ABSTRACT

On 3rd March, 2016, there occurred a massive roof fall incidence in one of the major caverns of Punatsangchhu-II Hydroelectric Project (PHEP-II), Bhutan which halted the operations in the major caverns and required additional strengthening measures. Prior to concluding anything on the treatment measures for the muck flown into the cavern and the cavity formed over the crown of Downstream Surge Chamber, there was a strong need to determine the extents of cavity. Even to understand the influence of cavity formation on adjacent caverns, the cavity needs to be delineated. Therefore, the management of PHEP-II adopted several techniques to decipher the shape and dimensions of the cavity like, surveying, geophysical, cross-hole seismic surveys, borehole scanning, and exploratory drilling. The tentative shape of the cavity could finally be established. The findings from each method are explained in this paper.

ARTICLE Delineation of Cavity in Downstream Surge Chamber at Punatsangchhu-II Hydroelectric Project, Bhutan

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1. Introduction

Punatsangchhu Hydroelectric Project Authority (PHPA) of Bhutan is implementing two mega projects with an installed capacity of 1200 MW and 1020 MW respectively. Both the projects spread over a distance between 20 km and 35 km downstream of Wangdue Bridge along Wangdue - Tsirang National Highway in Wangdue Phodrang Dzongkhag of Bhutan and it is approximately 115 Km east of Thimphu, the capital of Royal Kingdom of Bhutan. The project area lies in the Eastern Himalayas between Lat. 26° 70’ and 28° 40’N and Long. 88° 70’ and 92° 20’E covering a geographical area of 38,394 km². This project is undertaken by the Royal Government of Bhutan (RGoB) and Government of India (GoI) for the mutual benefit of both the countries. Punatsangchhu-II Hydroelectric Project (PHEP-II) envisages construction of concrete gravity dam (CGD) across Punatsangchhu river, head race tunnel (HRT) and an underground powerhouse complex (PHC) comprising of three major caverns, viz. machine hall cavern (MHC - 241m × 23.9m × 51m), transformer hall cavern (THC - 216m × 14m × 26.5m) and downstream surge chamber (DSC - 314m x 19.8m x 58.50m). The major caverns are aligned at N10° E and is shown in Figure 11. Major roof rock fall incidence took

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place on 3rd March 2016 starting from RD 135m of DSC. Initially, the total quantity of muck flown into the cavern is assessed to be around 50,000 m$^3$. The bouldery muck fill covers from the bottom to the crown of cavern and there is no access towards the northern side of DSC.

It was necessary to determine the cavity’s extent, dimension, volume and orientation to design suitable remedial measures. Hence, the project management explored different options to decipher the cavity dimensions by application of surveying, geophysical techniques, cavity monitoring system, exploratory drill holes and other feasible methods. Therefore, the studies on delineation of the cavity in DSC has been taken up and the pros and cons of each method is mentioned in this paper in detail.

2. Geology
Regionally, PHEP-II area is located within a part of the Tethyan Belt of Bhutan Himalayas, which lies north of main central thrust (MCT) and the rocks of Sure and Chekha Formations of Thimphu Group of Precambrian age are exposed in this region\(^\text{[2]}\). The rocks of Thimphu Group in general are characterized by coarse grained quartzo-feldspathic, biotite-muscovite gneiss, with bands of mica schist, quartzite and concordant veins of pegmatite, leucogranite and migmatites with minor bands of limestone/dolomites and metabasics.

Different rock variants are encountered in DSC of the powerhouse complex comprises of quartzo-feldspathic-biotite gneiss, biotite gneiss, biotite schist, micaceous quartzite, leucogranite and pegmatite. Pegmatite shows the crystal growth of the quartz, feldspar, mica and tourmaline. In the banded rock of darker and lighter bands, the ductile bending is reflected in the form of folded structure whereas the crushed material indicates the shearing effect in the leucogranite and pegmatite. Generally the foliation has gentle dip, ranging between 5° and 25° directed between N190° and 240°. The 3-dimensionally mapped geological features of DSC are shown in Figure 2.

3. Geotechnical Assessment of DSC
The excavated surface of the downstream as well upstream wall indicated highly deformed rock mass. The variation in the attitude of foliation is mainly attributed to warping and minor folding. In totality, about 40%, 51% and 9% of the rock mass encountered during excavation of caverns falls in Class III, IV and V respectively. The class V rock mass (Q value ranging from 0.19 to 0.58) mainly occurs in the region of major shear zone and its vicinity. Rock mass is intersected by six prominent joint sets with different characteristic of joints and are listed in Table 1. 3D geological mapping has been carried out in DSC.

During excavation of the cavern, several geotechnical problems were faced in DSC like occurrence of major shear zone (45°- 60°/030°), presence of low dipping foliation joints posing slabbing conditions in the crown portion, erratic occurrence of intrusive bodies of variable dimensions, minor shearing along foliation joints and other joints at few locations. Besides presence of water (seepage / dripping) along shear zone and ingress of water on the downstream wall between RD 308m and RD 313.5m (EL 599m).

4. Excavation Sequence in DSC
Excavation in DSC started in the month of March, 2013 by excavation of central gullet at EL 623.70m (crown) followed by widening of the crown, both on upstream and downstream sides. The excavations were proposed in two phases, in the first phase it was excavated from RD 0m to RD 210m (EL 623.70m) and in the second phase benching from RD 0m to RD 210m (from EL 615m) and excavation of heading of its remaining length from RD 210m to RD 314m (EL 613.70m) was carried out simultaneously. The excavation sequence in central gullet, headings and benches for DSC on both upstream and downstream sides are depicted in Figures 3 and 4 respectively\(^\text{[3]}\).

4.1 Rock Mass Failure Mechanism and Cavity Formation
On 3rd March, 2016, first major rock fall occurred in DSC and thereafter intermittent loose falls occurred, followed by two major falls on 11th and 22nd March, 2016. The
The condition of the cavern with muck flown from the crown blocking the approach towards northern end after different major falls are shown in Figures 5 and 6 respectively. The view of cavity and the rock mass inside cavity as observed on 22nd March, 2016 is shown in Figure 7. Failure of the rock mass was initiated from the crown of DSC between RD 135m and RD 140m along a major shear zone (45°-60° / 030°) extending on either wall dipping towards face (i.e. gable end wall). The rock mass gave up within a very short span at an odd hour, around 1 AM on 3rd March, 2016.

Table 1. Prominent joints and their characteristics recorded in DSC

<table>
<thead>
<tr>
<th>Joint No.</th>
<th>Dip Direction</th>
<th>Amount &amp; Joint Roughness</th>
<th>Continuity (m)</th>
<th>Aperture (mm)</th>
<th>Spacing (cm)</th>
<th>Infilling / Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>5°-25°/S20°-70°W 15°/S45°W</td>
<td>Rough, Planar to undulating</td>
<td>1 – 10</td>
<td>1 – 15</td>
<td>2 – 100</td>
<td>Foliation joint, low dipping, at places warped intensively, on the northern side at some locations it shows different attitude 5°-25°/N 20°-40° E (warping). Shearing along foliation joint. Minor clay and rock flour filling.</td>
</tr>
<tr>
<td>J2</td>
<td>50° - 65°/N33°-60°E 58° / N40°E</td>
<td>Moderately smooth planar to roughly undulating</td>
<td>1 – 10</td>
<td>1 – 5</td>
<td>10 – 500</td>
<td>Forming wedges with other joints, clay coating.</td>
</tr>
<tr>
<td>J3</td>
<td>55° - 70°/S30°-65°E 63° / S48°E</td>
<td>Rough and planar to undulating</td>
<td>4 – 16</td>
<td>2 – 8</td>
<td>30 – 200</td>
<td>Forming wedges with other joints, at places alteration observed.</td>
</tr>
<tr>
<td>J5</td>
<td>55°-78°/N35°-45°W 66°/N40°W</td>
<td>Moderately smooth planar to rough planar</td>
<td>4 – 8</td>
<td>2 – 6</td>
<td>15 – 400</td>
<td>Forming wedges with other joints. Rock flour filling, Stained.</td>
</tr>
</tbody>
</table>

Figure 3. Excavation sequence in DSC – plan of central gullet & section of upstream wall

Figure 4. Excavation sequence in DSC – section of downstream wall
The impact of this incident was also noticed in the adjacent caverns / structures in the form of development of new cracks in shotcrete, widening of already existing cracks particularly on the downstream wall of THC and Bus Duct No. 2 and 3. Cracks particularly in the bus ducts and penstocks indicated development of stresses but could not pinpoint the location of stress concentrations or distress leading to failure of rock mass in DSC.

Way back in 2013, the shear zone along which failure of rock mass has taken place was identified prior to the start of excavations in DSC and it was demarcated in adit to DSC (at RD 440m) and Main Access Tunnel (at RD 420m). The demarcated zone was projected onto the major caverns after shifting as per the structural features of the shear zone and the projection predicted the intersection of the shear zone to the major caverns at certain RDs which may result in instability of the caverns due to their location. In order to prevent any such intersections to the maximum extent possible, machine hall cavern and transformer hall cavern were shifted 36m southerly due S10°W. The projected shear zone intersecting the major caverns is presented in Figure 8. During excavation of central gullet of DSC, similar shear zone was encountered in the crown of DSC between RD 121m and RD 129m confirming the above mentioned projections and thus assuring the decision of shifting of caverns.

Along the shear zone water seepage was also noticed in central gullet which might have lowered the shear strength parameters as well. Over breaks of the order 4m to 8m were observed between RD 121m and RD 129m of DSC. During the excavation of central gullet, a cavity with a dimension of 5m to 6m height was formed at crown level and it was back filled with concrete before widening and entire zone was supported with steel ribs. During widening of the cavern, no adverse effects such as cavity formation, destressing in rock mass and deformations in already erected ribs were noticed. However, during benching on the 26th February, 2016, fresh cracks and widening of old cracks were noticed on the cavern walls near the shear zone.

4.2 Characterization of Fallen Rock

The failed rock mass comprised of fragmented rock pieces of varied sizes, sandy clay and dry clay fractions with big rock blocks (max. size ~9.0m x 1.5m x 3.0m). The shapes and size of the fallen boulders clearly indicated that failure of rock mass was not limited to shear zone alone but extended much beyond. Failure might have taken place along the major shear plane due to sinking of rib toe support at the haunch level. The low shear strength material within the shear zone and its associated weak rock mass
gave up initially and later, the jointed and blocky overlying rock mass with slabbing conditions in the vicinity of shear zone slid down under gravity swiftly. The disintegrated blocks expanded its volume after disintegration and filled the cavern. These blocks which were flown into the cavern led to the development of cavity above the muck. Since then, there was sufficient time lag in treatment of the cavity which further gave rise to the lateral and longitudinal expansion of the cavity due to the presence of sub-horizontal strata traversed by different joint sets forming potential structural wedges.

Sequence of failure could be sliding of rock mass along plane of separation due to sinking under loading pressure followed by structural failure, i.e. detachment of rock slabs and structural wedges under gravity from hanging wall after failure of steel rib support. In totality, it was a complex structural failure rather than a simple rock mass failure along the shear zone. The failed ribs did not show any sign of deformation, i.e. bending, shearing or twisting which suggests that ribs have failed due to sudden impact of overlying dead load or failure of toe of the ribs at the spring level. It was also noticed that the shear zone is flaring towards crown and pinching towards wall sections.

4.3 Effect on Adjacent Structures

The downstream walls of powerhouse caverns are greatly affected and the bulging in both the walls of DSC was observed and as compared to the upstream wall, downstream wall cladding along shear zone was more vulnerable which was apparent from the cracks formed on freshly applied shotcrete after collapse. The downstream wall from RD 130m to RD 145m between EL 623m & EL 598m showed minor bulging on the concrete cladding wall and development of cracks along the cladding wall, whereas on the upstream wall bulging was observed between RD 125m and RD 135m (EL 608m to EL 600m).

4.4 Cavity Delineation and its Extents

Initially, cavity size and its direction or extension is unknown, however, attempts have been made to assess the extension and dimension of cavity above crown and it seemed that the extension of the cavity towards downstream wall is greater than towards upstream wall and receding backward due to inclination of shear zone. In order to treat the cavity and proceed with further excavation works in major caverns, it was crucial to determine the dimensions of the cavity. However, it was not a simple job. There were inherent complexities in determining the actual extents and dimensions of the cavity, viz. steep and unfavorable topography, inaccessibility to the northern end of DSC, 240m – 280m of overburden, risk to person and equipment involved in exploration. However, several options to deal with the cavity were explored and the following methods were taken up.

4.4.1 Visual Estimations

Initially, on the basis of visual estimations cavity dimensions were assumed to be extending around 40m vertically and around 50m spread towards northern gable end wall between RD 120m and RD 170m. As the crown of the cavity was visible after first fall to a certain extent upto RD 140m, an attempt to determine the true coordinates of the longitudinal extents of the cavity from the southern side using a Total station was made. As per the surveyed coordinates along the center line of DSC, the longitudinal extents of the cavity were determined to be 58m from RD 135m to RD 193m. However, the eastern and western extents could not be established.

4.4.2 Cavity Exploratory Drilling

Attempts were made to drill NX sized boreholes from the surface at apt locations intending to daylight into the cavity so that at least point data information can be obtained which could provide the coordinates of the apex of the cavity above DSC crown. Three holes punctured into the cavity indicating the cavity apex at an elevation of 694.5m at RD 153m of DSC. Additional drilling of boreholes was not feasible due to unfavorable topographical conditions. This provided some insight into the height of the cavity but this approach too could not help in determining the complete extents of the cavity. Figure 9 shows the layout of projection of cavity on the surface. Figure10 shows the longitudinal section along the center line of DSC with the extents of cavity determined through visual estimation and the exploratory drill holes.

To know the exact extension of the cavity towards transformer hall, four probe holes through a drill jumbo were attempted from EL 604.5m on downstream wall of THC aiming at EL 630m on upstream wall of DSC. None of the holes punctured into the cavity which may be possible to non-extension of the cavity near the explored area. No concrete results could be ascertained from this exercise.

4.4.3 Cross-Hole Seismic Tomography

Several geophysical exploration methods were thought of adopting but due to topographical and space constraints along with over 250m overburden rock cover, cross-hole seismic tomography was only found to be suitable geophysical technique for application. In order to execute the said survey, drill holes must be made available around the cavity. To delineate the shape and size of cavity above the DSC crown, seismic cross-hole tomography and scanning
of the probable cavity area was carried out. The first phase of tomography was conducted by drilling ten boreholes from DSC top and tomography results suggested that apex of the cavity height is 91 m above DSC crown (apex at EL ~ 714 m, between RD 142 m and RD 148 m), length ~ 82 m, and extending due north however, width of cavity could not be established. Subsequently, six additional holes were proposed for second phase tomography to know the width of cavity. The second phase of tomography was carried out from the six drill holes and could tentatively develop the 3-D tomograms to find the extents of cavity. The cavity profile as determined through seismic tomogram is shown in Figure 11 [3].

4.4.4 Cavity Monitoring System

One borehole with casing having an inner diameter of 204 mm was drilled at RD 146.5 m of DSC from surface at EL 827.5 m, to insert a sophisticated high precision laser guided scanner into it so that it can scan the cavity on lowering. Teledyne Optech’s Cavity Monitoring System – CMS V500 was used for scanning the cavity [4]. The scanning results reveals that cavity is extending towards western side of the cavern and has a void volume of around 45,000 m$^3$ which extended from 46 m to 91 m above DSC crown and below the void, the zone is assumed to be filled with muck till DSC crown. In order to determine the extents onto the northern end of DSC, a horizontal borehole was drilled from the cable tunnel, puncturing into the northern end of DSC and CMS was inserted and scanning was carried out and the extents and the profile of the fallen muck was determined which helped in determining the actual longitudinal extents of the cavity along the center line on DSC crown to be 52 m. Figure 12 shows the 3-D view of cavity above DSC crown determined by the help of CMS.
4.4.5 Approach Tunnel to DSC in Northern Gable End

In order to treat the fallen material and the cavity, an approach towards the northern end of DSC was highly required. In order to gain access, a tunnel was driven through cable tunnel puncturing into the northern gable end of DSC. Post breakthrough, the scanning results were confirmed through surveying methods. The exact profile of the fallen muck from DSC crown could be established.

5. Conclusion

As on date, all the methods adopted at the project site have provided some insights into the extents and dimensions of the cavity. The delineation of the cavity could be extending due N67°W. The longitudinal and transverse extents of the cavity ranged about 52m and 40m respectively. The height of the cavity extended upto 91m above the DSC crown. As on date, the objective of delineating the cavity is fulfilled satisfactorily to go ahead with treatment of cavity and the muck flown into the cavern and the same is shown in Figure13.

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References


Figure 13. Tentative shape of cavity along with the muck to be treated