflow of 160 l/s (Perello et al. [3]).
- A fault zone in granite striking sharply to the tunnel axis of the Aica-Mules exploration tunnel: due to the deformation a four month stop of TBM followed (Barla et al. [4]).
- A fault zone striking perpendicular to the tunnel axis of the shallow tunnel "Saxen": the tunnel crossed a principal nappe fault with approx. 20 l/s instationary inflow.
- Main fault zones in the phyllite, striking parallel to the exploration tunnel Innsbruck-Ahrental and flat lying fault zones as crossed by the access tunnel Ahrental with approximately 15 l/s instationary inflow.

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2.2. Specifics for tunnels at great depth derived from design projects and experiences in fault zone crossing

Specifics for tunnels at great depth, which have to be considered in the Fault Zone Management Plan:

Regional character of tunnel projects at great depth:

- Due to the depth of the tunnels, the involved volume of the rock mass is large; this means that regional knowledge of the geology and hydrogeology is required.
- Long tunnels at great depth usually cross multiple tectonic units, therefore tunnels at great depth usually cross regional fault zone systems. Additional literature on this topic see e.g. Damiano et al. [8] and Eusebio et al. [9].
- Due to the regional character of the fault zone systems, similar faults may be crossed several times and even by different lots (e.g. NE-SW and N-S striking faults in the BBT project).
- Events may have a regional impact, larger than the actual construction lot limits.

Complex shear zones:

- Deformation along shear zones leads to the characteristics of the rock mass, including the fabrics and mineral assemblages.
- Major shear zones that cross the crust down into the upper mantle show both brittle and ductile sectors. Brittle fault related rock masses, such as breccias or gouges, are obviously related to most of the critical conditions for tunnels, both during excavation and operation.

Complex project:

- Tunnels at great depth have more construction lots.
- Tunnels at great depth have huge project teams, often situated in different places and even in different nations.

2.3. Risk management

The Risk Management paper published by the International Tunnelling Association (ITA) [5] is widely considered as a guideline. The AFTES Recommendations [6] follows this conceptual approach.

The insurance and re-insurance groups are very actively promoting the use of Risk Management at all stages of a project in order to minimize insurance losses. An International Code of Practice, (german version: Richtlinien zum Risikomanagement von Tunnelprojekten) which follows the ITA guidelines closely, has been published by the International Tunnelling Insurance Group (ITIG) [7].

In simple terms, the risk management approach consists in identifying and listing the potential hazards associated with the tunnelling activities, assigning a probability of occurrence to each hazard, and allocating an index of severity to the consequence. The next steps involves a definition of the measures to reduce the probability of occurrence of an event and to reduce the severity of the consequence (the so called "mitigation measures").

The analysis process prosecutes reassessing the remaining risk level after the application of the mitigation measures, obtaining an updated risk level, a "residual risk level". This "residual risk level" should be examined for acceptance (and then shared among the parties involved in the project) considering the "global cost" necessary for reducing or completely eliminate the source of risk.

The adoption of a RMP enhances the conceptual framework given by the "observational method" establishing a previously planned, sound and rational, framework for the design changes during construction that finally creates a favourable environment for cost or time savings and avoid unnecessary claims.

The proposed BBT approach for the risk management related with fault zones gives a comprehensive map of actions that shall be followed to avoid accidents together with the necessary countermeasures in presence of unfavourable conditions. But also it introduces a procedure for their continuous updating during construction, based on the registered evidences and feedbacks implementing appropriate amelioration if necessary.

3. FAULT ZONE MANAGEMENT - WORK PROCESS

3.1. Flow chart

The general structure of fault zone management in terms of working steps, necessary decisions and additional input is illustrated in the BBT Fault Zone Management Flow Chart (see Figure 1).

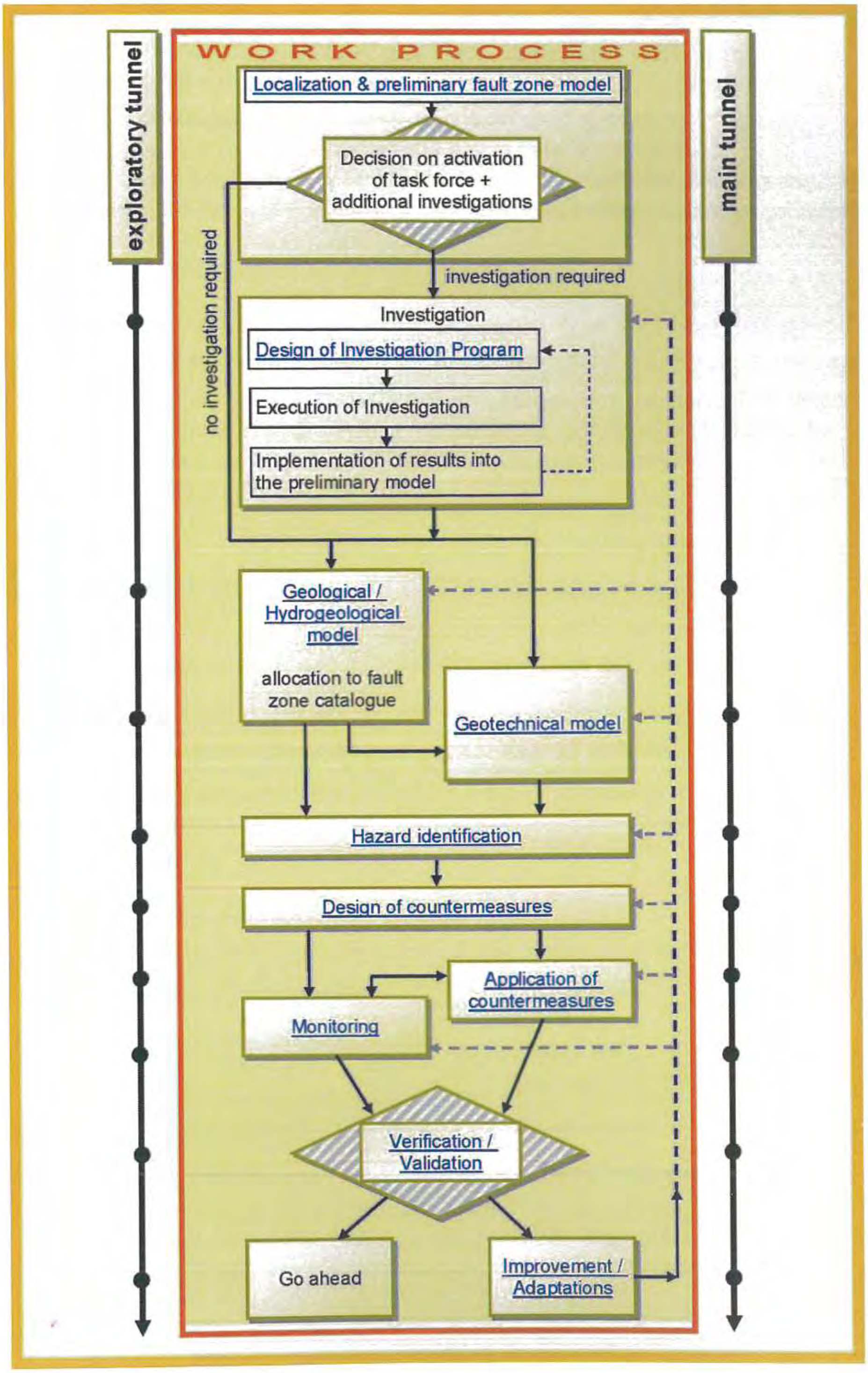

Figure 1: Fault Zone Management Plan – flow chart with main packages of the working process in the case of an event.

As can be seen from the flow chart, the Fault Zone Management Plan can be applied during the construction of the exploratory tunnel (see left black line on the flow chart) and the main tunnels (see right black line on the flowchart). The major steps (boxes) are described in the following chapters.

3.2. Localisation and preliminary fault zone model

On account to the large size of the project team it becomes necessary to provide a first characterization of the fault zone. The first fault zone model has to be distributed to all members of the project. Therefore a simple template has to be filled out by the site geologist, the site geotechnical engineer and the responsible person for the construction lot.

Main contents of the template are:

- Localization of the fault zone in relation to the tunnel
- Preliminary geological fault zone model including graphic illustration
- Decision whether or not the fault is situated in a zone with applicable authority requirements
- Decision about necessary additional investigations from a geological and / or geotechnical point of view
- Definition of the event class (minor, critical, major)
- Activation of required members

3.3. Investigation

If the first characterisation shows that an investigation programme is recommended for preparing the final geological and geotechnical model, a detailed investigation programme including the aim of the investigations has to be drawn up. The purpose of the investigation programme is to characterise in detail the fault zone with respect to:

- Localisation, orientation and geometry
- Material
- Hydraulics

A tool box with investigation methods and the related investigation interests is included in the fault zone management plan.

3.4. Geological, hydrogeological and geotechnical model

The geological / hydrogeological model shall contain at least all parameters included in the template of the fault zone catalogue (see Figure 2).

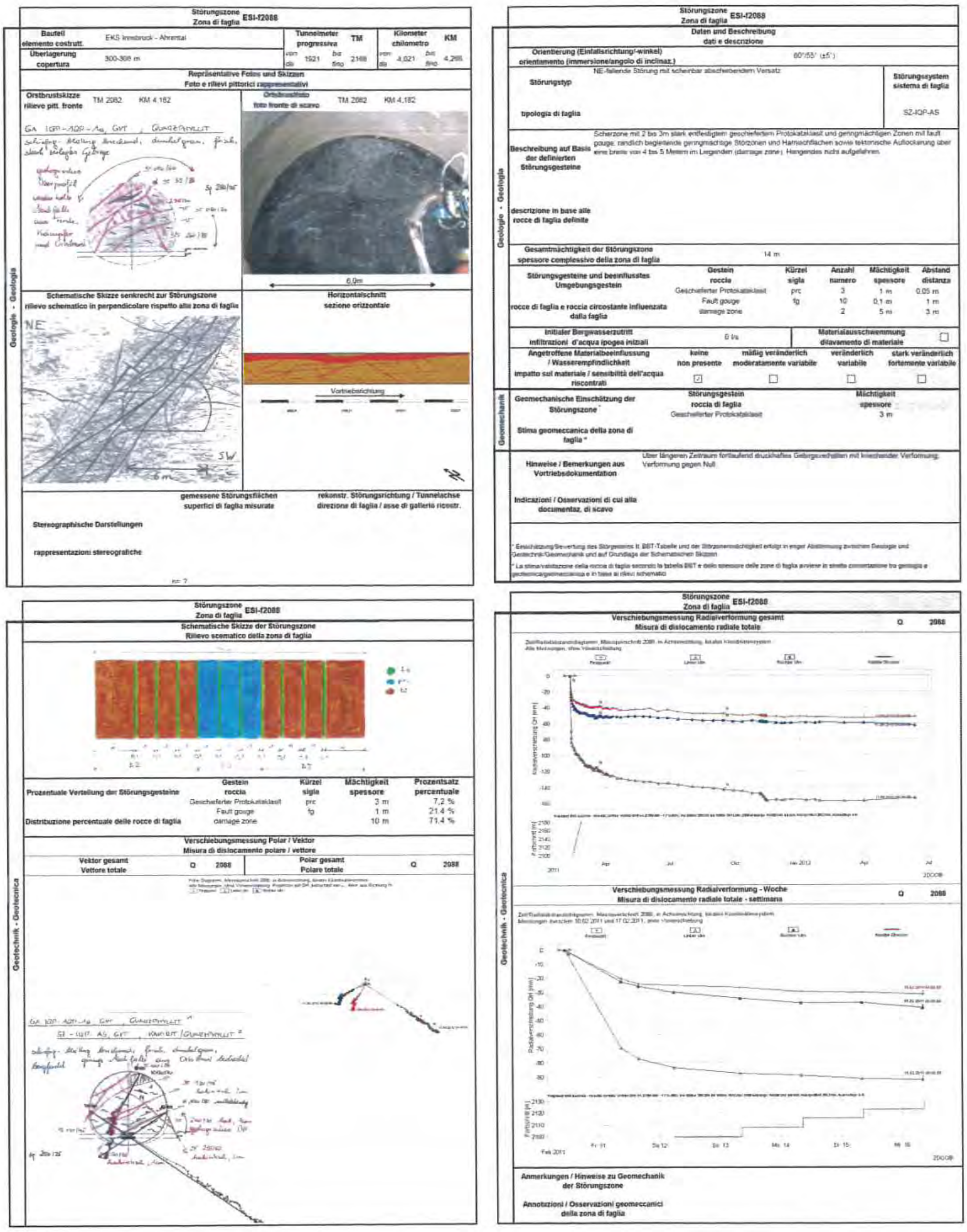

Figure 2: Template for the fault zone characterisation. The upper 2 sheets include a description, illustration and characterisation of the geology and geotechnics of the fault zone. The lower 2 sheets of the template contain information on the deformation behaviour in the case of available data from exploration tunnels. The example shows the information for a fault zone inside the Quartz phyllite striking parallel to the Innsbruck-Ahrental exploration tunnel and dipping east.

3.5. Hazard identification and definition of countermeasures

With the information obtained from the geological/hydrogeological and geotechnical model, the dominant hazard has to be identified and defined (hazard identification).

A table shall be used for the definition of the hazards (type) and their description (in columns). An excerpt of such a table is provided in the tool box (see Table 1). In the column labelled "indicators", parameters which could give an indication of the type of hazard are provided.

Table 1: Definition of possible hazards (excerpt).

Hazard Scenario for both Cyclic and Continuous Excavation		
Type	**Description**	**Indicators**
Tunnel face instability	Due to high primary stresses, favored by interfaces, jointed rock bodies and insufficient strength, blocks may detach themselves from the face thus rendering the face instable (see also instability ahead of TBM).	- Results from investigations ahead of the face provide information on the degree of fracturing - Observation of the unsupported tunnel face
Caving behind the shield / tunnel face	Uncontrolled rock fall of a large volume of rock mass behind the shield due to the retrograde process of a collapse ahead or above the TBM or due to insufficient support measures.	- In particular in areas consisting of brittle tectonic, cohesionless rock and materials similar to loose rock. - Sometimes announced by the occurrence of fissures in shotcrete and audible cracking in the rock mass.
Unacceptable deformations of tunnel	Squeezing rock can lead to inacceptable deformations at the edge of the excavation or of the applied support measures which may cause the need for a reconstruction of the lining or support measures.	- High primary stresses and low strength of the rock mass
Ingress and flooding (water / mud)	Intersecting water-bearing fault zones may cause significant water ingress. If the joints are filled with loose material or if a zone with hydrothermally altered rock is intersected, this may lead to an ingress of mud.	- Results from investigations ahead of the face - Progress of water pressure and of water flow - Progress of rock temperature
Rock bursts	Rock bursts describe a spontaneous process of stress redistribution in compact, brittle rock under high overburden. Rock bursts lead to audible shocks in the rock and to explosive separations at the surface.	- Warning signs: crackling and cracking - Peeling and flaking due to stress
Unacceptable deformation of above-ground surface	Tunneling has a drainage effect on the surrounding rock mass. This causes a change in the effective water pressures in the rock mass which may lead to above-ground surface settlements	- Continuous recording of the water leakages during the excavation facilitates early detection. - Monitoring of above-ground surface settlements.

For the design, a distinction is made between preventive countermeasures and those applicable in the case of the occurrence of an event.

- Preventive countermeasures
- Event-related countermeasures and equipment

A list with fault zone phenomena and proposed countermeasures from experience made during tunnel construction under comparable boundary conditions and corresponding references is given in a tool box (see Table 2).

The definition of possible hazards and preventive countermeasures are based on experience and on literature, e.g. Amberg [10], Bonzanigo et al. [11], Daller et al. [12], Fellner et al. [13], Ferrari et al. [14], Röthlisberger et al. [15], Sausbriber et al. [16], Stadelmann et al. [17], Weh et al. [18], Wildbolz [19], Ziegler [19].

Table 2: Fault zone phenomena and proposed countermeasures (excerpt). Cases A to D are referred to the knowledge of a fault zone: Case A = assumed fault zone; Case B = fault zone localized with investigations ahead of the tunnel; Case C = close to the tunnel lying fault zone localized by interpretation of monitoring data; Case D = intercepted fault zone.

Hazard Scenario for both Conventional and Continuous Excavation		
Type	**Preventative measure (Case A/D)**	**Countermeasures in the case of an event (Case B/C)**
Tunnel face instability	– Visual observation of material flow on conveyor belt – Maintain cutter head under permanent thrust – Limit the number and size of openings in the cutting wheel – Inclined Tunnel face / wedge	– Excavation with reduced thrust – Blasting or manually breaking up of blocks – Enhanced investigation ahead of the face and in case of possible cave-in, see Collapse ahead of TBM.
Caving behind the shield / tunnel face	– Installation of spiles – Provision of support measures – Strengthening of support measures – Drainage drilling – Grouting / injections	– Immediate installation of support – Installation of more support elements if needed – Installation of spiles – Grouting / injections
Unacceptable deformations of tunnel	– Systematic investigation ahead of the face – Strengthening of support elements – installation of provisional runway	– Systematic investigation ahead of the face – Strengthening of support elements – installation of provisional runway
Ingress and flooding (water / mud)	– Monitoring and interpreting water ingress in tunnel – Drilling using a preventer in case of mud – Provision of pumps and tubes – Controlled drainage of the rock in case of clear water – Grouting / injections in case of mud	– Controlled drainage of the rock in case of clear water – Grouting / injections in case of muddy water / mud – In case of ingress of hot water: additionally check tunnel climate

3.6. Application of countermeasures and monitoring

The designed countermeasures are applied in order to overcome the construction difficulties in the fault zone. Main steps are:

- The countermeasures have to be applied according to the design.
- During the application, the behaviour of the fault zone has to be observed and monitored intensively in order to be able to validate the design.
- A report on the application of countermeasures and the excavation has to be prepared (e.g. as-built reports from ÖBA/DL).

4. CONCLUSIONS

The proposed BBT fault zone management plan provides a comprehensive action plan that shall be followed in the case of an event. The plan includes different tool boxes such as proposals for required countermeasures in presence of unfavourable fault zone conditions during the excavation process.

The presence of a permanent team of specialists, specifically working within the framework of the "fault zone management approach", facilitates transferring the continuously identified design and construction "best procedures and solutions" into the subsequent design and tunnel construction packages.

The advantages derived from this ongoing "learning, test, apply and transfer" sequence will provide a wealth of experience to the whole project team.

Experience in the next BBT construction lots may provide the opportunity to validate and verify the action plan and to improve and adapt it.

References

[1] ITA WG 17. 2010. *Long Tunnels at great depth.* http://www.ita-aites.org/en/wg-committees/committees/itatech/downloads/content/22/working-group-17-long-tunnels-at-great-depth. (last access 08/2013).

[2] Bergmeister, K. 2011. *Brenner Basistunnel – der Tunnel kommt.* pp. 263, Lana: Tappeiner.

[3] Perello, P., Baietto, A., Burger, U. & Skuk, S. 2013. Excavation of the Aica-Mules pilot tunnel for the Brenner base tunnel: experience gained on water inflows in tunnels in granitic massifs. *Rock Mechanics and Rock Engineering.* In press.

[4] Barla, G., Ceriani, S., Fasanella, M., Lombardi, A., Malucelli, G., Martinotti, G., Oliva, F., Perello, P., Pizzarotti, E.M., Polazzo, F., Rabagliati, U., Skuk, S. & Zurlo, R. 2010. Problemi di stabilità al fronte durante lo scavo del cunicolo esplorativo Aica - Mules della Galleria di base del Brennero. In: Barla, G. & Barla, M., Proc. *XIII ciclo di conferenze di meccanica e ingegneria delle rocce MIR 2010, Torino.*

[5] ITA Working Group No. 2. 2004. Guidelines for tunnelling risk management. *Tunnelling and Underground Space Technology* 19, pp. 217-237.

[6] AFTES Recommendation GT32.R2A1. 2012. Recommendations on the characterisation of geological, hydrogeological and geotechnical uncertainties and risks.

[7] International Tunnelling Insurance Group (ITIG). 2006. Richtlinien zum Risikomanagement von Tunnelprojekten ("*A Code of Practice for Risk Management of Tunnel Works*").

[8] Damiano, A., Venturini, G., Alzate, M., Mancari, G., Dematteis, A., Soldo, L. & Vendramini, M. 2011. The Reference Geological Model for the Corredor Bioceanico Aconcagua project. In: *Congrés International AFTES*: Lyon.

[9] Eusebio, A., Soldo, L., Pelizza, S. & Pettinau, D. 2005. Preliminary geological studies for the design of Mercantour base tunnel. *AFTES Tunnelling for a sustainable Europe*: Chambery.

[10] Amberg, F. 2006. Geologie, Vortriebsmethoden und Bauhilfsmassnahmen in der Multifunktionsstelle Faido. *Geologie und Geotechnik der Basistunnels*, pp. 225-237, Zürich: Löw Hochschulverlag.

[11] Bonzanigo, L. & Oppizzi, P. 2006. Low Angle fault zones and TBM excavation in Bodio section of Gotthard Base Tunnel. *Geologie und Geotechnik der Basistunnels*, pp. 156-184, Zürich: Löw Hochschulverlag.

[12] Daller, J., Atzl, G. & Weigl, J. 2011. The new Semmering base tunnel – tunnel design in the fault zone. *Geomechanics and Tunnelling* 4 (3), pp.237-253, Berlin: Ernst & Sohn.

[13] Fellner, D., Bachmann, M. & Bönsch, W. 2007. DS-TBM over its Limits" / Schwierigkeiten mit Zuckerkörnigem Dolomit beim Bau des Shanggongtunnels in Südwestchina. In: *Internationales Symposium BBT*: Innsbruck.

[14] Ferrari, A., Fabbri, D. & Sidler, M. 2007. Bewältigung von unerwarteten Störzonen beim TBM-Vortrieb im Gotthard-Basistunnel Baulos Bodio. In: *Internationales Symposium BBT*, pp. 56-62: Innsbruck.

[15] Röthlisberger, B., Stadelmann, R. & Wei, Z.Q. 2007. Bewältigung der Herausforderungen im Bauabschnitt Faido des Gotthard Basistunnels. In. *International Symposium BBT*: Innsbruck.

[16] Sausbriber, T. & Brandner, R. 2001. The relevance of brittle fault zones in tunnel construction. Lower Inn Valley Feeder Line North of the Brenner Base Tunnel, Tyrol, Austria. *Mitt. Osterr.Geol. Ges.* 94, pp. 157-172.

[17] Stadelmann, R., Rehbock-Sander, M. & Rausch, M. 2007. Crossing of fault zones in the MFS Faido by using the observational method. *Underground Works under Special Conditions*. Romana, Perucho, Olalla (eds). London: Taylor & Francis.

[18] Weh, M. & Bertholet, F. 2011. TBM advance in the main adit to the Nant de Drance pumped storage power plant. *Geomechanics and Tunnelling* 4 (5), pp. 284-591, Berlin: Ernst & Sohn.

[19] Wildbolz, A. 2006. Befreiung der Tunnelbohrmaschine Gabi II in Amsteg. *Schweizer Baujournal.*

[20] Ziegler, H.-J. 2011. 150 km Vortrieb durch die Alpen – Ingenieurgeologische Erfahrungen. In: *Swiss Tunnel Congress 2011.*

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