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Adverse Tunnelling Conditions Arising from Slope Instabilities – A Case History

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ABSTRACT

Adverse tunnelling conditions may arise when active landslide processes are encountered at or near the excavation site. Such slope hazards act to increase the complexity of the geological conditions, induce tunnel instabilities, cause costly delays, interference with construction logistics and shorten the life span of the final structure. Consideration must also be given to auxillary structures, for example the influence of slope hazards on access roads, secondary adits and shafts. In this paper, a case study from India is presented to demonstrate some of the difficulties arising from tunnelling within an active landslide region.

INTRODUCTION

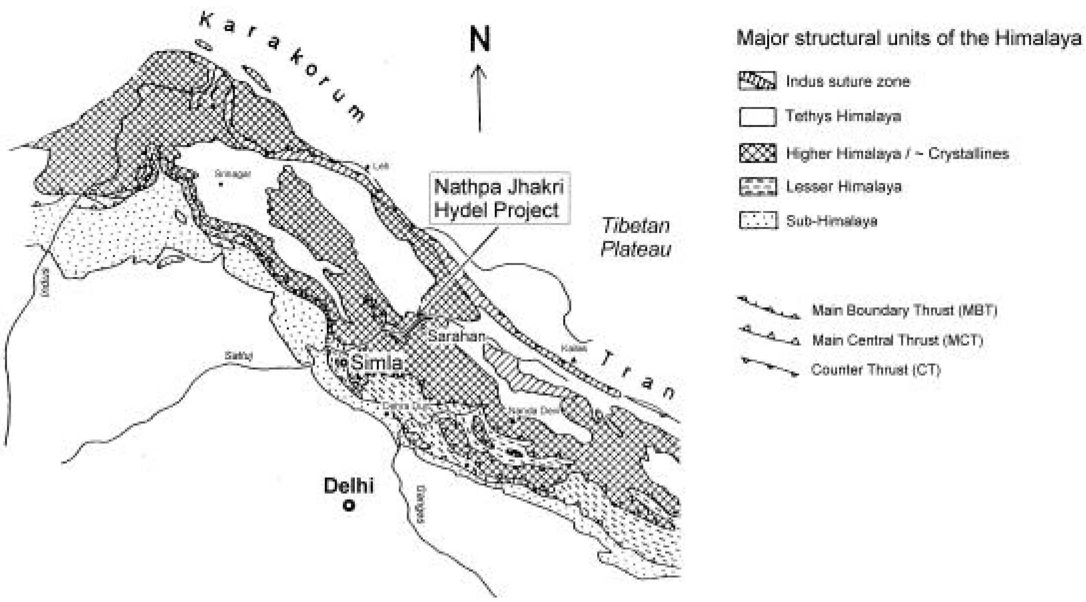

Figure 1. Geological and tectonic environment of the project area in the Himalaya (after Schwan (1)).

Since 1993, the Nathpa-Jhakri Hydroelectric Project (NJHP) has been under construction. The project includes a 60.5 m high concrete gravity dam, an underground desilting arrangement, a 27.3 km long headrace tunnel, a 300 m deep surge shaft and an underground power house which will eventually generate 1500 MW of power. The project, one of the largest civil works in India, is situated in the higher Himalya in the middle reaches of the river Satluj in the northwestern part of India (Himashal Pradesh). Figure 1 provides an overview of the geological and tectonic environment. The project´s headrace tunnel was driven through quartzites, gneissic schists, quartz-mica-schists and amphibolites of low to medium grade metamorphism. Foliation strikes parallel to the tunnel axis over long distances and dips towards the river valley. The Satluj river valley is typically overdeepened due to glaciation with steep valley-side slopes.

SURFACE INSTABILITIES

Due to foliation parallel sliding planes and cross cutting orthogonal joint systems, numerous landslides and rock falls have occured in the vicinity of the tunnel works. Figure 2 shows the base of an extensive planar sliding surface, the rock slide debris from which can be found at the bottom of the valley. Features relating to active sliding blocks include deep, open, valley-parallel tension cracks which further suggest creeping mass movements.

Figure 2. Typical planar sliding surface of a large landslide due to valley-dipping foliation.

The Hindustan-Tibet-Highway

The main access road for the project, the “Hindustan-Tibet-Highway”, also serves as the primary connecting road in the valley-axis of the Satluj river between the provincial capital Simla of Himachal Pradesh and the nearby city Sarahan. Parallel to the project works, the highway was rebuilt and the slopes supported and cleared of rock debris. Nevertheless, instabilities could not be completely avoided and the road was frequently blocked by both small and large rock falls (Fig. 3 LEFT). These failures resulted in repeated closures of the highway for hours and sometimes days, leading to major traffic jams and affecting project-based traffic. Tragically, a project engineer and two members of his staff were buried under the debris of one such rock fall.

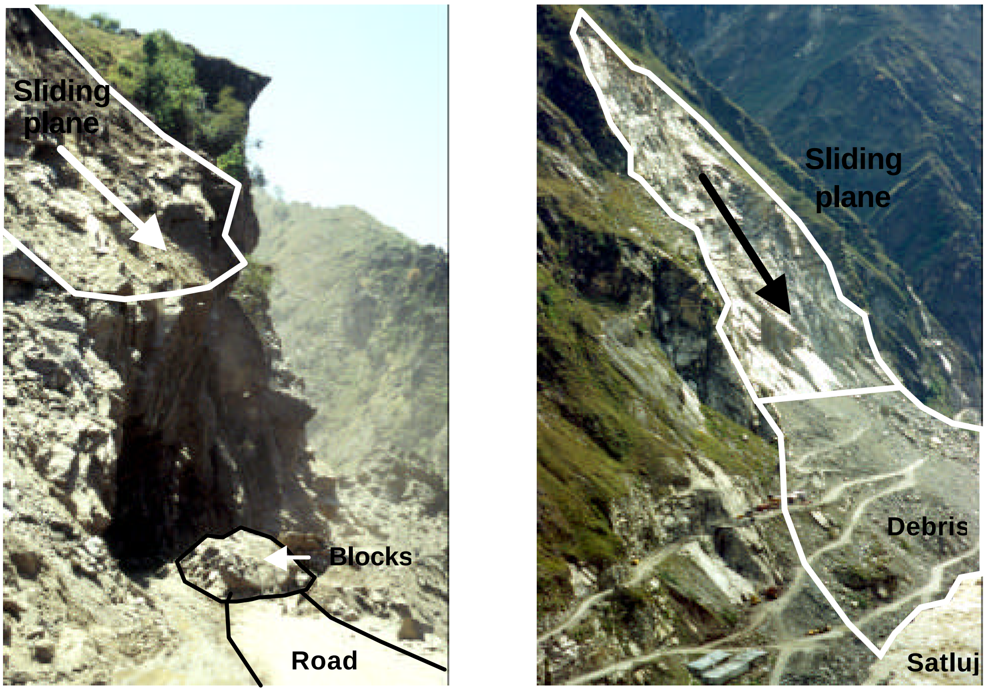

Figure 3. Blocking of the Hindustan-Tibet-Highway by a rock fall (LEFT). Rock slide at the dam site blocking the Satluj River (RIGHT).

Access Roads and Access Tunnels

Access roads and access tunnels built at 5 – 6 km intervals perpendicular to the headrace tunnel alignment and intersecting the valley wall, were greatly affected. Rock falls at these locations frequently endangered surface works and workers. The access tunnel "Daj Khad" had to be abandoned completely after 3 months due to severe stability problems, relating to the portal being located within a creeping rock mass consisting of fractured and weathered material. This required the tunnel adit to be relocated to a more favourable position. Similarly, the works at the dam site and intake were delayed for over one year by a rock slide that blocked and dammed the river (2). Water heights reached 10 m behind the rockslide dam at this narrow location (Fig. 3 RIGHT). Afterwards, costly scaling works along the slope and the clearing of the river bed were required before the abutments of the dam could be exposed.

UNDERGROUND STABILITY PROBLEMS

Tunnel Deformations and Ground Control Problems

Due to the inhomogenous rock mass conditions, the tunnel was excavated by drill and blast techniques. Support measures consisted either of wire meshing, shotcrete, steel ribs and rock bolts, or steel lining with steel ribs, steel plates and concrete bars with sand or concrete packing. Along the Manglad and Rattanpur sections, the headrace tunnel was severely affected by stabillity problems associated with the orientation of the schistosity. Large deformations were especially problematic along intervals with high rock cover. Examples of the type of damage encountered can be seen in Figure 4 Cracks in the shotcrete developed shortly after installation of the support with deformations continuing for longer periods of time. As a consequence, the support along certain sections had to be stiffened by additional wire mesh, steel ribs, shotcrete and rock bolts or welded steel beams.

Figure 4. Buckling and bending of 150x150 mm steel ribs with steel lining between crown and right spring line (LEFT). Shearing of shotcrete lining along left bench (RIGHT).

Figure 5 shows the typical springline settlements observed during the excavation period. The two parallel lines show the thickness between the mean rock excavation and the inner tunnel lining versus absolute elevation. The recorded maximum settlements are provided with the time of measurement following excavation indicated below.

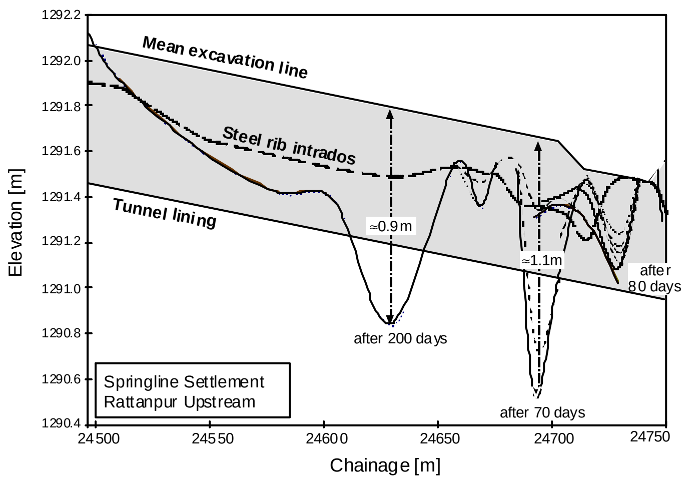

Figure 5. Recorded settlement of the crown / spring line versus absolute elevation in the headrace tunnel near the Rattanpur adit intersection.

These squeezing ground conditions were observed along several tunnel sections with high rock cover (e.g. “Manglad Upstream”, “Rattanpur Upstream” and “Rattanpur Downstream”) from which a repeating deformation pattern could be discerned (Fig. 6):

- Opening of cracks in shotcrete and sagging of crown;
- Continued opening of cracks in shotcrete with subsequent rock and shot-

crete falls (cracking becomes audible);

- Rockfalls with pulling out of rockbolts, and formation of chimneys in the crown / springline areas;
- Reapearance of cracks in shotcrete following application of second shotcrete layer;
- Breakdown of steel and concrete lagging;
- Buckling, bending and twisting of steel ribs with breakdown of steel and concrete lagging (rock falls occur in places where steel lagging has failed).

In areas where these effects were most severe, the 150x150 mm ribs had to be removed and replaced with heavy section ribs 300x140 mm.

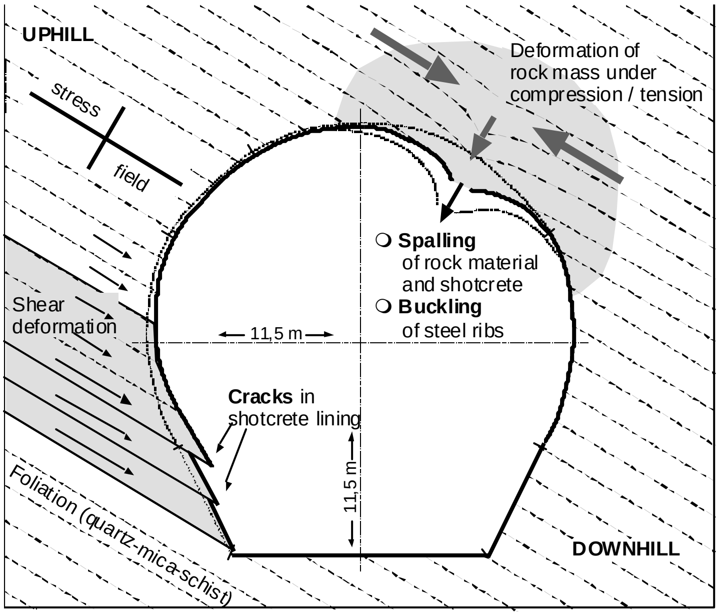

Figure 6. Typical deformation pattern in the headrace tunnel near the Rattanpur adit intersection due to foliation orientation and deep seated slope movements.

Acting Instability Mechanisms

The orientation of the schistosity was found to be unfavourable with respect to the axis of the Rattanpur and Manglad headings. In Figure 7, favourable and unfavourable orientations of foliation versus tunnel axis are shown. The Manglad and Rattanpur headings of the headrace tunnel plot in the “highly unfavourable” area of the stereo net. In these headings the foliation is nearly parallel to the tunnel axis and dipping at an angle of 25° to 60°.

The primary underlying factor for this unfavourable condition is the alignment of the far-field stresses as illustrated in Figure 8. This figure shows a cross-section through the mountain valley and the location of the NJHP headrace tunnel as it appears near one of the intersecting access tunnels. Slope instabilities (shaded grey) involving downslope creeping displacements along the dipping foliation, is believed to be controlled by slope angles steeper than the expected angle of friction. Furthermore, observations have been made of several active landslides above the tunnel alignment showing visible open cracks within the body of the slope. It is likely that these valley-parallel open tension cracks also appear at the head of the slide body and would thus provide additional evidence for deep creeping mass movements of the valley slope. Unfortunately the 2,500 m ridge above the tunnel axis is in a restricted military area due to its near proximity to Tibetian China.

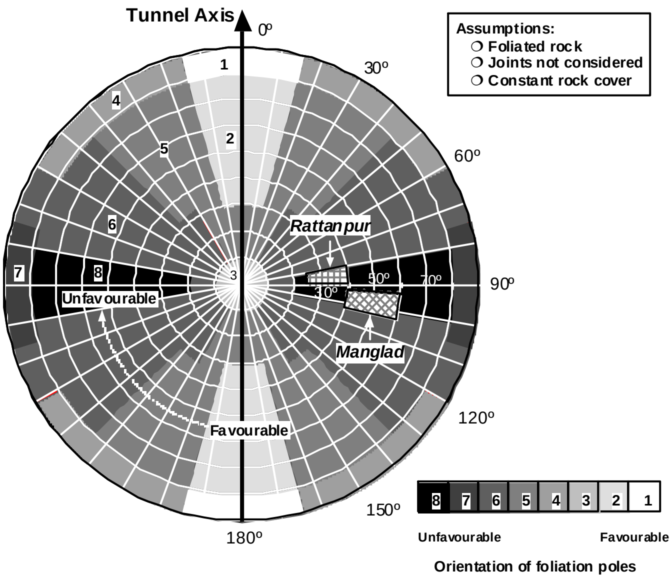

Figure 7. Pole plot of favourable and unfavourable orientations, with respect to foliation, versus tunnel axis alignment.

Tunnelling in high stress conditions close to steep valley walls have been reported by various authors (e.g. 3). Given the topography and orientation of the geological structure, the major principal stress would be expected to be aligned parallel to the slope. Thus simple calculations of stress based on overburden loading are not applicable. High stresses parallel to the slope are also believed to be contributing to the instability of the slope. Furthermore, rapid uplift of the Himalaya may factor into the observed phenomen.

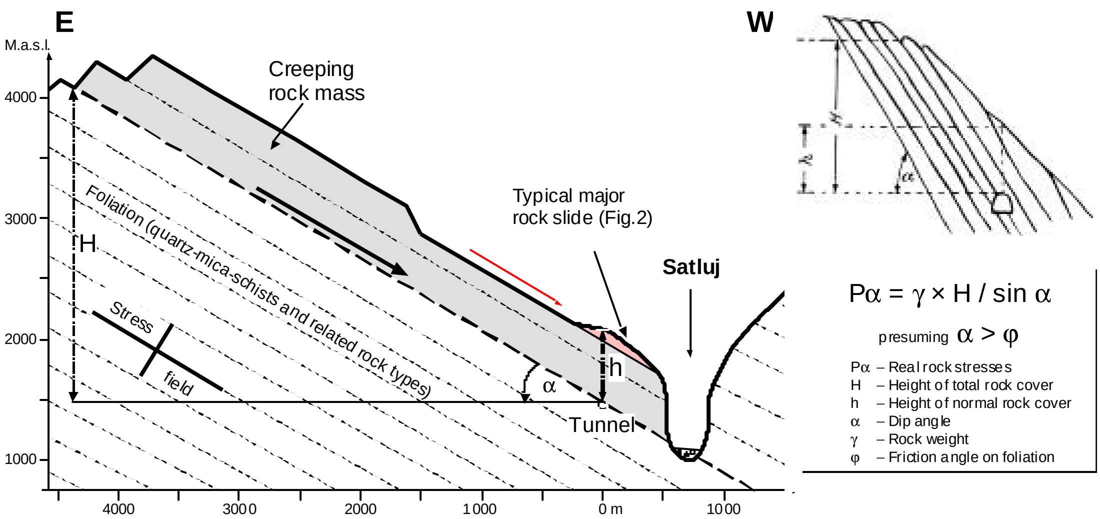

Figure 8. Cross section of the headrace tunnel and mountain valley showing the assumed *in situ* stress conditions (LEFT). Influence of inclined schistosity on the *in situ* stress condi-

tions of a valley tunnel after Stini (3) and calculation of real rock stresses Pα (RIGHT).

Analytical estimations of *in situ* stress based on overburden loading can be adjusted to account for the dip angle of the structure (Fig. 8). However, these calculation methods do not consider several key factors, e.g. cohesion, and provide largely conservative overestimations of the acting rock stresses.

To better understand the *in situ* stress state, a series of overcoring measurements were made (Fig. 9). These tests were performed in horizontal boreholes drilled into the uphill tunnel wall and face. The results show increasing stress values with depth and reorientation of the major principal stress axis towards the dip angle of foliation (approx. 40°).

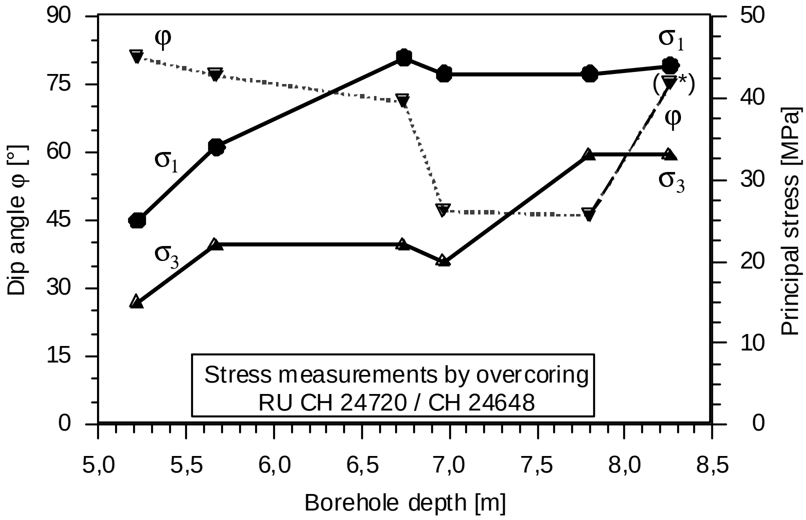

Figure 9. Stress measurements by overcoring performed in “Rattanpur Upstream”. Legend: * disturbed, σ_1 – major principal stress, σ_3 – minor principal stress.

Numerical Modelling

The distinct-element program UDEC (4) was used to investigate the effects of slope displacements on potential tunnel instability mechanisms. Of particular concern was the role that foliation, and fractures parallel to the foliation, play when driven by small-scale velocities derived from slope mass movements. Two series of models were generated, one examining the large scale instability of the slope (Fig. 10) and one focussing on smaller-scale deformations of the headrace tunnel (Fig. 11). Through this combined modelling process, results from the large-scale models were used to constrain boundary conditions for the detailed tunnel model (e.g. slope velocities). The detailed analysis was performed for two different scenarios based on variations in the geological structure, i.e. foliation joint spacings of 1 m and 0.5 m parallel to the slope surface (Fig. 11). Material properties were used based on laboratory and *in situ* testing campaigns performed for the Nathpa Jhakri Hydro Project. Table 1 includes the material properties used, where variations in the normal and shear stiffness values reflect variations in the finite-difference element dimensions across different element zones. Initial stress conditions were incorporated based on values determined through *in situ* overcoring measurements (Fig. 9).

Table 1. Material parameters and values used for UDEC modelling.

Material Parameter	**Value**
Density, ρ	2700 kg/m^3
Young's modulus, E	20 GPa
Poisson's ratio, ν	0.2
Cohesion, c	20 MPa
Internal friction angle, ϕ_i	25°
Joint friction angle, ϕ_j	20°
Joint cohesion, c_j	0 MPa
Joint normal stiffness, jkn	100 – 560 GPa/m
Joint shear stiffness, jks	20 – 120 GPa/m

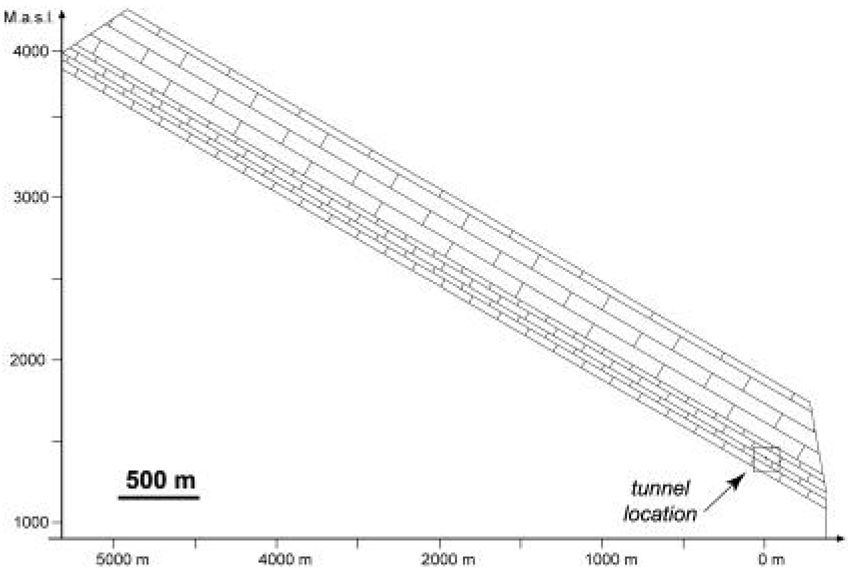

Figure 10. UDEC Model for the large scale instability of the Rattanpur slope section.

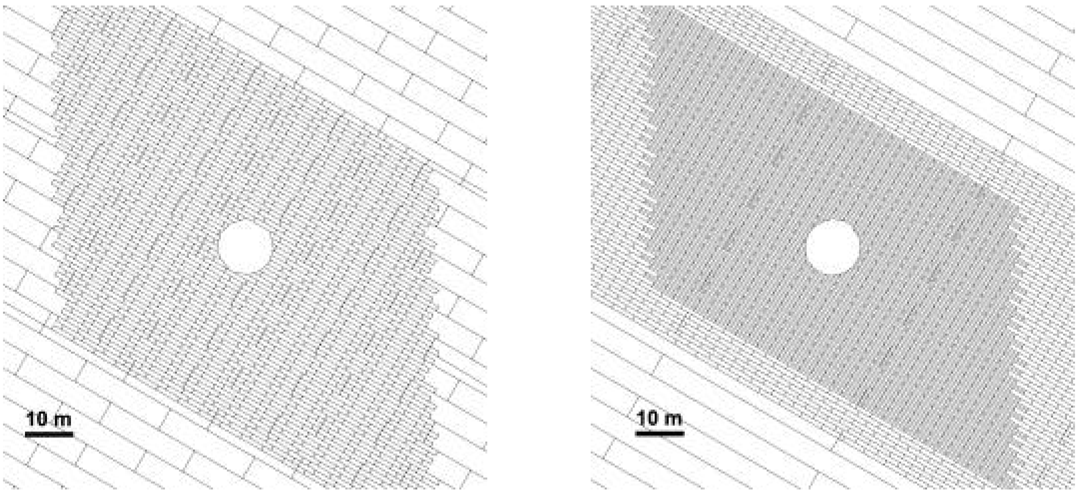

Figure 11. UDEC models focussing on mechanisms involving the headrace tunnel for foliation joint spacings of 1 m (LEFT) and 0.5 m (RIGHT).

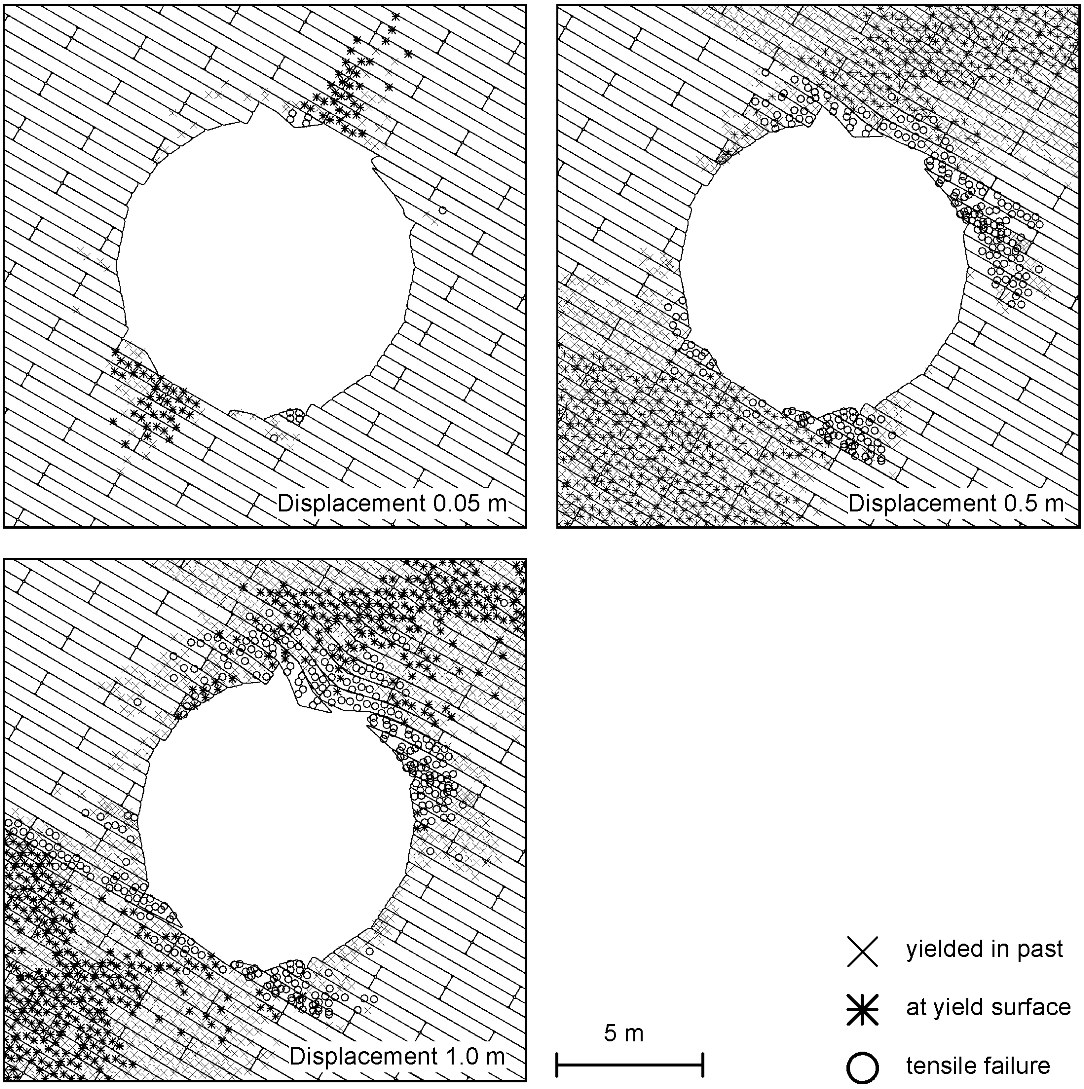

Figure 12. Progressive stages of tunnel failure for down-slope displacements of 0.05 m, 0.5 m and 1 m, respectively. Note that the tunnel diameter is 11 m.

Results from these models show that the tunnel remains stable if the slope conditions are also in a stable state. However, if the slope is unstable, subsequent slope movements begin to induce buckling failures in the tunnel roof once down-slope displacements exceed 0.5 m. Figure 12 shows the progressive stages of tunnel failure after down-slope displacements of 0.05, 0.5 and 1 m, respectively. This correlates well with *in situ* observations (Fig. 6).

Drillability Problems

In addition to the stability problems experienced with the underground structures, the unfavourable geological conditions had an adverse effect on the excavation works by drilling and blasting. Along several large sections, especially between the Manglad and Daj valleys, foliation was typically parallel to the tunnel axis (Fig. 7), and thus parallel to the direction of drilling. These experiences correspond to similar ones encountered by Thuro (5), where lower drilling rates (up to 50%) were recorded when drilling parallel to schistosity as opposed to those for the perpendicular case. Figure 13 for example indicates the close relationship between drilling velocity and tensile rock strength as a function of foliation angle. This figure clearly shows, that the tensile strength parallel to orientation (load perpendicular) is relatively high and the corresponding drilling rates are low. Blasting conditions can also be related to drilling rates, and, in cases where the tunnel axis was oriented parallel to the main foliation, poor blasting conditions were encountered (6).

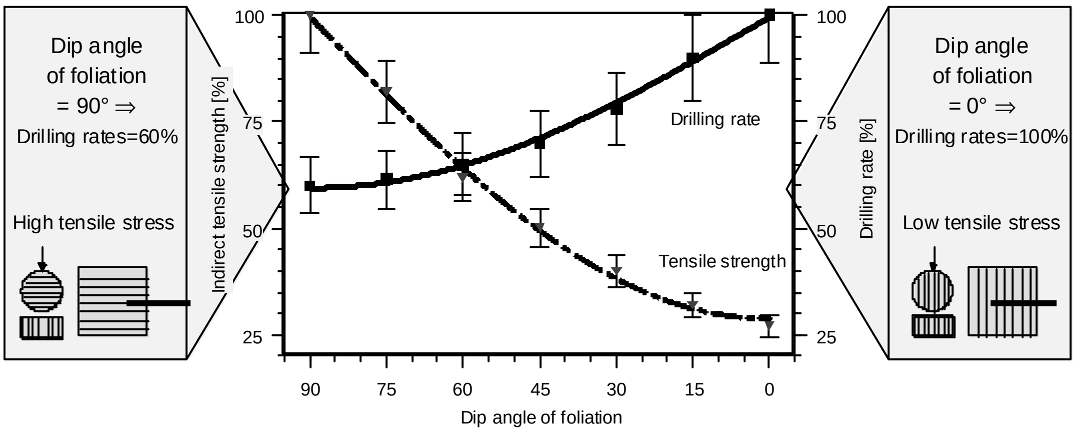

Figure 13. Drilling rate and tensile strength plotted against foliation orientation for quartz-mica-schists (after Thuro (5)).

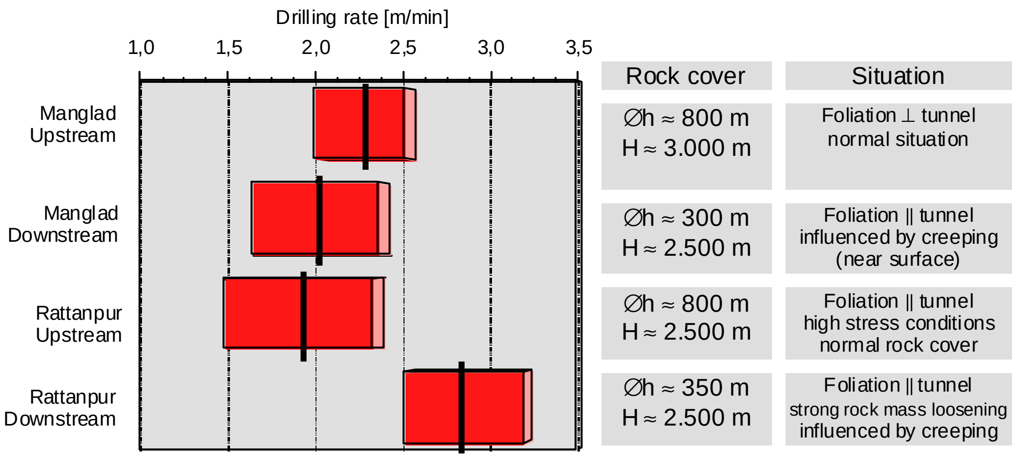

Figure 14. Drilling rates with mean value and standard deviation for the mica-schists in the Manglad and Rattanpur sections of the headrace tunnel. Rock cover above tunnel (∅h), total slope height (H) and geological situation are also provided.

Examination of the drilling performance (Fig. 14) revealed, that a distinct pattern could be seen with respect to the velocity ranges:

- In the Manglad Upstream adit tunnel, drilling rates were found to be quite good due to favourable foliation orientations (i.e. normal to the tunnel axis and drilling direction). No adverse effects were recorded with respect to induced or disturbed stress conditions relating to creeping slope movements.
- In Manglad Downstream, drilling velocities were seen to be significantly lower and were attributed to subsurface stress effects relating to the creeping slide mass.

- High stress conditions were observed in the Rattanpur Upstream drifts, which in turn experienced the lowest mean drilling rates and the widest range of velocities. In sections having undergone large deformations, drilling rates were considerably higher owing to brittle fracture damage, plastic yielding and the subsequent redistribution of accumulated stresses.
- At the Rattanpur Downstream drill location, the highest drilling rates were achieved owing to rock conditions which were much poorer, especially when approaching the Daj Khad creeping rock mass. Here, the rock mass was extremely disturbed and broken down to a loose material.

CONCLUSION

Several observations have been presented with respect to both small and large rock slope falls and mass movements encountered in a Himalayan hydroelectricity project. Key amongst these were the adverse effects that large scale creeping rock slide displacements had on near-field tunnel stresses, deformations and failures. As such, the focus was extended towards the effect these stresses had in combination with the foliated rock mass on observed tunnel deformation patterns and drilling performance. In sections where the foliation was aligned parallel to the tunnel axis, a typical, almost symmetrical deformation pattern including convergence along the spring line and shear deformation along the walls, was observed. These mechanisms could be explained and validated through distinct element modelling with UDEC. Drilling rates were also found to be lowest along these sections due to higher principal stresses at the tunnel face, i.e. resulting in higher confining pressures. Accordingly, high stresses required increased drilling effort to fragment the rock. Only in regions where high stresses induced large deformations and stress-induced brittle microcracking, did the observed drilling rates considerably increase.

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