Instrumentation: A key to stability analysis of large caverns in hydroelectric projects

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Abstract

Importance of instrumentation during construction and implementation stage for large caverns of hydroelectric projects is highlighted. Systematic instrumentation provides vital information w.r.t. stability of the structure. This paper deals with the case histories of three major hydroelectric projects viz., Nathpa Jhakri, Sardar Sarovar and Tala hydroelectric projects.

1. Introduction:

Underground caverns are increasingly used to house the equipments in hydroelectric projects due to environmental and other operating constraints. Construction of such large cavern, in many cases multiple caverns in close proximity, is fraught with stability issues mainly due to complex rock mechanics problems. Stability of these large caverns during the construction and implementation stages is a vital issue and attracts attention from the owners and designers. Routine and continuous assessments of certain critical parameters which are beyond the human perception are required to evaluate the stability of caverns during all the stages. Only systematic instrumentation can provide vital information regarding the health of the structure and ensuring safe and economical operation of the power plant. Instrumentation also aids other stability analysis tools like numerical modeling, empirical relationships etc.

The interaction of underground structures with the surrounding rock medium influences their stability during construction and post construction stage. The interaction initiates with the commencement of excavation process and continues for a period after excavation till both the structure and rock mass attain equilibrium conditions. Throughout this period, the characteristic of ground mass continuously changes with development of stress and consequent relaxation in the form of displacements. The influence of these changes should be accounted into design and construction of the structures. A continuous monitoring at all stages helps in checking the design assumptions. An overdesign may result in costly cavern and an under design may result in unsafe cavern. Thus, systematic instrumentation is the key in achieving economical and safe caverns for long term use (1).

2. Necessity of instrumentation in caverns:

Underground caverns often present the ultimate measurement challenge, partly due to their initial lack of definition and negligence during planning and design stage along with non-responsibility of the contracting agency in generating and maintaining the data. Similarly, the objective of measurement is complicated by the fact that data acquisition is required from a coarse scale to a fine scale and involves a number of instrumentation techniques. The ultimate goal is to select the most sensitive measurement parameters with respect to stability and safety of underground cavern. However, due to physical limitations and economic constrains, all parameters cannot be measured with equal ease and success. Procedure of planning for instrumentation is explained in detail by 1, 2 and 3. The monitoring instruments can be useful to ascertain following aspects (Figure 1):

a. Design verification- Instrumentation can be used to verify deign assumptions and check the predicted behaviour of workings. Results of field monitoring in initial stages may help in modifying the design for further stages.
b. Excavation control- It can be used for monitoring the dynamic effects of excavation, which helps to modify the sequence to minimize deformation. Likewise, it also helps in timely implementation of support system.
c. Quality control- Performance of excavation method and installed support system can be monitored in order to ascertain the sustainability in adverse conditions.
d. Safety- Field monitoring provides early warning of impending failures, allowing time for safe evacuation of the area and to implement remedial measures by continuous monitoring, quick processing and presentation of data.
e. Legal protection- Instrumentation can provide evidence for a legal defense in case of mishaps and fatalities.

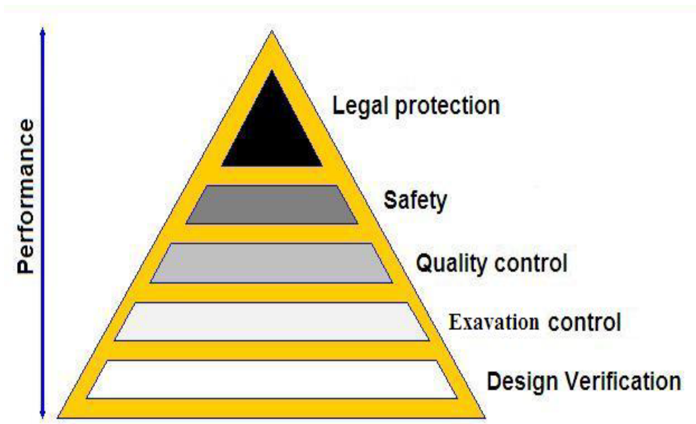


Figure 1 Influence of instrumentation on performance of structure

3. Suitable Instruments for Cavern Monitoring:

The common parameters which are monitored in underground caverns are:

a. Convergence: The wall closure measurements can be monitored by using:
- Mechanical instruments like tape extensometer, basset convergence systems and Convergence indicators
- Optical instruments like total station with reflective targets and prisms
- Laser aided convergence systems

Optical instruments provide better flexibility and accuracy for measuring convergence during all stages of excavation in caverns compared to the other types.

b. Displacement measurements: The deformations at various horizons of the rock mass can be monitored using:
- Borehole extensometer with single point and multipoint anchors
- Inclinometers

Inclinometers are suitable for monitoring dams and slopes wherein horizontal displacements are predominant, whereas for caverns multipoint borehole extensometers provides insight into the separation and displacements of different horizons.

c. Induced stress measurements: Change in stress during the excavation process can be monitored using uniaxial and biaxial stress cells.

d. Pore water pressure: In order to measure pore water pressure, following instruments are used:
- Open stand pipe piezometers
- Electric piezometers
- Pneumatic piezometers

Electric piezometer are more sensitive but expensive as compared to pneumatic type. However, they offer rapid response and negligible time lag.
e. Instruments for monitoring the performance of supports: Axial load on the rock bolts can be monitored using load cells. However, for monitoring the load induced on rock bolts at different depths, instrumented rock bolts are generally used.

f. Regional Instability: Acoustic or Micro seismic monitoring techniques can detect low intensity, high frequency noises emitted by any activity within the rock mass.

4. Case histories of instrumentation in large caverns:

This paper discusses the extensive instrumentation carried out by National Institute of Rock Mechanics (NIRM) at Nathpa Jhakri power project, Sardar Sarovar project in India and Tala hydroelectric project, Bhutan.

4.1 Nathpa Jhakri Power Project:

Nathpa Jhakri hydro-electric project (1500 MW) is the largest run of river scheme underground hydroelectric power project in India. The project has 4 desilting chambers (525m x 16.31 m x 27.5 m) and powerhouse complex with machine hall of size 222 m x 20 m x 49 m. The head race tunnel of 27.39 km long and 10.15m dia is one of the longest tunnels in the world. NIRM carried out stress analysis and instrumentation of powerhouse and desilting complexes and recommended the support design (4) NIRM is currently carrying out analysis of instrumentation data of powerhouse and desilting complex supplied by SJVNL to ascertain the stability of caverns during operational period (5).

4.1.1 Desilting chamber instrumentation:

MPBX of resistance type and piezometers of vibrating wire type were installed in desilting chambers. MPBX observations at few locations are shown in figure 2. Displacements in the desilting chamber were found to be within 5mm and overall long term trend showed stabilization trend. MPBXs at other locations also exhibited similar trends.

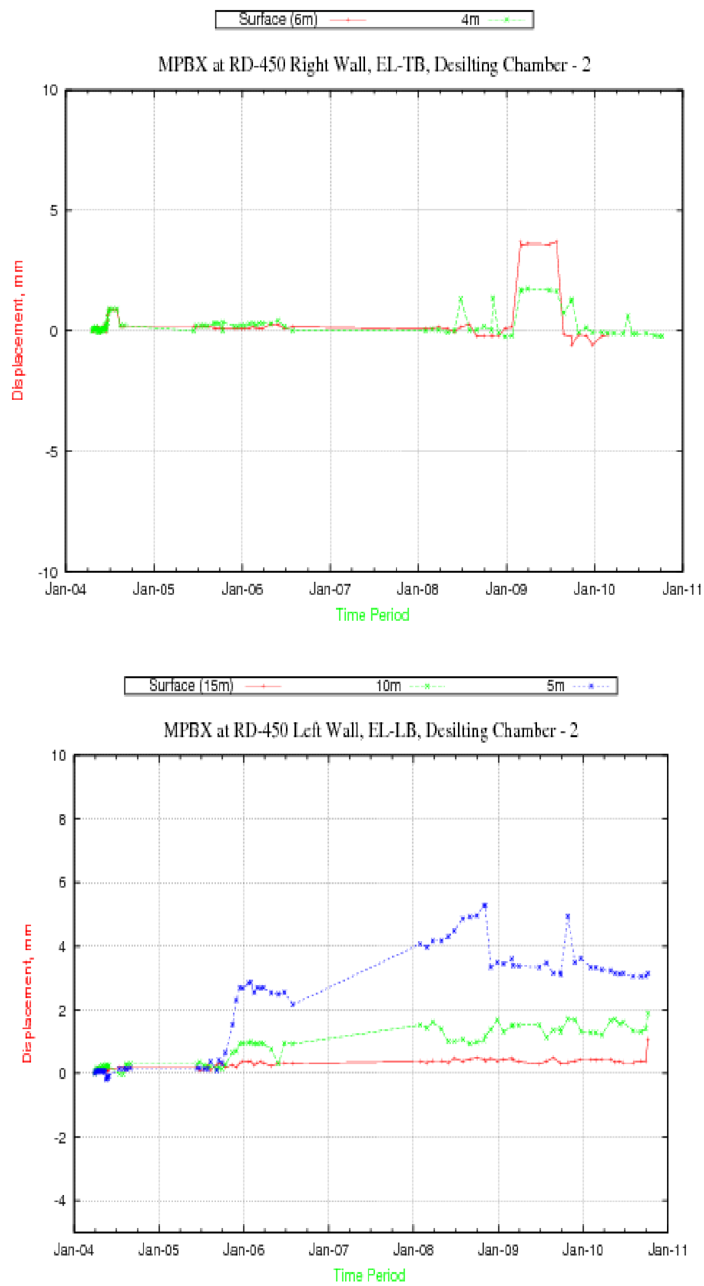


Figure 2 Displacement at RD 450 left & right walls at Desilting Chamber 2

The piezometer observations are shown in figure 3. Results revealed that the pore water pressures were consistent with the water levels in reservoir and do not show any abnormal increase in pore water pressures at any of the locations. Convergence measurements were carried out using prism points and total station in the upper and lower access gallery walls between chambers indicated no significant convergence. The cumulative convergence in the desilting chamber was found to be within 2-3mm.

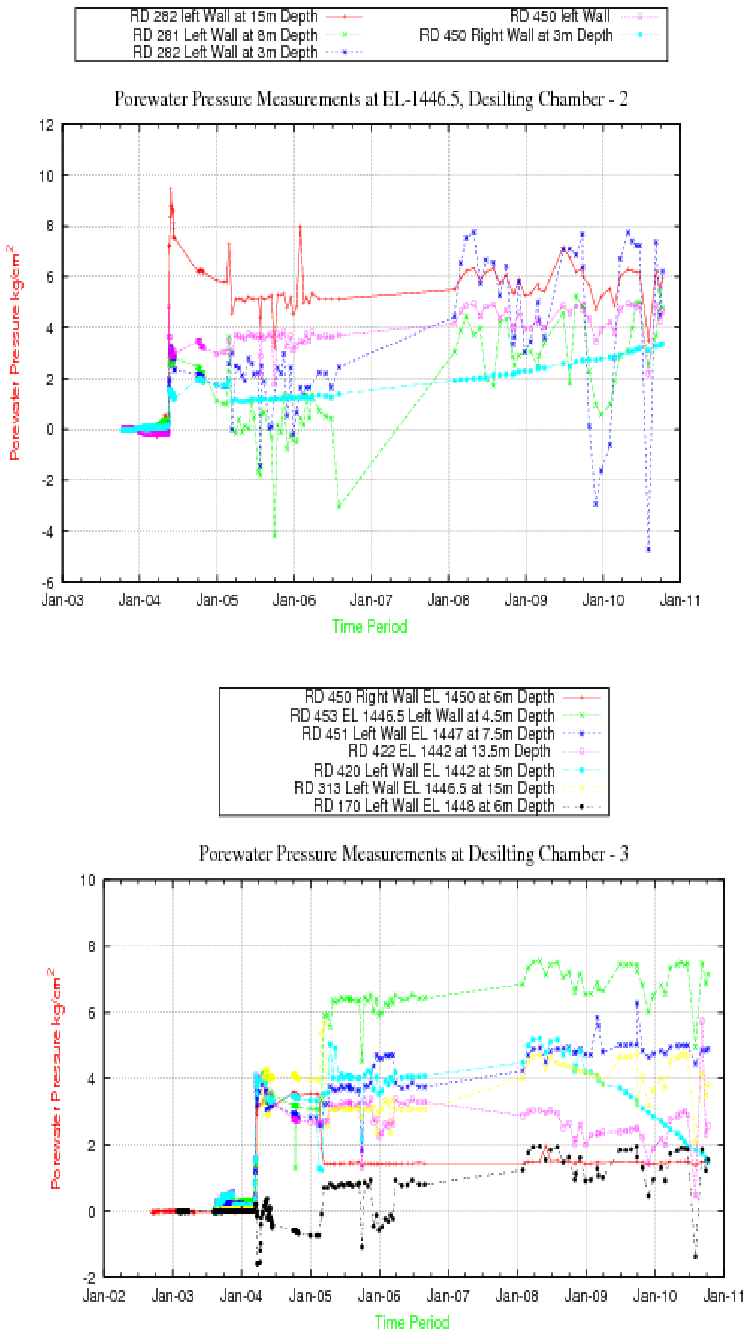


Figure 3 Piezometer observations at Chamber-2 and Chamber-3

4.1.2 Powerhouse instrumentation:

MPBX were installed from the drainage galleries. The MPBX observation at few places in the downstream wall of Machine Hall Cavern is shown in Figure 4. Analysis of the MPBX observations at powerhouse cavern indicated that the displacements at RD160, RD 123 and RD 41 at EL 1014 on the downstream wall showed stabilizing trend. MPBX at RD 248/EL showed an increase in displacements at 4m horizon. MPBX at RD135/EL 1014-drainage gallery shows stabilizing trend. At one location i.e. RD 80 EL 1014 right side, there was an indication of development of crack.

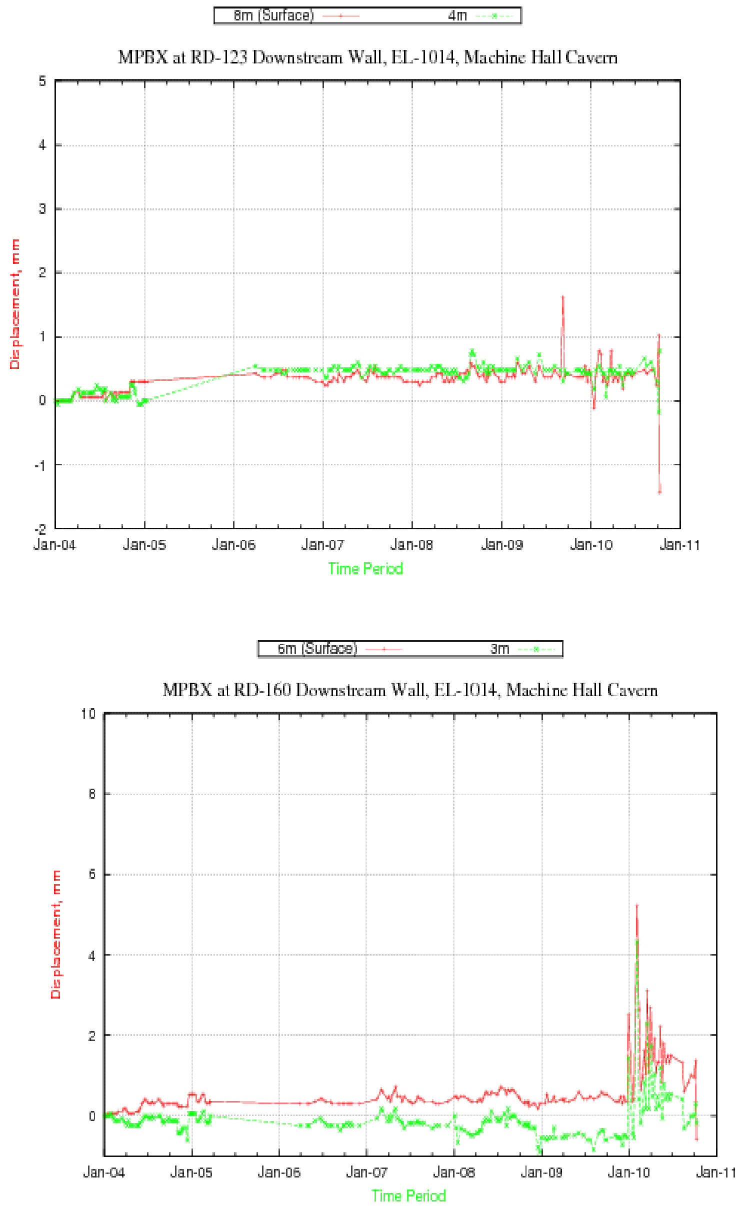


Figure 4 Displacement at RD160 & RD123 at EL1014 on d/s wall of machine hall cavern

Analysis of the instrumentation results at powerhouse cavern and desilting chambers indicated a few locations where there is an indication of development of the cracks. It was suggested to the management to install additional instruments to get the confirmatory behaviour. It was also suggested to install convergence stations close to the MPBX for confirming the surface displacements.

4.1.3 Sardar Sarovar Project Instrumentation:

The Sardar Sarovar Project, on right bank of river Narmada, includes an underground powerhouse. The underground powerhouse complex consists of powerhouse of 23m wide, 57m high and 210 m long. There are six pressure shafts of 9m diameter for intake of water from the reservoir to the powerhouse and six draft tubes of 16m wide double D shaped for drawing out water to collection pool. On the downstream side, there are three D-shaped bus galleries of 12m wide and 7.5m high connected to bus shafts. There are a few interconnecting tunnels and access tunnels, which are close to the powerhouse.

The instrumentation layout was designed with a view to assess long term stability of the caverns. Accordingly, Magnetic Ring Multi-point Borehole Extensometers (MRMPBX) were installed for measuring the displacements at various depths and reflective target points for measuring the surface movements and wall convergence (6). The schematic layout of instrument locations is shown in figure 5.

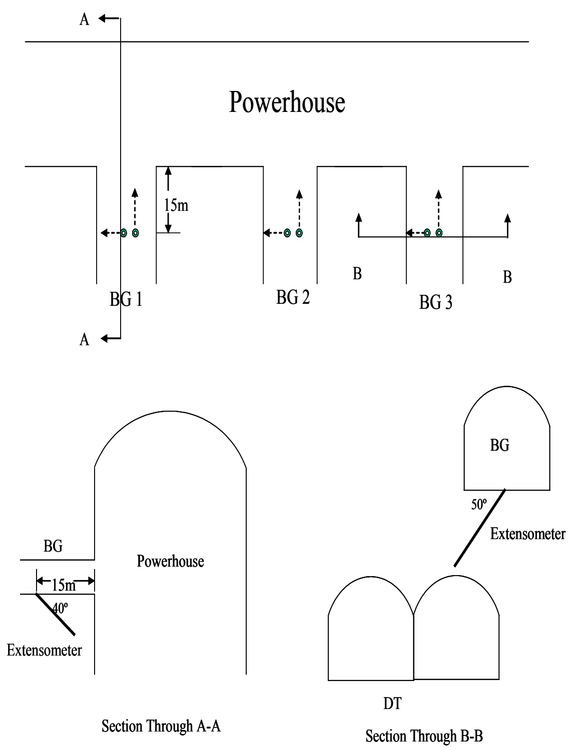


Figure 5 Schematic diagram of PH Cavern showing locations of MRMPBX in Bus Galleries

The total displacement observed during 10 year period is about 10-30mm (Table 1). It may be noted that the displacement rate ranges from 0.003 to 0.008 mm/day.

Table1
Summary of displacements observed by MRMPBX

Locations	**Depth, where max displacement occurred**	**Displace-ment, mm**	**Days**	**Period of monitoring**	**Displace-ment, mm**	**Days**	**Period of monitoring**
BG1MH	7.10m	19.20	3861	Feb 2000-Aug 2010	2.30	662	Nov-2008-Aug 2010
BG2MH	9.38m	26.74	3861	Feb 2000-Aug 2010	5.36	662	Nov-2008-Aug 2010
BG1DT1	8.35m	12.04	3863	Feb 2000-Aug 2010	4	662	Nov-2008-Aug 2010
BG2DT3	10.74m	27.72	3862	Feb 2000-Aug 2010	6	662	Nov-2008-Aug 2010
BG3DT6	1.35m	13.17	3703	Feb 2000-Aug 2010	4	662	Nov-2008-Aug 2010
DS-CH 1515 –EL0	Surface	14.24	3028	May2002-Aug 2010	3	663	Nov-2008-Aug 2010
DS-CH1580 – EL17.5	Surface	24.22	3066	Dec 2001-April 2010	2	537	Nov-2008-April 2010
US-CH 1552- EL0	Surface	29.37	3861	Feb 2000-Aug 2010	4	662	Nov-2008-Aug 2010
US-CH1580 – EL17.5	Surface	11.21	3191	Dec 2001-Aug 2010	3	662	Nov-2008-Aug 2010

The displacement plots with time on the downstream wall of machine hall cavern and between bus gallery and the draft tube (Fig. 6). The individual wall displacements on the columns and beams on both upstream and downstream side were measured with total station utilizing fixed reference targets in service bay.

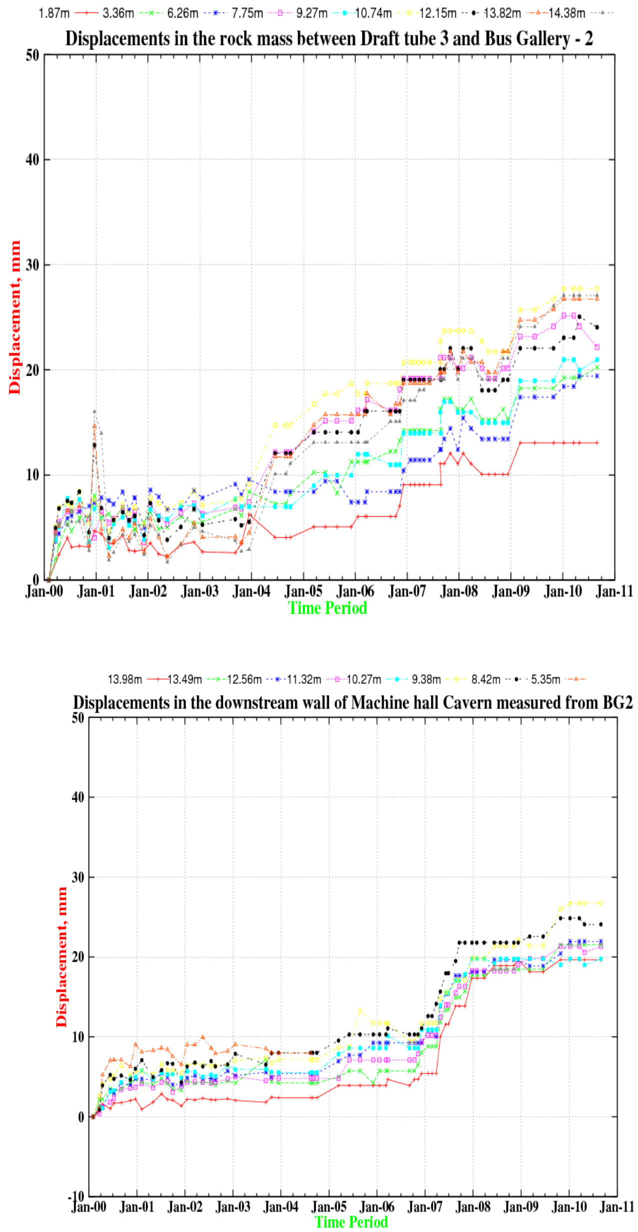


Figure 6 Displacement plots in d/s wall of cavern and between bus gallery and draft tube.

Based on the instrumentation data and visual observations, few more additional instruments were also suggested. Few MPBXs were installed from the surface up to the crown of the cavern. Regular monitoring of the instrument and analysis is helping the project in ensuring the long term stability of the cavern

4.1.4 Tala Hydroelectric Project, Bhutan Instrumentation:

Tala hydroelectric project is a 1020 MW power project in Bhutan. The powerhouse complex consists of a machine hall cavern of 206.4m x 20.4m x 44.5m and transformer hall cavern of 191m x 16m x 24.5m with a 40m pillar in between. The behaviour of cavern is monitored using various geotechnical instruments (7, 8 and 9). An effective instrumentation program was implemented during excavation of the caverns and continued during the operational phase. Instruments on the walls of machine hall consisted of following (Fig. 7):

- Anchor load cells for measuring the load on the rock bolts
- Multi-point mechanical borehole extensometers (MPBX) of groutable type with four to five anchors for measuring the deformations at various horizons along the wall rock
- Measurement of wall convergence using the reflective targets and total station
- Measurement of stress changes along the length of bolt
- Measurement of pore water pressure using vibrating wire piezometers.

Stability of the machine hall cavern was assessed based on the convergence observations of side walls, load on the rock bolts, stress distribution along the length of instrumented bolts and piezometric observations in the side walls. Visual observations of the walls of cavern also aided the analysis. Some of the important conclusions are as follows:

Convergence during the excavation stage was found to be considerably higher as compared to operational stage as shown in figure 8. Total convergence recorded at various elevations is given in table 2. Convergence at the cavern was found to be continuing at the rate of 0.009 to 0.016mm/day during the operational stage.

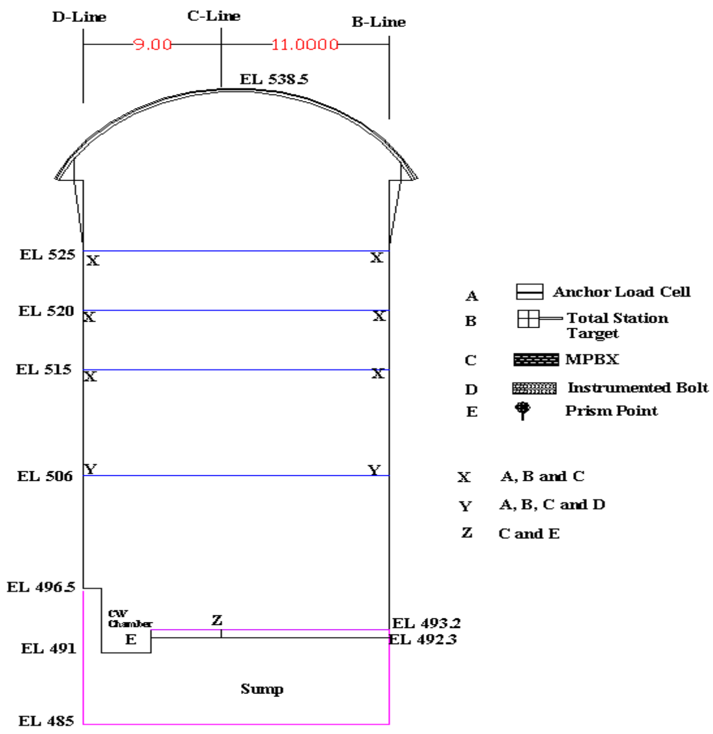
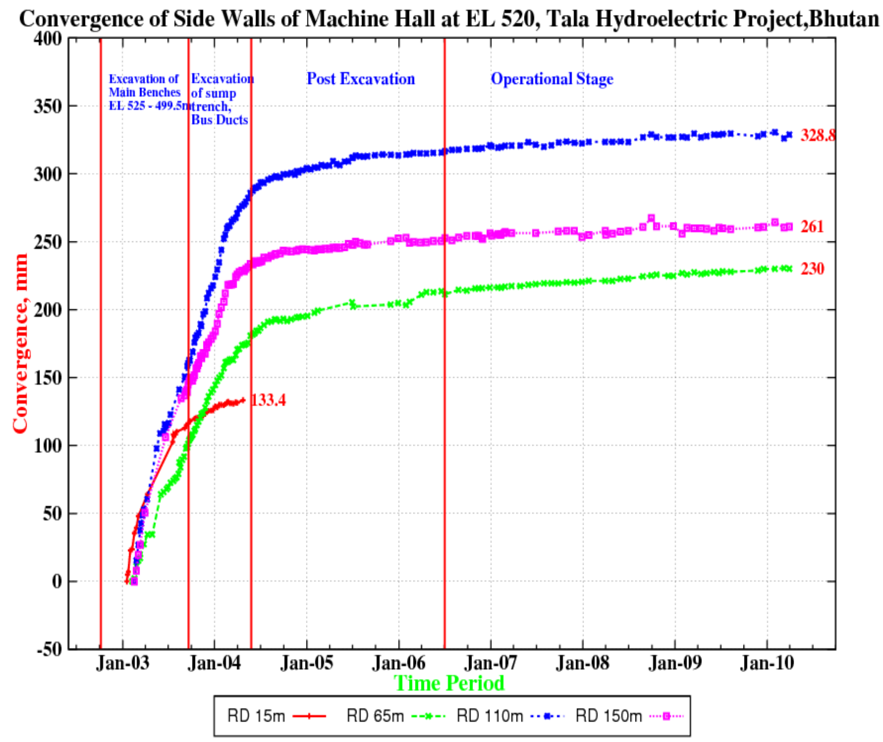


Figure 7 Locations of instruments at machine hall cavern



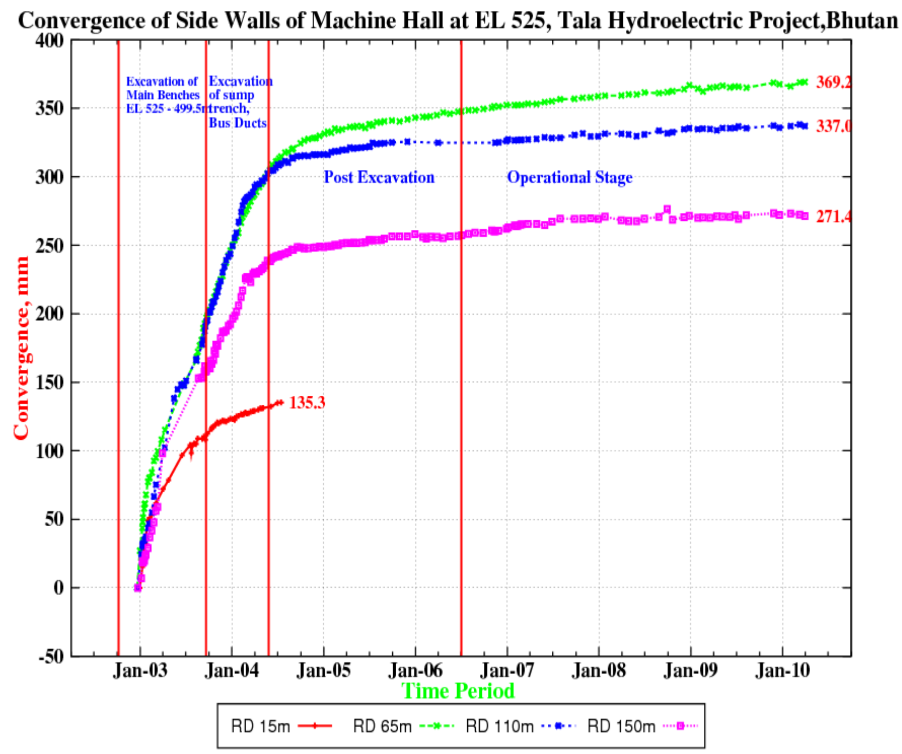
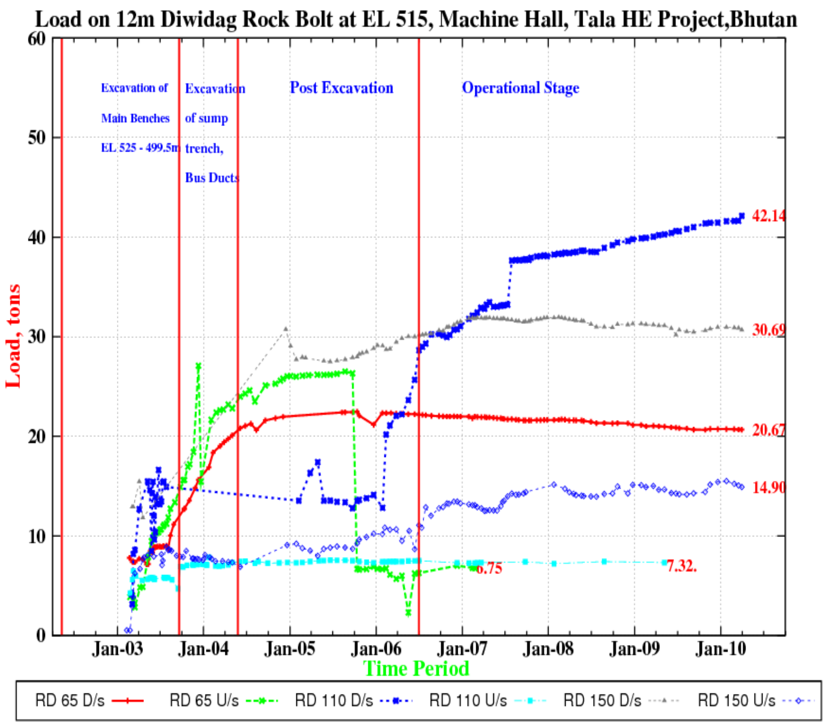


Figure 8 Convergence of side walls of Machine Hall Cavern at EL 525

Table 2
Summary of convergence observations at machine hall cavern

Elevations	RD	Total Convergence	Convergence during operational period
EL 525	RD 65 RD 110 RD 150	369.2mm 337mm 271.4mm	21.4 mm 11.4 mm 14.1 mm
EL 520	RD 65 RD 110 RD 150	230 mm 328.8 mm 261 mm	18.7 mm 11.2 mm 9.9 mm

Maximum axial load on the rock bolts was up to 45-50t. Load on the rock bolts have stabilized at higher elevations (EL 525 and EL 520), whereas at some of the lower elevations, particularly at 150 u/s at EL 506 and 110 d/s at EL 515 (3 to 13.5t during operational period) as shown in figure 9. Instrumented bolts also showed some activity during the operational period. At RD 150m downstream, at EL 506m, compressive stresses on the bolt are increasing steadily at 7m, 6m, 5m and 4m depths. At RD 150m upstream EL 515, tensile stresses at 1m depth shows mild increasing trend and at 11m, compressive stresses are increasing at a slow rate. Maximum tensile stress induced on the rock bolt was 394.50MPa and in general varied from 25-200MPa at various depths. Maximum compressive stress measured on the rock bolt was 269.05MPa and in general varied from 10 –125MPa at various depths. Instrument observations at transformer hall and bus ducts also indicated similar behaviour. Thus, the cavern is undergoing time dependent deformations and stress induced deformations due to its close proximity to the Main Central Thrust.



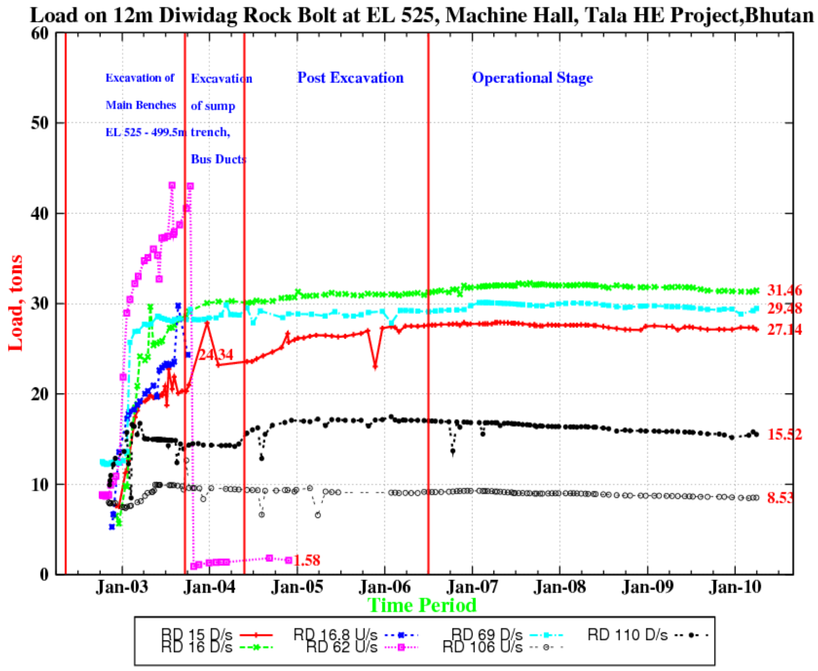


Figure 9 Load on 12m long rock bolts on the walls of Machine Hall

Tala powerhouse has witnessed failure of 176 bolts in the machine hall and 4 bolts in the transformer hall. The bolts (136 bolts - about 3.73 % of the installed bolts) have failed mainly on the upstream side of machine hall cavern. The data provided by conventional instruments proved that the stress redistribution is still continuing in the rock mass. However, the identification of exact location becomes difficult due to limited number of instruments at few locations. This drawback can be overcome by the use of acoustic or micro-seismic monitoring. The micro-seismic experiments, conducted by NIRM in powerhouse cavern have demonstrated usefulness of the techniques in identifying the areas of stress activity.

5. Conclusions:

Instrumentation is the integral part of any stability studies conducted in underground caverns, initiated at the construction stage and continued even during the implementation stage. The monitoring programme taken up at various underground caverns have revealed that variation in stresses and deformation continues even during production stage. Thus, the rock mass around the caverns undergo time dependent deformations which has to be monitored in order to ascertain stability of caverns. Location of instruments should be judiciously selected to obtain maximum possible detail and recordings must be reviewed regularly. This would help in updating working instruments and requirement of additional instruments at critical locations.

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