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Use of Plastic Concrete Cut-Off Wall for Seepage Control in Underground Excavations - A Case Study

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ABSTRACT

Advancements in the construction of plastic concrete cut-off walls have enabled the construction of large zoned earth fill embankment dams on deep pervious foundations. It comprises a mixture of cement, water, aggregate and bentonite, which has low hydraulic conductivity and excellent ductility after reaching failure compared with conventional concrete.

A conventional concrete cut-off wall, a simplest structural form is a rigid diaphragm wherein deformations of earth embankment due to increase in reservoir level or seismic activity could cause its rupture which would greatly decrease the flow efficiency of the cut-off wall and jeopardize the safety of the dam. However, with plastic concrete, which has deformation characteristics similar to the earth dam, produces ductile material with addition of bentonite clay.

Plastic concrete cut-off wall is a cast in place wall, excavated with specialized equipment i.e., with trench cutter under bentonite slurry and subsequently concreting with deformable, watertight, plastic concrete, composed of 100-220kg/m^3 cement, 1,500-2,000kg/m^3 well graded aggregate and 30-40kg/m^3 bentonite. Typical wall thickness is 0.6 m. This method allows to install very deep walls (50 m or more), but for very large depths, wall thickness needs to be increased to 1 or 1.2m in order to reduce the risk of gaps near panel joints which may be caused by deviations.

The paper focuses on recent state-of-art technology governed by geotechnical parameters & site-specific requirement, various aspects encompassing design and construction related issues, construction methodology and its efficacy in terms of seepage control.

Keywords: Recent technology; Plastic concrete cut-off wall; Seepage control; Deep excavation; Bentonite

1. INTRODUCTION

Presently, the generating installed capacity is only about 26% of hydropower potential i.e., 39,340 MW. The pace of Hydropower development in India has slowed down especially in last few decades. The circumstances arising out of compulsion of utilization of the available remaining sites necessitates compensating it with invent of state of art technology, suiting to ground conditions and functional requirement.

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The conceptualization and execution of Mega Hydro Electric projects at an unprecedented pace is the need of an hour, before the rift between demand and supply scenario of electricity could reach a critical point. This warrants construction of projects in more rugged, inaccessible, geologically difficult sites, where the alternatives for better site selection are limited.

This implies that the technology more responsive to geological conditions and geotechnical parameters fulfilling the construction standards and meeting technical requirements is the solution to this challenge, which has become a recent trend.

A befitting illustration to this is construction of plastic concrete cut-off wall as a seepage barrier mechanism where reservoir seepage upstream needs to be arrested upto considerable appreciable depths as a mark of recent technology.

2. PLASTIC CUT-OFF WALL - MEANING AND APPLICATION

A plastic cut-off wall is a deep-foundation technology, employed to form impervious, permanent, underground ‘diaphragm’ (or barrier), to seal off certain underground areas and prevent passage of fluids, generally water, through it.

The use of the word ‘plastic’ is to describe the very nature of the diaphragm, barrier or membrane created with this technology, in fact the plastic cut-off wall is made of a mix of bentonite, cement, water and other components, proportioned in such a way to remain indefinitely plastic and impervious with time.

The word ‘cut-off’ is meant to define the specific purposes of this technology, i.e., to either stop the flow to dam or the underground stream, or to surround and seal-off an area, to prevent water inflow and water outflow from the encircled area. For this technology, the medium employed to ‘cut-off’ is the plastic wall, or plastic diaphragm that has the effect of completely stopping the water flow at a chosen section of a river bed under laid by deep alluvium, or sealing-off an area (typically under laid by alluvium), surrounding it, with a cut-off wall along the entire perimeter.

3. PLASTIC CUT-OFF WALL - PROBLEM APPRECIATION IN PUNATSANGCHHU - I H.E. PROJECT (1200 MW), BHUTAN - A BEFITTING SOLUTION

Punatsangchhu - I Hydro-Electric Project (PHEP-I) is a run-of-river scheme, comprising 130m high, 240m long, concrete gravity Dam, 4 nos. 330m long desilting chambers, 8.95km long 10m diameter HRT and underground Power House complex.

The dam, a critical component in the project, is designed to rest on foundation grade rock, which is surprisingly 76m (even more than the height of monument Qutub Minar in India) below the river bed. In fact, the rock is available at depth more than 70m within the entire reach of the river in project proximity. A view of deep-seated rock and huge overburden in the vicinity of dam area is depicted in Fig. 1.

This involves large quantity of excavation below river bed which is about 20 x $10^5 m^3$. An upstream view of dam indicating the excavation below river bed i.e., dam pit is presented in Fig. 2.

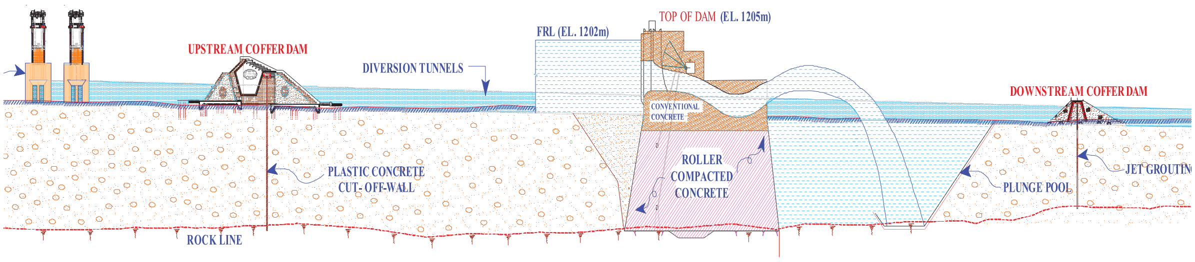

Fig. 1 - A view of deep-seated rock and huge overburden in the vicinity of dam

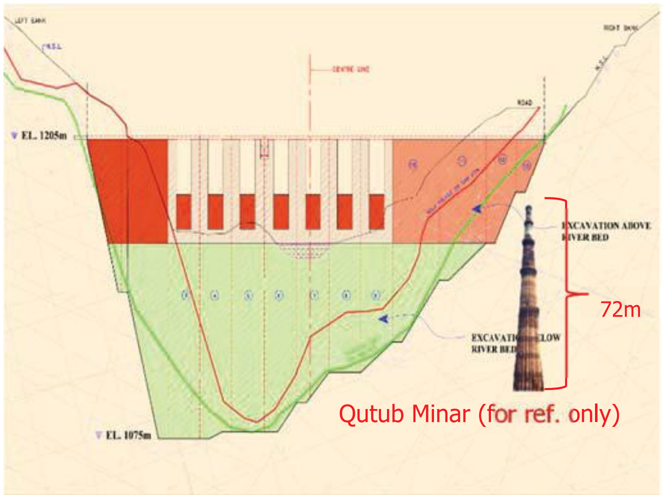

Fig. 2 An upstream view of dam indicating excavation below river bed

For safe and uninterrupted operation, seepage free pit during excavation below river bed is a prerequisite. Therefore, having diverted the river through twin diversion tunnels (11m dia.) and with up stream (U/s) coffer dam in place, the ingress of 7 seepage water in the dam pit could not be avoided, due to huge overburden underneath the U/s coffer dam foundation. So, for seepage control, a fool proof mechanism underneath U/s coffer dam needs to be ensured for which conventional Jet grouted cut off wall or plastic cut-off wall (CoW) were the possible alternatives, been explored. A schematic section indicating view of dam and U/s & D/s coffer dams, with a cut-of wall piercing colluvial/alluvial material intercepting upto bedrock (Fig. 3).

In view of the bouldary strata encountered beneath the river bed and the merit of technology available, plastic concrete cut-off wall (CoW) was found to be more favorable, as per site conditions. Limitations of jet grouted cut-off wall are explained briefly below.

3.1 Deviations During Drilling

The presence of high strength boulders underneath the river bed may cause deviation in alignment of jet grout columns. This may form windows between the jet grout columns triggering the formation of the seepage path. Further, with the present technology available, deviations in the drilling alignment cannot be ruled out. For such high depths of grouting as exist at PHEP-I, even a 1% deviation may cause formation of sufficiently large windows. This will dilute the very purpose of constructing this cut-off wall (Fig. 4).

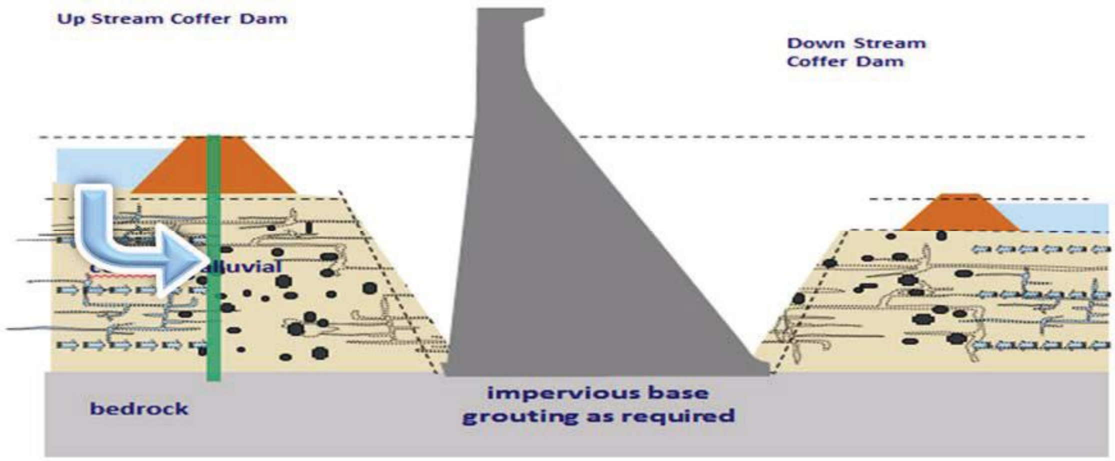

Fig. 3 - A schematic section of U/s coffer dam, dam & D/s coffer dam, showing plastic cut-off wall (CoW) as a seepage control mechanism

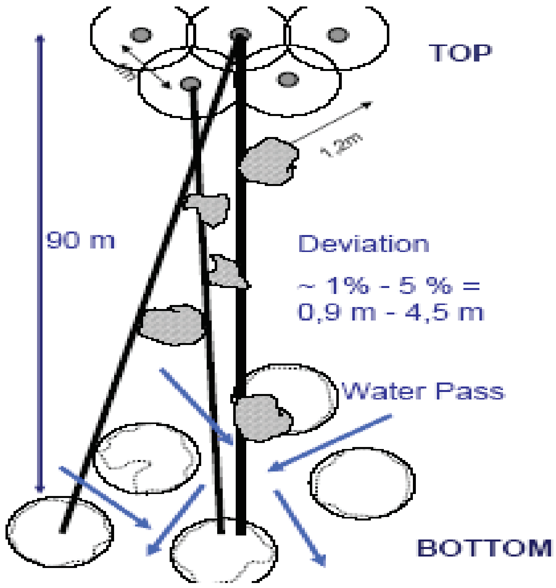

Fig. 4 - Jet grouting CoW- deviations during drilling

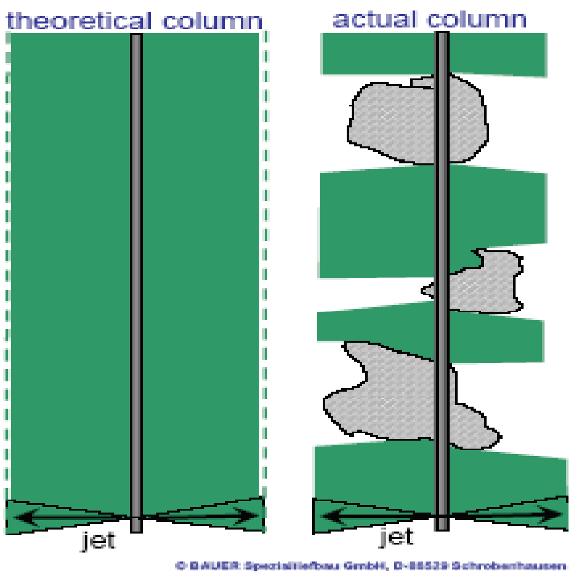

Fig. 5 - Jet grouting CoW - jetting shadows

Diameter of the jet grouted column is much bigger than the diameter of drill hole. However, in the case of large boulders encountered in the drilling path the diameter of jet grouted column will almost be same as that of drill hole. This would cause formation of jetting shadows in the cut-off wall (Fig. 5).

These major issues could be avoided by constructing additional jet grouting columns, supplemented with permeation grouting to cover the windows formed. However, there still remains the possibility of these windows remaining unplugged. Further, there is no mechanism of physical measurement of the efficacy of this additional exercise.

Taking into account the limitations of the jet grouted cut-off wall, as brought out above and the importance of this structure on the project construction, the alternate option of plastic concrete cut-off wall (PCCoW) was adopted.

The plastic concrete cut-off wall is physical and measurable replacement method in which the deviation measurement and control systems are highly reliable through trench cutter technology resulting in well-defined impermeable cut-off wall. A comparison between jet grouted and plastic concrete cut-off wall is given in Table 1.

Table 1 - Difference between jet grouting CoW & plastic concrete CoW

Sl. No.	Parameters	Jet grouting CoW	Plastic concrete CoW
1	Impermeability	Non continuous and uncontrolled due to drilling deviations and jetting shadows arising out of big boulders within the treated mass	Well defined, continuous and controllable cut off wall, cutting across massive boulders within the treated mass
2	Mobilization	Relatively small mobilization	Voluminous mobilization
3	Cost	Can end up in high costs	Relatively higher initial costs
4	Time schedule	Can end in unknown time extensions	Defined time schedule with little possibility of time overrun

In view of evident reasons explained above, plastic concrete cut-off wall is definitely a better choice for deep excavations, as a recent trend in technological advancement.

4. PLASTIC CONCRETE CUT-OFF WALL - DESIGN ASPECTS, CONSTRUCTION EQUIPMENT & METHODOLOGY

An insight of the construction and related equipment required to be deployed for two phase slurry trench cut-off wall works are elaborated as below:

4.1 Main Equipments

The main equipment being used for excavation/construction is as follows:

- Diaphragm wall trench cutter on carrier crane (Fig. 6),
- Grab cutter on carrier crane (Fig. 7),
- Chisel on carrier crane (Fig. 8),
- Desander units (2 for cutters, one for grab or spare),
- Bentonite mixer (1 working, 1 spare),
- Habermann KPKT slurry pump 400 m^3/h for cutter (feeding pumps), and
- Pipeline system for bentonite handling, circulation and storage.

Fig. 6 - Crane mounted BC-40 trench cutter

Fig. 7 - Crane mounted grab cutter

Fig. 8 - Chisel unmounted from crane unit

The work being specialized in nature has been executed by an expert agency "M/s Bauer", a Germany firm.

4.1.1 Brief description of trench cutter BC-40

The trench cutter is a reverse circulation excavation tool (Fig. 9). It consists of a heavy steel frame (1) with two gear boxes (2) attached to its bottom end, which rotate in opposite direction around horizontal axis. Trench cutter wheels (3) are mounted onto the gear boxes. As they rotate, the soil underneath the trench cutter is continuously removed, mixed with the bentonite slurry in the trench and sucked towards the openings of the suction box (4). The bentonite slurry charged with is pumped by a centrifugal pump (5), located right above the cutter wheels, through the slurry pipe within the cutter frame, via the mast head into the slurry pipe system to the desander plant, where it is treated in desander and returns back into the trench.

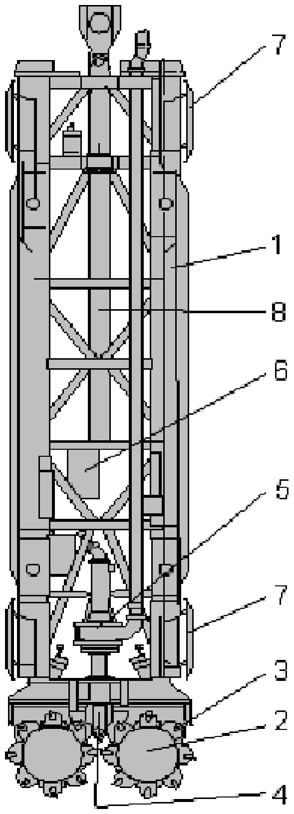

Fig. 9 - BC 40 Trench cutter

The torque of the cutter wheels in combination with the weight of the cutter is sufficiently strong to cut into any kind of soil, and even to crush small cobbles or weak rock, and to overcut the concrete of adjacent panels.

Depending on the soil conditions, different types of cutting teeth can be deployed, ranging from aggressive teeth for cutting fine-grained soil to percussive teeth for crushing boulders.

The verticality of the trench cutter and thus the trench alignment will be measured in (y-axis) and perpendicular to (x-axis) the panel axis by means of two independent inclinometers (6). The data provided by these inclinometers is processed by the on-board computer and displayed online, so that the operator can continuously monitor and, if necessary, correct the verticality of the cutter. Adjustment of the verticality in both directions can be achieved with a system of steering plates, (flaps) (7). Throughout the correction process the rig operator is constantly guided by measures proposed and shown by the computer. The "milling report" can be downloaded after completion of each panel excavation, printed out and thus used for QA/QM purposes.

Cutter progress can be controlled selectively by using of push buttons in relation to rate of penetration (in soft soil) or cutter weight (crowd force in hard soil). This is done by the crowd cylinder (8) or by way of the highly sensitive main winch.

4.2 Concrete Properties and Design Mix

The properties of the plastic concrete used for the cut-off wall production have basically to comply with the following requirements:

4.2.1 Hardened concrete

- Water permeability not exceeding k-value of 10^{-8} m/s, and
- Unconfined compressive strength around 2.0 MPa at 28 days.

4.2.2 Fresh concrete

Sufficient flowability in terms of Slump especially regarding the concrete batches cast at the upper parts of the cut-off wall with Slump not less than 180 mm. Adequate stability with respect to bleeding, segregation and water losses by filtration.

Ample duration of workability considering the time frame needed for the casting of subsequent concrete batches, where the concrete around the outlet of the conveyance pipe (tremie pipe) has to be flowable enough to be displaced by the subsequent discharge batch.

4.2.3 Design mix

Design mix of Plastic cut-off wall i.e., ingredients per m^3 of concrete is given in Table 2.

Table 2 - Design mix

Sl. No.	Material	Quantity
1.	Cement	210kg
2.	Bentonite	30kg
3.	Water	378 litre
4.	Aggregates 0-10 mm	1500kg
5.	W/C ratio	1.8
6.	Retarder (for depths >50m)	0.5% by weight of cement

4.3 Working Platform and Guide Walls

Working platform at a suitable elevation in U/s coffer dam, which is safe against monsoon floods has been utilized for construction of guide walls and plastic cut-off wall. A typical section of U/s coffer dam indicating working platform (EL. 1176m) is presented in Fig. 10.

Guide Walls are in-situ concrete walls constructed prior to the cut-off wall construction to provide:

- Guidance to ensure the correct alignment of the diaphragm wall,
- Protection against instability of the top soil zone of the trench caused by fluctuating bentonite, levels and agitation of the slurry during excavation, and
- Support for the trench stability at the top zone, affected by the vertical surcharge weight of the trench cutter and other heavy jobsite traffic adjacent to the trench.

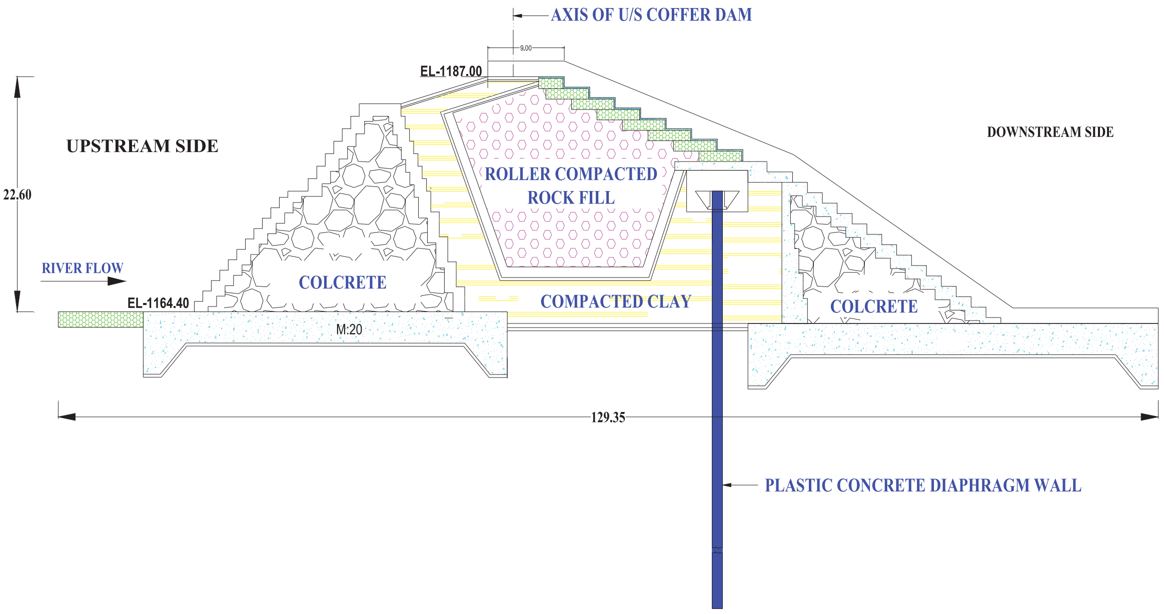

Fig. 10 - A typical section of U/s coffer dam indicating working platform and cut-off wall

Top of guide wall is kept lower than the working platform to limit bentonite or concrete spill during operation. Guide walls are considered to be temporary construction measure and may/may not be removed after completion of the cut-off wall, which they were kept intact in this project. A typical guide wall is shown in Fig. 11.

Fig. 11 - A guide wall

The gap between the 2 guides is to be backfilled with proper, non-cohesive material (such as gravels), to avoid overconsumption of bentonite or concrete, when excavating or casting concrete in neighbour panels. Drilling of holes upto bedrock on either side of guide walls along with pressure grouting was also conducted for ensuring stabilization of trench during excavation.

4.4 Excavation of Primary and Secondary Panels

In a typical cut-off wall, primary panels are excavated at a predefined spacing. The secondary panels are excavated between two primary panels, with an overcut length varying from 0.3 to 0.4m on each side, to account for deviation of alignment during excavation of panels (Fig. 12) and section of primary and secondary panels (Fig. 13).

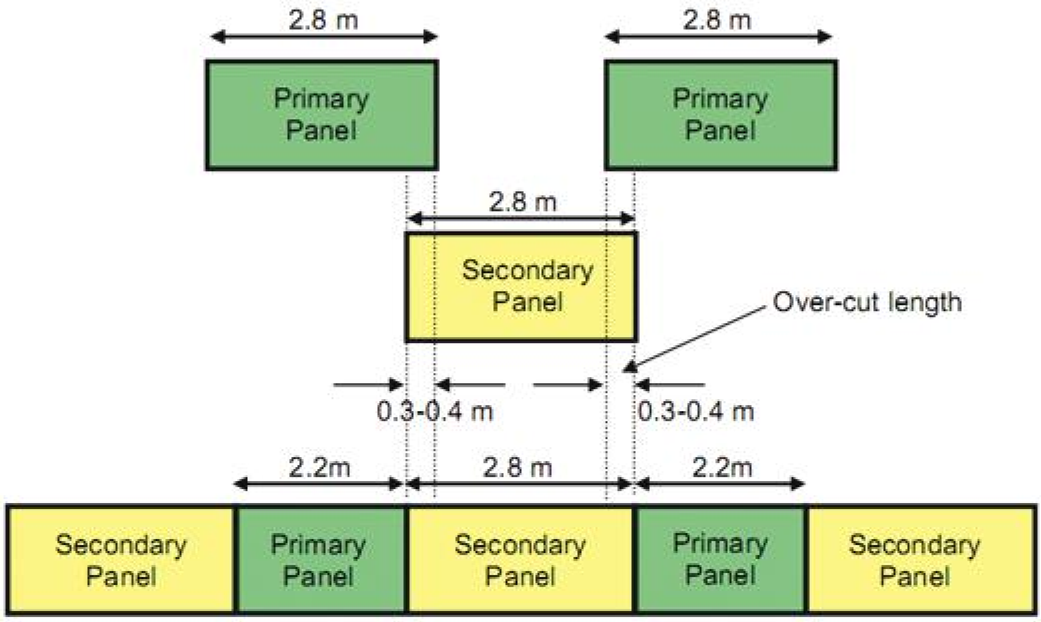

Fig. 12 - A schematic view of primary and secondary panels of CoW

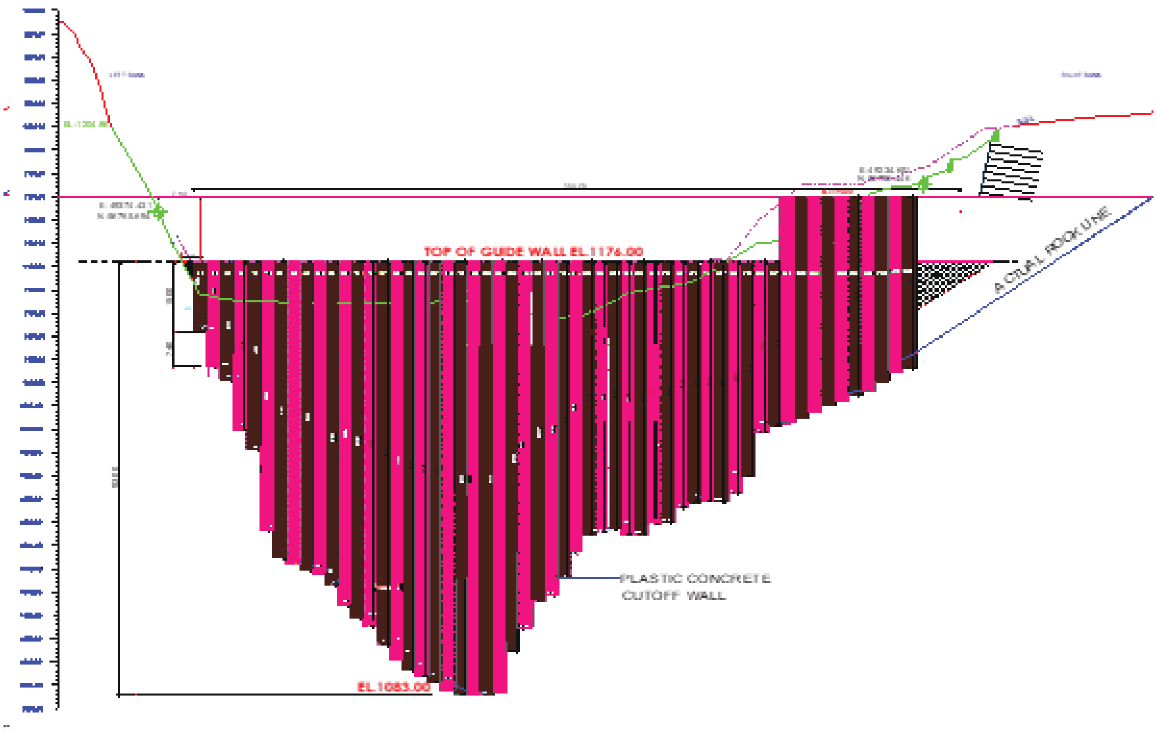

Fig. 13 - A section of primary and secondary panels executed at site

Cut-off wall panel excavation process is accomplished by using a combination of trench cutter and grab. The grab system been used to excavate the cut-off wall panels through the overburden soils to an economic depth of about 12m below work platform. The trench cutter is used for excavation to the designed final depth (0.6m within foundation grade rock) and the over-cutting of adjacent (primary) elements. A schematic diagram of cutting process is presented in Fig. 14 and a diagram showing excavation sequence is presented in Fig. 15. Chisel mounted crawler cranes were used, when obstacles had to be removed or cutting performance require support by application of chisel.

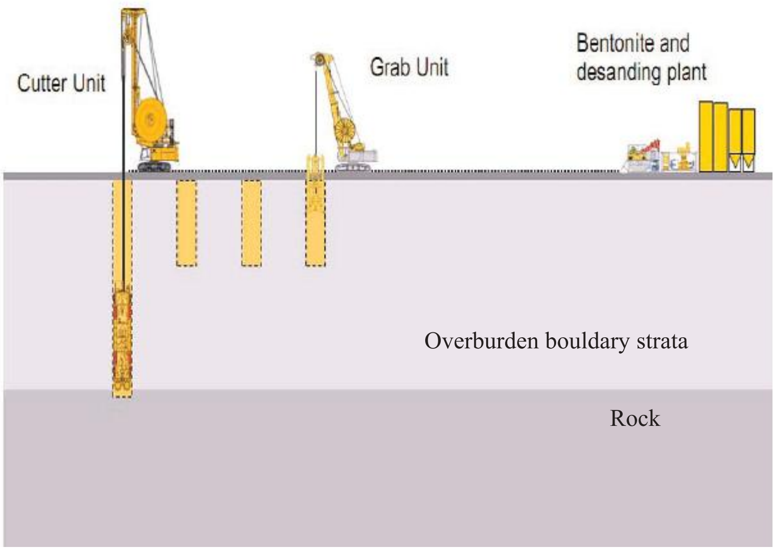

Fig. 14 - A Schematic diagram of cutting process

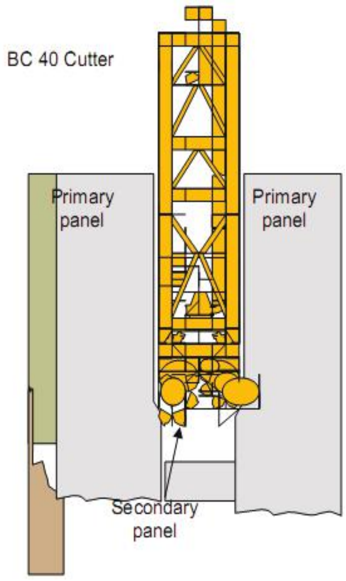

Fig. 15 - A Schematic diagram of excavation sequence

The verticality alignment of the panels was kept 0.5% of the designed depth in order to achieve a minimum wall thickness of 0.45m in overlapping areas which was the minimum requirement for a temporary cut -off wall at the envisaged maximum design depth of 73m. Accordingly, width of cut-off wall was kept as 1.2m. For trench support during panel excavation bentonite suspension has been used.

4.5 Bentonite Suspension

4.5.1 Suspension mix

Bentonite was kept at site in 50kg bags. Mixing of bentonite and water was done at the mixing plant. The bentonite content of the fresh slurry ranged from 30 to 50kg/m^3 of powdered bentonite per cubic meter of water. After mixing, the slurry was pumped to the storage basins for concreting bentonite, where it was agitated and hydrates to allow for proper swelling of the slurry (Figs. 16 and 17).

4.5.2 Suspension level control

The level of the bentonite slurry within the excavated trenches was continuously monitored and checked to ensure stability of the open trench. While cutting, the level should not be lower than 0.5 m below top of guide wall, as presented in Figure 18. While grabbing or casting concrete, it should not be lower than 1.0 m below top of guide wall or depending on the actual river level/ groundwater situation (Fig. 18).

Fig. 16 - Bentonite mixing plant

Fig. 17 - Bentonite mixing containers

Fig. 18 - Panel immersed in bentonite

Fig. 19 - Desander unit

4.5.3 Circulation and desander

Bentonite suspension is required for stabilizing the trench excavation. Additionally, the suspension is used for transporting the excavated material out of the panels when working with the trench cutter. For recirculation and desander, the suspended soil, sand, gravel and rock debris was pumped to the desander unit with a maximum capacity of 500m^3/hr (water). For the trench cutter-units a dedicated independent desander and recirculation system were provided (Fig. 19).

Due to the time duration of trench cutter excavation in the rock socket area, the bentonite suspension was automatically re-circulated several times by the trench cutter bentonite circuit, and the fines content be reduced significantly. In any case, replacement of suspension and re-circulation prior to concreting is performed.

4.5.4 Bentonite handling system

The bentonite slurry was stored in earth ponds. Earth ponds were constructed as a combination of excavation and surrounding dykes to avoid a huge amount of excavation (Fig. 20).

Fig. 20 - Dykes for storage of bentonite

The basins or tanks were connected with a fixed pipe / pump system to allow a continuous operation and communication, and to mobilize sufficient quantities should an unintended loss of bentonite slurry occur.

For circulating the bentonite, a 4" and 6'' steel pipeline system was set up between the plant areas and the actual working locations. It consists of
(i) 4" feeder pipelines to the trench,
(ii) 6" return pipelines from the trench (cutter suction hose), and
(iii)4" return pipelines from the trench during concreting, circulation pipelines.

A view of piping network is shown in Fig. 21, while feeder and return pipelines connected to trench cutter is shown in Fig. 22.

Fig. 21 - Pipe network for bentonite circulation

Fig. 22 - Feeder and return pipes connected to trench cutter for bentonite circulation

A Schematic view of a typical trench cutter site is presented in Fig. 23. Typical properties of in-trench slurries are given in Table 3 as follows:

Table 3 - Properties of in-trench bentonite slurry circulation

In-trench properties	Working slurry	Concreting slurry
Density (g/cm^3)	< 1.25	< 1.15
Marsh value (s)	32 - 60	< 50
Fluid Loss (ml)	< 50	< 40
pH	7 - 12	7 - 12
Sand content (%)	n.a.	< 5%
Gel strength (N/m^2)	> 15	n.a.

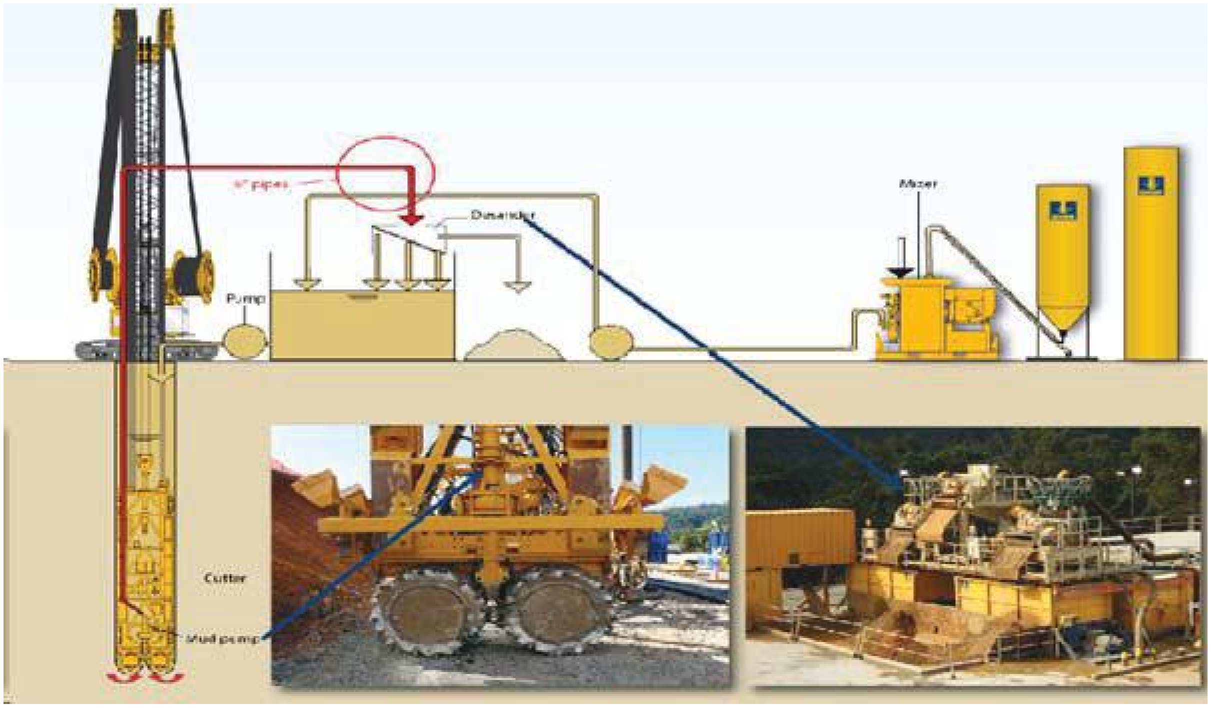

Fig. 23 - Schematic view of a typical trench cutter site

4.6 Excavation Process

During the excavation process the level of the bentonite slurry within the excavated trench was continuously monitored and checked to ensure stability of the open trench.

After having reached the final depth, the bentonite slurry was recycled to fulfil the specified criteria for concreting.

As explained earlier, after construction of two adjacent primary panels, an intermediate secondary panel was excavated. The distance between adjacent primary panels was chosen to provide clearance for the excavation of a secondary panel, thus creating a pre-defined over-cut distance into the adjacent primary panels.

For this purpose, the BC 40 trench cutter with its frame width of 2.8 m was used. It cuts into the concrete of the two adjacent primary panels resulting in a rough grooved surface in the cast primary panel further ensuring a higher quality joint between cut-off wall panels.

Once the secondary panels were poured, the grooved / serrated surface within the exposed faces of the primary panels provided an intimate contact surface between the primary panels and the freshly poured concrete of the secondary panels, thus ensuring a tight vertical joint. The overcut will be carried out not before the minimum concrete strength has reached at least 0.5 MPa, which is common practice in cut-off wall construction.

A curing period of 3 days was generally observed before excavation of a secondary panel, between the two Primary panels. Excavation sequence is presented in Fig. 24.

Fig. 24 - Excavation sequence of a typical panel by trench

4.7 Verticality Control

To verify the verticality of the trench during excavation, the BC trench cutter is equipped with electronic inclinometers which continuously record trench cutter deviations online in both horizontal axes. Actual deviations of the excavation tool were monitored online at the computer screen within the operator's cabin (Fig. 25) and were downloaded & printed. In addition, the inclinometer readings were regularly checked and verified by KODEN-measuring device. Actual narrowing or necking of the trench is also detected by KODEN imaging prior to the concreting. In the event of narrowing of trench, stabilization of the condition will be monitored by several rounds of KODEN imaging prior to concreting operations. A KODEN measuring device, its output device and output is shown in Fig. 26.

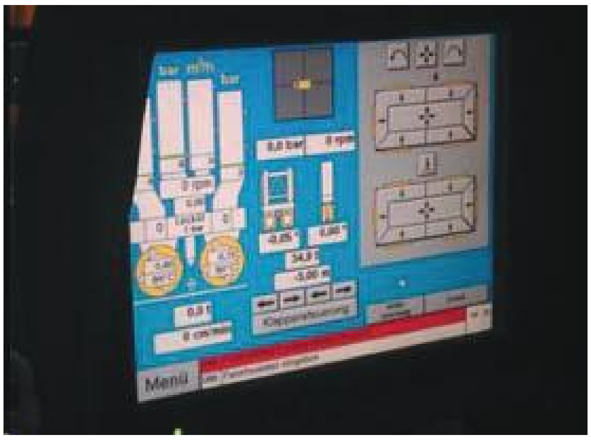

Fig. 25 - Monitor output of operation's cabin

Fig. 26 - KODEN measuring device, KODEN output unit (top left), output (top right)

4.8 Concreting

Concrete was supplied to the trench locations by concrete trucks at a rate sufficient to ensure a minimum pouring rate of about 60 m^3 per hour via tremie pipe. A view of Concrete being poured in shown in Fig. 27.

Prior to commencement of each pour a sacrificial buffer (a Plastic Ball) was placed between bentonite and plastic concrete in each tremie to hinder mixing and concrete segregation, as presented in Fig. 28.

Fig. 27 - Concreting of panel

Fig. 28 - A plastic ball is placed in tremie pipe to prevent mixing and concrete segregation

The plastic concrete was poured directly from the truck mixer into the hopper of the tremie pipe string. During concreting the tremie pipes were kept continuously immersed in the fresh concrete by a minimum of 2 meters. While the concrete is rising from bottom to top, sections of the tremie pipe string were taken out to fulfil the requirement of a minimum 2m embedment of the bottom of the string into fresh concrete.

Tremie pipe connections with wire rope coupling were additionally sealed by a rubber ring inside and black tape or foil outside of the pipe to avoid ingression of bentonite into the tremie pipe. A view of tremie pipe being inserted in panel for concreting is presented in Fig. 29. Concreting was carried out panel wise upto top of guide wall.


Fig. 29 - Tremie pipes being inserted for concreting of panel


Fig. 30 - Wastebin for dumping waste bentonite at site

4.9 Discharge of Wastewater / Bentonite Waste

Wastewater was not released into the river without adequate treatment by sedimentation. Bentonite waste was stored in the disposal pit / waste basin which allowed for transportation and dumping by trucks, without using slurry suction trucks (Fig. 30).

5. CONCLUSIONS

The construction of mega hydroelectric projects at an accelerated pace, in view of the huge gap between demand and supply scenario across the nation, warrants exploitation of inaccessible, geologically challenging project sites, which could only be made possible with the use of state-of-art innovative technology.

An illustration exhibiting the fact the recent technological development of plastic cut-off wall as a fool-proof and effective seepage control mechanism has been extensively used for deep excavations. The excavation of about 76 m in dam pit of Punatsangchhu-I H.E. Project (1200 MW), Bhutan would not have been feasible without arresting seepage beneath U/s coffer dam with plastic concrete cut-off wall in place. An insight of problem appreciation, design aspects, construction equipment and methodology and various quality control issues are deliberated in the paper.

Reference

H.E. Project Report (2017). Construction of plastic concrete cut-off wall at Punatsangchhu - I H.E. Project (1200 MW) Bhutan - Internal documentation. Website: www.wikipedia.com