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Abstract

Presented and discussed are aspects of changes to the hydraulic properties of rock mass due to tunnelling, but in particular the change due to the opening or making of new fractures and voids in the rock mass as a result of deformation or relaxation of the tunnel opening and hence an associated increase in the permeability of the rock mass surrounding the tunnel. This process principally occurs in tunnels where high stress fields persist effecting rapid and large scale deformation or relaxation (>100 mm) in the presence of (heavily) jointed rock mass and fault zones. Examples and observations from water and ground inflow events, associated with hydraulic property changes which have occurred during the mining of the Tapovan-Vishnugad Head Race Tunnel, India, are given and which have caused trapping of the Tunnel Boring Machine (TBM) resulting in time delays and cost increases.

Keywords

Ground deformation • Increased permeability • Water inflow • Ground inflow

170.1 Introduction

A change in the hydraulic properties of rock mass due to tunnelling has been observed in the Garhwal Himalaya, Uttarakhand, India during construction of the deep seated 12.1 km long head race tunnel (HRT) for the NTPC Ltd 520 MW Tapovan-Vishnugad Hydro Electric Project (HEP). The project area lies within the Dhauliganga and Alaknanda Valleys and consists of high strength medium to high grade metamorphic rocks belonging to the Central Himalayan Crystalline Series (Heim and Gansser 1939; for a recent review see Yin 2006).

Since October 2008, 8.6 km of the HRT has been under construction by a Herrenknecht Double Shield—Tunnel Boring Machine (DS-TBM). The rest of the HRT is been constructed by drill and blast methods. During TBM driving, a steel reinforced 0.3 m thick concrete hexagonal segmental

lining is inserted behind the machine, pea ballasted and grouted making the internal finished diameter of the TBM-HRT 5.64 m; the excavation diameter is 6.57 m.

To date three TBM trapping events—all associated with subsurface water inflow—have severely hampered the HRT excavation resulting in time delays and cost increases. The first trapping event occurred in December 2009 at chainage (Ch) 3,016 m at a depth of some 900 m in a heterogeneous fault zone (Brandl et al. 2010; Millen and Brandl 2011). During trapping the front and telescopic shields were jammed in and dented by major wedge slides. Approximately 24 h later, massive surges of high pressure subsurface water, containing faulted rock material, broke two crown segments of the segmental lining immediately behind the tailskin with the initial flow rates reaching circa 700 L/s compounding the trapping problem.

The second and third trapping events—which to date have not been reported on—happened in February and October 2012 at Ch 5,840 and 5,859 m respectively in the same circa 20 m wide fault zone at a depth of some 700 m. This fault zone lies at a very acute angle to the tunnel axis meaning the TBM had (will have) to drive through this zone

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for at least 35 m. At the time of writing the TBM was still trapped at Ch 5,859 m.

When the second event occurred, the face and surrounding conditions were initially dry and due to over excavation and collapse a cavity of several cubic metres had developed around the cutter head and front shield of the machine in the soil-like stiff clay-rich fault gouge and breccia of which the fault zone consists of. As in the first trapping event, water inflow (1–2 L/s) started some 20 h later. The situation then greatly deteriorated as the water rapidly eroded the water sensitive fault gouge and breccia causing further cavity development, ground creep and ground inflow through the cutter head and shield openings trapping the TBM.

Interestingly, in both described events, the water inflow started approximately 1 day after the initial trappings. The events caused subtle and rapid major changes to the hydraulic properties—particularly increased permeability—of the rock mass within several metres and probably many tens of metres of the tunnel walls.

170.2 Hydraulic Properties of Rock Mass

The hydraulic behaviour of rock mass is much more complicated than in granular soil and there can be huge differences in properties over short distances caused by the distribution of rock types, their tectonic history and distribution in relation to a drainage basin or system.






Subsurface water flow in rock mass is generally governed by (1) the (unaltered) rock porosity and permeability and (2) the rock mass porosity and permeability. In tunnelling geology the usual concern is with the flow of subsurface water through a granular soil or rock mass as is the case in this paper.

Porosity is the measure of the voids in a material and is given in a percentage. However, the voids in a rock must be in contact otherwise the rock is impervious. Permeability is a general term which describes the ability of a porous medium to allow the flow of fluid through it. Permeability is given in K (the coefficient of permeability) after experiments by Darcy (1856) and is also called *hydraulic conductivity* and has the unit m/s. For flow to take place through a saturated material there must be a difference in total head across the medium.

The hydraulic permeability of rocks is generally very low and ranges commonly from 10^{-13} to 10^{-10} m/s. Exceptions are for example coarse grained porous sandstones.

Hydraulic conductivity or permeability and subsurface water flow in rock mass is mainly governed by the inter-connection of fractures (bedding, schistosity, joints, faults, etc.) in the rock mass or *fracture permeability*. The hydraulic

Fig. 170.1 The hydraulic permeability of rock mass with a fracture system of defined width and an average distance between fractures of 1 m in comparison to the hydraulic permeability of granular soils from (Wittke 1984) taken from Prinz (1997)

Fracture Width	k [m/s]	△ (Soil)
0,1 mm 	0,6 E-06	Silt
	0,3 E-06	
0,2 mm 	0,5 E-05	Sand
	0,2 E-05	
0,4 mm 	0,4 E-04	Gravel
	0,2 E-04	
0,7 mm 	0,2 E-03	
	0,1 E-03	
1,0 mm 	0,6 E-03	
	0,3 E-03	

permeability of rock mass is not only inhomogeneous but also highly anisotropic.

In Fig. 170.1 is given an idealised and homogeneous rock mass model in comparison to the hydraulic permeability of granular soils.

The rows of values show that the permeability in the direction of wider fractures is the 3rd–4th negative power (10^{-3} – 10^{-4}) of the mean fracture width in relation to the cubic law for fluid flow in rock fractures (Witherspoon et al. 1980). This means that a single wide fracture or narrow distances between multiple fractures, for example in joint and fault zones, can or on the whole control the permeability of the rock mass.

The subsurface water flow is also extremely dominated by the geometry of the fractures and their extension. Fracture walls are also generally rough and the fracture width can change over short distances.

Where there are sequences of low and high permeability in a rock mass there is not only fracture anisotropy to consider in the horizontal direction but also the bedding or schistosity anisotropy of the rock mass to be considered in the vertical direction.

In dissimilarity to granular soil aquifers, where homogeneous and isotropic characteristics are not fully given but a quasi homogeneity and isotropy, fractured rock mass aquifers, with very different fracture widths and grades of opening, have very anisotropic and turbulent flow regimes (Prinz 1997).

170.3 Change in Hydraulic Properties of Rock Mass

Changes to the hydraulic properties of a rock mass are achieved principally by the following: (1) chemical processes such as precipitation, dissolution and weathering; (2) erosion processes; (3) closure of fractures and voids by physical processes (4) opening or making new fractures and

voids by physical processes. Process (1) can either decrease or increase the hydraulic permeability, process (3) causes a decrease and processes (2) and (4) cause an increase.

Long term erosion and dissolution and weathering of rock mass causing hydraulic changes (or increased permeability) has been examined before particularly in relation to problems with the long term operation of water transport tunnels (e.g. Gysel 2002; Lipponen et al. 2005) and will not be discussed further.

There are plenty of examples of large scale water and related ground inflows and hence the development of cavities caused by short term erosion events (e.g. Schwarz et al. 2006; Wenner and Wannemacher 2009). However the recognition that such events radically change the hydraulic properties and framework of the rock mass surrounding the tunnel up to several tens of metres from the tunnel walls has not been considered to date in discussion of the same.

As stated in the introduction (Chap. 1), events surrounding the development of water and ground inflow during the excavation of the Tapovan-Vishnugad HRT led to changes to the hydraulic properties of the rock mass around the tunnel. Not only the processes (1) and (2) played major roles but also process (4), the opening or making of new fractures and voids. The changes occurred in high stress fields and effected rapid and large scale deformation or relaxation (>100 mm) in sections of (heavily) jointed rock mass and fault zones surrounding the TBM.

As presented in Chap. 2, hydraulic permeability in rock mass is principally governed by fracture permeability. If say some 10 mm of deformation occurs and this affects, for discussion purposes, some 10 m of jointed rock mass evenly away from the tunnel walls and this deformation is taken up evenly by the opening of 10 existing fractures from 0.1 to 1.1 mm at 1 m spacing, then there will be an automatic increase in the hydraulic permeability of several orders of magnitude according to the model given in Fig. 170.1. Of course in reality, at such low levels of deformation, this will not be the case and the deformation will be taken up within the first 1–2 m of the tunnel walls and be much more anisotropic. However, when >100 mm of deformation or relaxation is registered then the range of impact will be much greater reaching at least several if not tens of metres into the tunnel walls.

In the case of the TBM trapping event at Ch 3,016 m (see Chap. 1), the water inflow reaching circa 700 L/s started approximately 24 h after the initial trapping. The TBM over cuts the shields by a maximum of 200 mm at the crown and it is known from observations during the recovery of the TBM that the gap or over cut between the bore and shields closed completely in the upper arch during the event therefore large scale deformation of the jointed and faulted rock mass took place. In this case the processes of change included (1) opening of new and/or existing fractures leading

to increased hydraulic permeability around the tunnel and (2) high pressure subsurface water wash out or erosion of joints and the fault core zone, which contained clay and other soil-like materials, into the tunnel leading to development of a conduit-like structures and associated water and ground inflow.

The conduit-like structures were quickly generated in the fault zone i.e. the opening of water bearing joints in connection with the fault core zone containing soil-like material led to rapid erosion of the fault core and the development of an extensive interconnected 3-D network of erosion channels and hence a radically changed hydraulic framework. The fault core was also found to be in direct connection with a sequence of pervious water bearing heavily jointed quartzitic gneiss and quartzite some 40 m above Ch 3,016 m. This sequence of rocks was later encountered between Ch 3,110 and 3,250 m where the combined flow-rate reached up to 60 L/s and an immediate decrease in the water inflow at Ch 3,016 m was observed confirming the water inflow model as given in Millen and Brandl (2011). At the time of TBM restart at Ch 3,016 m in March 2011 the water inflow at Ch 3,016 m had reduced to circa 120 L/s. By the time the TBM had past Ch 3,250 m the water inflow at Ch 3,016 m had reduced to circa 60 L/s.

In the event at Ch 3,016 m the dilemma was not the fact that relaxation and an increase in permeability took place close to the tunnel, but that a nearby pervious water bearing aquifer was short circuited through a fault zone due to the relaxation and hence the large high pressure water and ground inflow developed. If no water bearing pervious sequence had been tapped, then there would have been little water inflow, however a deterioration and increase in permeability of the rock mass surrounding the tunnel would still have taken place.

In the case of the TBM trapping event at Ch 5,840 m, the water inflow of some 1–2 L/s started 20 h after the event. The undisturbed soil-like stiff clay-rich fault gouge and breccia which make up the 20 m wide fault zone are impervious and were acting as an aquitard to the above lying semi-pervious but highly pressurized saturated jointed gneiss and schists sequences. In one of the exploratory bore holes carried out, a water inflow was recorded during drilling of circa 1 L/s emerging out of jointed augen gneiss and a pressure of 14 bar was measured after installation of a packer and manometer after completion of the bore hole. As at Ch 3,016 m, large scale deformation took place resulting in complete closure of the gap between the bore and shields and the development of new cracks or fractures in the stiff soil-like fault gouge and breccia hence allowing water from the overlying jointed rock sequences to penetrate through into the TBM causing erosion of the same and a rapid deterioration of the ground conditions surrounding the machine (see Chap. 1).

170.4 Consequences and Conclusions

To date the authors have found no specific literature on changes to hydraulic properties related to large scale rock mass deformation or relaxation around tunnels and the related increase in permeability due to the opening or making of new fractures and voids but believe it to be important aspect of water inflow into tunnels and understanding its control.

The increase in permeability of the ground by one or two orders of magnitude due to loosening created by blasting and the delay before the installation of temporary support has been recognised for some time (Howard 1991). It is noted here that the observations of increased permeability occurred during DS-TBM mining where the segment support is first installed and finalised (pea ballast and grouting) behind the 12.5 m long shields.

Generally it is important to control water inflow but it is even more important to try and stop erosion by the same and the generation of ground inflow as this has a more detrimental effect on the rock mass surrounding the tunnel and the tunnel advance itself. Preventative measures to stiffen up ground include grouting, ground freezing or the installation of grouted pipe roofs and the like ahead of the face into suspected poor water bearing geology. However, such measures are expensive and often met with scepticism about whether or not they will work and or reduce costs in the long term.

Remedial measures to fill cavities and the like are costly and cause time delays. All three areas where the Tapovan-Vishnugad TBM has become trapped to date will require extensive grouting and other works to be carried out such as replacement of the segmental lining with a more robust lining as the HRT will be a pressure tunnel during operation.

The measures carried out to achieve TBM recovery in the three cases quoted included (1) Ch 3,016 m: the building of a 143 m long by-pass tunnel, a 25 m long water diversion drift and an extensive drilling and grouting campaign as described in Millen and Brandl (2011); (2) Ch 5,840 m: installation of an extensive 2 layer chemically grouted pipe roof above the machine and then over mining under the same using a steel girder, shotcrete and rock anchor support systems by access through the telescopic shield; (3) Ch 5,859 m: over mining from behind the tailskin using a fore poling, steel girder, shotcrete and rock anchor support systems.

The information on hydraulic change presented here should also be considered during the implementation of grouting schemes and during the determining of the behaviour of subsurface water inflow into underground structures in the short, middle and long term i.e. prior, during and after construction.

Further thought has to be given as to where these changes occur i.e. in what types of rock or rock mass can they be expected and whether such changes are more dependent on the existence of competent (brittle deformation) or incompetent (plastic deformation) rock mass and the prevailing hydrogeological framework.

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