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Pull-out test of rock bolts: Analyzing the causes of failure

Sahoo, R. N.
Senior Manager (Geology),
CVPPL, Jammu-180012, J&K, India
Singh, Ajay
Deputy General Manager (Geology)
NHPC Ltd., Faridabad-121003, Haryana, India
Dash, A. K.
General Manager (Civil),
CVPPL, Jammu-180012, J&K, India

E-mail of the Corresponding Author: radhendra.sahoo@gmail.com

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Abstract

To stabilize the roof and walls of the tunnels/caverns, tensioned rock bolts (Mechanical/Cement or Resin grouted end anchorage type) are the modern support system used worldwide. These rock bolts (post-stressed active anchors) installed in pattern create a stress field around the excavated area of tunnel. The effectiveness of these rock bolts are evaluated through the well-known 'Pull-out test' conducted as per IS 11309:1985 guidelines, wherein a rock bolt is considered to pass the test, if it registers a displacement of ≤40mm with designated load applied. While conducting pull-out test, failure of the rock bolts is generally attributed in the order of assertion to - (a) poor ground/geology, (b) poor material quality of rods, but hardly attributing to (c) improper testing methodology and/or (d) poor workmanship. This paper discusses non-geological reasons of failure for Pull-out tests conducted on 28 nos. in-situ rock bolts in the Powerhouse Cavern, Pakal Dul HE Project, J&K (1000MW); out of which only 2 no. rock bolts passed. In this case, inapt testing method/approach i.e. inadequate torque application on the bolt (for the purpose of tightening/stressing); evincing ineffective end-anchorage at bolt head which caused failure of rock bolts during Pull-out-test.

Keywords: Rock bolt, Pull-out Test, Torque

1. Introduction:

Rock bolt typically is a rod having (mechanical/cement grouted/resin grouted end anchorage) and provisioned with a bearing plate and nut. It is a tensioned reinforcing element to be stressed immediately after installation by torqueing or jacking, by means of a calibrated stressing device. The rock bolt is synonym with active rock anchor. The instant case confers mechanical end anchorage type expansion shell rock bolts installed in Powerhouse Cavern, Pakal Dul HEP.

Pull-out test is the test of effective anchorage and bond strength between reinforcing element (bolt) & the rockmass housing the bolt. This test in tunnels/caverns are typically performed to assess the anchorage or pull-out capacity of rock bolts. The instant case dealing with mechanically anchored bolts, Pull out test is done in un-grouted bolts. Pull-out capacity becomes very much important because rock bolts are anchored into the stable rock mass located beyond the plastic zone/zone of failure. Rock bolts reinforce and mobilize the inherent strength of rockmass by offering confining pressure, increase the stiffness of the rock and contribute shear resistance to the rock joints. The rock bolts are tested by incremental loading until total extension of reinforcement from hole/rock face reaches 40mm or till it yields/fractures, whichever is early.

The maximum load generally applied on the rock bolts (expansion shell type) during pull-out test is 60% of Yield Strength of Bolt. The range of load for different bolt dia with corresponding Torque range is shown in Table-1 below.

Table 1
Range of Load & Torque for different Bolt dia

S. No.	Dia of rock bolt (mm)	Max. Load applied (Ton)	Corresponding torque (Newton meter or N-m)
1.	25	15	750
2.	32	24	1536
3.	36	30	2160

Pakaldul HE Project (1000MW) is located in Kishtwar district of Jammu and Kashmir state (UT) of India. It is a storage scheme on the river Marusudar, a tributary of Chenab. The project envisages construction of 184m high CFRD near village Drangdhuran, two nos. 9.6km long each having 7.2m dia HRTs and an underground power house (166m x 20.2m x 51m) located in the right bank hill of Dul Reservoir. Presently, project is under construction by CVPP Ltd.

By the end of Nov’2019, excavation of PH cavern for top heading part (from EL 1285 to 1278M) and benching up to EL 1259.5M was completed and further benching being in progress. The results of pull out tests conducted on 7.5 m long and 32Ø rock bolts installed in crown/top heading of power house cavern has been taken for this study.

2. Geological setup of Project area:

Geologically, the project area lies in inner Lesser Himalaya (Kishtwar window) under Kishtwar group of rocks. Dam complex & part of HRT lie in Kibar gneisses whereas power house complex is housed in Quartzite-Phyllite sequence of Dul formation.

As per geological data collected while excavation, the PH cavern heading zone encompasses fresh to slightly weathered, moderately jointed and strong quartzite with thin (<5cm) bands of weak phyllites at places. Rock mass is dissected by primarily 4 set of joints including sub horizontal hill side dipping foliations (355°-030°/15°-20°). No significant shear zone observed during excavation of the cavern. The rock class encountered in the central gullet as 35 % Class-II and 65% Class-III.

3. Rock supports installed in PH crown:

After completion of the central heading and side slashing, the crown of the cavern has been supported by 32Ø 7.5 m & 36Ø 9m long rock bolts (@ 3m c/c) & 200mm thick SFR shotcrete. The excavation drawing of central heading (From EL 1285M to 1278M) showing stages of excavation and details of rock supports is shown in sketch as under (Figure-1):

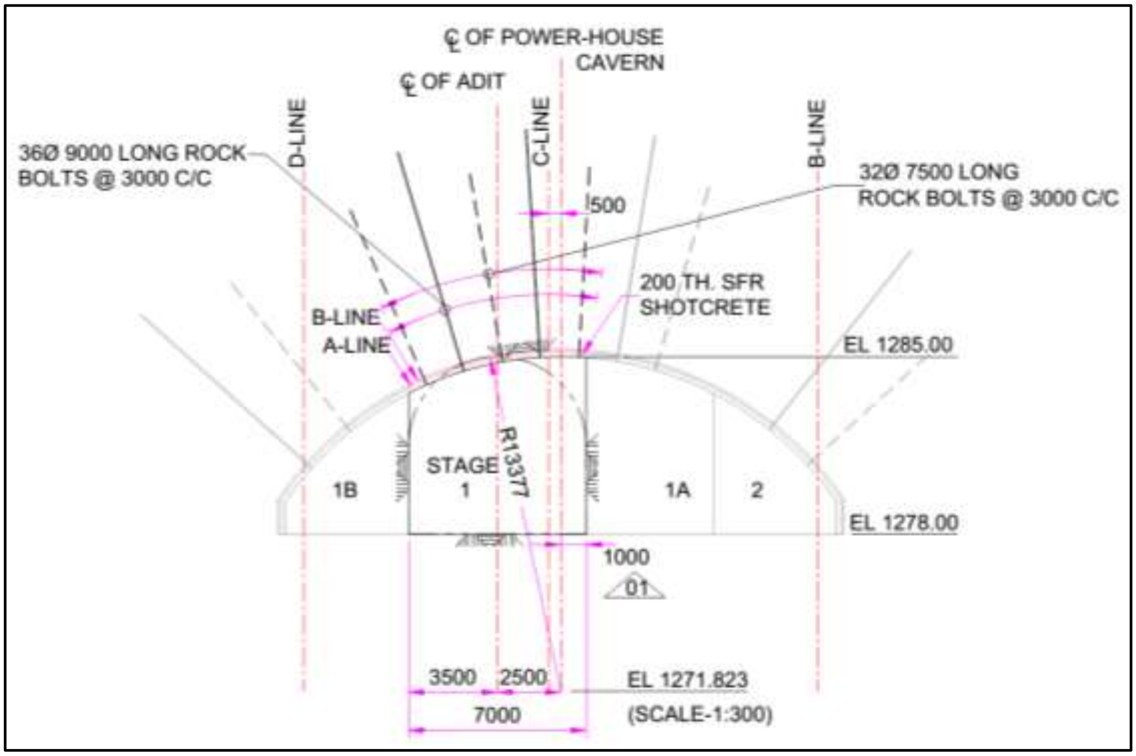


Figure 1 View of PH Cavern from Top Adit to PH Crown towards Main Access Tunnel

4. Pull out tests:

Subsequent to installation of desired 440 nos. (365 nos. of expansion shell type and 75 nos. resin capsule type) 7.5 m long, 32Ø rock bolts in the PH cavern (heading part, between EL 1278M to 1285m), **Pull-out tests** were carried out. It is to mention that Project had previously conducted pull-out tests in 28 no. rock bolts in heading part of cavern. Out of all the tested bolts, only 02 nos. expansion cell type rock bolts installed at RDs 114 & 123 side slash wall portion i.e. confining to Stage-1B & Stage-2 passed, showing less than 40mm displacement with the designated 24-ton load. Accordingly, few permutation & combination of bolt assemblies of different makes/brands were also tried by Project but registered failing results during pull-out test. Hence, it was apprehended by the Project & Contractor that poor geology is responsible for the failures of majority of the rock bolts.

In view of above, the geology encountered while excavation of PH cavern (heading part) was reviewed and it was observed that the rock mass in the entire structure area falls under fair to good category and devoid of any remarkable weak geological feature. So, to understand the real cause of Rock bolt failure vis-à-vis material property of bolt & its accessories/geology of the cavern or any other cause, two confirmatory pull-out tests with the details given here under were carried out in PH cavern area (Refer Table-2).

Table 2
Details of 2 Nos. Confirmatory Pull-out Tests in Powerhouse Cavern

Test No.	Location	Type of rock bolt	Load applied (Ton)	Displacement (mm)	Geology of the Testing location
1.	At RD 127m (R-8 hole-Right SPL, EL 1280M) in Stage-2 i.e. at rightmost side slashing wall heading portion of PH Cavern	32mm dia. 7.5m long Expansion shell rock bolt	4	6	Strong to very strong Quartzite with thin bands of Phyllite having Rock class III (Fair) with RMR value 58.
			8	12	
			12	18	
			16	24	
			20	32	
			24	**36**	
2.	At RD 126m (R-1 hole-Left SPL, EL 1279.8M) in Stage-1B i.e. at leftmost side slashing wall heading portion of PH Cavern		4	7	
			8	14	
			12	23	
			16	34	
			20	46	
			24	**53**	

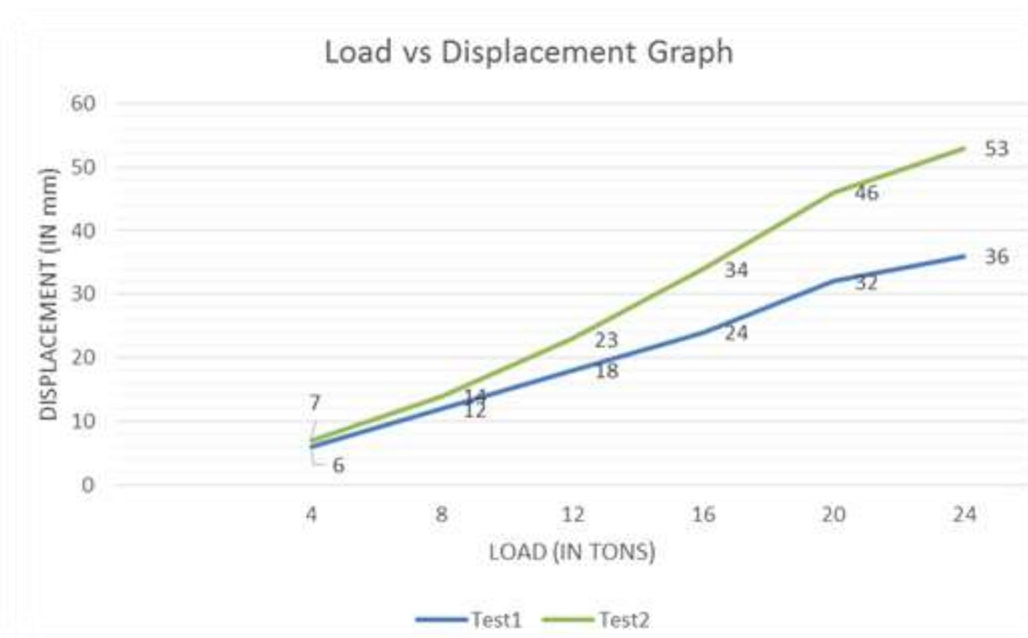


Figure 2 Load Vs Displacement Graph for Confirmatory Pull-out Test No. 1&2
at RD 127m & 126m respectively

From the above Table-2 & Graph (Figure-2), it can be seen that despite being conducted in similar geological environment, the pull-out Test no. 1 got passed registering 36mm displacement with application of designated 24-ton load, whereas Test no. 2 failed registering 46mm displacement at 20 ton load and subsequent 53mm displacement with designated 24 ton load. From these test results, it could be conclusively inferred that local geology was not responsible for the failure of said pull-out tests conducted in PH cavern.

Further, to analyse the real cause of rock bolt failures, another confirmatory test (Test No.3) was done through re-tightening of nut & re-torqueing of the same bolt to go for another round of Pull-out test. Re-testing of already tested rock bolt i.e. R-1 hole, EL 1279.8m at RD 126 (Stage-1B) of PH cavern was carried out. Results of the same are shown as under in Table-3 & graphical representation of Load Vs Displacement in Figure-3, as under:

Table 3
Details of Another Confirmatory Pull-out Test (Test No.3) on Previously Tested Rock bolt at RD 126m (Stage-1B) in Powerhouse Cavern

Test No.	Location	Type of rock bolt	Load applied (Ton)	Displacement (mm)	Geology of the testing location
3.	At RD 126m (R-1 hole-at Left SPL, EL 1279.8M) in Stage-1B i.e leftmost side slashing wall heading portion of PH Cavern	32mm dia. 7.5m long Expansion shell rock bolt	4	2	Strong to very strong Quartzite with thin bands of Phyllite having Rock class III (Fair) with RMR value 58.
			8	4	
			12	8	
			16	10	
			20	12	
			24	14	
			26	16	
			28	21	

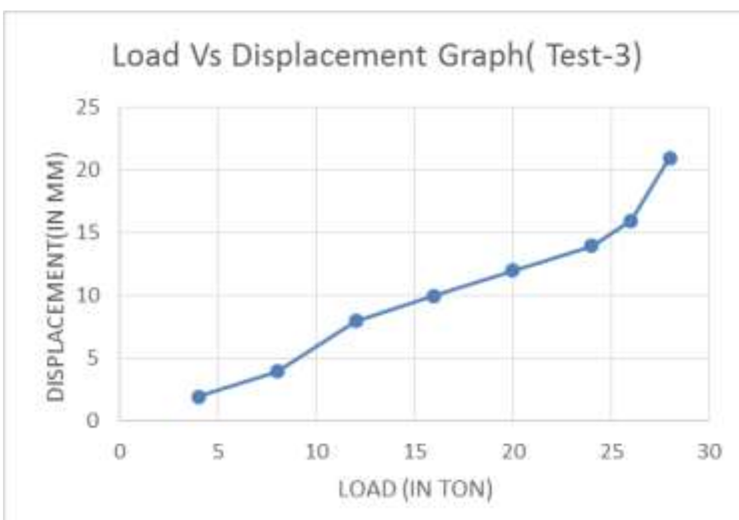


Figure 3 Load Vs Displacement Graph-Pull-out Test No.3 - RD126m (Stage-1B)

From the above observations in Table-3 & Figure-3, it could be understood that the rock bolt that had previously failed at 20ton load registering 46mm displacement, *after re-tightening* & *re-torqueing* showed passing value of 12mm displacement on the same load & 14mm displacement at designated 24 ton load for 32mm dia bolt (as per Technical specification). The results also indicate that these bolts could even take up further load beyond this designated 24ton load (60% of Yield strength of Fe 500 bolt) registering 21mm (<40mm) displacement at 28ton load during Pull-out test.

The above discussion indicates that probably proper torqueing was not done during pull-out testing of previous failed rock bolts. However, the 2 rock bolts (though under-torqued) that had previously passed prior to experimentation; successful pull-out result could be attributed to better bond strength of bolt (expansion shell) & rock due to higher competency and/or mere coincidence.

In this regard the range of torque provided by the testing personnel in previous tests were analysed and it was observed that the torque provided for 32mm dia rock bolts in the previous test was 226N-m against the desired torque of 1536 N-m (Refer Table-1). It means that the said rock bolt was torqued at quite lower value i.e. 15% of design stress value. Though the torque value was too less than the required, but during testing the bolt was being pulled out at its maximum/full designated stress value of 24 ton. Hence, it was apprehended that lower range of torque application might be causing failure of rock bolts.

5. Experimental Pull-out tests:

Now to validate this theory/working concept of "Designated value of Torque" for bolts to undergo stressing, prior to Pull-out test; the need for carrying out few additional validating experiments in PH cavern was felt. Accordingly, two experimental Pull-out tests were carried out with the available Torque wrench at site (Max. Capacity 540 N-m). The details of these experiments are mentioned as under.

5. (a) Experiment-1:

Experimental pull-out test was conducted with a better quality (SAIL make) 25mm dia, 3m long rock bolt available at site. Testing was done in similar geology at RD 125m (R-1 hole, EL 1279.6m) in Stage-1B (left side wall heading portion) of PH cavern i.e. near previously failed rock bolt which was installed and subjected to test (R-1 hole, EL 1279.8m at RD 126 of Stage-1B). This bolt was stressed with 540 N-m torque against the designated 750N-m. Subsequently, Pull-out test was done and results are given in Table-4 and corresponding Figure-4, as under.

Table 4
Details of Pull-out Test (Experiment-1) at RD 125m (Stage-1B) in PH Cavern

Load Applied (Ton)	Displacement (mm)
3	2
6	3
9	6
12	10
13	15

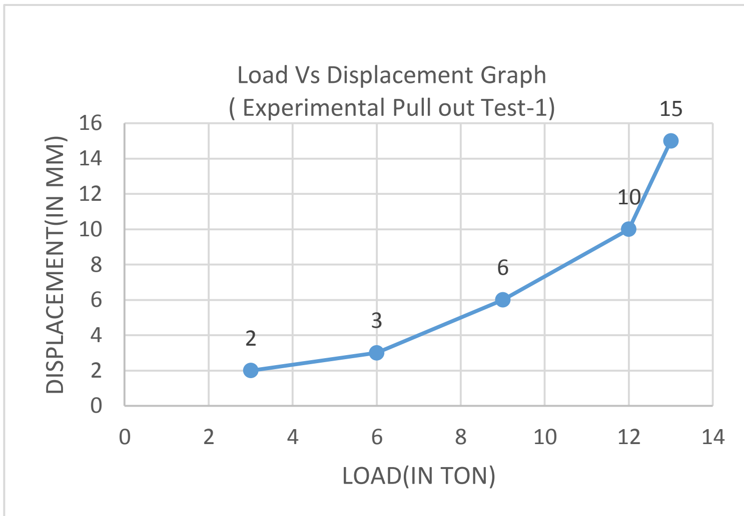
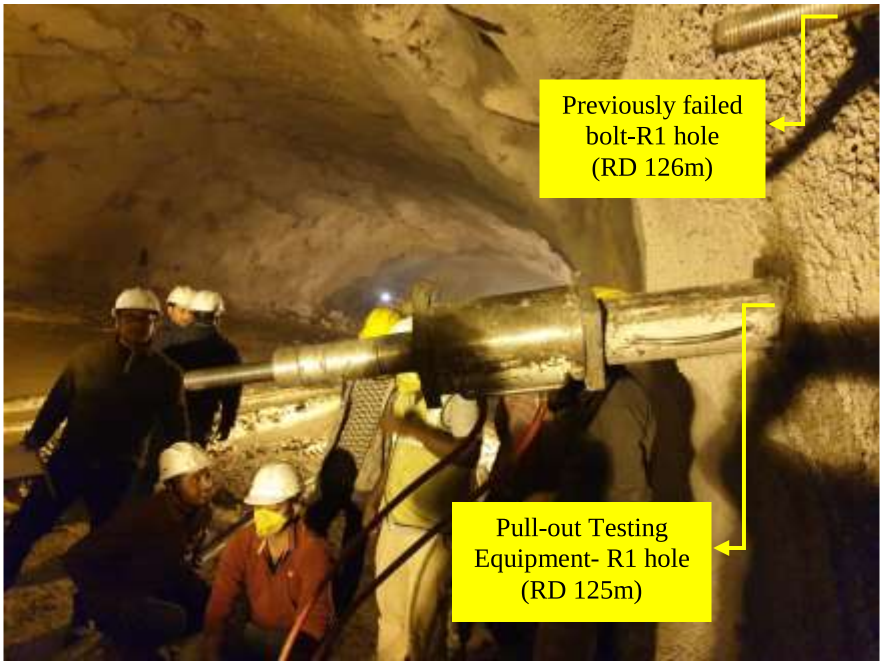


Figure 4 Load Vs Displacement Graph-Experiment-1 Pull-out Test
at RD 125m(Stage-1B) in Powerhouse Cavern

During testing, after applying 12 ton load, vibrations was observed in the testing element and subsequently when load increased up to 13 ton, there was a sound of slippage/breakage of rock bolt and could not take up further load. So, to see the mode of failure in the bolt; the bolt assembly was removed from the hole. It was observed that there was a slippage failure of shell/flange from the bolt thread.

From the above experiment, it could be clearly inferred that in similar geologic set up, the rock bolt (at R-1 hole, RD 125m) showed better statistics i.e. lesser displacement under higher torque application. It could easily take 13 ton load against designated 15 ton load and even registered very less displacement of 10mm at 12 ton load as compared to the bolt (at R1 hole, RD 126) that registered 23mm displacement at 12ton, which obviously had failed previously with lower torque application (Refer Test No.2 in Table-2). Further, it was observed that due to mechanical defect in the shell attached at bolt head, upon higher load application slippage failure occurred at bolt threading.

Pull-out test set-up for Experiment-1 at RD 125m (Stage-1B) in PH Cavern is shown in Picture-1 below:



Picture 1 Showing Pull-out Testing Equipment & Experiment-1 Pull-out at RD125m (R-1 hole, EL 1279.6m, Left SPL- Stage-1B heading portion of PH cavern) in sound rock mass–View from Top Adit to PH Crown towards Main Access Tunnel

5. (b) Experiment-2:

After satisfactory and better test result registered with Experiment-1 in sound rock mass, it was decided to do the same experiment in weaker rockmass (sheared/fractured zone) so as to understand the behaviour of expansion shell rock bolt with similar installation procedure, adopting similar testing methodology.

A thick sheared/fractured zone(±1m) was observed within Quartzite rockmass near Right SPL at RD132m. The rockmass being fractured, a smaller dia hole (38mm) was preferred therein for the experiment. Designated Hole dia being 38mm for 25mm dia bolt; Experiment-2 was planned to be conducted on a 25mm dia, 3m long rock bolt with its insertion in R-8 drill hole (Right SPL) at EL 1279M in Stage-2 (right side wall heading portion) of PH cavern. During insertion of the rock bolt jamming was experienced, probably due to partial collapse of hole or presence of drill cuttings due to drilling in fractured zone.

Similar as that of Experiment-1, this expansion shell rock bolt (25mm dia, 3m long) was stressed with the new Torque wrench made available at site thereby applying Torque value of 540N-m subsequent to opening of the shell at bolt head inside the hole bottom. Thereafter, Pull-out test was done on this 25mm dia 3m long bolt in presence of Senior Officers & site representatives of Pakal Dul HEP, CVPP and Senior officials of M/s Afcons (Power House Contractor)-Refer Picture-2 shown below. The results of Pull-out test are shown below in Table-5&6 with their graphical presentations in Figure-5&6 respectively.

Picture 2 Showing Pull-out Testing Equipment & Experiment-2 (a,b) Pull-out at RD132m (R-8 hole, EL 1279, Right SPL- Stage-2 heading portion of PH cavern) in sheared & fractured weak rock mass–View from Top Adit to PH Crown towards Main Access Tunnel

Table 5
Details of Pull-out Test (Experiment-2a) at RD 132m (Stage-2) in PH Cavern

Load (Ton)	Displacement (mm)
3	3
6	7
7	27

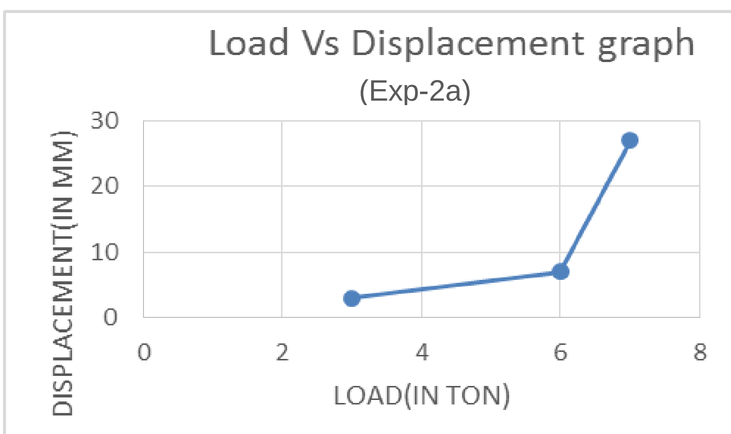


Figure 5 Load Vs Displacement Graph-Experiment-2a
Pull-out Test (1st attempt) at RD 132m(Stage-2) in Powerhouse Cavern

In the above Experiment-2a, the bolt couldn't take further load beyond 7 ton (Refer Table-5 & Figure-5). Hence, it called for re-testing (Experiment-2b) to check and verify the effectiveness of bolt. Results of Re-testing after releasing (zeroing) the hydraulic load in the jack are represented as under at Table-6 & corresponding Figure-6.

Table 6
Details of Pull-out Test (Experiment-2b) at RD 132m (Stage-2) in PH Cavern

Load (Ton)	Displacement (mm)
3	1
6	5
7	17
8	18

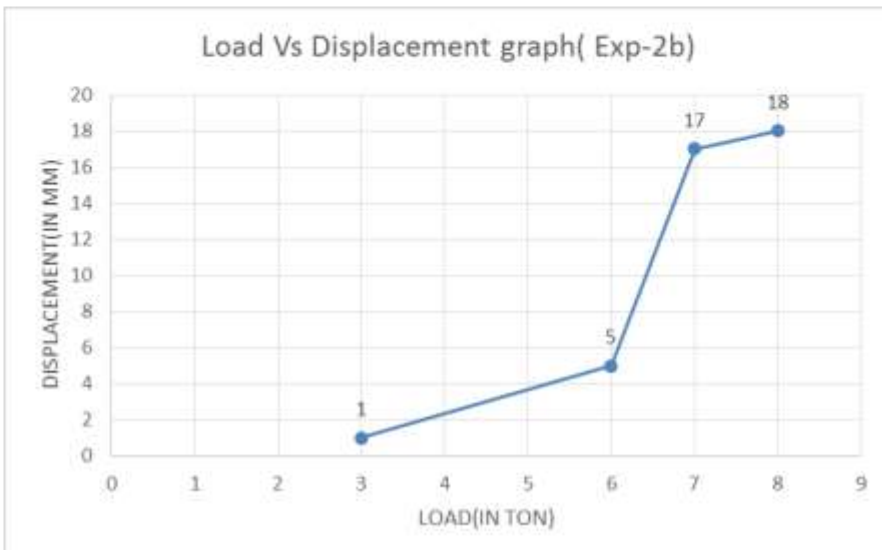


Figure 6 Load Vs Displacement Graph-Experiment-2b
Pull-out Test (2nd attempt) at RD 132m (Stage-2) in Powerhouse Cavern

Even in this second attempt (Experiment-2b, Table-6& Figure-6), Rock bolt couldn't take further load in Pull-out test beyond 7-8 ton, but showed better statistics with lesser displacement in such fractured rockmass as compared to Experiment-2a (Refer Table-5). Though effort was made to un-tighten the nut and remove the bolt from the hole to understand the failure mechanism, however couldn't retrieve the bolt due to jamming.

Nevertheless, it could be inferred that the Rock bolt could take Avg. 7.5 ton (i.e. 50% of the designated Load of 15 ton meant for 25mm dia) load registering an avg. satisfactory displacement value of ~18-27mm (<40mm) in weak (fractured) rockmass.

Above experiments (Experiment-2a & 2b) clearly show the role of proper/adequate torque application prior to pull-out testing of rock bolts that limits the displacement below 40mm as specified in IS 11309-1985. Further, it could also be inferred that geology should not be attributable for rock bolts' failure in pull-out tests executed in Power House Cavern heading portion, rather designated application of torque range is playing a key role.

The location plan of Rock bolts those have undergone Experimental-Pull-out testing at RDs 125,126,127 & 132 in PH cavern heading portion have been demarcated on 3D geological log, shown below at Figure-7.

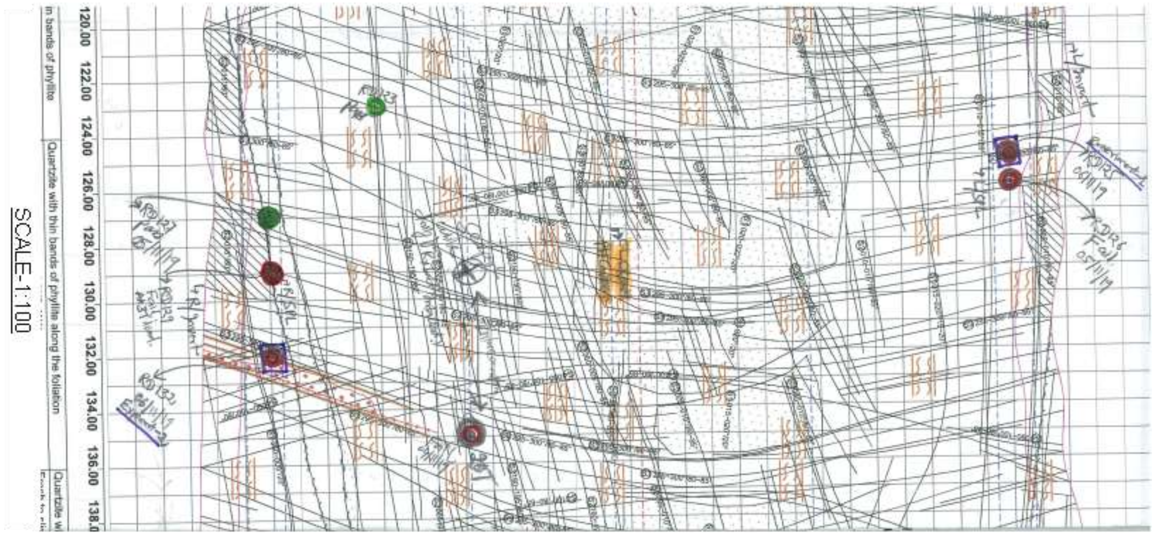


Figure 7 3D-Geological log of Power House Cavern Heading between EL 1285-1278m, showing location of Observed Confirmatory & Experimental Pull-out tests carried out on Expansion shell Rock bolts.

6. Project's Compliance & Final Results:

In view of the above experiments done in PH Cavern, conclusively inference was drawn in attributing under-capacity torqueing of rock bolts as the primary cause of failure during their pull-out tests. Accordingly, Project & Contractor were advised to avail 2 new calibrated Torque Wrenches with higher designated capacity (as per Torque Range mentioned in Table-1) on priority & re-torque the already installed un-grouted rock bolts with the same & re-install new bolts near the failed ones in compliance to Technical Specifications as dictated in Contracts. Consequent upon adoption of revised methodology at site with higher Torque range as per designated capacity, the first phase of pull-out tests done during Mid-November to 1st week of December 2019 showed remarkable results with passing of 30 bolts out of 34 re-torqued/newly installed bolts. The 4 no. bolts those still failed were due to end-anchorage flange & shell junction slippage that in-turn owed to material defect of threading in the bolt head (i.e. non-geological reason).

Subsequent compliance at site with higher-designated capacity torqueing of bolts & dedicated installations, further benching excavation in PH Cavern below heading (i.e.

below EL 1278m) could be successfully resumed at site after a considerable hold & delay.

7. Conclusion and Recommendations:

From the above discussed confirmatory Pull-out tests & Experimental Pull-out test results, it could be inferred that geology/rockmass condition has no such pronounced impact/attribute to failure of rock bolts during Pull-out tests conducted in heading part of Power house cavern. Rather, improper/under-torqueing of bolts after installation was the main causative factor behind the said failures.

As torqueing keeps the reinforcing element as well as surrounding rock in stressed condition, it was also observed that, upon further stressing, the bolt was able to take up higher load registering lower displacement value. Hence, the role of torqueing of rock bolt to its design stress/tension value prior to Pull-out test is imperative & needs to be done for effective support of underground structures. Further, it is pertinent to mention here that Project executing representatives need to ensure availability of Torque Wrench/testing equipment at site which should be capable of stressing the largest diameter of rock bolt to the yield stress of the bolt. Based on the experiments conducted, it is also suggested that stressing of bolts in fractured rockmass need to be done at lower stress value (less than 50% of design value), as observed during experimentation at site.

Conclusively, it can be remarked that testing of rock support elements, their behaviour (in addition to site geology), deficiencies (if any) in the material property, site executional procedures & technical know-how of stressing/testing equipment vis-à-vis methodology adopted at site; for rock support installation to be successful & effective, all these parameters need to be comprehensibly looked into instead of having stereotype approach at site.

References:

1. Pull-out Test results at PH cavern of Pakal Dul HE Project, J&K- Site visit of Design Team, CVPP, CO, Jammu to Project during 04/11/2019 - 09/11/2019: *Design Tour Note No. CVPP/GM/Design/2019/1201dtd.23/11/2019; Office Note No. CVPP/GM/Design/2021/325 dtd. 23/04/2021.*
2. Ziping Huang, Einar Broch, Ming Lu (2002): *Cavern roof stability-Mechanism of arching and stabilization by rock bolting (Article)/Tunneling in underground and Space technology, July 2002.*