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Geotechnical risk management approach for TBM tunnelling in squeezing ground conditions ☆

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ABSTRACT

Historically, attempts to use tunnel boring machines (TBMs) in Himalayan geology have been unsuccessful, particularly where weak rocks exist at the significant depths often required for hydroelectric hydraulic tunnels resulting in squeezing ground conditions. The use of segmental tunnel linings erected by shielded TBMs presents additional risk, such that the advantages of potentially high rates of advance using this form of construction have not previously been realised. Programme demands for the 330 MW Kishanganga Hydroelectric Project in India required that 15 km of the 23 km headrace tunnel be constructed using a double-shield TBM erecting a segmental lining. Preliminary studies suggested difficult ground due to squeezing conditions along the 1400 m deep tunnel through weak meta-sedimentary rocks. To allow planning and construction to commence, a risk management approach to design and construction was formulated with contingency procedures and criteria developed to allow the risks to the TBM and the lining to be managed effectively. Advanced numerical modelling included analysis of the tunnel with the ground represented by a Stress Hardening Elastic Viscous Plastic (SHELVIP) model to take account of time dependent loading. The Kishanganga tunnel represents the first segmentally lined TBM tunnel to be successfully constructed in the Himalaya. This paper describes the risk-mitigation approach, the special measures developed to address the risks, the numerical modelling and laboratory testing undertaken, and includes results from the segmental lining monitoring. Recognition of the risks, the development of an innovative methodology and the provision of the means by which geotechnical risk could be managed effectively during construction, gave confidence to all stakeholders to proceed with a method of construction that had not previously been implemented successfully in the Himalaya.

1. Introduction

The Kishanganga 330 MW Hydroelectric Project is located in the Bandipora district of the state of Jammu and Kashmir in north-west India. The underground components for the scheme include a 23 km water transfer tunnel. The site has limited access due to geographical and climatic restraints and programme demands required that 15 km of the headrace tunnel be constructed using a double-shield TBM erecting a segmental lining.

Preliminary studies suggested difficult ground at depths of up to 1400 m due to squeezing conditions through weak meta-sedimentary rocks over significant portions of the TBM tunnel. Attempts to use TBMs in Himalayan geology have previously been unsuccessful (Goel, 2014), particularly where weak rocks existed and squeezing ground conditions occurred. The use of segmental tunnel linings erected by shielded TBMs presents additional risk, such that the advantages of potentially high rates of advance using this form of construction have not previously been realised.

There was therefore an early requirement to gain assurance that the segmental lining would be of a practical and manageable thickness suitable for a wide range of conditions. Specifically, there was an immediate need to formulate a robust strategy for the design and construction of the segmental lining, with minimum residual risk, such that manufacture of the TBM could proceed. This work involved collaboration between the designers (CH2M), the contractor (Hindustan Construction Company Ltd (HCC)) and the TBM sub-contractor (SELI S.p.A), and included specialist laboratory testing and advanced numerical modelling by Politecnico di Torino.

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1.1. Geology

Ground investigations at the start of the project were limited to surface geological mapping. The project is located on the western edge of the Himalayan mountain range with the Indus Suture to the north and the Main Boundary Thrust and Panjal Thrust located to the south. In Kashmir a gigantic synclinorium comprises basement rocks overlain by a thick sequence of sediments and volcanics ranging in age from Cambrian to Triassic. Table 1 provides a simplified summary of the litho-stratigraphic rock units present.

Fig. 1 shows a cross section of the geological conditions anticipated along the tunnel. The Cambrian Madmati Group comprised weak to moderately strong meta-sediments of the Hafkhalan, Hasthoji and Razdhan Formations and presented the greatest risk of squeezing ground.

With the exception of some limited Unconfined Compressive Strength (UCS) results from pre-tender investigations, values of Geological Strength Index (GSI), *in situ* stress, and associated parameters had to be estimated initially from specialist interpretation, expert knowledge and established geomechanical correlations. The GSI of the Madmatti Group was anticipated to be in the range of 15–60 with low UCS. UCS test results available at the start of the project were from samples taken from surface exposures from unknown locations; the results typically ranged between 15 MPa and 50 MPa. Further ground investigation associated with the design phase of the project commenced during 2009.

Three boreholes were drilled within the meta-sediments along the tunnel route to depths between 100 and 250 m at selected locations. Although these boreholes were significantly shallower than the tunnel, they served to provide samples of the rock mass below the weathered zone and the ability to undertake hydraulic fracture tests to measure *in situ* stress (discussed in the following Section). In addition to rock cores, block samples were taken from surface exposures representative of the meta-sediment lithologies for routine and specialist testing. The laboratory tests from samples collected during the 2009 ground investigations suggested that the UCS values, were, in general, higher and therefore more favourable to resist squeezing than indicated by the earlier studies, with UCS values of between 15 MPa and 135 MPa, and average values of 60 MPa. Further specialist laboratory testing was undertaken during the detail design stage, which gave additional data for UCS and time dependent parameters.

1.2. In situ stress

Predicting *in situ* stresses is difficult without the availability of direct measurements. Even *in situ* stress measurements from elsewhere in India and the Himalayan region (*e.g.* Kumar et al., 2004) are difficult to extrapolate as the available results tend to be from shallow depths (less than 500 m, with no results reported for depths of 1000 m), and show a large scatter. However, initial estimates were made using these and inferences from the world stress map database (www.world-stress-map.org). The best estimates for the *in situ* stress ratio σ_H/σ_v (k_H) (with σ_H and σ_V being the horizontal and vertical principal stress respectively), lead to a range of 1–2.5 for depths between 600 and 1000 m and 1–2 for depths greater than 1000 m. *In situ* stress measurements using hydraulic fracture tests were undertaken in the vicinity of the powerhouse and along the tunnel route. The results for the maximum horizontal stress are plotted on Fig. 2. A linear best fit model of the test data would suggest a k_H equal to approximately 1.75. An alternative approach is to consider the stress gradient in terms the 'excess stress' concept of Mark and Gadde (2008) where:

$$\sigma_H = B0 + B2\ (\text{Modulus}) + B1\ (\text{Depth})$$

An assessment of an excess stress interpretation of the data is shown in Fig. 2 which includes an excess stress of 2 MPa. The interpretation of this model involves some subjectivity and the depth range of testing is limited compared to tunnel depths of 1000–1400 m. A k_H value of 1.7 was adopted for design of the powerhouse cavern (depth approximately 370 m). Based on *in situ* stress models, which generally suggest a decrease in the stress ratio with depth, then a k_H value of 1.5 was considered representative of the stress ratio at depths of 1000 m or greater and was applied to the design of the TBM tunnel.

2. Preliminary assessments of squeezing and available options

2.1. Programme requirements

The project programme required an early decision on the thickness of the segmental lining as this was a critical dimension to allow TBM procurement to proceed. There was therefore a need to undertake preliminary, but sufficiently robust, studies of squeezing ground conditions in order to reach a point at which a segment thickness could be confirmed. Also the studies needed to include consideration of any special design and/or construction measures that might be necessary to allow the TBM and the segmental lining to construct as much of the planned length of tunnel as was feasibly possible, with minimum risk to the project.

Although there is a large amount of technical literature available on tunnelling in squeezing ground, the majority applies to tunnels excavated by drill-and-blast methods, much less is directed to the use of TBMs and segmental linings in these conditions. However, focussing on the conceptual problems, and identifying and applying available methods for the assessment of squeezing potential and squeezing loads on segmental linings, highlighted some of the more important issues and conclusions which are summarised below (a full review of these studies is beyond the scope of this paper).

2.2. Preliminary assessment of squeezing potential

A preliminary assessment of squeezing potential was undertaken using Hoek and Marinos (2000) based on 'typical' rock mass conditions. The method uses a strain criterion to assess likely

Table 1
Summary of lithostratigraphy (after Prakash et al., 1984).

Age	Group	Formation	Lithology
	Panjal Volcanics		Green andesitic and basaltic volcanic flows
Upper Cambrian	Madmatti	Hafkhalan	Green and greenish grey phyllites, siltstone with bands arenite and wacke and occasional lenticles of limestone
Middle Cambrian		Hasthoji	Thinly foliated earthy and olive coloured silty shales with minor bands of siltstone and wacke
Lower Cambrian		Razdan	Massive and thick bedded quartz- arenite, wacke and grey to dark grey siltstone and inter bedded silty shales
		Hanti Granitoid	Granodiorite