Engineering Geological Investigations for Underground Excavations

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Introduction

Underground space offers a stable and safe place for many purposes. From the very early days of civilization, man has sought shelter, security and comfort by going underground. In the modern times, the underground openings or spaces are being utilized for various installations like underground power houses, storage of crude oil and gas, storage of radio active waste, waste-water treatment plant, storage of heated water, storage of grains, cold storage, stadium, auditorium, archives, cable tunnels, traffic tunnels, subway stations, hydraulic tunnels, dry docks in naval base, air bases, mining tunnels, other utility tunnels, etc. Modern construction techniques are bringing down the cost of underground installations, and they offer the almost price-less advantage of having a minimum impact on the environment, both during construction and operation periods. The attributes like site geology, insitu and laboratory rock properties, design and construction methodology are of over-riding importance and they have significant bearing on cost, safety and useful life of underground structures.

The earth's crust is composed of different geological materials of heterogeneous nature and no two segments on the earth's crust are exactly similar when viewed in terms of natural conditions. Geological settings usually vary from one site to other site, though located within a single geotectonic block (Nawani 1994). Each underground project is unique and vast uncertainity and risk exist in these projects. Experiences from many underground works have shown that it is very challenging and formidable task to execute underground construction in geologically unfavourable conditions due to high insitu stresses, tectonised/deformed rock mass, shear zones, faults, squeezing, swelling and heaving, high or low rock cover, ingress of water high geothermal gradients, ingress of gases etc. Therefore, geology and hydrogeology, along any proposed underground opening – tunnel or cavern, play a dominant role in planning, designing and constructing the underground structures. The tunnels that have been investigated more thoroughly have fewer cost overruns and fewer disputes during construction.

In nature intact rock is rare, and rock material is not uniform and homogeneous. The rocks are affected by polycyclic tectonic activities in earth's crust like folding, faulting, shearing etc. The result is inhomogeneties in rock mass in form of foliation, joints, fractures, crushed zones, shear zones, etc. That is the reason why at any project site same rock depending upon the degree of tectonisation under different geological setting, will geotechnically behave as different rock masses. For example, rock mass at the closure of fold is highly jointed, sheared and deformed than at the limbs of folds.

Faults and fractures in the rock masses often carry ground water, which is a potential problem during tunneling or underground excavation. Water leakage makes the tunnel difficult to drive and if it is excessive leakage it may lead to lowering of the ground water level in the vicinity. On the contrary, sometimes the ground water in rock mass can also be advantageous like in case of

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storage of oil in unlined rock caverns the seeping water serves as an effective barrier preventing the oil leaking out.

At many sites, throughout the world, suitable geological and geotechnical conditions exist for underground construction, and for this reason underground space should be regarded as an important natural resource to be utilized wisely. Success in underground construction means constructing in the best geological environment. Hence, the key or overriding factor is the availability of suitable ground condition or favourable geological set up.

Inadequate engineering geological investigation can substantially increase the risk of encountering unknown adverse conditions or "geological surprises" that can seriously delay or even stop construction, with costly consequences. Owners, planners and designers who have little experience in underground projects frequently do not appreciate the vital importance of geological and geotechnical services to underground project. Conventional projects in uniform geology might require less investigation than the average.

The adequacy of a site investigation plan cannot be measured by cost alone, because the cost, however, large or small, is not always a valid condition of effectiveness.

Need for Proper Geoplanning

The planning process for underground structures – tunnels / rock caverns, differ fundamentally from the planning of surface engineering structures. This is true because mostly the construction of underground structures is through complex rock medium – which is initially unknown and requires thorough investigation. The aim is to obtain as complete a picture as possible of the sub-surface geological conditions and arrive at techno-economic evaluation of the project.

By carrying out appropriate investigations during the initial planning stage, great savings can be made. This is where really expensive mistakes can be avoided. Infact investigations do not cease when construction or excavation has started. Throughout the construction phase rockmass behavior is observed for adapting the design and later during operation period (post-construction) monitoring of health of the structure is essentially required.

Geoplanning is a continued process of adapting the design to rock mass conditions encountered in different phases of project execution. Geoplanning also includes studies of the effects on the surrounding in terms of stability, effects on ground water condition etc. Most crucial in the planning stage is the selection and orientation of the underground facility in accordance with the actual rock structure and insitu stresses, as it often has a major influence on stability of the structures and also the total economy of the project. Hence, geoplanning is of great strategic importance.

Some Expected Challenges of Underground Projects

Underground projects pose some formidable challenges to the geotechnical and design teams, each underground project (tunnel, cavern) is unique. Some are -

- Underground projects have vast uncertainity – in terms of geology, hydrogeology and insitu stresses.
- The cost and indeed feasibility of the project is dominated by geology and geological complexities – which are inadequately explored or known.
- Every aspects of geological investigation for underground structures is more demanding than investigation for traditional engineering projects.
- One of the most difficult and controversial aspects of any geotechnical investigation is deciding how much exploration to do.
- Ground water is the most difficult condition to predict and it is more troublesome during construction.

- Engineering properties of rock mass change with wide range of conditions such as time, seasons, rate and direction of loading etc., sometimes drastically.
- Very limited information is obtained from exploratory drilling planned for exploring subsurface geological conditions at depth. Exploration by drilling gives point information and drill core volume is less than 0.0005% of the future excavated volume of a tunnel.
- Geotechnical information is needed from the very moment planning begins of any tunnel/cavern project. Very often the final alignment of a major underground cavern is not the alignment established at the time of initial exploration programme.

When to go for Geological and Geotechnical Investigations

Without any reliable geological and rock mechanical data input, planning decisions may be incorrect. Information obtained from geological mapping, exploration and rock mechanical investigations, insitu and laboratory testing is of great help in selection of alignment of underground openings and construction methods, and thus, in cost saving. It all depends on the situation whether conditions exist that may warrant further investigations, and the phased exploration concept is based on this premise. The planning of each geological investigation and sub-surface exploration should be based on the results of previous phase. The report must be available to the decision makers of the design team in a timely manner. The sooner the geological and geotechnical information is obtained and evaluated, the greater the potential of optimization of the project layout. Based on the detailed investigations, a Geotechnical Baseline Report (GBR) should be prepared which is also required for bidding, construction and post-construction phases.

Strategy of Acquiring Geological and Rock Mechanical Data

The ultimate goal is to determine, with reasonable accuracy, the nature of subsurface rock mass condition and how it will react to or behave during underground excavation. These information can be gathered from the state of prior tunneling done in the area as well as from the available data on geological/tectonic complexity of the proposed site. It has been observed that the knowledge and skills necessary to prepare a road map for a sound and thorough geological and geotechnical investigation are not possessed by all investigators which is why critical problems could not be anticipated or discussed during planning period designing stage. Besides, the investigations are also to be value added where specialized tunneling equipment like – Tunnel Boring Machine (TBM) are to be used in addition to the conventional Drill and Blast Method (DBM).

Therefore, the emphasis of geological and rock mechanics investigations must be directed towards optimizing the scope of investigations for generating a comprehensive geotechnical report for each site. Investigation methods and predictions should be improved for three specific conditions – insitu stresses, stand up time and ground water. Critical attention must be given to the prospective use of new tunneling equipment and techniques, and to the ability of the investigation to prepare an effective exploration programme suited to the equipment and techniques of tunneling. This is essential in view of expected significant physical and financial risks associated with underground excavations, which may increase with the use of new specialized equipment or methods. It must be also well understood that how detailed may be one investigation / exploration programme for underground structures, it is not that all problem areas can be predicted. Hence, there is possibility of encountering 'geological surprises' or adverse geological occurrences during construction stage which involve physical and financial risks.

The U.S. National Committee on Tunnelling Technology (USNC/TT) in 1984, made a comprehensive study of exploration practices in the US to determine if a greater level of geotechnical investigation effort could reduce the final construction cost of tunnel projects. It was found that claims of unexpected subsurface conditions were a significant part of the total cost of a tunnel. Claims payments averaged nearly 12% of the original basic construction cost. Some were as high as 50% over the engineers' estimate (of the completed cost).

Experience has shown that the best way to defining and allocating the risk and associated cost is by establishing a baseline of geotechnical data and interpreting the data by expert engineering geologists, and preparing a Baseline Geotechnical Report (BGR) which may also be provided to all bidding contractors. Further, if during construction of underground structure, the rock mass conditions encountered are at variance or vary substantially, then an equitable change in the design of support system and also in the contract clause must be made.

Cost of Investigations

The cost of geological and geotechnical investigations generally range from 0.5 to 3 percent of the total cost of the project, although sometimes cost upto 8% have been reported. As a matter of fact, the expenditures for geological/geotechnical investigation and explorations should be increased to an average of 3% of estimated cost of the project, for better overall results.

Stages of Geological and Geotechnical Investigations

The purpose of geological and geotechnical investigations is to provide information or basic data needed for economic and fail-safe design and construction of the underground structures. The investigation programme, planned in different stages or phases, should provide geological and rock mechanical data required for detailed rock mass characterization and also to identify potential geohazards that may exist at the project site. The investigation programme should cater to all stages of the site evaluation process.

The amount of exploration to be done on any given project site is usually determined by experience and budgetary provision. Major or complex projects like large underground power house caverns, oil and gas storage caverns, nuclear waste repositories, etc. demand a greater level of geotechnical information than the smaller or conventional project.

The multi-disciplinary investigations are carried out in four stages:

i. Stage I - Reconnaissance or Pre-feasibility stage

ii. Stage II - Preliminary investigation or feasibility stage

iii. Stage III - Detailed investigation stage

iv. Stage IV - Construction stage

Each stage should have a finite life or at least have milestones or check points where the results are carefully reviewed and a conscious decision made for further scope of work in the next stage. In fig. 1, it has been portrayed that risk of unforeseen problem can be minimized by more comprehensive investigation. Further, the constraints such as cost or schedule when imposed during the planning of an investigation are fairly widely understood to lead to data inadequacies and increased uncertainity.

The extent of work to be undertaken at each stage will depend on the complexity of geological conditions. However, 100% complete information is never attainable (fig.1). If critical factors are not identified during investigation stage and they only come into light during construction stage there will be delays and cost-over runs. If a latent adverse geological feature remains undetected during design or construction phases (fig.2), the potential of failure during operation phase remains (For example, presence of thrust zone in Tala Power House Complex, Bhutan).

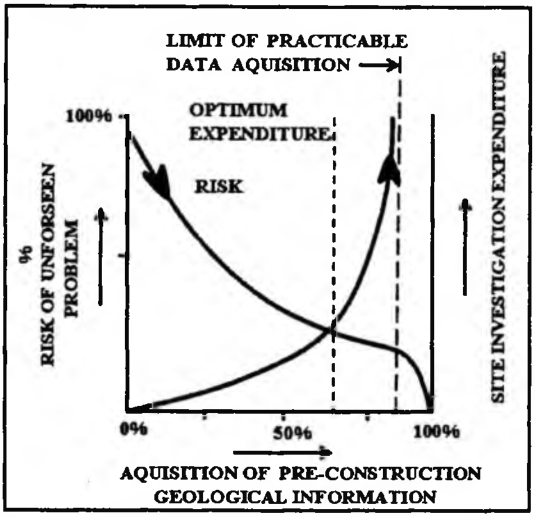

Fig. 1. Conceptual decrease in uncertainty achieved through increased investigation effort (after Carter, 1995)

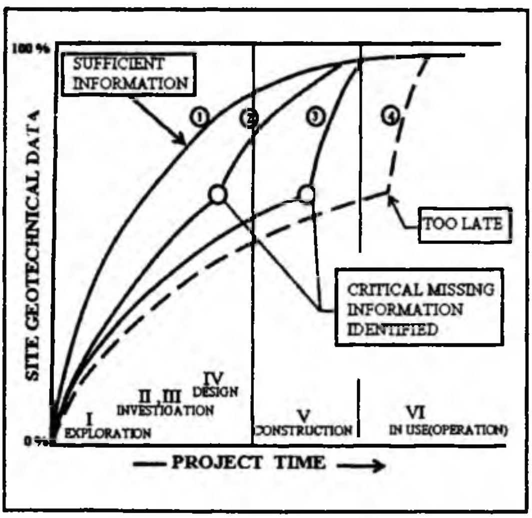

Fig. 2. Hypothetical effect of late identification of critical geological information (after Fookes, 1968; Ref. Carter, 1995)

Reconnaissance Survey or Pre-feasibility Stage

In this stage of the investigation of project planning, maximum use is made of the existing available data which includes :

- Past experiences of underground excavations in the area around the project site.
- Available literature/information related to geology/regional geology/tectonics of the area.
- Reconnaissance survey reports of all potential sites in the area.

The aim is to collect, synthesise and analyse as much information as possible at the lowest cost, since the viability of the project is still unknown at this stage. The emphasis should be on defining regional engineering geological aspects and conditions.

Preliminary Investigation or Feasibility Stage

The second stage of the investigations should be planned on knowledge gained or information collected in previous phase (Stage I) to begin establishing the site-specific geological/geotechnical characterization.

- Satellite imageries or air photo analysis – for identification and mapping geological/tectonic features.
- Geological mapping for identifying soil or rock units, litho boundaries, and geological structures like faults, shears, joints, etc.
- Subsurface explorations - pitting / trenching and drilling at selected locations to unravel subsurface geological conditions.
- Laboratory tests on selected drill cores emphasising the basic engineering properties (physical and mechanical) of rock materials.
- The available data should be analysed by experienced engineering geologists,

design engineers, construction engineers during this stage. The inter-disciplinary team helps identify unexplored potential problems that are required to be explored in detail in the next stage and which have bearing on design and construction.

- A preliminary design is often prepared on the basis of Stage II investigations.

Detailed Investigation Stage

Consistent geological field data can be obtained if the geologist is well informed of the geological conditions of the area before starting the actual mapping. The description of the geological and structural features and their inter-relationship is refined during the mapping. Rock exposures, out crops and rock walls in the underground openings offer the best localities for studying the bedrock structures. The surface explorations by geophysics and drilling help in understanding the bed rock conditions at deeper levels.

The multi-disciplinary investigations in this stage need to be planned carefully. It is often during this stage that rock mass characteristics and specific features – such as fault zones, shear zones, lithologic contacts, hydrogeological conditions and parameters like strength and deformation properties of rock mass, insitu stresses, lab testing etc. – are explored and tested. Detailed surface geological mapping on large scale (1:1000 scale) is carried out and subsurface explorations by drilling, drifting, pilot tunneling etc. are planned and executed. 3-D geological mapping (on 1:100 / 1:200 scale) is carried out in the exploratory drifts or pilot tunnels to assess rock mass characteristics in terms of Q and RMR. Drill core logging by geologists and also by using acoustic / optic televiewers is also done for getting continuous information.

Using the data generated from geological and structural mapping, subsurface explorations, insitu and lab testings, the engineering geologists and design engineers will be able to provide answers to specific questions regarding the alignment and dimension of the underground structures – caverns, tunnels, shafts, etc.

Although the third phase of investigation normally concludes the pre-construction explorations, in special case additional explorations may continue if data required are most essential.

Geological Mapping

- Study of high resolution satellite imageries/cartosat data – for identifying major lineaments/faults, shears etc. in and around project site.
- Identification and mapping of geomophological features.
- DEM using digitized maps for slope analysis – for portals of the underground openings.
- Large scale geological and structural mapping (on 1:500 / 1:1000 scale) using high precision Total Station / GPS. On line transfer of digitized data to laboratory/office for computer aided analysis and map preparation.
- Mapping of regional features on small scale and detailed features on large scale.
- Mapping done directly on aerial photographs can be transferred to planimetric maps using plotting devices that are rapid and accurate.

This study will be helpful in mapping regional discontinuities (length > 10 km, width > 100 m) local discontinuities (length 1 km – 10 km, width 5-100 m), minor discontinuities (length 10 – 1000 m, width 0.1 – 5 m) and discrete fractures which is required for geological and structural modeling of the project site (Table 1).

Geophysical Surveys

Geophysical methods have wide application in site investigation where additional detail

Table 1: Systematisation of major structural discontinuities around Tehri Dam (Nawani et.al. 2006)

Order	Description	Continuity (km)	Thickness of the Zone (m)	Disposition	Examples
I	Fault/thrust large deep seismogenic (?)	> 1000	1000	Trending NW-SE dipping northerly	MCT, MBT
II	Fault/thrust seismogenic (?)	> 100	50 - 100	Trending NW-SE, dipping at high angle northerly/ southerly	Srinagar thrust
III	Fault/tear	> 50	10 - 50	Trending NW-SE, E-W, NE-SW, NNE-SSW; steeply dipping	Gadolia tear, Tehri tear, Dewal tear, Chamba fault
IV	Fault/shear/tear	> 1	1 - 10	Trending NW-SE, NNW-SSE, dipping southerly/ northerly	L and D type mega shears at the dam siter.

is required on conditions between point sources of known data. For the successful development of 3-D model of subsurface, oriented data are essentially required. Available methods that produce such information are, for example, vertical seismic profiling (VSP), cross hole seismic tomography, reflection surveys, ground penetrating radar (GPR) and resistivity surveys. For underground works, geophysical surveys (seismic, resistivity, radar etc.) are best used for defining the attitude and overall distribution of major geological structures such as faults, shear zones, intrusious etc. In the early investigation stages geophysics has a place as a planning tool for layout of drill holes. At more advanced stages of investigation for cavern crown optimization studies, some down hole techniques and cross-hole tomography are applied for establishing variation in rock mass and fracture properties.

- Using GPR, seismic refraction/reflection and resistivity methods – for unraveling subsurface geological features, structural features – faults, shears, hydrogeological condition including geothermal occurences etc.
- GPR Surveys work on the principle of a persistent contrast in the electromagnetic properties of the subsurface medium. The depth of penetration of radio waves depends upon the input frequently band and the attenuation properties of the medium for the radio waves.
- In seismic refraction technique, elastic waves (also called seismic waves) travel with different velocities in different rocks. By generating seismic waves at a point and observing the time of arrival of these waves at a number of other points on the surface, it is possible to determine the velocity distribution (corresponding to different rock types) and locate the subsurface interfaces where waves are reflected or refracted.
- Electrical Resistivity Survey determines the subsurface distribution of resistivity by making measurements on the ground surface. The ground resistivity is related to various factors in rocks, such as – mineral / fluid content and porosity or degree of water saturation. The resistivity measurements are made by inducing current into the ground through two current electrodes and measuring the developed voltage between two potential electrodes. Thus the apparent resistivity is calculated in Ohm.m.
- Use of cross hole tomography – GPR and seismic.
- Use of bore hole seismic and GPR surveys.

Geophysical surveys should be done intensively and extensively to get fast and reliable subsurface information and also to rationally plan exploratory drilling programme.

Exploratory Drilling and Logging

Exploratory drill holes are planned at project sites with the objective of exploring quality of rock mass likely to be encountered, depth of overburden, depth of weathering/ destressing, existence of shear zone/weak zone, rock cover above the proposed underground structures. The pattern and depth are planned depending upon the nature and size of the project. For underground structure drilling is done 10-20 m below the proposed invert level of tunnel/cavern. Based on the geological and geophysical information, the exploratory drilling is planned. Drilling is done by core and non-coring or reverse circulation (RC) drilling.

The layout of borehole and subsurface measurement at a site will, in general, affect the spatial distribution of residual uncertainity in the site characterization. Borehole investigations provide a continuous record or geology of the bed rock or physical properties of the bed rock. A single drill hole log can locate intervals with increased fracturing. Using combinations of logs correlated with recorded the features in other drill holes, existence of a fracture zone or shear zone or fault zone can be inferred.

Core drilling is a very time consuming and costly operation and mostly delay during explorations is due to poor and less drilling rate/day. Accuracy in interpretation of subsurface geological conditions depends on quality of drilling, core recovery and condition of drilling machine/equipment. Poor core recovery is a very common complain registered by the site geologists. The reasons for poor or faulty drilling could be due to -

- Old conventional drilling rigs / machines
- Poor quality drilling bits
- Poor knowledge of drilling techniques / unskilled drillers

To overcome these problems it is necessary to adopt the following measures:

- Old drilling rigs / machines be replaced by most advanced drilling machines which can achieve a rate 50 – 70 m/day/ rig. These machines be used by qualified drillers.
- Double tube barrel/triple tube barrel drilling also give good results. Now-a-days, triple-tube drilling is considered standard practice for most detailed rock mechanics investigations.
- Core drilling which takes more time can be done at selected locations in order to get drill cores for physical examination, geologging, testing and broad interpretation of subsurface geology.
- Reverse circulation (RC) or Non-core drilling (which takes less time) be done in the gaps so as to confirm the continuity or bed rock profile, structural features etc., which are already interpreted by examining drill-cores.
- Significant time and cost saving can be achieved by using RC and core drilling in a balanced combination.
- Shortcomings of conventional core drilling are that orienting the core is a tideous process and in severely fractured rock it is difficult to restore the core, so that orientation is practically impossible. A logical way to overcome these difficulties is to analyse the borehole wall with a high resolution camera or logger capable of recording an omnidirectional image.
- Non-coring drilling holes can be logged using loggers like optical televiewer, acoutic, gamma ray (for lithology), gamma gamma ray (density/porosity or structure), caliper and nuetron loggers. Down hole measurements provide major complementary advantages, namely, data is acquired under insitu conditions and also data are acquired in continuous profiles measured throughout the interval with no missing sections. These images will allow comparisons of fracture zones

between adjacent boreholes. The following are some commonly used loggers :-

(i) Acoustic Borehole Televiewer

The Acoustic Borehole Televiewer provides continuous logs of oriented, unwrapped images of borehole walls (fig. 3). Further processing allows for the computation and display of standard information on fractures and other geological features. Unlike the Optical Televiewer, the Acoustic Televiewer can be run in both clear and opaque mud.

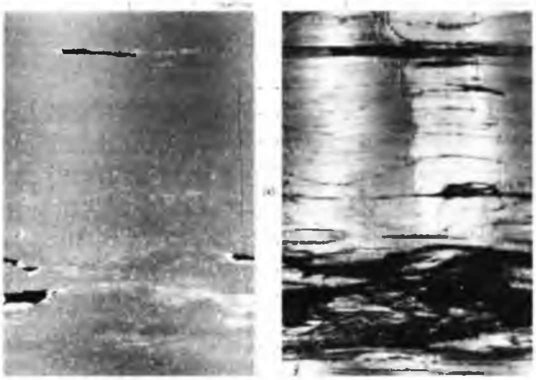

Fig. 3. Acoustic Borehole Televiewer provides continuous logs of oriented, unwrapped images of borehole walls

(ii) Optical Televiewer

The Optical Televiewer provides continuous logs of oriented, high resolution unwrapped video images of borehole walls (fig. 4). Further processing allows for the computation and display of standard information on fractures and other geological features and it provides a continuous, detailed and oriented 360° image of the borehole walls using a unique optical imaging system, this can be rapidly interpreted, using data from the internal orientation module, to obtain a complete feature analysis that includes dip, strike, frequency and fracture aperture. Unlike the Acoustic Televiewer, the Optical Televiewer can be in both air filled and clear water filled holes.

(iii) High Resolution Acoustic Televiewer (HRAT)

The HRAT is the latest RG development in acoustic borehole imaging and replaces the previous borehole televiewer probe (BHTV). It provides high-resolution oriented 'unwrapped' images of the borehole walls (fig.5).

Its applications include:

- Fracture identification and orientation
- Stratigraphic studies local stress studies (break-out)
- Core orientation

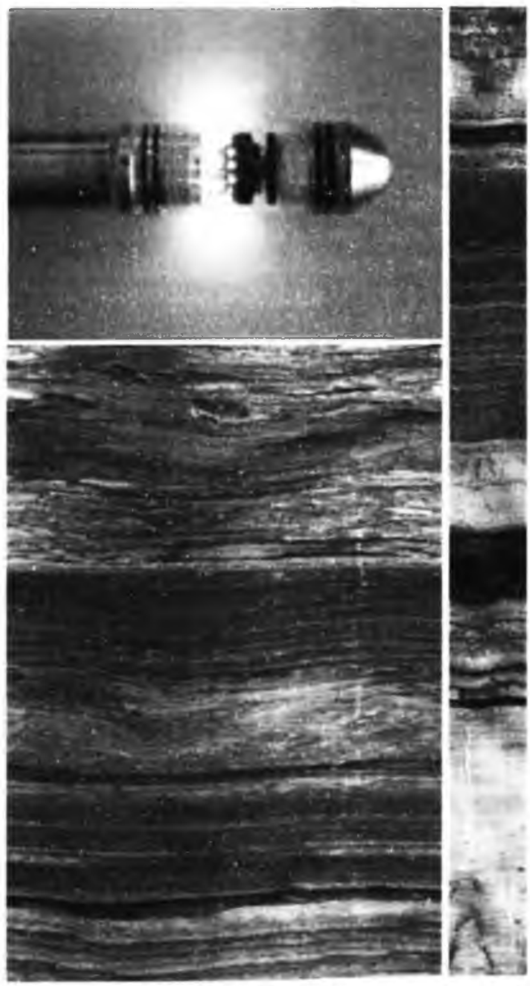

Fig. 4. The Optical Televiewer provides continuous logs of oriented, high resolution unwrapped video images of borehole walls

The probe uses a fixed acoustic transducer and a rotating acoustic mirror to scan the borehole walls with a focused ultrasound beam. The amplitude and travel time of the reflected acoustic signal are recorded simultaneously as separate image logs. Features such as fractures reduce the reflected amplitude and often appear as dark sinusoidal traces on the log.

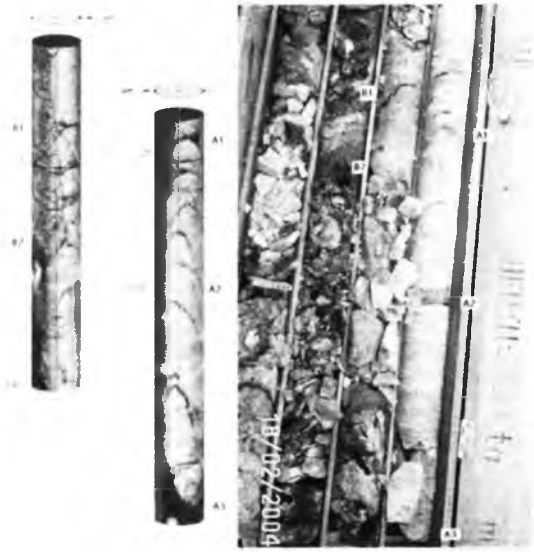

Fig. 5. HRAT provides high-resolution oriented 'un-wrapped' images of borehole walls

(iv) Sonic Tool

Effectively the sonic log measures the velocity of the strata immediately adjacent to the drillhole wall. This velocity measured in-situ will provide data on the particular lithology. This value is also influenced by formation fluids and their saturation, structural features, weathering and shale content, porosity is obviously a strong influence.

Apart from indications of rock strength, the main role of the sonic log is to provide a measure of porosity -

The accurate detection of the Shear waves (S) and Compressional waves (P) and have interesting geotechnical application through relationships between the S and the P waves from which Poisson's Ratio can be calculated.

Exploratory Drifting and 3-D Logging

Exploratory drifts (1.8 m x 2 m size) give better access to assess rock mass condition at the proposed location of any underground opening – cavern or tunnel. These not only provide an excellent means for examining the geology and rock mass conditions, they also allow monitoring of the excavation response characteristics of the ground. These drifts are also used for insitu testing for stress measurement and deformability of rock mass.

- Explorations by drifting are direct and reliable. The drifts are planned at different levels.
- Exploratory drifts are driven for reaching the locations of underground studies generally are manually driven, using drill and blast method. Current practice of driving drifts manually cause enormous delay, needs to be replaced by mechanized drifting for speedy progress.
- Tunnel Boring Machines (TBM) of small diameter can be used for faster excavation of drifts or pilot tunnels.
- Timely completion of drifting paves way for timely conducting insitu tests, which otherwise are usually delayed and this leads to further delay in designing the underground structures and also in freezing their orientation.
- 3-D geological logging (on 1:100 scale) of exploratory drifts/pilot tunnels are carried out by engineering geologists to identify and map different structural features and lithounits. Using 3-D laser scanner LARA (Laser Radar) which can scan 3-D object with high speed data sampling rate upto 6,25,000 points per second and simultaneously record both 3-D coordinates and image of the same target points, will be faster.
- Utilising the geological logs of drifts/pilot tunnels, rock mass characterization and classification is done using Q and RMR rating. These parameters in combination

with depth of excavation and insitu stresses are used for analyzing and providing suitable rock mass stabilization measures.

- Exploration by drifting has an edge over drilling particularly in demarcating the zone of slumping.

In-situ testing

For designing underground structures, insitu stresses and deformability parameters are most essential. Different field methods are applied to determine these parameters.

In-situ Stresses

- Insitu stresses in rock mass are induced by geological loading which may be by tectonic activity (active or remanent) and gravitational loading due to mass of overburden or glaciation in the past. During the excavation of an underground opening, rock mass behavior undergoes significant changes due to changes in stress condition and in pattern of readjustment of stresses around the opening. The ratio of insitu stress to the strength rock mass determines the scope and degree of deformation or failure that can occur. If the stress is much higher than the strength, local to large failures can occur, and in the extreme case rock mass may behave in a plastic manner in a way similar to soil. Pressure tunnels and penstocks in hydropower projects can be constructed and operated in rock without any lining, if virgin stress is greater than the internal water pressure which also leads to cost saving.

- The in-situ stresses are defined as horizontal and vertical stresses in x, y and z axes which are perpendicular to each other. The horizontal stresses are of two types – major horizontal principal stress ($\acute{o}_h$) and minor horizontal principal stress ($\acute{o}_h$) and the vertical normal stress ($\acute{o}_v$) is equal to the weight of the weight of overlying rock material (which is 0.027 MPa/m on an average).

- The orientation of underground caverns is mainly dependent on the direction of the major horizontal principal stress ($\acute{o}_h$) axis. The longer axis of the underground cavern is normally kept parallel to the major horizontal principal axis ($\acute{o}_h$) in order to ensure maximum stability of the structure.

- In large underground rock caverns, high horizontal stress causes instability of the caverns by inducing stress concentrations and rock displacements in the roofs and side walls. Especially, when the magnitude of the insitu major principal stress is greater than a certain percentage of the rock compressive strength, localized brittle failure accompanied by popping and spalling may possible occur in rock mass.

Methods of In-situ Stress Measurement

There are mainly two widely accepted methods of in-situ stress measurement, viz., hydro-fracturing method and over-coring method. Another technique – Flat Jack technique is also used but it has less reliability.

- Hydro-fracturing method – tests in deep drill holes.

- Over-coring method – tests in shallow drill holes (USMB gauge and CSIRO Cell)

Hydro-fracturing Technique involves isolating a test section of drill hole by means of two inflatable rubber packer and then pressurizing this section with hydraulic fluid until a tensile fracture is induced, presumably perpendicular to the minor principal compressive stress. The initial breakdown pressure is recorded as Pc. Considerable volume of fluid is pumped into to reopen and extend the fracture. The fracture reopening pressure is recorded as Pr. Impression packer is used to determine the orientation and inclination of fracture on the drill hole wall. When pumping of fluid is stopped, an instantaneous drop in pressure i.e. shut-in pressure Psi is recorded. From these repeated experiments, in-situ stresses are determined. For fracture orientation software – Plane is used and to calculate the magnitude and direction of principal stresses using shut in pressure (Psi) software – GENSIM is used. The magnitudes of stresses óH, $ó_h$ and $ó_v$ are expressed in MPa and direction of óH is given in respect of north. Insitu stress measured by NIRM at different project sites is given in the Table 2.

In Over-coring Technique tests are conducted by overcoring of a drill hole gauge capable of measuring the change in drill hole diameter in different directions using USBM (United States Bureau of Mines) deformation gauge or measuring the strain that occurs on the walls of drill hole when the stresses are relieved by overcoring using CSIRO (Common Wealth Scientific and Industrial Research Organisation) hollow inclusion cell.

Factors affecting ground stresses : The factors which affect the ground stress are :

- Depth
- Anistropy
- Stratification
- Geological structures
- Topography
- Adjacent underground openings

The expression horizontal to vertical stress ratio K = óH / óv varies because of anisotropy of rock mass. Stratification which is common in sedimentary and volcanic rock masses creates heterogeneities depending on the lithology and the relative stiffness between

Table 2: Insitu stresses measured (by NIRM) by Hydrofrac method at different project sites (Sengupta, et.al)

Name of the Project	Major Insitu stress parameters			Direction of σ_H
	Max.Horiz. (σ_H) MPa	Min. Horiz. (σ_h) MPa	Vertical σ_v MPa	
1. Himalayan Region:				
(a) NW Himalaya: (India)				
- Baspa_ Hydroelectric Project,H.P.(U/G PH)	10.80	5.40	9.71	N180°
- Sawara Kuddu Hydroelectric Project, H.P. (U/G PH)	8.855 ± 0.0332	2.53 ± 0.0095	3.685	N140°
- Dulhasti Hydro Electric project,J&K (U/G PH)	10.40	5.40	7.15	N070°
- Uri Hydroelectric Project,J&K (U/G PH)	9.16	2.29	8.07	N130°
- Vishnugad-Pipalkoti Hydroelectric Project,Uttarakhand (Desilting Chambers)	U/S 11.25 + 0.0481 D/S 12.925 + 0.1665	4.50 ± 0.1926 5.19 ± 0.066	7.28 8.07	N070°
(b) Bhutan Himalaya:				
- Mangdechu Hydroelectric Project	8.38 ± 0.6496	5.59 ± 0.4331	4.76	N070°
II. Peninsular Region (India):				
- Underground LPG (Gas) Cavern at Mangalore,Karnataka.	6.22 ± 1.003	4.15 ± 0.6669	3.67	N140°
- Rajpur Dariba Lead - Zinc Mines, Rajasthan.	16.17	8.35	11.09	N320°
- Devpura Soap Stone Mines, Udaipur, (Rajasthan)	7.74 ± 1.1091	2.58 ± 0.3697	1.76	N140°
- Malshejghat Pump Storage Scheme (Hydel Project) Maharashtra.	6.24 + 0.929	2.08 ± 0.3099	3.40	N140°

different layers. In general, abrupt changes in horizontal stress can take place across contacts between strata with different properties. It is noted that when crossing a persistent discontinuity like faults or intrusive bodies, the changes in direction and magnitudes of stresses are expected. The vertical and horizontal stresses are greatly influenced by valley slopes, mountains or big excavations. Below a flat ground the principal stresses may remain horizontal and vertical but not in mountainous region. Near the slope of the valley, under the valley and below mountain peaks the stresses get reoriented.

From the experience gained at different project sites, it is to be underlined that at any project site insitu stress measurements must be done at different locations wherever, based on geological investigations, the rock masses are expected to behave differently because of geological and structural complexities. This will give enormous data for understanding the actual relationship between insitu stresses and geological/structural parameters at the project site and also for identifying the adverse conditions in relation to the location of the proposed underground structures – long tunnels/caverns.

Moreover, at some of the test locations the drill holes should be kept intact or preserved and during construction the changes in ground stresses may be monitored so that necessary improvements in the design are adapted for improving stability of the structures.

Deformability of Rock Mass

The stress-strain behavior of rock mass, i.e. response of rock mass towards loading and unloading and the failure criteria of rock mass play a vital role in engineering of surface and underground structures. Many hard rocks (intact) are elastic when tested in laboratory, but in field, since rock mass has many discontinuities it may not show linearity as well as recoverable displacements. For the design of pressure tunnels it is desirable to know the affects of loading and unloading on rock mass and lining under operating pressure (loading) as well as the amount of recovery when the pressure is lowered (unloading). The values of deformability for different classes of rock mass are given in the Table 3.

Table 3: Values of deformability for different classes of rock mass (Chappel, 1984)

Deformability Ed (GPa)	Quality Classes	Description
0.05 - 0.5	V	Very bad
0.05 - 4.0	IV	Bad
4.0 - 5.0	III	Fair
5.0 - 25	II	Good
25 - 50	I	Very Good

Rock mass deformability is tested by -

- Static Methods – plate loading, flat jacks and bore hole jacks.
- Dynamic Methods – measurement of P-wave velocity (geophones), P-wave and S-wave velocity and measurement of Direct wave velocity in drill hole (sonic coring).

Insitu testing of deformability of rock mass is mostly done using static methods. In plate loading method, a rigid circular plate is used to load the rock mass through flat jacks or hydraulic jacks and response of rock mass towards the applied loading and unloading in form to five cycles (with load increasing in successive cycles) is recorded to get a pressure versus deformation curve. In bore hole pressuring methods, the most commonly used instruments are pressure meter and dilatometer. Pressure meter is a bore hole probe that applies hydraulic pressure through a flexible membrance to the drill hole wall in different cycles of loading and unloading. Dilatometer consists of cylindrical bore hole probe. It is a radially expandable rock pressure used mainly to determine the short-term deformability of rock mass and operates in 76 mm drill hole and has a maximum working pressure of 30,000 kPa.

Laboratory Testing for Physico-Mechanical Properties of Rocks

A specimen of rock tests in the laboratory is a specimen of intact rock. The material properties of both the intact rock and joints (discontinuities) are required for numerical modeling. The following physico-mechanical properties of intact rock, are determined in the laboratory.

Intact Rock Properties:

(i) Physical Properties:

- Density
- Porosity
- Water absorption
- P&S wave velocity
- Hardness

(ii) Mechanical Properties:

- Uniaxial compressive strength (UCS)
- Young's Modulus, Poisson's ratio, Bulk Modulus and Shear Modulus.

These are elastic constants.

- Tensile strength
- Cohesion and friction angle – shear strength
- Triaxial compressive strength

The samples are prepared for testing by cutting to the required length, and end faces are ground and polished using surface grinder. All the tests are conducted as per the ISRM suggested methods.

Joint Properties: Rock joints are formed by fracturing process involving tension/shear stresses. The most important properties are its roughness, frictional angle and joint wall compressive strength. The following joint properties are important as input parameters for numerical modeling of rock mass for underground projects.

- Joint roughness coefficient (JRC)
- Basic friction angle and residual friction angle
- Joint wall compressive strength (JCS)
- Peak shear strength
- Normal stiffness (Kn)
- Shear stiffness (Ks)

Laboratory strength parameters of intact rocks are used in estimating the rock mass strength properties using rocdata software using the appropriate field parameters like geological strength index (GSI) and disturbance factor (D) and the corresponding application like tunnel, slope etc.

Engineering Geological Modelling

Underground caverns require from the site selection towards the design and construction phase the integration of various geological, hydrogeological and rock mechanical data. Before developing hydrogeological modeling (for assessing water seepage rate for example) and rock mechanical modeling (for stability and reinforcement issues), a geological model is required.

When working in one single geological formation, the 3D geological model is often simplified into a 3D structural model in which rock is not represented while only the structural features joints, faults, shears etc. are shown. In addition weathered layers arte also included to enrich the 3D structural model. This approach simplifies the creation of the 3D model (using Auto CAD (R)) and emphasizes on discontinuities, which are the crucial aspects regarding stability issues as well as hydrogeology. This way visualization is greatly enhanced and non-geologists easily appreciate the model to work with. All other parameters like seismic surveys, ground surface measurements, GPS data etc. can also be used as most of them are now compatible with Auto CAD (R).

Enormous geological, structural and geotechnical data base is generated during field and laboratory investigations during pre-construction stages of the project; however, quite often there is a lack of systematization in data processing, analysis and synthesis and this leads to vagueness in the data feeding system for their use in design. To overcome this situation an innovative approach of engineering geological modeling (fig. 6) has been evolved in which various attributes of key parameters of rock mass, viz. lithology, interblock tectonics, exogenic alterations, permeability or hydraulic conductivity, discontinuities and geomechanical properties, are used (Nawani 1994). This is helpful in meeting the design needs and has an edge over the conventional approach of viewing the foundation with rock mass parameters individually or in isolation.

It is to be emphasized that the geological and structural modeling is continuous process which often starts at the same time as observations are made. This implies that geological/structural modeling is an iterative process and as such the flow of information forwards and backwards – updating new data, new ideas, modification of nomenclature etc. In a multi-disciplinary characterization of a project site, all performed investigations generally describe different aspects of the site.

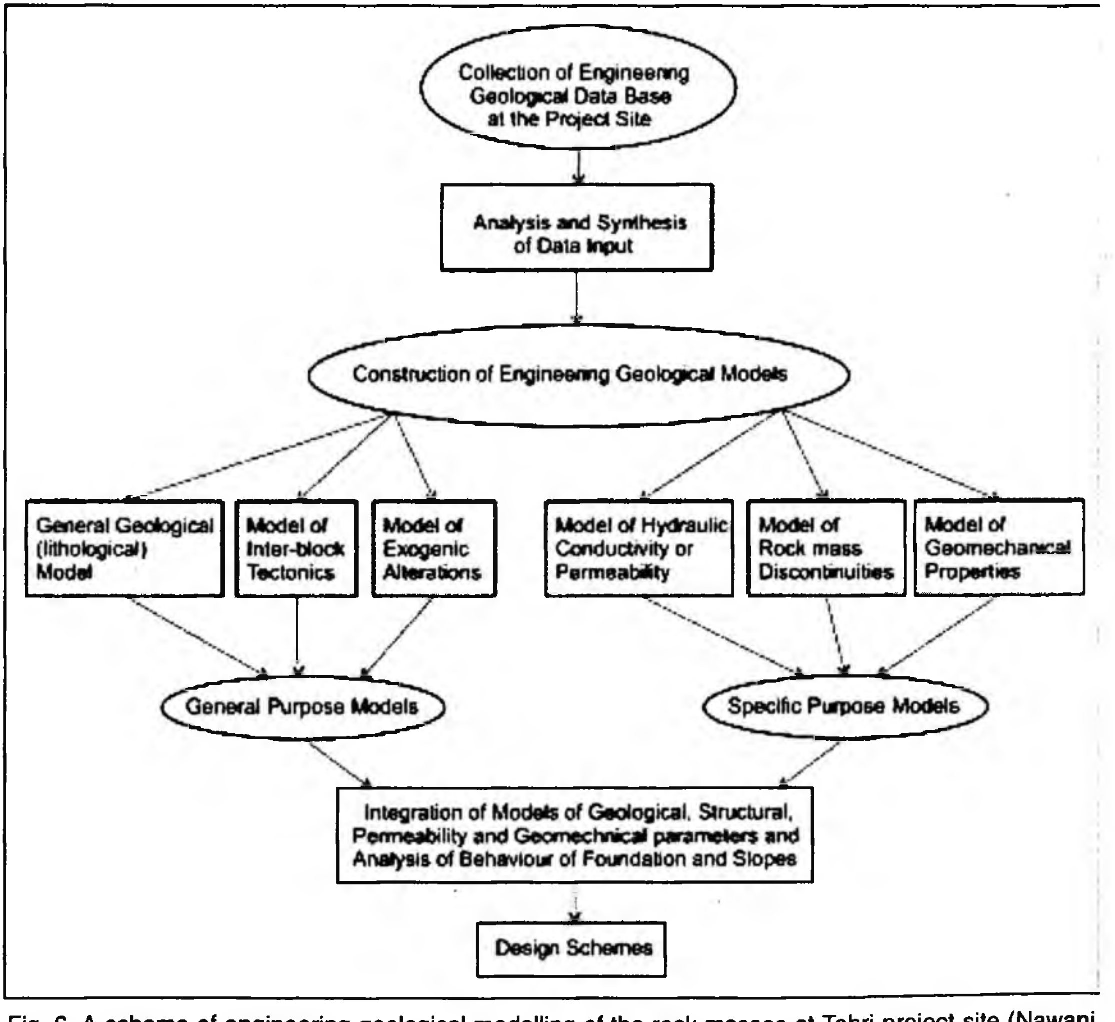

Fig. 6. A scheme of engineering geological modelling of the rock masses at Tehri project site (Nawani, 1996)

Numerical Modelling

The complex nature of rock mass and associated geotechnical problems together pose a complex engineering problem. The interest of the design engineer is to assess the stability of a tunnel or cavern when no support is installed and when suitable support is installed. Numerical approach is useful for simulating the rock characteristics and failure behaviors under various stress fields along with the effects of various rock parameters. Numerical analysis can also provide useful information for excavations and construction activities in soils and rocks. It is a very useful technique for the assessment of stress and displacement around excavations.

Different numerical modeling modules are available like finite element method, distinct element method, finite difference method, etc. The areas of application for each of the modules vary depending on the problem encountered. The advent of faster computing capabilities, large number of commercial software like ANSYS, NASTRAN, 3DEC, FLAC etc. can be utilized. Analysis can also be chosen between two dimensional or three dimensional based on the requirement of the designer. Two dimensional modelling can overestimate the resulting stress ?eld around an opening, thereby making it a more conservative estimate of induced stresses. However it gives results quickly and can be used for indicative analysis, followed by detailed three dimensional analysis.

Numerical analysis has been effectively used for prediction of displacements, stresses and failure zones around multiple underground caverns and tunnels. This requires understanding of rock mass in terms of geological/structural, geotechnical, insitu stress and hydrogeological parameters to be input into the model. The sequential excavations in case of large caverns can be simulated and results can be obtained after each stage of activity. The factor of safety values along the excavated caverns helps in deciding suitable support requirement like rock bolts and cables. The lining elements like steel ribs and shortcrete can be simulated in the model and their efficacy can be analysed.

The process of designing underground workings in the mines, includes study of interaction between different rock mass during extraction, effect of extraction process on the stress fields, estimating loading on the workings and their stability. In addition to this design safety factor is based on designer's experience. Therefore, the accurate estimation of stress concentration needs detailed studies. Analytical methods may not be able to solve these complex and site dependent parameters and conditions due the varying size, position and nature of working, thus compromising on the accuracy of analysis. However, numerical modeling can not only consider large domain in analysis but can also perform parametric study in order to decide on proper and judicious design. The subsidence and caving of the rock mass can be effectively be modeled to attain better response in the analysis.

The dynamic effect due to rock blasting and seismic activities can also be modeled effectively to analyse their influence on the structures. These analyses can be useful both during construction as well as post construction stage. During the construction stage, blasting activity can damage rock mass beyond the working face. The damage may not be evident initially but it can significantly affect the deformability characteristics of rock mass. Based on numerical modeling results, the blast design can be reformulated or necessary remedial actions like rock bolting can be considered. Many underground powerhouse in Himalayan region is situated close to the zones. Seismic activities and dynamic events due the movement of this thrust zone can significant affect the performance and stability of the caverns. These disturbances can be suitably modeled and its influence on long term stability can be analysed using numerical modeling.

Construction Stage

Underground Geological Mapping

The major problem during construction stage is the rock mass in underground excavation behaving differently than what was anticipated. In order to assess the rock mass behavior, 3-D geological mapping on 1:200 scale is carried out in the underground openings – tunnel or cavern, continuously with the progressive advancement of excavation, on shift to shift or day to day basis. These 3-D geologs of tunnel / cavern show disposition of different litho bands, structural features (prominent joint sets/ shears/faults), water seepage, overbreaks etc. at crown portion, spring level and upto invert level of the underground openings. Based on the rock mass characteristics, the rock mass encountered in different tunnel sections are classified into different classes using Q values (Barton, 1974) and RMR rating (Beiniawski, 1973). Accordingly, suitable stabilization measures such as active (rock bolts with shotcreting), or passive (steel ribs) are recommended depending upon the rock mass characteristics or classes.

Geotechnical Assessment of Tunnelling Medium

The behavior of the rock masses existing in different geological and tectonic setting is geotechnically assessed, before and during tunneling operations, by adopting two important rock mass classification viz., Q and RMR systems developed by Barton (1974) and Beiniawski (1989). The Q system of rock mass classification of Barton et.al (1974) is primarily based on six factors:

- Rock quality designation RQD
- Joint numbers (Jn)
- Joint roughness (Jr)
- Joint alteration (Ja)
- Joint water (Jw)
- Stress Reduction Factor (SRF)

These rock mass parameters are related by the equation:

Q (Rock mass Quality)	=	RQD/Jn (Measure of Block size)	x	Jr/Ja (Measure of Interblock shear Strength)	x	JW/SRF (Measure of active stresses)

Depending upon the number, orientation and nature of the discontinuities, the rock mass will translate, rotate or crush in response to the stresses imposed. The Q system provides a very flexible and useful tool for the estimation of support designs in underground structures over a wide range of spans. The rock masses are classified into six classes from Class I (Q = 40 - 100) to Class VI Extremely poor (Q = 0.01 - 0.1) on the basis of Q values.

In Rock Mass Rating (RMR) of Beiniawski (1989), five classes of rock mass are defined based on five geotechnical parameters.

- Strength of intact rock (Compressive 6_c)
- Rock Mass Designation (RQD)
- Spacing of closest joint sets
- Condition of discontinuities
- Ground water

These parameters are added and the aggregate is adjusted against tunnel alignment to get the final values which represent different classes. These classes can be inpreted in terms of stand up time. These rock classes are four Class I (RMR > 80) to Class V (RMR < 20)

The support system comprising rock bolts, shotcrete with wire mesh and steel ribs are given as per the rock classes. Although the RMR and Q-systems of rock mass classifications utilize some different parameters, yet there are broad similarities when the two are compared. However, in case of high stress or low strength, these two systems tend to diverge, as the SRF term in Q value ($6_c/6_1$) does not appear in the RMR, and 6_c compressive strength does not occur directly in the Q-system.

Hoek has also introduced a new term Geological Strength Index (GSI) which resembles RMR upto a value of 25 and differs afterwards. GSI which depicts the geological condition of rock mass and range from 10 to 100 has been found to be very useful in design of cavern. The GSI of a rock mass can be calculated by substracting 5 from its RMR value.

Instrumentation

Instrumentation of a structure are usually undertaken in order to gather information about the existing stress field in surrounding rock mass, redistribution of stresses during excavation and any change in the geotechnical conditions, verification of effectiveness of remedial measures and long term monitoring of structure and the rock mass. Instrumentation data is necessary to plan, design, verify and recommend any construction and alteration in a particular structure. The safety of the structure as well as men and machinery can be continuously monitored with a well planned instrumentation programme. In the underground openings, critical areas can be identified by instrumentation, where rock mass behavior shows variations like dilation, convergence etc. and provision for additional support system/rock mass strengthening can be made. Field measurements of deformation of rock mass are also required to validate results obtained from numerical simulation and to improve input data.

The following instruments can be installed in a cavern or tunnel to measure the different rock mass parameter.

- Multiple Point Borehole Extensometer (MPBX) measures movement of rock mass at different locations, away from the opening. The recordings are helpful to identify occurrence of crack inside the surrounding rock mass.
- Stress cells can be used to monitor change in stress field during excavation activity. It is installed into a borehole drilled into the rock mass at predetermined locations.
- Load cells to measure the rock load coming on supports. It is mounted on steel supports. Load cells can be mounted on rock bolt in order to measure the load being transferred on the bolts.
- Pressure cells can be placed between lining and the rock mass to measure the rock load on lining and transfer of internal pressure to surrounding rock.
- Total station targets are placed on the surface of walls of cavern. These targets can be monitored using optical devices to measure the surface movements.
- Strain meters can be attached to existing cracks on the walls of openings in order to monitor the progressive extension and further widening.
- Piezometers can be installed to monitor the seepage of water into the openings.
- Stress pattern and rock mass behavior around the underground openings monitored by the microseismic or acoustic emission techniques. Real time online monitoring can be conducted which provides important information about the stress built up, time dependent deformation and micro cracking in the rock mass.

Site in underground structures are often quite inaccessible, either due to terrain or due the construction features. Geological information is usually incomplete and restricted to tunnel working spaces, and even a small variation can involve major safety hazards and cost over runs. It is necessary to have remote and continuous monitoring of the rock mass in order to gather maximum information from the installed instruments. Data acquisition system combined with well planned instrumentation must be essentially adopted for successful and safe construction activity in underground rock mass.

Geological Complexities in Underground Excavation

Major problems, related to complex

geological conditions, encountered during underground excavation, which need to be studied in detail for providing engineering solution to tackle them, are:-

- Blocky or slabby rock mass
- Flowing water condition (water ingress)
- Squeezing, swelling and spalling condition
- Stand-up time
- Rock cover
- Insitu stress
- Gases
- Hot water

- Blocky / very blocky or slabby rock mass is defined as interlocked, partially disturbed mass with multifaceted angular blocks formed by 4 or more joint sets. The rock mass has a tendency to move during excavation, thus causing problem of stability.

- Ground water problem means presence of water in higher volumes than predicted, or worse, the unanticipated presence of water during tunneling. Ground water in rock mass is trapped along fault zones, deformed zones, interconnecting joints and in synformal structures. The water ingress of the order of 500 – 2000 litres/sec has been observed in some of the underground excavations in hydro power projects in Himalaya e.g. Maneri Bhali Stage I, Maneri Bhali Stage II, Tapovan-Vishnugad HE Project etc. The presence and movement of water strongly influences ground behaviour, and thus creates a requirement of handling and affects productivity and thus cost. If the water moves throughout the medium having fault/gouge zones, the water may wash away infilling material/loosened particles into the excavated opening. This causes instability in rock mass. This was noticed in some of the deeper underground excavations for hydro electric projects in Himalaya (e.g. Tapovan-Vishnugad HE Project in Uttarkakshi of India. The ground moves inward often resulting subsidence above or adjacent to the excavation. Subsidence in soft ground excavation may be critical particularly in urban areas because of potential for damage to the structures.

- Swelling occurs when ground having clay mineral – montmorillonite expands in volume by absorbing or adsorbing water and then tends to move into available openings or to exert pressure. Squeezing occurs when weak material behaves plastically under the weight of overlying ground and slowly advances inwards without perceptible volume increase. Spalling is related to highly brittle and hard rock mass and where depth of excavation is more. These phenomena were observed while tunneling for HRT in Maneri-Bhali Stage II in Uttarkhand Himalaya, India.

- Shear zones are characterized by highly deformed, sheared, water changed, poor rock mass conditions. Serious tunneling problems have been experienced when rock mass is affected by multiple shear zones. In anticlinal structures rock mass is highly fractured / jointed / sheared in the closure of fold and structurally controlled failures are anticipated at the crown of tunnel/cavern. In thrust zones, in Himalayan region, the tunneling problems are related to extremely poor rock mass with less stand-up time and high closure rate leading to distress of support system. Some of the important examples are head race tunnels in Maneri Bhali Stage II, Giri Hydel Project, Ranganadi Hydel Project in India and Tala Hydel Project in Bhutan.

- A stand-up time problem occurs when the ground will not support itself for a time sufficient to accommodate the construction. Stand-up time dictates when the support system must be installed and if it not timely completed, it may lead failure or collapse. Loose fall, chimney formation and collapses due to less stand up time of rock mass of Class VI and beyond Class VI (Q= 0.01, PMR <0). In some extreme cases, a combined system of rock bolts, steel ribs and shotcrete may be required, immediately after the excavation advancement by fore-poling and multiple drifting as the case may be.

- Vertical rock cover above the tunnel periphery has direct influence on insitu stress (vertical) which inturn has significant influence on the behavior of rock mass around the opening. Rock mass undergoes major changes/ squeezing when the depth of tunnel exceeds 350 x $Q^{1/3}$. Rockbursts in the tunnel reaches with high rock cover (> 1 km.) has been recorded in many hydro electric projects in Himalaya. In deeper mines of Kolar Gold Fields (Karnataka, India) which are at 3.3 km depth, frequent rockbursts were recorded and now also these rockbursts are being recorded although the mines are already closed. In shallow rock cover areas, due to predominance of horizontal major stresses, deterioration in the rock mass conditions is observed in many hydel tunnels.

- Insitu stresses are very high in thrust zones, other highly tectonised zones and high cover reaches and obviously there the rock masses are heavily stressed. If rock mass is characterized by high ratio of rock mass strength ($σ_c$) and insitu stress ($σ_1$), the stability of tunnel will not be jeopardized. Stress induced deformation have been noticed in many underground openings in Himalaya region.

- Gases encountered underground can be noxious, toxic and hazardous posing significant problems to construct. If unanticipated, such gases can obviously be dangerous; if anticipated and planned for, the danger may be minimized. The tunneling equipment may have to be 'spark proof' if explosive gases (Methane CH_4) are contemplated. A special ventilation and absorption system have to be installed for noxious and corrosive gases. During investigation stage itself, all exploratory holes should be checked for the presence of gases. Highly inflammable gases (methane) were encountered while tunneling in Ranganadi Hydel Project and Loktak Hydel Project in north eastern part of India.

- Tunnelling through hot water or geothermal zone is very difficult due to deteriorating working condition because of high temperature and humidity. The chemicals present in hot water have corrosive effects on concrete lining. In Higher Himalaya, which is marked by young granite intrusions and deep seated faults, occurrence of hot water springs and high geothermal gradient is recorded, eg. Nathpa Jhakri Hydel Project in Himachal Pradesh (India), hot water zones (Temp. 54° – 60°) were encountered with a discharge of 60 lit/ sec. in some reaches of the head pace tunnel (27 km. long). These geothermal occurrences were already identified during investigation stage. Hence, high temperature inside the tunnel was brought down by sprinking cold water and placing ice blocks near the working face.

- During underground excavation, if highly complex ground conditions are encountered due to the existence of poor rock masses, in that case tunneling is carefully done by adopting forepoling, multiple drifting, controlled blasting and instant rock mass strengthening and stabilization measures like instant rock bolting by resin type / swellex type or even by self drilling anchors (SDA), reinforced shotcreting (steel fibres) and provision of drainage holes. For providing effective design solution, in order to minimize or control stability problems related to rock mass characteristics, it is necessary to have geotechnical assessment of tunneling medium which is based on the geological inputs generated during construction stage engineering geological investigations.

Concluding Remarks

- The underground spaces are being utilized for various important installations in many high-end projects. Each underground project is unique and vast uncertainity and risk exist in these projects. Further, it is very challenging and formidable task to execute underground construction in geologically complex conditions due to high insitu stresses, tectonised/deformed zones, shear zones, fault zones, squeezing, swelling and heaving, high or low rock cover zones, ingress of water, high thermal gradient, ingress of gases etc.
- Success in underground construction means constructing in the best geological environment. Prior knowledge of impending geological complexities is helpful in considering pre-emptive engineering solutions. Need for adequate engineering geological investigations is emphasized so as to minimize the risk of encountering unknown adverse geological conditions. The purpose of geological and geotechnical investigation is to provide basic data for economic and fail-safe design and construction of the underground structures.
- Site investigation should be considered the first part of the design process. Successful final designs can only result from thorough and effective investigation planning. The engineering geological investigation programmes which are planned in four stages – reconnaissance or pre-feasibility stage, preliminary or feasibility stage, detailed investigation stage and construction stage – should provide geological and geotechnical data required for rock mass characterization and also to identify potential hazard zones at project sites. The extent of work to be undertaken at each stage will depend on the complexity of geological conditions. For each investigation stage, as additional data on the final site is acquired, ideally a better understanding of site conditions is achieved; however, 100% complete information is never attainable. Some times, critical factors are missed in pre-construction stages and only come to light during design stage or during the construction phase. If the critical factors are also not identified during construction, extensive delays and cost overrun are seen. If a latent adverse geological feature remains undetected during both the design and construction phases, the potential failure during operation always remains.
- Critical attention must be given to the prospective use of state-of-the-art techniques of geological/structural data collection, geophysical surveys, exploration by drilling, hydrogeological studies, insitu stress measurements and laboratory studies followed by modeling by numerical methods. Problems can be minimized by good site investigation practice. At times, poor or no geological mapping is done at sites and an excessive number of holes of dubious drill quality are put down with the result that unrealistic or erroneous projections of the subsurface geological conditions are prepared.
- Investigation methods and predictions should be improved for three specific conditions – insitu stresses, stand up time and ground water. The ultimate aim is to determine, with reasonable accuracy, the nature of subsurface rock mass condition and how it will react to or behave during underground excavation.
- Besides, the investigations are also to be value added where specialized

tunneling equipments like Tunnel Boring Machines (TBM) are to be used in addition to conventional Drill Blast Method (DBM).

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