Importance of Geo-technical Instrumentation in Underground Caverns

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Abstract

In Dam complex of Mangdechhu Hydro Electric Project (720MW), Bhutan; two parallel underground desilting chambers of 340M length and 14m width are under advance stage of completion. In order to understand the behavior of these caverns, during excavation and after its completion in post construction stage; net work of geotechnical instruments such as an Multi Point Borehole Extensometer, Single Point Borehole Extensometer, Load Cell & Piezometer etc. have been installed. The data obtained through the instrumentation assisted the implementing agency to evaluate the cause of the unexpected behavior of rock mass deformation and extent of problems. Even if there was no visible sign of distress, instrumentation provided an early indication of potential problems, which inter alia facilitated taking remedial actions; which were technically viable, economical and practical and thus avoided rock mass failure. To check the efficacy of support system, instrumentation of excavation is of utmost importance. This not only facilitated demonstrating the sufficiency of the design measures, but also helped in initiating action before occurrence of any adverse event, if support measures were insufficient. Monitoring the performance of the desilting chambers is a continuing process not only during excavation but also in post construction stage.

1. Introduction:

Mangdechhu Hydro Electric project is 720MW (4x180MW) under construction in Bhutan. It is a run-of-the-river scheme on the Mangdechhu River in Trongsa district. The project envisages construction of one Diversion Tunnel (681m long 8.5m dia. Horse shoe shape); Concrete Gravity Dam (114m high, top length and width is 156m and 10m respectively); 4nos. Spillways (orifice type, 109m long, 10m wide); 2nos. Intake Tunnels (127m and 175m long 5m dia.); 2nos. Desilting Chambers (length 340m width 14m & height 17.7m each); 2nos. Branch HRT (129m & 119m long, 5m dia.); HRT 13522m long, 6.5m dia. Horse shoe shape); Surge Shaft (13.5m dia.,152m high); 2nos. Pressure Shafts (1873m long steel lined, 3.5m dia. each); Underground Power House and Transformer Hall (Size- Length155m, width 23m, height 41m and Length 135m, width 18m, height 28m; TRT (1334m long, 8m dia. Horse shoe shape).

2. Regional Geological Setting:

The project area lies in the Central Crystalline belt and is surrounded by rocks belonging to Thimphu Gneissic Complex (TGC) and meta-sediments. A large body of Tertiary Leuco Granite is also present, emplaced in the otherwise Archeozoic to Proterozoic TGC

& Meta sediments. Overall the Trongsa area is covered by Greater Himalayan Sequence (GHS) as indicated by Grujiic et al. (2002).

For engineering geological appraisal, the rock units in the project area have been divided into four units as given below:
Unit-A: Granite gneiss with sub-ordinate bands of schist & granite intrusions.
Unit-B: Mica schist and gneiss.
Unit-C: Leucogranite and granitic gneisses.
Unit-D: Quartzite with mica schist.
Intrusions of granite, quartz-pegmatite and mafic rocks are present in Unit-A, B & D, whereas Unit-C is presumed to be a batholithic body.
The area is falling under Litho Unit – D.

Table 1
The Stratigraphic succession of Project Area is given as under

Group/ Formation	Age	Lithology
Leuco granite Thimphu Chukha Group (Chukha Formation)	Tertiary (10-30 MY) Palaeo-Proterozoic	Leuco granite Tourmaline granite Garnetiferrous Micaceous Quartzite, Mica Schist, Granite, Pegmatite and Mafic Intrusions
---------- Thrust ----------		
Thimphu Gneissic Complex	Proterozoic	Granite Gneiss, Augen Gneiss, Hornblende Gneiss, Garnet- Staurolite Mica Schist, Graphite Schist, Calc Gneiss, Intrusion of Granite

(With references drawn from Grujic et. al, 2002, Jangpangi B.S. and Department of Geology & Mines, Royal Government of Bhutan).

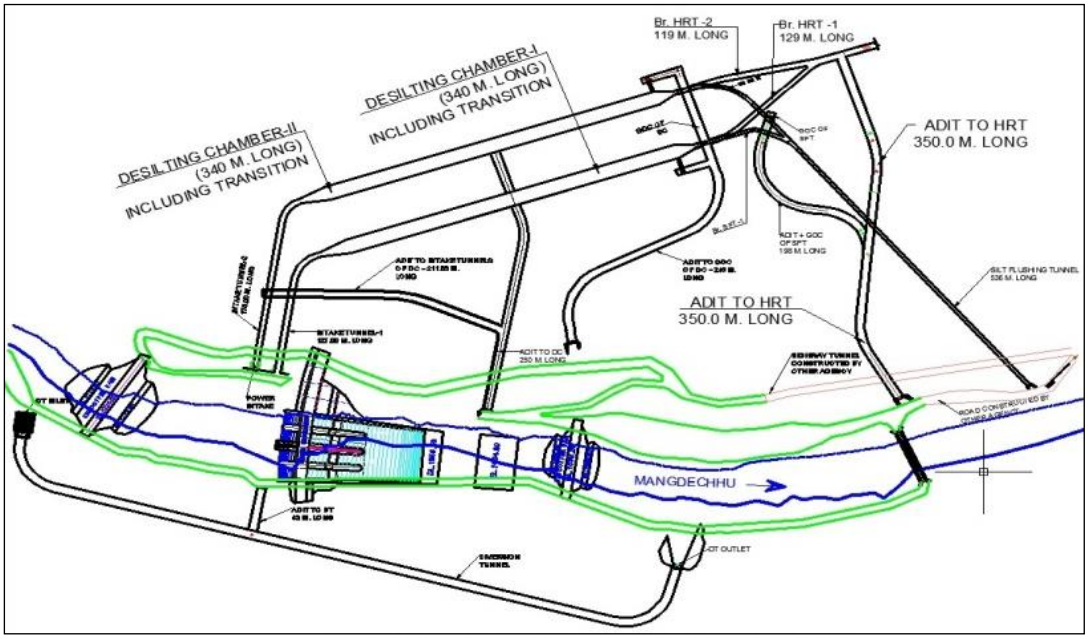
3. Tunneling Methodology:

The methodology has been adopted for tunneling: Drilling, Blasting & Mucking.

3.1 Excavation Methodology and Support System:

The Adit-1 (350m long, 7.5mØ) is access tunnel for the HRT and is also the access to Desilting Chamber-1& 2 (length 340m each) through branch HRT 119 & 129M long respectively. The excavation of both Desilting Chambers has been completed up to El. 1715m through Adit-1 and below this level through construction Adit to DC bottom. The pertinent structures are shown in (Picture 1). The excavation of Desilting Chambers has been completed mainly in 6 (16) stages, shown in figure 1.

Initially the central gullet/Stage-1 (7.5x7.5m) of both chambers (I & II) has been excavated from D/S end with specified support system i.e. Rock bolt 32mmØ 6m long, 1.5m both ways staggered and 100mm thick SFRS (Shotcrete) from 16.07.13- 03.12.13 & 10.07.13- 29.11.13 respectively. After completion of central gullet excavation, widening started from 04.12.13-26.04.14 & 01.12.13- 03.06.14 in both the chambers with a lag of 40-50m left between (Stage-1A & Stage- 1B).



Picture 1 Plan of Dam Complex and pertinent structures

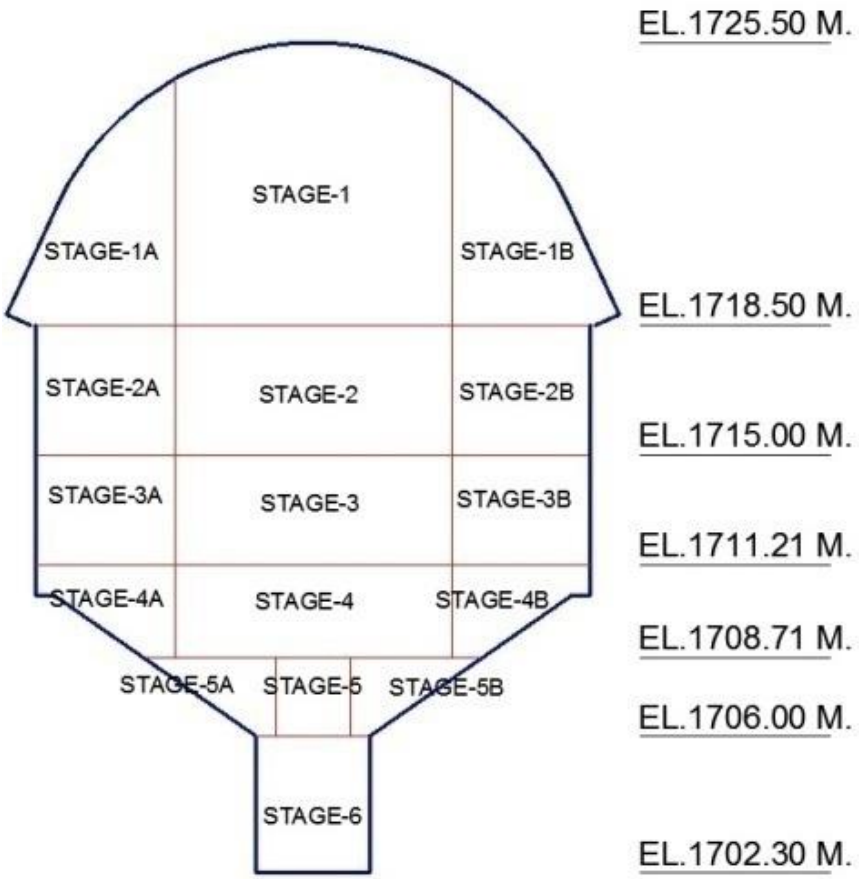


Figure 1 DC Excavation Stages

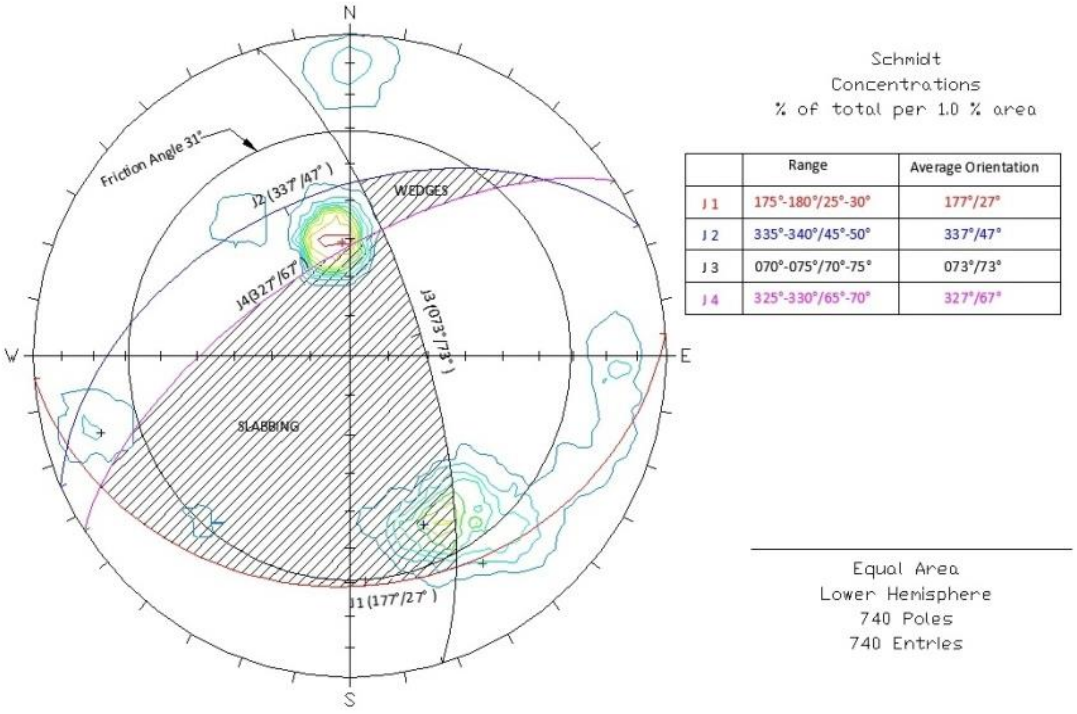
During the excavation of Desiliting Chambers, the rock mass encountered was thinly foliated Micaceous/Biotite Schist, thinly foliated, clay filled, stained, fine-medium grained, jointed with pegmatite intrusion. Shear Seams/Shear bends (±100cm thick) filled with clay/gauge material along the foliation with dry-dripping/minor seepages. The rock mass encountered in Desilting chamber -I from RD. 9.5- 104m, 159-340m as Class III (81%) & RD. 00-9.5m, 104-159m Class IV (19%) RMR ranging between 50-30 and in desilting chamber- II from RD. 00-78.5m, 150-340m class III (79%) & RD. 78.5- 150m class IV (21%) RMR ranging is between 51-33. The Chambers has an alignment of N006˚.

3.1.2 Desilting chamber-I:

In this chamber, the rock mass encountered was Class IV between RD. 104-159m. In this reach, the rock is Micaceous/Biotite Schist, thinly foliated, clay filled, stained, jointed with pegmatite intrusion & no. of interfolial shear seams/Shear bends (30-100cm thick) filled with clay/gauge material. During excavation, it has been observed that 3-4 shears (± 1m) filled with clay/gauge around the RD. 115M. A shear encountered 3-4m (30-100cm) over the chamber crown at Instrument location RD. 115m. The prominent discontinuities encountered in above reach are table 2. The encountered rock mass features are as shown in figures 2 to 4 (Geological 3D log & sections). In Stereographic projection of Desiliting chambers, it has been observed that intersection between discontinuities set J2 low angle, J3 & J4 high angle, resulted the formation of wedge. Slab failure by discontinuity set J1 low angle J3 & J4 high angle, resulted in formation of slabbing with apex height 1-1.4 (aprox.). The large size of slab failure may be attributed to open joints with clay infilling observed in this reach. Stereo plot is showing the formation of wedge & slabbing in figure 2.

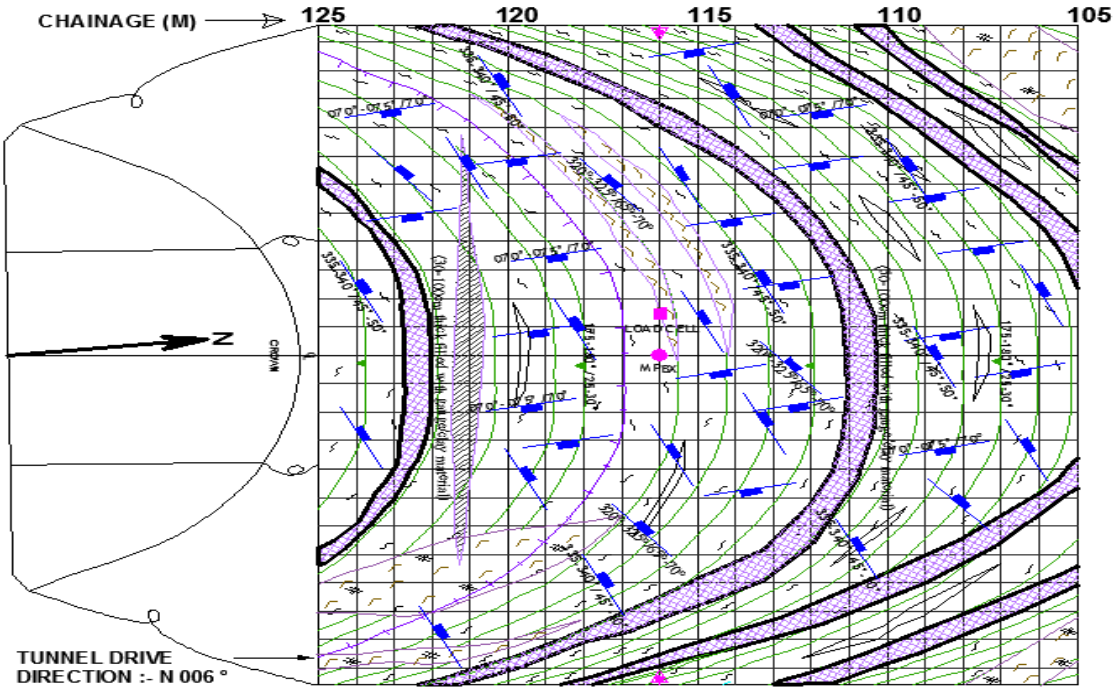
Table 2
Prominent discontinuities observed & tabulated below

Joint Sets	Dip Direction & Dip	Spacing (cm)	Persistence (m)	Aperture (mm)	Infilling	Roughness
J1	175˚-180˚/ 25-30˚	5-20	10-12	2-5	Clay	RU/UN
J2	335˚-340˚/ 45-50˚	30-100	2-5	1-5	Clay	RU/PL
J3	070˚-075˚/ 70˚	50-300	1-3	1-2	Clay/Staining	RU/PL
J4	325˚-330˚/ 65-70˚	30-60	1-4	1-5	Clay/Staining	RU/PL



	Range	Average Orientation
J 1	175°-180°/25°-30°	177°/27°
J 2	335°-340°/45°-50°	337°/47°
J 3	070°-075°/70°-75°	073°/73°
J 4	325°-330°/65°-70°	327°/67°

Figure 2 Stereographic projections of various joint data in desilting chamber



	125	120	115	110	105
ROCK TYPE	Micaceous / Biotite Schist with thick shear (30-100cm) filled with gauge / clay material and intrusion of crushed pegmatite rock.				
ROCK STRENGTH	R3-R4	R3-R4	R3-R4	R3-R4	
JV / RQD	16-17/58	17-18/55	20-22/49	20-22/49	
SPACING OF DISCONTINUITY	60-200 mm	<60-200 mm	60-200 mm	60-200 mm	
CONDITION OF DISCONTINUITY	1+3+3+0+5=12	1+3+3+0+5=12	1+3+3+0+5=12	1+3+3+0+5=12	
GROUND WATER	DRY TO DAMP	DAMP	DAMP TO WET	DRY TO DAMP	
RATING ADJUSTMENT FOR OREINTATION	DRIVE AGAINST DIP	DRIVE AGAINST DIP	DRIVE AGAINST DIP	DRIVE AGAINST DIP	
REPORTING RATING	36-38	34	36	36	
ROCK CLASS	IV/ POOR	IV/ POOR	IV/ POOR	IV/ POOR	

LEGEND :

Schist, Foliation, MPBX, Pegmatite, Joint, Load Cell, Shear, Slip Planes, Tape extenssometer stud

Figure 2A Geological 3D log of Desilting Chamber-I

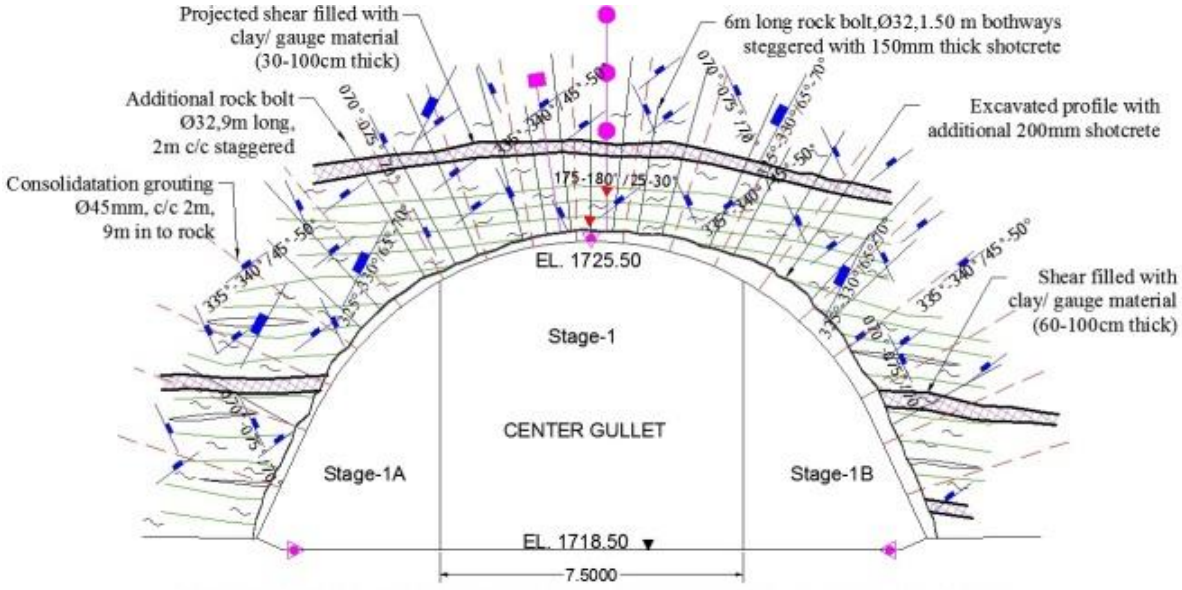


Figure 3 Cross Section of Desilting Chamber at RD 116m

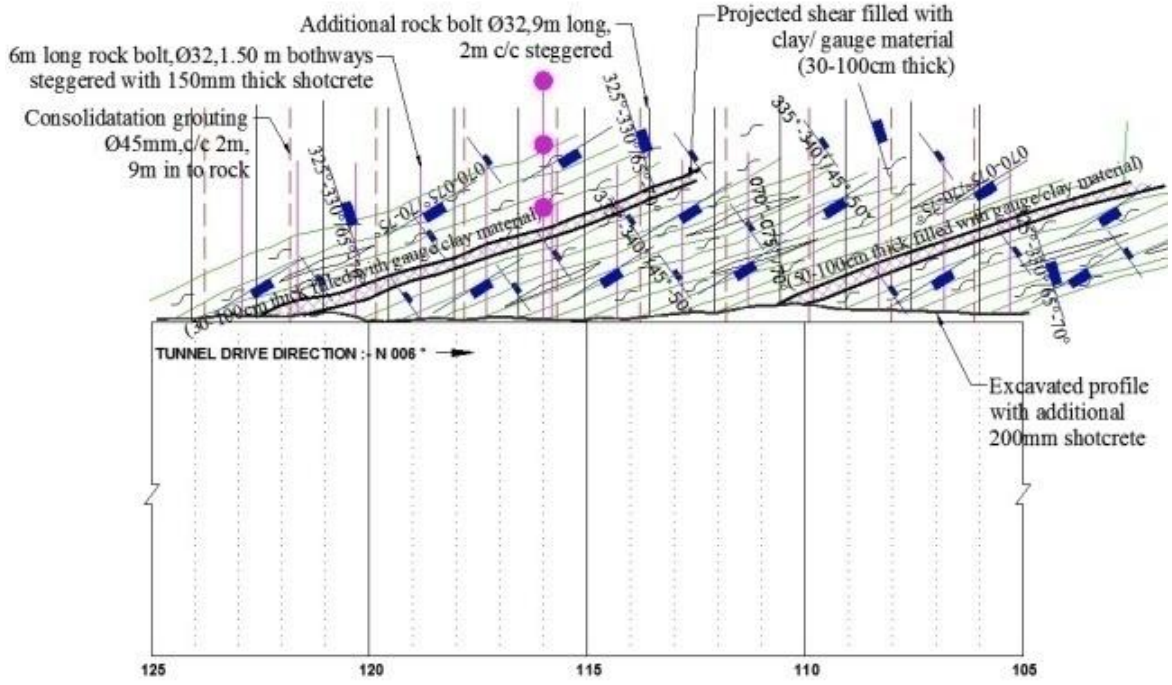


Figure 4 L-section of Desilting Chamber-I

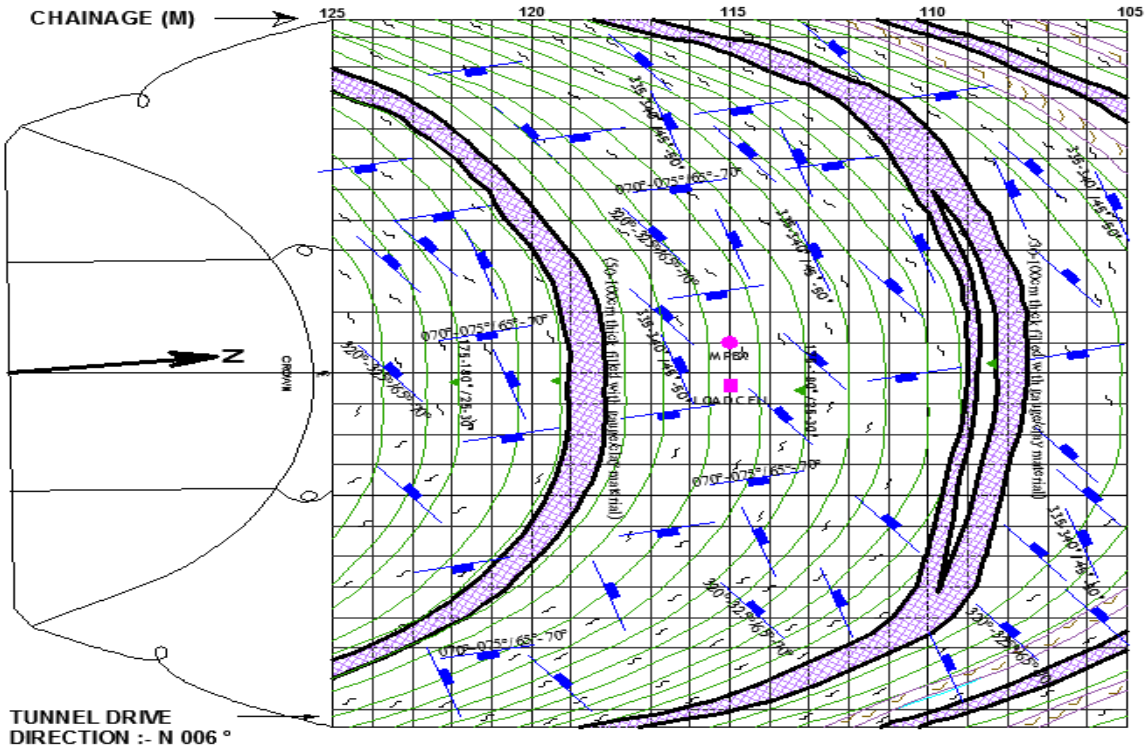
3.1.3 Desilting chamber- II:

The rock mass encountered was Class IV between RD. 78.5- 150m. In this reach the rock mass & features are same as Desilting Chamber-I. The prominent discontinuities observed in above reach are shown in table 3. The encountered rock mass features are as shown in figure 5 to 7 (Geological 3D log & section).

Table 3
Prominent discontinuities observed in chamber-II tabulated below:

Joint Sets	Dip Direction & Dip	Spacing (cm)	Persistence (m)	Aperture (mm)	Infilling	Roughness
J1	175˚-180˚/ 25-30˚	5-20	10-12	2-5	Clay	RU/UN
J2	335˚-340˚/ 45-50˚	30-100	3-4	2-4	Clay/Staining	RU/PL
J3	070˚-075˚/ 70-75˚	50-300	1-3	1-2	Clay/Staining	RU/PL
J4	325˚-330˚/ 65-70˚	20-60	1-5	1-5	Clay	RU/PL

Note: T=Tight, PO=Partially Open, S/U= Smooth Undulatory, S/P+ Smooth Planer



	125	120	115	110	105
ROCK TYPE	Micaceous / Biotite Schist with thick shear (20-100cm) filled with gauge / clay material and intrusion of crushed pegmatite rock.				
ROCK STRENGTH	R3-R4	R3-R4	R3-R4	R3-R4	
JV / RQD	16-17/58	20-22/45	20-23/42	20-23/42	
SPACING OF DISCONTINUITY	60-200 mm	60-200 mm	60-200 mm	60-200 mm	
CONDITION OF DISCONTINUITY	1+3+3+0+5=12	1+3+3+0+5=12	1+3+3+0+5=12	1+3+3+0+5=12	
GROUND WATER	DAMP	DAMP	DAMP	DAMP	
RATING ADJUSTMENT FOR ORIENTATION	DRIVE AGAINST DIP	DRIVE AGAINST DIP	DRIVE AGAINST DIP	DRIVE AGAINST DIP	
REPORTING RATING	36	34	34	34	
ROCK CLASS	IV	IV	IV	IV	

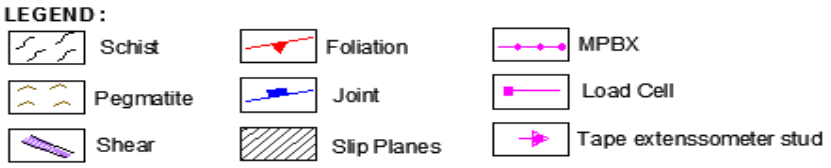


Figure 5 Geological 3-D log of desilting chamber-II

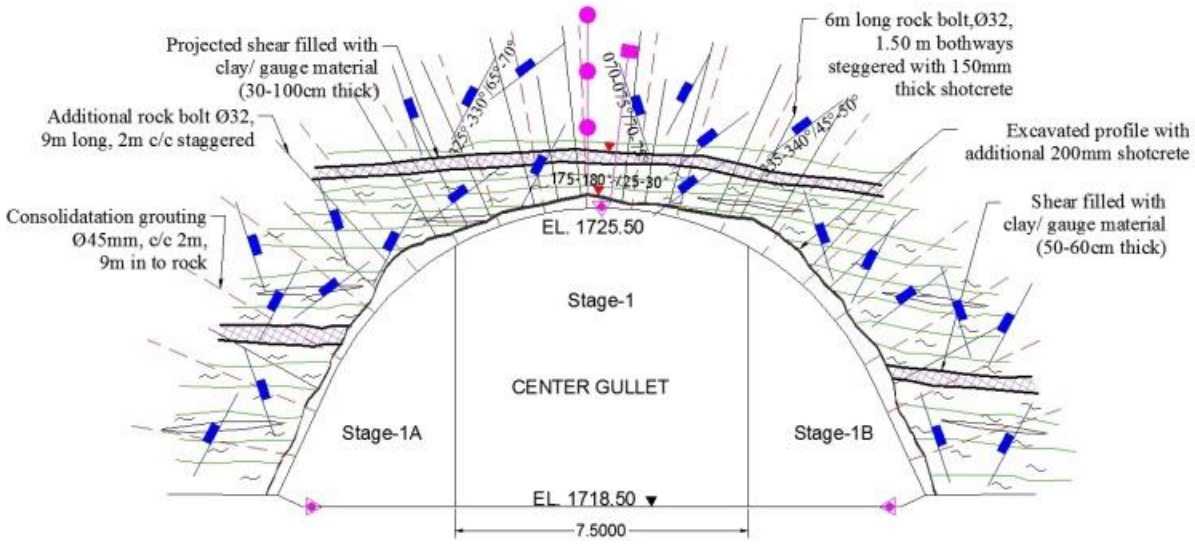


Figure 6 Cross section of desilting chamber –II at RD 115m

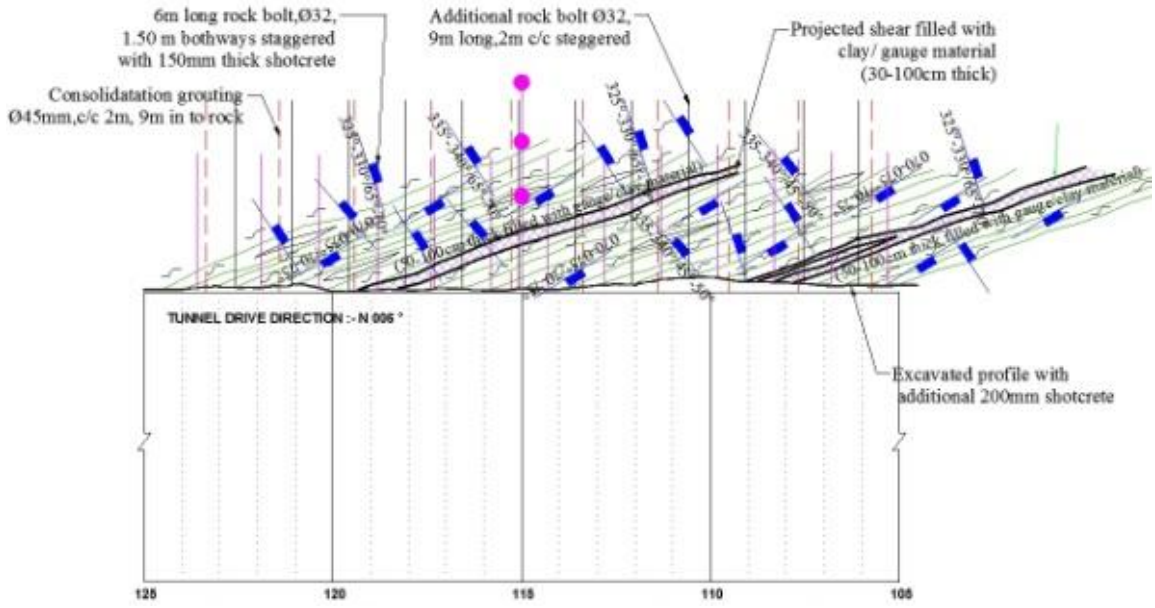


Figure 7 L-section of desilting chamber –II

4. Instrumentation:

During the stage-1 (central gullet) excavation of chamber, the instruments, MPBX (3points 4,7,10 m; Electrical type), Load Cell (300kN) have been installed simultaneously in the crown at the locations as shown in Figure 8 & 8A **(**Instrumentation location plan & section of Desilting Chambers). The five locations i.e. RD. 55, 115, 176, 243& 304m in chamber- I and RD.55, 115, 176, 242 & 300m in chamber- II. The instruments installation details are given in table 4.

Table 4
Details of Geotechnical Instrumentation

S.No.	Desilting Chamber- I			Desilting Chamber- II		
	R.D (M)	Date of Installation		R.D (M)	Date of Installation	
		MPBX	Load Cell		MPBX	Load Cell
1	55	14.12.13	14.12.13	55	06.12.13	18.12.13
2	115	03.12.13	03.12.13	115	26.11.13	30.11.13
3	176	19.11.13	29.11.13	178	26.11.13	30.11.13
4	243	19.11.13	29.11.13	242	26.11.13	30.11.13
5	304	19.11.13	29.11.13	300	26.11.13	30.11.13

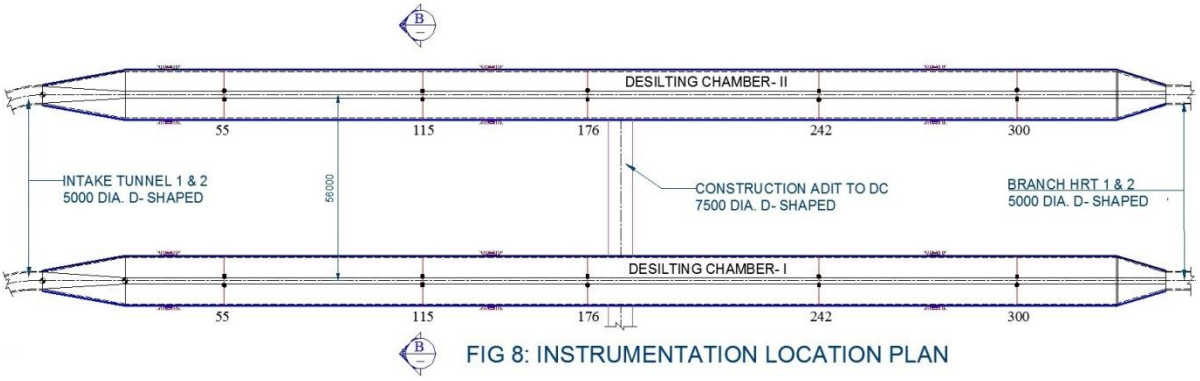


Figure 8 Instrumentation location plan

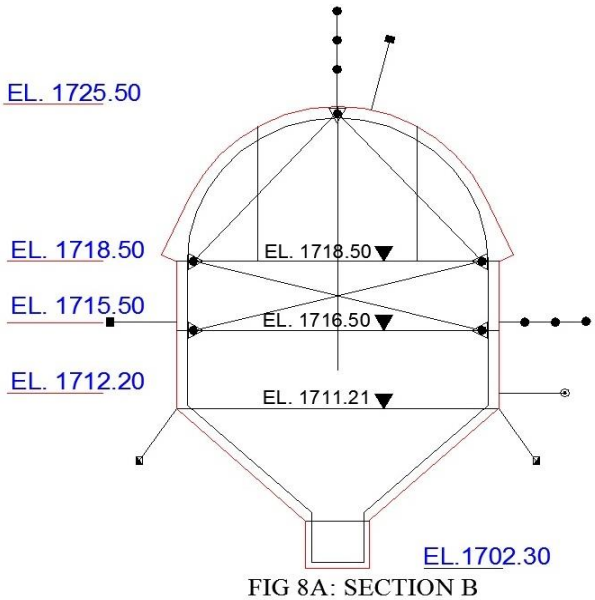


TABLE			
S.NO.	NAME OF INSTRUMENT	LEGEND	TOTAL NOS.
1	MULTIPOINT BOREHOLE EXTENSIOMETER (THREE POINTS) ELECTRICAL		20
2	SINGLEPOINT BOREHOLE EXTENSIOMETER		10
3	CONVERGENCE BOLT		50
4	PIEZOMETER		20
5	LOAD CELL		20

Figure 8A Section B of desilting chamber –II

4.1 Desilting Chamber-I:

In Desilting chamber-I, It has been observed that from stage-1 excavation to stage- 1A & stage-1B, the all instruments showing the permissible movements from 3.9-17.5mm and rock mass dilation load 67.5- 107kN, except one location i.e. RD.115m.

Instruments (MPBX & Load Cell) has installed at RD.115M on 03.12.13. The MPBX reading on 15.02.14 were, A1sensor 2.8mm, A2 sensor 2.4mm, A3 sensor 1.6mm & Load Cell 3.10kN. A blast was taken for stage-1B excavation at RD. ± RD. 124-121M on 16.02.14. After blast instruments reading increased as A1 5.7mm, A2 5.9mm, A3 4.5mm & Load Cell 4.50kN. In continuation of blast was taken on 17.02.14 between RD. ± 121-118M, the reading increased as A1 8.9mm, A2 9.4mm, A3 6.3mm & 9.30kN. On 18.02.14 blast was taken between RD. ± 118-115M, the reading were reached A1 14.4mm, A2 14.6mm, A3 11.1mm & Load Cell 20.0kN. The excavation of same stage has been reached up to RD. ± 98M on 01.03.14 and instrument reading also showing increasing trend and reached A1 23.9mm, A2 23.7mm, A3 18.7mm & Load Cell 48.0kN. The excavation of above stage has been stopped at RD. 98M for monitoring the rock mass movement behavior. It has been found that rock mass movement is continued and reached A1 29.3mm, A2 28.2mm, A3 22.6mm & Load Cell 53.90kN. Further stage- 1A blast has been taken on 12.03.15 from RD. ± 95-100. During continuous monitoring, it has been observed that rock mass dilation is not stable, reached up to A1 39.7mm, A2 37.6mm, A3 31.8mm & Load Cell 73.10kN on 25.04.14. Some rock mass patches detached, falling from the crown near instruments location & cracks in shotcrete (3-10 mm) developed at places. This type of continuous movement i.e. 0.4-1.0 mm daily indicates the possibility of in depth rock mass distress leading to cavity/wedge formation.

On the basis of above monitoring instrument data & Stereographic projection of discontinuities , it has been decided to provide immediately the additional supports between RD. ± 105-125M to control the rock mass dilation and avoid any rock mass falling/cavity formation. Stereo plot & MPBX data indicates that mainly the movement is from shear plane which is encountered 3-4m above the crown and hence 6.0m long rock bolts are not holding the rock mass load. It has been decided to provide additional support i.e. Rock bolt 9m long, 32mm Ø, 2m c/c staggered; 200mm thick SFRS and consolidation grouting hole 9m long, 45mm Ø 2m c/c staggered with pressure 2kg/cm². After providing the additional supports, it has been observed that the instrument reading's increasing trend frequency got decreased/ became constant. The MPBX reading has been recorded- A1 40.2mm, A2 38.6mm, A3 32.8mm & Load Cell 76.50kN on 09.05.14 & total displacement of A1 0.5mm, A2 1.0mm, A3 0.4mm & load 3.40kN from 25.04.15-09.05.14. The MPBX reading are constant from 15.05.14 to 30.04.15 and Load cell reading is constant from 01.06.14 to 30.04.15. It has been also observed that maximum rock mass movement was got in excavation stage- 1A, 1B, 2A, 2A& 2B & from stage- 3-6 was more or less constant. It indicates that the rock mass dilation got stable, even though excavation from stage 1-5 has been completed and a stage- 6 excavation is under progress. The data recorded by MPBX, Load cell (RD.115M C/C) is as shown graphically in Figures 9 & 9A. Other instruments (i.e. MPBX, SPBX, Load Cell & Piezometer etc.) in both walls have also been installed during excavation as mentioned in

Instrumentation location plan Figures 8 & 8A. All other instruments have been monitored and data recorded but, there is no significant information of movement of the rock mass and found that the chamber crown / walls are stable.

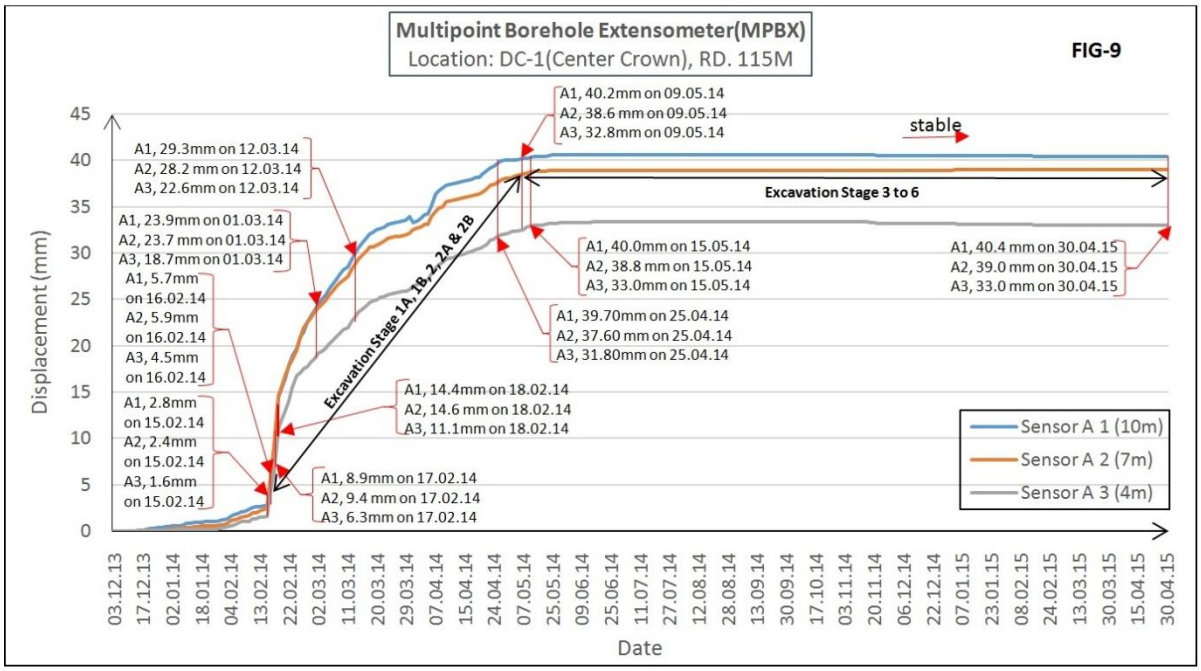


Figure 9 Multipoint borehole extensometer (MPBX) located in DC-I

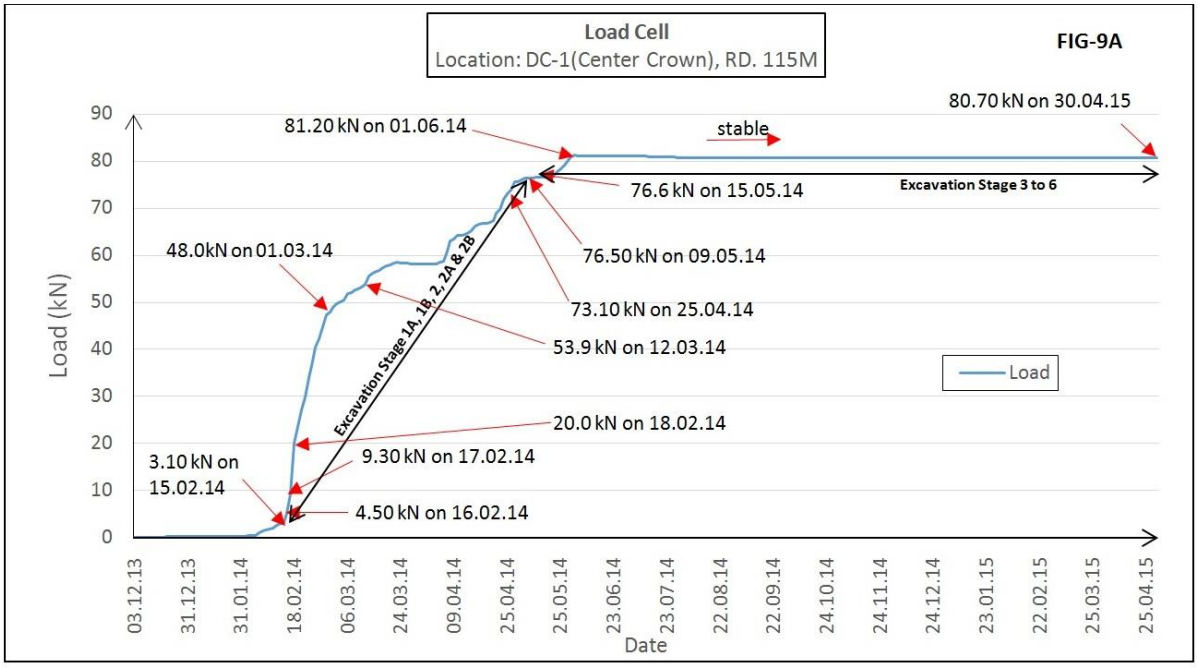


Figure 9A Load Cell installed in DC-I

4.2 Desilting Chamber-II:

In Desilting chamber-II, it has been observed that from stage-1 excavation to stage- 1A & stage-1B, all the instruments showed the permissible movements from 1.3- 7.0 mm and rock mass dilation load 20.40- 65.10kN, except at one location i.e. RD.115m.

Instruments (MPBX & Load Cell) have been installed at RD.115M on 26.11.13 & 30.11.13. The MPBX readings on 14.01.14 were A1sensor 1.5mm, A2 sensor 1.6mm, A3 sensor 1.0mm & Load Cell 0.90kN. A blast was taken for stage-1B excavation at RD. ± RD. 107.5-110M on 14.01.14. After blast, instruments reading was recorded on 15.01.14 as A1 3.2mm, A2 2.6mm, A3 1.4mm & Load Cell 1.00kN. In continuation, blast was taken on 15.01.14 between RD. ± 110- 112M, the reading gradually increased up to as A1 8.2mm, A2 7.6mm, A3 6.9mm & Load Cell 15.10kN on 12.03.14. On 12.03.14 blast of stage-1A was taken between RD. ± 124-121-119M. After the blast, the readings got abruptly changed and were recorded as A1 11.9mm, A2 11.0mm, A3 11.8mm & Load cell 46.60kN on 13.03.14. The excavation of same stage has been completed up to RD. ± 99M and instrument reading was also showing increasing trend and reached A1 18.7mm, A2 17.7mm, A3 16.6mm & L cell 55.90kN on 18.03.14. The excavation of above stage-1A was stopped at RD. ± 99M. It has been observed that rock mass movement continued to increase 0.6mm- 1.4mm & 1.4-3.70kN daily and reached A1 19.3mm, A2 18.3mm, A3 17.0mm & Load cell 56.60kN on 19.3.14. It has also been observed that cracks in shotcrete (5-10mm) got developed near instrument location. This type of continuous movement indicates the possibility of in depth rock mass distresses leading to & cavity/wedge formation.

On the basis of above monitoring instrument data & Stereographic projection of discontinuities, it has been decided to provide immediately the additional supports between RD. ± 105-125M to control the rock mass dilation and avoid any rock mass falling/cavity formation. MPBX data indicates that movement was mainly from shear plane which is encountered 3-4m above the crown and 6.0m long rock bolts are not holding the rock mass load. Additional support has been decided to be provided as in chamber-I. After providing the additional supports, it has been observed that the instrument reading's increasing trend frequency got decreased from 20.03.14- 17.06.14. The MPBX reading has been recorded as- A1 25.7mm, A2 23.8mm, A3 29.4mm & load cell 61.20kN on 17.06.14 & total displacement of A1 6.1mm, A2 5.1mm, A3 11.9mm & load 4.10kN from 20.03.14- 17.06.14. The MPBX and Load cell readings are constant from 19.06.14 to 30.04.15. The MPBX reading has been observed as - A1 25.5mm, A2 23.4mm, A3 28.7mm & load cell 61.20kN on 30.04.15. It has been also observed that rock mass movement trend was got same as excavation stages of Desiliting Chamber-1. It indicates that the rock mass dilation has been stable, even though excavation in all the stages from 1-5 has been completed and stage- 6 excavation is under progress. The MPBX, Load cell (RD.115M C/C) instruments data is as shown graphically in figures 10 & 10A. Other instruments (MPBX, SPBX, Load Cell & Piezometer etc.) in both the walls have also been installed during excavation as mentioned in Figures 8 & 8A. All other instruments have been monitored and data has been recorded but, there is no significant

information of movement of the rock mass and it was found that the chamber crown/walls are stable.

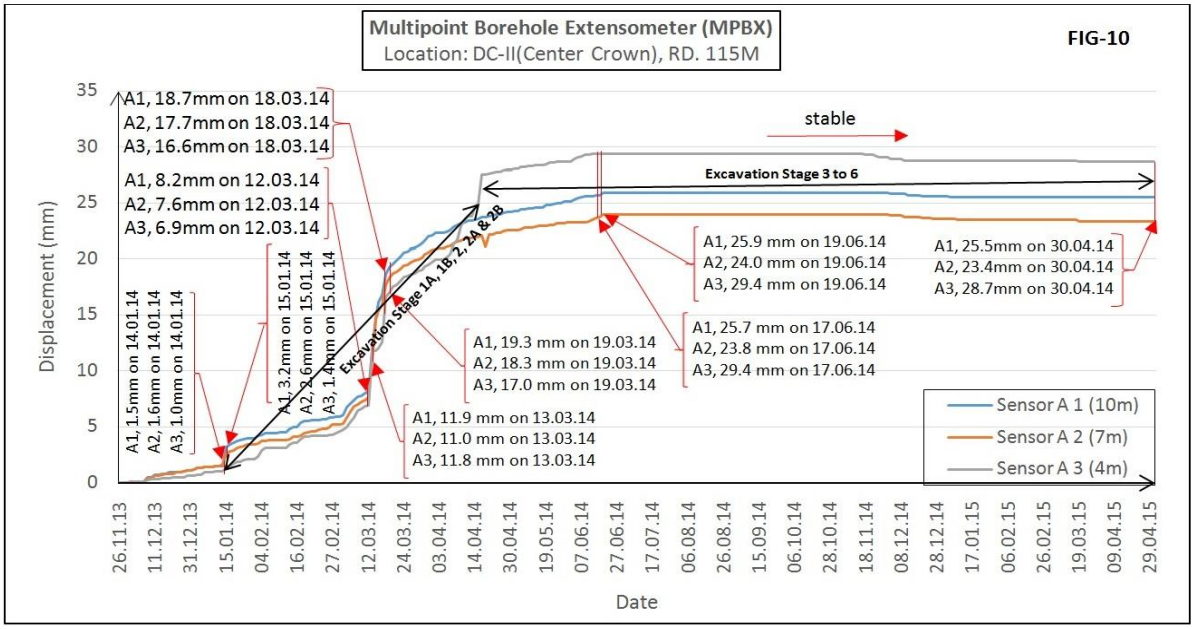


Figure 10 Multipoint borehole extensometer (MPBX) located in DC-I

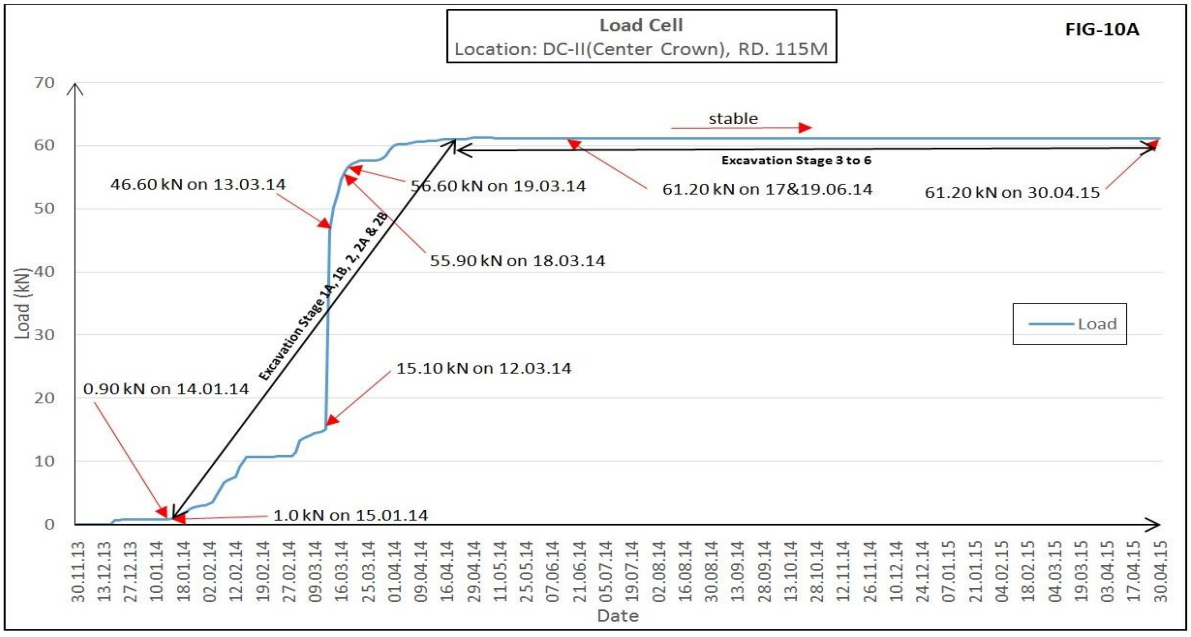


Figure 10A Load Cell installed in DC-I

5. Conclusion:

The instruments (MPBX, SPBX, Load Cell & Piezometer etc.) have been installed at five specified locations in each chamber to understand the rock mass behavior during excavation and after its completion in post construction stage. On the basis of data observation from date of installation till date (19.11.13- 30.04.15), it has been observed that Instrument location RD. 115m of each chamber are showing abnormal reading, while rest four location instruments are showing normal movement in chamber-I i.e. 3.9-17.5mm, 67.5-107kN and in chamber-II is 1.3-7.0mm, 20.40- 65.10kN. In chamber-I, around the instrument location RD.115M the rock was micaceous schist, thinly bedded with multiple interfolial shears, wedge/slab formation in nature, class IV (RMR 34-38). A shear (30-100cm) filled with clay/gauge encountered 3-4m above the crown at RD.115M. During the excavation of stage-1,1A,1B& 2,2A,2B, the instrument(MPBX, Load Cell) data showed abrupt changes in rock mass movement and also the continuously increasing readings reached up to A1 39.7mm, A2 37.6mm, A3 31.8mm & 73.10kN on 25.04.14, developed shotcrete cracks(3-10mm). This is prior information of unexpected behavior of rock mass deformation and extent of problem by instrument. Remedial action has been taken as additional supports provided immediately to avoid the loose fall cavity. After the completion of additional supports, the reading has been constant from 15.05.14-30.04.15(till date) as A1 40.4mm, A2 39.0mm, A3 33.0mm & 80.70kN. It is clearly an indication of rock mass stability brought about by remedial measures such as revalidation of support system till excavation of all stages.

In chamber-II, around the instrument location RD.115M the rock lithology/features were same as chamber-I i.e. class IV (RMR 33-36). A shear (50-100cm) filled with clay/gauge encountered 3-4m above the crown at RD.115M. During the excavation of stage-1,1A, 1B& 2, 2A, 2B, the instrument (MPBX, Load Cell) data showed abrupt changes in rock mass movement and also the continuously increasing readings reached up to A119.3, A2 18.3, A3 17.0mm & Load cell 56.60kN on 19.03.14. It has also been observed that cracks in shotcrete (5-10mm) got developed near instrument location. This is prior information of unexpected behavior of rock mass deformation and extent of problem by instrument. Remedial action has been taken as additional supports provided immediately to avoid the rock mass falling. After the completion of additional supports, the reading has been constant from 19.06.14- 30.04.15(till date) as A1 25.5mm, A2 23.4mm, A3 28.7mm & load cell 61.20kN on 30.04.15. It is clearly an indication of rock mass stability till excavation of all stages. Even if there was no visible sign of distress, instrumentation provided an early indication of potential problems, which inter alia facilitated taking remedial actions; which were technically viable, economical and practical and thus avoided rock mass failure. To check the efficacy of support system, instrumentation of excavation is of utmost importance. This not only facilitated demonstrating the sufficiency of the design measures, but also helped in initiating action before occurrence of any adverse event, if support measures were insufficient.

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