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ORIGINAL ARTICLE

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Risks and hazards caused by groundwater during tunnelling: geotechnical solutions used as demonstrated by recent examples from Tyrol, Austria

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Abstract As demonstrated by recently excavated reconnaissance tunnels, uncontrolled water ingresses frequently pose a risk to tunnels and the tunnelling crew despite ever-improving tunnelling methods. This is regardless of the type of rock encountered and can result in significantly increased construction costs.

Keywords Tunnelling · Water and material ingress · Geotechnical solutions · Austria

Introduction

Despite constantly improving tunnelling methods, groundwater remains a decisive influencing factor in tunnel construction, when using NATM (New Austrian Tunnelling Method). During the exploration phase of the Feeder Line North, which is part of the future Munich–Verona High-Speed Railway Route (Fig. 1), five reconnaissance tunnels were recently excavated in the Lower Inn Valley, Tyrol, Austria, to clarify open project strategic and project-relevant geological, geotechnical and hydrogeological questions on the one hand and to obtain the information necessary for compiling the main tendering documents on the other hand. Three of these are used as examples to highlight the risks and hazards, which arise from uncontrolled groundwater ingresses during excavation, for the tunnel as a structure, the tunnelling crew and the environment. The reconnaissance tunnels, with a total length of approximately 8.5 km, were excavated along the geotechnically most demanding route sections of the approximately 42 km long stretch through the Lower Inn Valley, where 85% of this stretch is underground.

The project area lies at the southern boundary of the Northern Calcareous Alps comprising thick sequences of Permo-Mesozoic sedimentary rocks, including carbonates, siliciclastic sediments and evaporates. Besides hard rock, the route includes several soft rock sections. These are formed by thick sequences of Quaternary deposits of a proglacial environment, building up terraces along the mountain front, and younger fluvial sediments of the Inn river.

Vomp East reconnaissance tunnel

Rock mass structure and hydrogeology

The western section of Vomp East reconnaissance tunnel traverses Pleistocene deltaic deposits. Within this sequence the distal delta, where coarse-grained sediments of the foresets alternate with fine-grained sediments of the bottomsets, constitutes the geotechnically most demanding tunnel section. The rock mass is characterized by fan-shaped sequences of gravels of varying grain size intercalated with sandy silts, dipping moderately

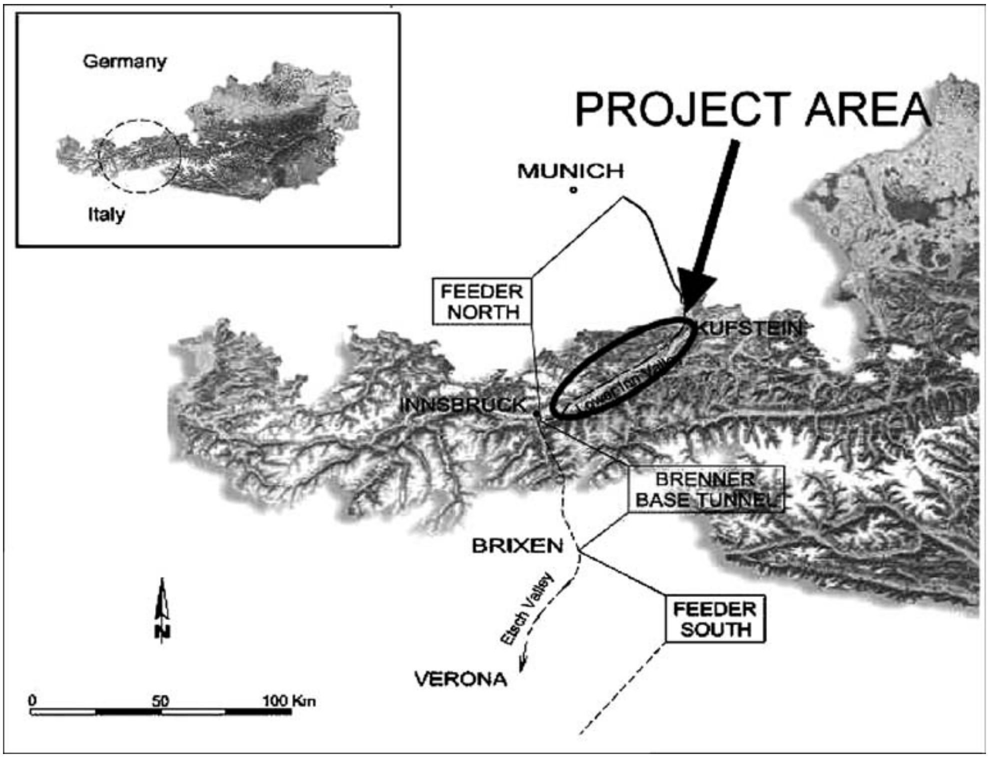

Fig. 1 The High-Speed Railway Project Munich–Verona including the Feeder Line North between Kufstein and Innsbruck which runs parallel to the Lower Inn Valley, the 55 km long Brenner Base Tunnel and the Feeder Line South

against the direction of advancement. The litho-structure, alternating with water-bearing and impermeable sequences, results in a system of confined water bodies where the water pressure varies between 3 and 5 bar (Fig. 2).

Relevance to tunnelling methods: tunnelling hazards

When the fine-grained sequences were intersected, a hydraulic ground failure occurred twice in the bottom left corner of the bench. Due to the water pressure (3–5 bar), they were accompanied by water ingresses of up 50 l/s which developed extensive erosive forces (Fig. 3). Those processes resulted in the formation of cavities of up to several 100 m^3 next to the tunnel structure. Possible scenarios during further advancement varied between stability problems of the tunnel face and sudden failure of the tunnel structure due to redistribution of rock mass loads. Besides economic damage due to advance stops, all of them posed an incalculable risk for the tunnelling crew and the tunnel itself.

Tunnel construction measures

From the available soil investigation data (reconnaissance tunnel and core drillings) it could be assumed that the geological conditions ahead of the face were not going to change significantly for the next 150 tunnel metres. Therefore, the tunnelling concept was adapted. Injection measures turned out to be unsuitable due to the high percentage of very dense and fine-grained sediments. It soon became apparent that tunnel excavation using mining methods in such ground conditions could only be carried out by lowering the groundwater table to tunnel level.

The section was finally managed by a combination of drainage umbrellas in the invert and pipe umbrellas covering the top heading and the bench (Fig. 3). By doing so, the geological and hydrogeological information from the drainage and pipe umbrellas was evaluated to continuously adjust the geological model and to consequently use it for optimizing the number and position of drainage drillings. This proved to be very important for the success of the measure.

Brixlegg West reconnaissance tunnel

Geological model and tunnelling concept

Over a length of 170 m the Brixlegg West reconnaissance tunnel crosses the Matzen Park syncline which is filled with Quaternary, proglacial sediments, a heterogeneous sequence of sandy gravels and fine-grained sediments (Eder et al. 2003; Nemec 2002). The structure of the syncline can be put down to glacial activity,

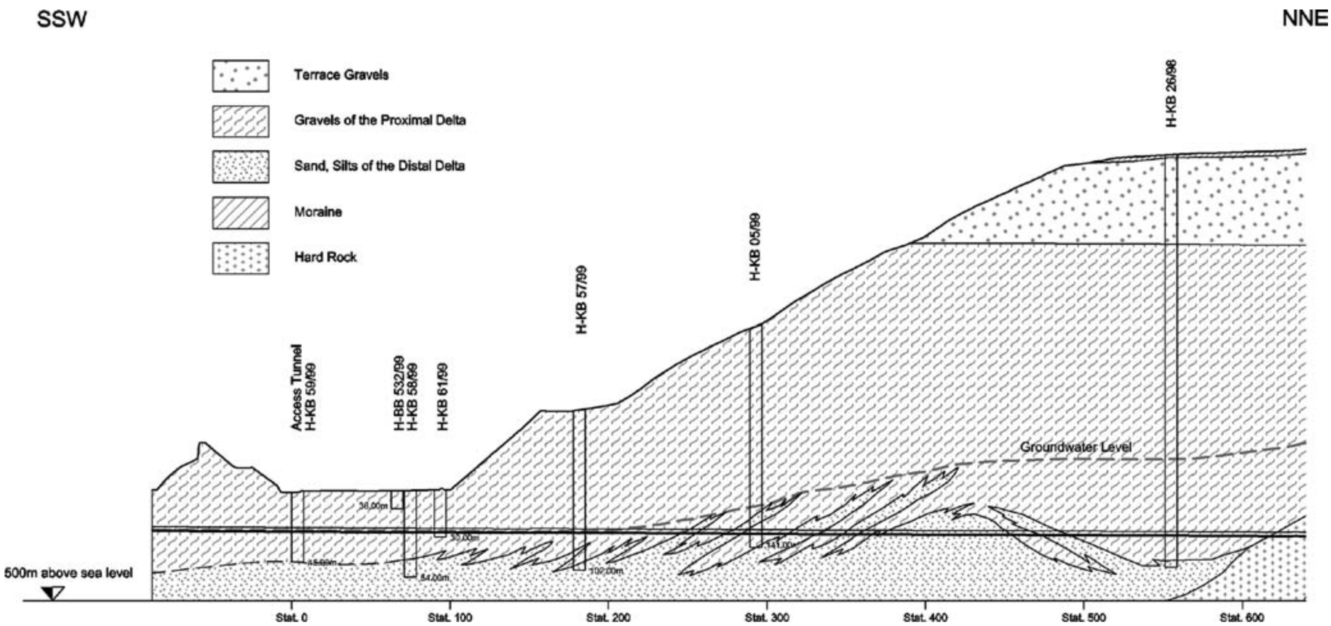

Fig. 2 Longitudinal section of the soft rock stretch of the Vomp East exploratory tunnel. Groundwater level refers to the project stage when the tunnel entered the distal delta section with interbedding of sand/silts and gravels

creating a hanging valley which joins the over-deepened Inn Valley below the current valley bottom. The varying litho-structure results in a complex hydrogeological system of slope-water aquifers which communicate with the main Inn Valley aquifer, reaching water pressures at tunnel level of up to 1.5 bar. As a result of the extensive reconnaissance works, the authors were able to identify three major groundwater horizons and several small, confined water bodies within the Matzen Park syncline.

Tunnelling concept

As the ‘‘Matzen Park’’ is a protected natural area, the public authorities initially required that no above-ground construction measures (e.g. cut and cover) should be used. To meet this requirement and to cope with the difficult geological and hydrogeological ground conditions as well as the shallow overburden (maximum 20 m), special construction measures had to be applied. The initial excavation concept for crossing the Matzen Park syncline foresaw the construction of a system of overlapping cones of columns around the tunnel, with the face of each cone shielded by a stopper made of shorter columns (Fig. 4). The columns were produced using jet-grouting techniques. As an additional support measure, an injection umbrella was constructed prior to each jet-grouting cone. This measure was abandoned after a few tunnel metres for reasons of high costs.

Risk scenario

Difficulties arose when the columns could not be constructed in the necessary dimension and defective areas between them led to the danger of water and material ingresses.

At the sixth cone this scenario became a reality which culminated in the development of a sinkhole on ground level with a diameter of approximately 10 m. After additional strengthening of the ground around the tunnel by means of grouting, tunnel excavation was continued. However, ongoing problems in the construction of the jet-grouting columns finally made the client abandon this excavation concept due to the involved safety problems and disproportionally high costs.

New tunnel construction concept and measures

As a consequence of the encountered problems, the public authorities were convinced of the necessity of above-ground auxiliary measures, such as the construction of a diaphragm wall and groundwater draw-down (Fig. 5). Sealing off the Matzen Park syncline from the Inn Valley aquifer allowed this difficult route section to finally be successfully advanced. But additionally it has to be mentioned that, due to the complex geological and hydrogeological situation, the success of the measure depended more on the number of drainage wells (12) than on the amount of pumping. Furthermore, despite the large number of drainage wells, an element of risk

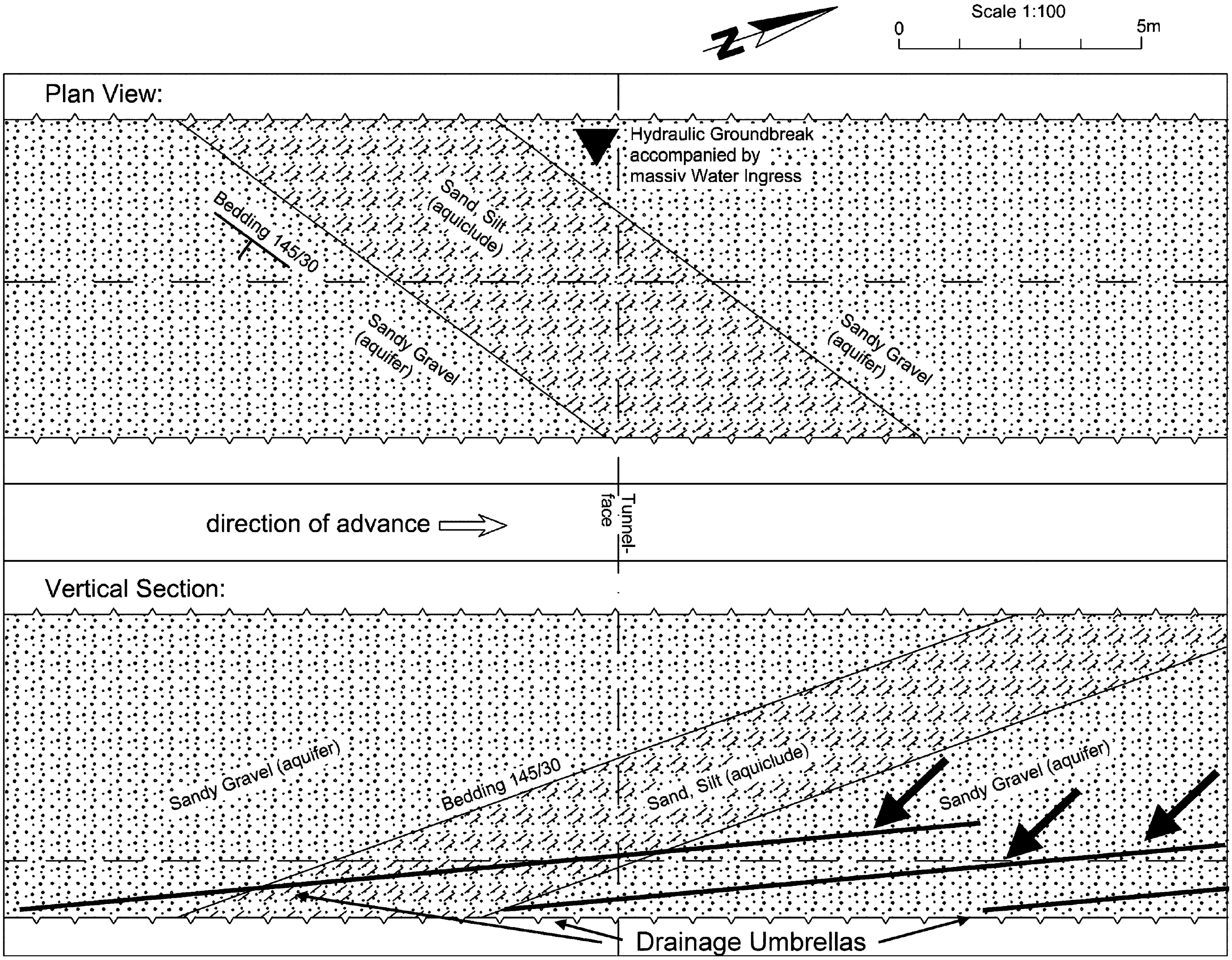

Fig. 3 Geological and hydrogeological situation in the distal delta section of the Vomp East reconnaissance tunnel. The *plan view* shows the position where hydraulic ground breaks occurred, due to the special lithological and structural situation. The *vertical section* shows the measures (drainage umbrella in the invert) to draw-down the groundwater table ahead of the tunnel face

remained due to small confined groundwater bodies, which could not be drained.

Brixlegg East reconnaissance tunnel

Geological model

The Brixlegg East reconnaissance tunnel runs along the tectonically complex southern boundary of the Northern Calcareous Alps. The rock mass structure along this 2.2 km long tunnel comprises heterogeneous sequences of carbonates, marls and slates with varying degrees of fracturing (Sausgruber and Brandner 2003). The tunnel was excavated using drill and blast techniques.

Shortly before the planned end of the tunnel, the drilling of an anchor hole led to an ingress of water (25 l/s) and a flushing out of a few cubic meters of soil-like material. At this point the tunnel crossed a sequence of carbonates with an increasing degree of fracturing of the rock mass.

The ensuing reconnaissance programme revealed a fault zone of up to several tens of metres in thickness, filled in part with unconsolidated soil-like material. This fault zone was predicted to cross the excavation line, at a low angle, only a few meters ahead of the tunnel face (Fig. 6). Furthermore, the investigations revealed that the fault zone was highly permeable containing water at pressures of up to 5.0 bar. The high mineralization of the water suggested a connection to nearby, commercially used spa-water springs.

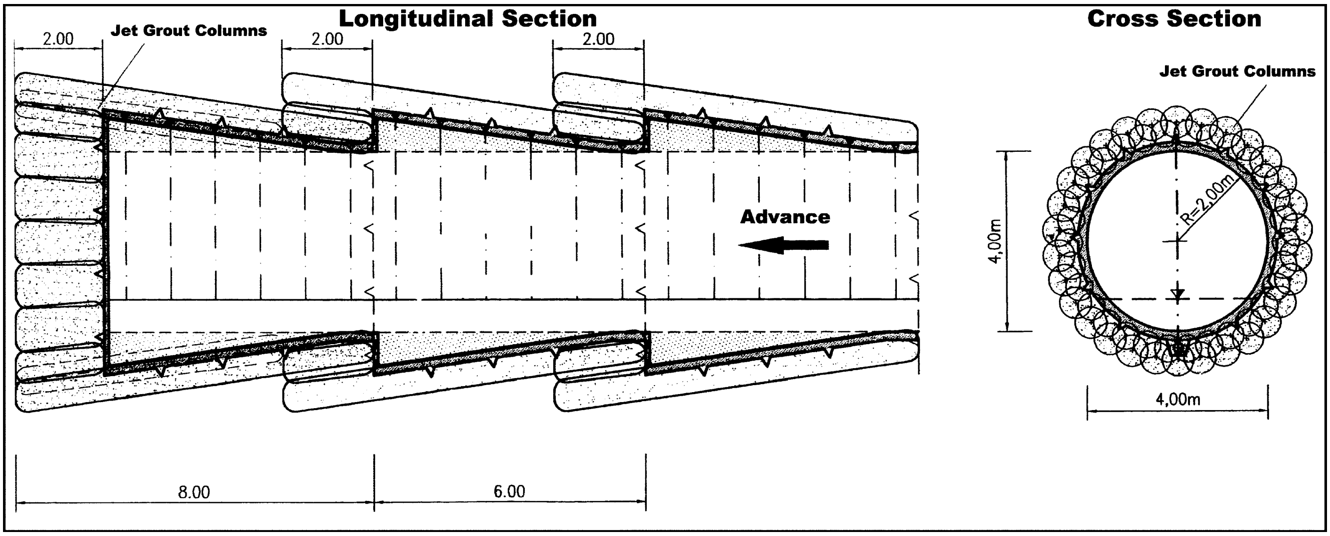

Fig. 4 Brixlegg West reconnaissance tunnel, initial tunnelling concept: overlapping cones of columns around the tunnel with the face shielded by a stopper system of shorter columns, using jet-grouting techniques

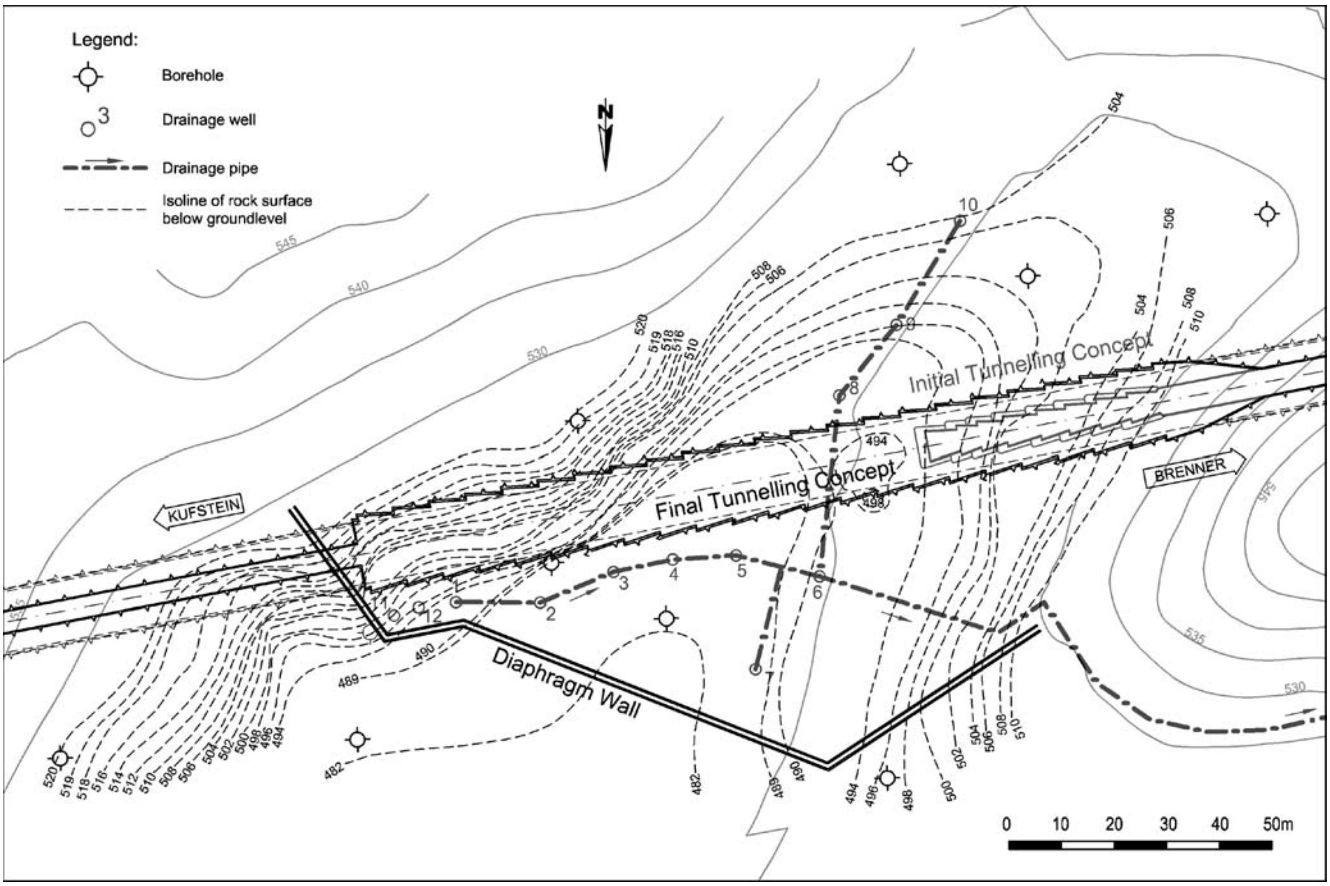

Fig. 5 Map of the Matzen Park section in soft rock showing the initial and final tunnelling concepts: initial tunnelling concept using jet-grouting techniques, final tunnelling concept using diaphragm wall, groundwater draw-down and pipe umbrellas

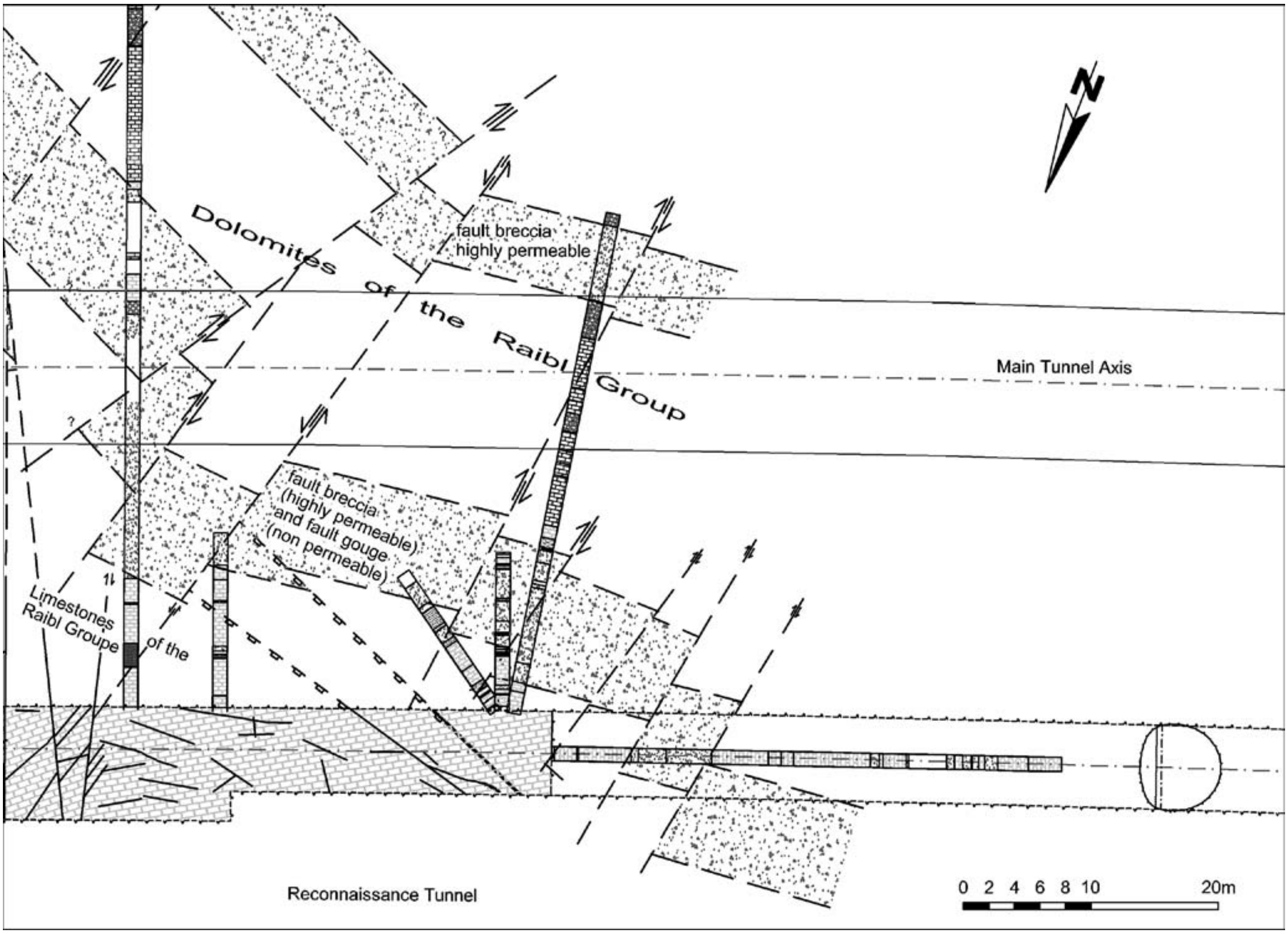

Fig. 6 Map of the fault zone encountered in the Brixlegg East reconnaissance tunnel (sectional plane is at tunnel level). *Columns* represent exploratory drillings. The bedding of the Raibl strata, consisting of marls, shales and carbonates, is nearly vertical and strikes at a low angle to the tunnel alignment. Kakirite zones are offset by sinistral and dextral strike-slip faults several times

The findings pointed to the following scenarios:

- Impacts on the stability of tunnel structure due to large-scale flushing out of material and the resulting change in load distribution within the rock mass
- Impact on groundwater aquifers and especially on the adjacent spa-water aquifer
- Danger to the tunnelling crew due to water ingresses in combination with large-scale flushing out of material

Tunnelling solutions

To manage this fault zone, the client explored alternative excavation concepts. A large-scale injection test did not lead to the desired result, namely the successful resumption of tunnelling (Reichl et al. 2002). Two draw-down tests were carried out to investigate the possibilities of lowering the groundwater table and exploring the effects. At the same time an extensive hydrological/geotechnical monitoring and testing programme was pursued to investigate the groundwater properties and to evaluate the impacts on the groundwater system and the above-mentioned spa-water aquifer (Mammel et al. 2003, Poscher et al. 2002). On the one hand, the results showed that artificial draw-down could be used to manage the fault zone; on the other hand they also provided clear proof of a quantitative and qualitative, but reversible, impact on the spa-water aquifer, which is why tunnelling has not been resumed for the time being.

Conclusions

As demonstrated by recently excavated reconnaissance tunnels, water ingresses still pose a major risk to tunnel advance despite modern tunnelling techniques. In any case, such incidents are always linked to economic damage.

However, it is not only the amount of water but also the combination of the amount of water and geological/hydrogeological situation which play a decisive role in the case of groundwater ingresses. All three previous examples have shown that, when tunnelling in poor ground conditions, only a few litres of water per second is sufficient to significantly increase the costs, cause major delays or even stop the tunnel advance.

Detailed geological and hydrogeological investigations are essential to recognize groundwater-related risks and hazards at early project stages and to consider them in the design. However, the authors have learned once more that despite extensive reconnaissance work during tunnel design as well as tunnel advance, groundwater-related incidents cannot always be recognized and prevented in time when tunnels are to be constructed in complex geological situations. However, the experiences have also shown that a flexible adjustment of the excavation concept, using NATM, allows such situations to be handled successfully. To reduce the risk of unexpected incidents, not only continued exploratory work during tunnelling but also continued extrapolation and adaptation of the geological and hydrogeological model are absolutely necessary.

References

Eder S, Poscher G, Schwarz L (2003) Geotechnical and hydrogeological models used for tunnelling in quaternary sediments: examples from the “Northern Feeder Line”, Railway-Axis Brenner, 14. Tagung für Ingenieurgeologie, pp 77–82

Mammel R, Reichl I, Schwarz L, Fisch H (2003) Does groundwater pose a risk to underground structures or do underground structures pose a risk to groundwater recourses? RMZ Mater Geoenviron 40(1):209–212

Nemec C (2002) Ausbau der Unterinntalbahn. Felsbau 20(5):87–95

Poscher G, Fisch H, Mammel R, Sedlacek C (2002) Konfliktfeld Untertagebau und alpine Wasserrecourcen. Felsbau 20(5):101–111

Reichl I, Wollmarker R, Stadler G, Schretter K, Eder E (2002) Erkundungsstollen Brixlegg Ost, Beispiel für die Grenzen der Wirksamkeit von Felsinjektionen. In: Proc 17, Christian Veder Kolloquium, pp 177–192

Sausgruber T, Brandner R (2003) The relevance of brittle fault zones in tunnel construction—Lower Inn Valley feeder line north of the Brenner Base Tunnel, Tyrol, Austria. Mitt Österr Geol Ges 94:157–172