Design-Construct Contract under Difficult Geotechnical Conditions – A Wise Decision?

By Terry Chen, Jason Hou, Alfred Fasching, Gunter Riedmüller and Wulf Schubert

In complex geological conditions there is an inherent uncertainty in the geological-geotechnical model developed during design. Such conditions require that during construction decisions on the applicable pre-treatment and support measures should be performed on site. Representatives from the owner, designer, and contractor must work together to solve the encountered problems in a cost effective and efficient manner. These provisions govern the type of contract issued for the construction. An example from Taiwan is used to describe how the geological conditions determined during the site investigation influenced the owners decision on the type of contract issued for the work.

Ist ein Planungs-Bauausführungs-Vertrag bei schwierigen geotechnischen Verhältnissen klug?

Im Nordosten von Taiwan wird eine 86,5 km lange Autobahn zwischen den Städten Suao im Norden und Hualien im Süden geplant. Aufgrund der topographischen Verhältnisse entlang der Steilküste zum Pazifik ist der Bau von insgesamt elf zweiröhrigen Tunneln mit einer Gesamtlänge von rund 40 km erforderlich. Die maximale Überlagerung beträgt 875 m. Aufgrund der komplexen geologischen Verhältnisse mit einer intensiven Überschiebungstektonik und Ausbildung von Strike-Slip Duplex Strukturen werden geotechnisch sehr schwierige Verhältnisse für den Bau erwartet wie große Verformungen und starke Wasserzutritte. Der Bauherr beabsichtigte, Teilabschnitte in Form von Planungs- und Bauausführungs-Verträgen international auszuschreiben. Diese Verträge würden die Baugrunderkundung für die Detailplanung, die Detailplanung sowie den Bau beinhalten. Unterschiedliche Modelle für die Aufteilung des Baugrundrisikos wurden bisher untersucht. Es steht zur Diskussion, ob die beabsichtigte Vertragsform unter den gegebenen Baugrundverhältnissen zielführend sein kann.

In the Northeast of Taiwan a 86.5 km long motorway is under design, linking Suao in the North and Hualien in the South. Eleven tunnels with a total length of about 40 km are required due to the rugged mountainous terrain. The alignment crosses mountain ridges with a maximum overburden of 875 m. Due to the complex geological environment, which includes imbricate thrusts and strike slip duplexes, great difficulties during excavation are expected, such as high displacements, heavy water inflow, and flowing ground. The owner intended to award a design construct contract in an international tender. This contract would include the investigations for the detail design, the detail design and the construction. Different models for sharing the geological risk have been evaluated, but a final conclusion has not been reached up to now. It shall be discussed, if such a contract model is appropriate for such conditions at all, and if so, which role the owner preferably plays to protect his interests.

The Eastern Expressway Project will connect the cities of Suao and Hualien along the East coast of Taiwan and has a total length of 86.5 km. The layout of the project is shown in Figure 1. For about three quarters of its length the alignment of the expressway runs more or less parallel to the steep coast, close to the shoreline. The rugged mountainous terrain with steep mountain slopes dipping towards the Pacific coast are intersected by deeply incised riverbeds. Optimizing the alignment required the construction of a total of eleven double-tube tunnels, which, in most cases, are connected by bridges. The length of the tunnels ranges from 190 to 10 143 m. The tunnel sections add up to a total length of 40 km. The size

Fig. 1 Alignment of the Eastern Expressway Project between Suao in the North and Hualien in the South.

Bild 1 *Trasse des Eastern Expressway Projektes von Suao im Norden nach Hualien im Süden.*

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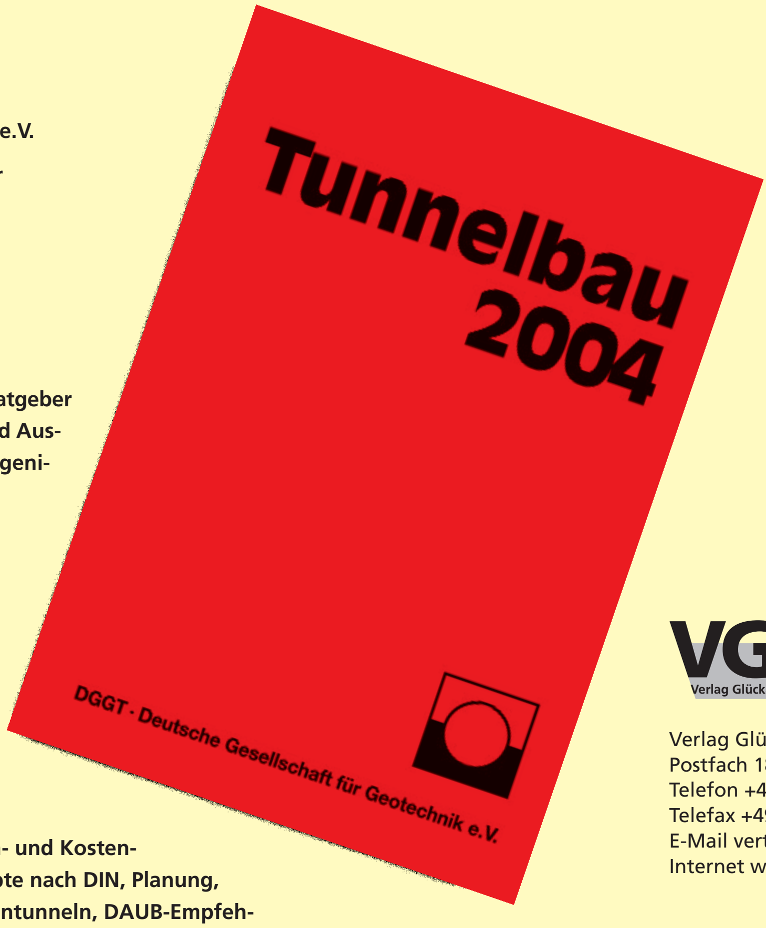

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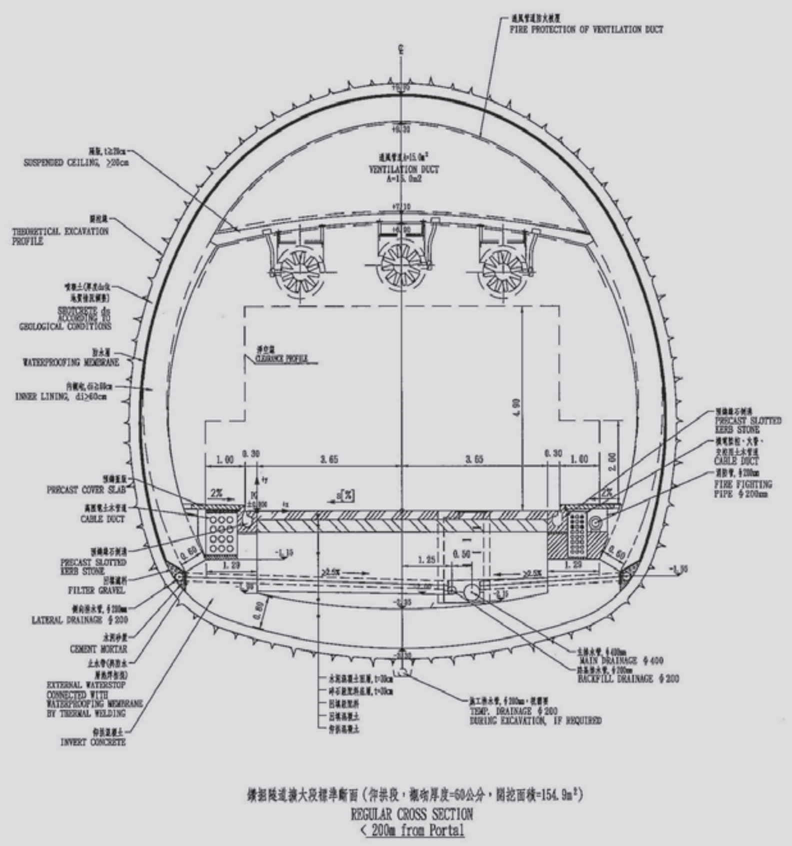

Fig. 2 Regular tunnel cross section with air duct and ventilation fans; size of excavated cross section 154,9 m².

Bild 2 *Regelquerschnitt für Tunnelabschnitte mit Luftkanal und Strahlventilatoren; der Ausbruchquerschnitt beträgt 154,9 m².*

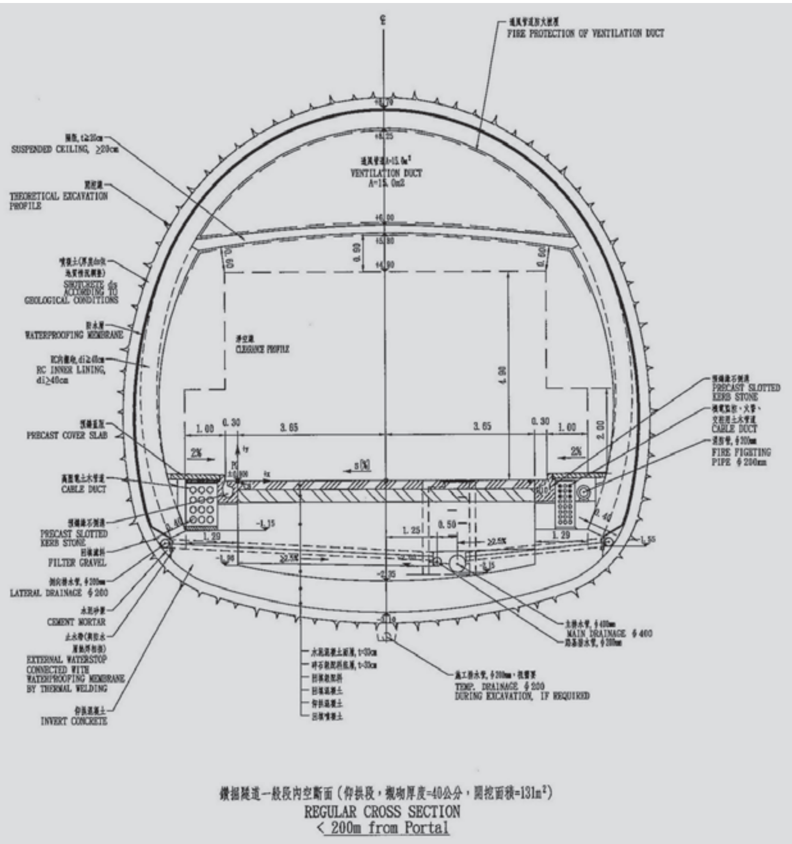

Fig. 3 Regular tunnel cross section with ventilation duct; size of excavated cross section 131 m².

Bild 3 *Regelquerschnitt für Tunnelabschnitte mit Luftkanal; der Ausbruchquerschnitt beträgt 131 m².*

of excavation cross section varies between 115.1 and 154,9 m², depending on ventilation requirements and the shape of the invert (Figures 2 and 3). To optimize the overall project construction time and to shorten the pre-tender design phases the owner had originally planned to choose a design and construct contract model for the long tunnels such as Tunnel No. 6 with a length of 7 750 m and Tunnel No. 7 with a length of 4 450 m.

During the earlier design stages ground investigation programs were executed, consisting mainly of geological mapping, a limited number of core drillings, geophysical investigations and laboratory tests on core samples. As the intention of the client was to go for a design and construct contract the investigation measures for these tunnels were limited to a basic design level. In addition, the execution of ground investigations in the field was hampered by the fact that parts of the project area are classified as natural protection areas. Other parts are not accessible at all by conventional means due to extreme topographic conditions. Access to proposed drilling locations could not be achieved within the project time schedule or was prohibited.

The ground investigation program and the engineering geological-geotechnical evaluation, which was performed by the Geotechnical Department of China Engineering Consultants Inc. with assistance of 3G Gruppe Geotechnik Graz ZT GmbH, revealed that the geological and geotechnical conditions of this area are of such complexity that the proposed contract model for Tunnels No. 6 and No. 7 had to be reconsidered (1, 2). A discussion on the applicable contract models follows the outline of the geotechnical conditions in the project area.

The complexity of the tectonic architecture of the project area became evident especially in the alignment study for Tunnel No. 4, which is located north of Tunnels No. 6 and No. 7. To ensure a consistent geological-geotechnical model a volumetric 3D model of the project area was developed by 3G as the basis for this alignment study (Figures 4 and 5).

Geological Setting

The island of Taiwan is located in a tectonically complex region where the Ryukyu and Manila Trenches meet at the northwestern corner of the Philippine Sea Plate (Figure 6). The northwestern movement of the Philippine Sea Plate at a rate of 8.2 cm/year, creates the Taiwan collision zone, which is made up of a series of sub-parallel thrust faults that run in north and northeast directions in Taiwan (3, 4, 5). Whereas the southern part of the island is affected by a compressional regime the northern part of the island is currently affected by extension. The project area is just north of the major strike-slip fault, the Longitudinal Valley Fault, which separates the

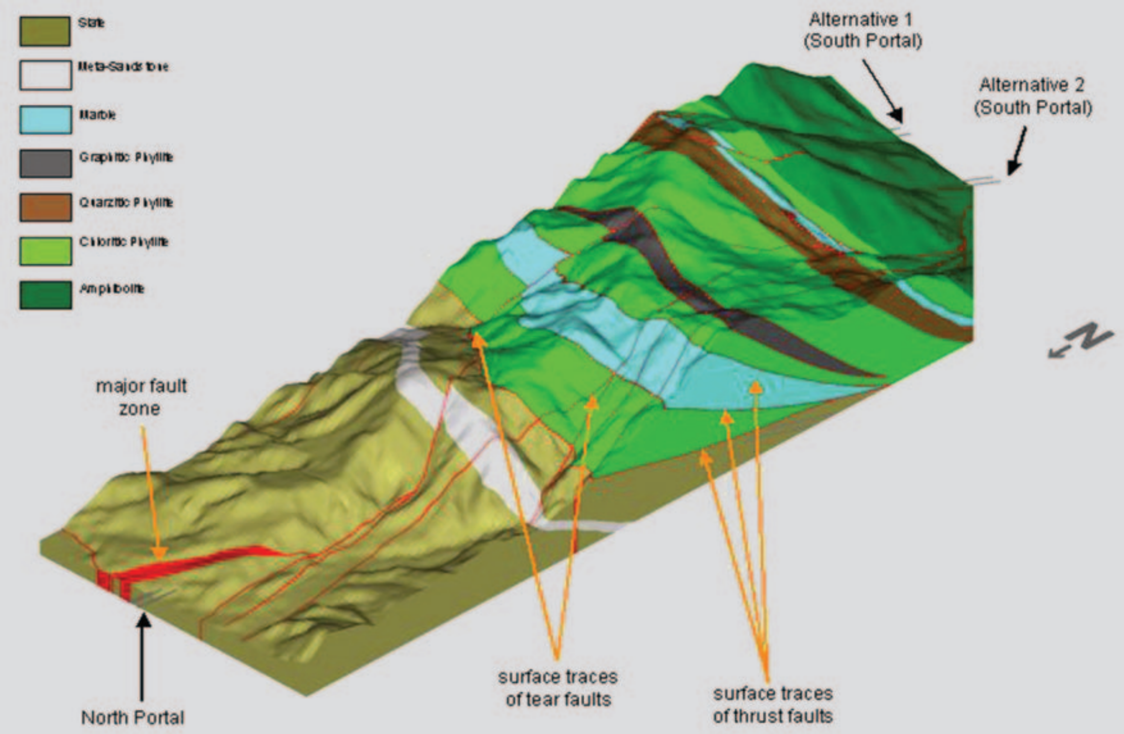

Fig. 4 Volumetric 3D model of the area of Tunnel No. 4. The model contains the lithological units and tectonic main structures (Figure 5).

Bild 4 *Volumetrisches 3D-Modell des Abschnitts von Tunnel Nr. 4. Das Modell beinhaltet die lithologischen Einheiten sowie die tektonischen Hauptstrukturen (Bild 5).*

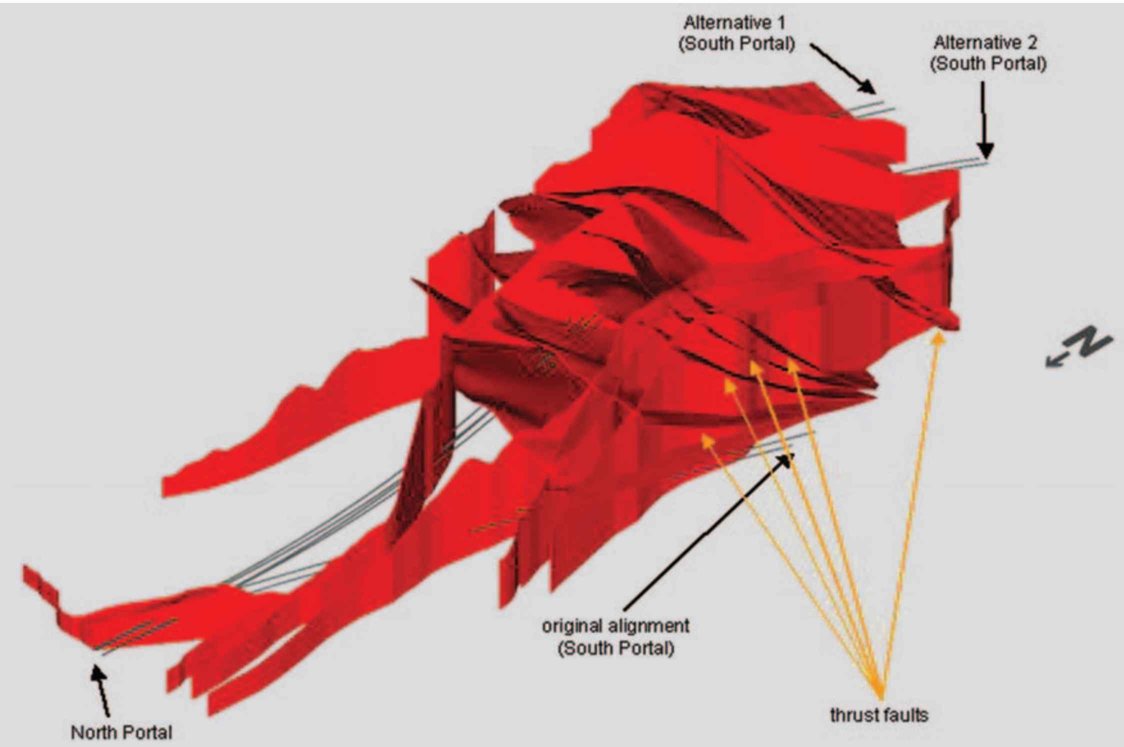

Fig. 5 3D model of fault inventory of Tunnel No. 4, dominating tectonic structures are imbricated thrust faults in combination with tear faults.

Bild 5 *3D-Modell der Störungszonen im Bereich des Tunnels Nr. 4. Dominierende tektonische Strukturen sind Überschiebungszonen in Verbindung mit Querverschiebungszonen.*

Eurasian Plate from the Philippine Sea Plate and south of the Ilan Basin, which is the western-most part of the Ryukyu Trench (6, 7). The project area contains all the tectonic features associated to this tectonic environment, such as ductile folding and brittle faulting.

The rock mass conditions for tunnels No. 6 and No. 7 are dominated by various phyllites such as graphitic phyllite, chlorite-phyllite, quartzphyllite, and quartzitic phyllite, with intercalations of marble. All the named lihologies belong to the metamorphic basement of Taiwan, specifically to the Tailuko Belt (8). The variety of encountered

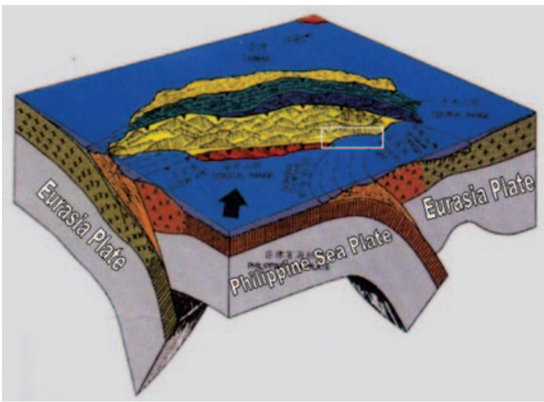

Fig. 6 3D model of the collision zone between Philippine Sea Plate and Eurasian Plate. The white frame indicates the area of the Eastern Expressway Project.

Bild 6 *3D-Modell des Kollisionsbereichs zwischen der Philippinischen und Eurasischen Platte. Der weiße Rahmen zeigt die Lage des Projektgebiets des Eastern Expressways an.*

Fig. 7 Tunnel No. 7, folded quartzitic phyllite.

Bild 7 *Tunnel Nr. 7, verfalteter quarzitischer Phyllit.*

Fig. 8 Tunnel No. 6, fault induced topography with hummocks shaping the contour of the slope; red lines trace faults.

Bild 8 *Tunnel Nr. 6, störungsbedingte Geländeformen, der Hang wird durch Scherkörper gegliedert; rot gestrichelte Linien markieren Störungszonen.*

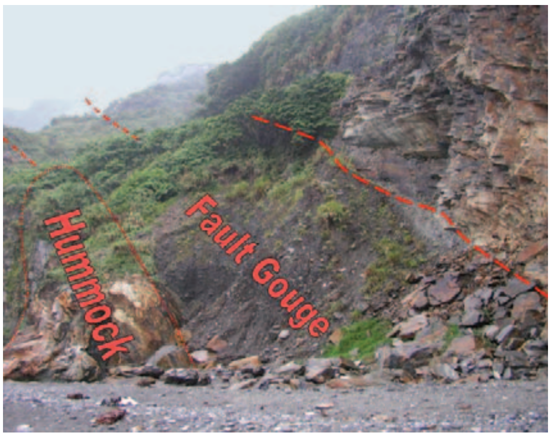

Fig. 9 Tunnel No. 7, prominent fault zone parallel to foliation with a width of several tens of meters. The toe of the fault gouge outcrop is instable due to shoreline erosion; red lines trace boundaries of fault zone.

Bild 9 *Tunnel Nr. 7, mehrere Zehnermeter mächtige, schieferungsparallele Störungszone. Der Fußbereich des Aufschlusses ist instabil aufgrund der Küstenerosion; rot gestrichelte Linien markieren die Begrenzung der Störungszone.*

rock types, sometimes with transitions between different types of phyllites, makes this sequence lithologically highly heterogeneous. The geological conditions of the southern section of Tunnel No. 7 are dominated by marble, where field observations indicate a quite high degree of karstification, including karst pipes, caves and collapse breccias.

All the phyllite varieties show at least one distinct foliation as well as jointing composed of a minimum of two joint sets. Discontinuities spacing varies in a wide range from extremely close spacing to moderate spacing, depending on the type of phyllite as well as on the degree of faulting. The foliation dips mainly towards north to northeast. Dip angles vary in a wide range between gentle to steep inclinations (≈ 20° to ≈ 80°). Variations of dip angles, as well as changes in dip directions are the result of intense internal folding (Figure 7) as well as brittle faulting.

The study of air photos, field observations, as well as results of core drilling confirmed that the area of Tunnels No. 6 and No. 7 is widely affected by faulting (Figures 8 and 9). This also coincides with the documentation of the New Kuan Yin Tunnel of the East Railway Improvement Project. During construction of this tunnel, which runs in the vicinity of the planned expressway tunnels, numerous large-scale collapses occurred in zones consisting of a faulted rock mass in combination with large water ingresses, causing frequent delays of the construction work.

Faults identified within the project area are interpreted as high angle strike-slip faults and tear faults oriented mainly NNW-SSE, and low angle thrust faults, oriented mainly parallel to foliation. In addition, normal faults have been observed, which are interpreted to be part of the extensional regime of the Ilan Basin. Fault gouges are developed frequently. Their thickness ranges from thin coatings on sheared foliation planes to several tens of meters. Larger fault zones consist of a fine-grained, partly clayey matrix with floating shear lenses ("block-in-matrix" material).

The orientation of the tunnel tubes in relation to foliation is considered advantageous, as they are oriented right – to obtuse – angles to each other. Depending on the overburden (maximum of 540 m), the rock mass behavior is expected to be widely governed by shallow to deep seated, stress induced shear failures with large and long lasting deformations. Variations in orientation and magnitude of the principal stresses may be encountered in the stretch where the alignment is located close to the coast escarpment. Most faults are expected to be running parallel to foliation and cross the alignment with favorable angles. The thickness of such fault zones may reach up to several tens of meters. In addition, faults interpreted as strike-slip faults may also be intersected by the alignment with acute angles. Attention has to be paid to the fact that in the vicinity of faults or in highly heterogeneous fault zones the rock strength of the undisturbed rock mass/shear lenses may become overstressed. Consequently sudden failure or excessive overbreak may occur.

The knowledge about hydrogeological conditions within the project area is very limited. Springs are located at least as high as 600 m asl, which is some 500 m above the tunnel alignment. For the phyllites low rock mass permeability can be generally be expected. Still, according to the documentation of the New Kuan Yin Railway tunnel, water seepages and inflows of few liters per second were observed frequently, deteriorating the rock mass properties. Water inflow from the phyllitic rock mass, exceeding 100 l/s, was registered at several places, especially in the vicinity of faults.

Special attention has to be paid to the marble sections. According to field observations the marble appears to be karstified in places. The marble layers may act as confined aquifers within the low permeable sequences of phyllites. Sudden inflow of water under high pressure may occur when penetrating through interfaces between phyllite and marble. The quantity of stored karst water depends on the volume of the marble layer and degree of karstification, both only roughly known. Depending on the degree of karstification the peak inflow may considerably exceed 100 l/s. Peak water inflow can be expected in combination with karstified or faulted marble. High inflow rates are possible in combination with fracture zones or in the vicinity of fault zones in phyllites.

To highlight the hazard of water inflow from marble sections reference is given to the New Yung Chuen Railway tunnel of the East Railway Improvement Project, which is close to the alignment of Tunnel No. 4 of the Eastern Expressway Project. During construction of this tunnel a maximum water inflow of approximately 1 000 l/s with a pressure of about 50 MPa, combined with a partial tunnel collapse, occurred at the boundary between phyllitic rock and faulted marble. A constant water inflow of about 500 l/s (Figure 10) caused a construction delay of about four years until the inflow could be stopped by technical means.

The following crucial engineering geological and geotechnical features of Tunnels No. 6 and No. 7 were identified:

- Shear failures in the phyllites due to excessive stress resulting in high and long lasting deformations,
- Excessive overbreak caused by unfavorable combinations of discontinuity orientations or due to fractured or faulted rock mass,
- Water inflow in general, decreasing the rock mass quality as well as the hazard of sudden inrush of high quantities of water,
- Geotechnical as well as hydrological nature and behavior of fractured or faulted rock mass,
- Amount of karstic marble encountered along the tunnel alignment.

Fig. 10 New Yung Chuen Railway tunnel, continuous water inflow of approximately 500 l/s. The image was taken about four years after the catastrophic water ingression occurred in October 1998.

Bild 10 *Neuer Yung Chuen Eisenbahntunnel, kontinuierlicher Bergwasserzutritt von rund 500 l/s. Das Bild wurde etwa vier Jahre nach dem katastrophalen Wassereinbruch im Oktober 1998 aufgenommen.*

Considerations for the contract model

As mentioned in the introduction, the owner originally had planned to award the tunnels No. 6 and No. 7 in the form of a design and construct contract. The objective was, to save time in the whole process, to deal with one partner only, and to shift risk to the contractors. It was also hoped to reduce disputes.

Due to the complexity of the geological situation revealed during the initial phase of investigation, and the difficulties expected during tunneling following issues have to be discussed in connection with the form of the contract model:

- The level of achievable accuracy in the geological model will be rather low even with an extensive investigation program due to high overburden, limited accessibility, and environmental aspects. This leads to an imprecise design. This naturally implies that many decisions have to be done on site during construction.
- As those decisions might have a major impact on the construction costs, would it be wise to leave them primarily to the contractor?
- The geotechnical and the design team during the investigation and design phase did have opportunity to familiarize itself with the conditions. The design of the required additional investigation can be done much more efficiently by those involved in the early project phases than by "new comers". Would it be a wise decision to run the risk of getting a completely new team, who never can catch up with the developed knowledge of the original team?
- With the level of uncertainty in the knowledge of the geological and hydrological conditions, a sound and continuous geological and geotechnical engineering is required during construction. Major decisions can be done on site without undue delay only if all partners involved in the project have a comparable level of information.

Considering the issues and questions above it appears to be quite clear, that the owner has to have a major involvement in the project, also during construction in this complex project. The required continuous decision making process on site can only be efficient if all parties involved have an appropriate and comparable knowledge basis. It is recommended that in this type of a situation that a permanent and competent presence of representatives of the owner, designer and contractor are on site.

A fair design-construct contract can only be established in cases where the geotechnical conditions are relatively well known, and the deviations encountered during construction from the predicted conditions are minor. In cases with complex geotechnical and hydrological conditions it is felt, that such a contract form would lead to undue risks for the contractor, which eventually cause unnecessary legal disputes.

Conclusion

Tunnels No. 6 and No. 7 are part of the Eastern Expressway Project at the East coast of Taiwan. The ground investigation for these tunnels, which were treated as standard projects with detailed and tender design phases, as well as the experiences during construction of railway tunnels in the same geotechnical environment revealed the extraordinary complex geological, hydrogeological and geotechnical conditions of this area. Qualitatively the hazards of large and long lasting deformation, a rock mass with a high risk of collapse due to unfavorable discontinuity orientation and frequent occurrence of fractured and faulted rock mass conditions, as well as of sudden ingress of high quantities of water have been identified. Additionally, the execution of appropriate ground investigation programs is hampered by legal or topographic restrictions.

For these two tunnels it was the original intention of the client to go for a design and construct contract to minimize the pre-tender design period and to optimize the overall project construction time. The complexity of the project, the high level of uncertainty, and the difficulty to establish a fair contract, allowing for a continuous adjustment and updating of the design, as well as the likelihood of major and in general unpredictable interruptions due to water inflow among other reasons eventually led to the decision to skip the idea of a design and construct contract model and execute the works under a "conventional" contract.

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