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Construction of Vertical Penstock Shaft: A Case study of Mathillo Mailung Khola Jalvidhyut Aayojana (14.3 MW)

Roshan Gyawali [a], Gyanendra Lal Shrestha [b], Kangada Prasai [c]

[a] *Department of Civil Engineering, Pashchimanchal Campus, IOE, Tribhuvan University, Nepal*
[b] *Visiting Faculty, Pashchimanchal Campus, IOE, Tribhuvan University, Nepal*
[c] *Mathillo Mailung Khola Jalvidhyut Limited*
[a] gyawaliroshan70@gmail.com , [b] glsanu@yahoo.com, [c] kangada1979@gmail.com

Abstract

This paper focuses on the study of the construction of a Vertical Penstock Shaft. The paper deals with the case study of Mathillo Mailung Khola Jalvidhyut Aayojana (14.3 MW) which comprises two deep vertical Penstock shafts. The main goal of this research is to study the selection of different excavation methods, their working methodology, and the role of geology in the excavation process. In the context of Nepal, the most popularly used equipment and methods are Raise climber, Shaft sinking and Raise boring techniques. Vertical shafts at MMKJA were excavated using the Raise Climber and Conventional Sinking method. The selection of the excavation method primarily depends on geological conditions. This paper evaluates the selection of excavation methods, their working methodology, and progress rate with respect to geological conditions and functional requirements. The raise Climber method was found efficient for long blind excavation of small-size shafts with rock mass quality varying from poor to good. On the other hand, the Conventional Shaft Sinking method was found a bit laborious and tedious involving great mucking time resulting in slower progress of excavation. However, the combination of these two methods for deep shaft excavation was found to be more effective in terms of progress rate.

Keywords

Deep vertical shaft,Raise Climber, Shaft Sinking, Geology

1. Introduction

Underground structures especially in the Himalayan region are important components of infrastructure projects such as Hydropower. Construction of underground deep vertical shaft in high-head hydropower projects is inevitable. Generally, vertical shaft refers to a long, cylindrical underground opening that runs vertically as water conveyance system in Hydropower projects. Construction of a vertical shaft is not an easy task. Generally, various challenges are presented during its construction regarding maintaining its verticality orientation, structural integrity and stability, managing groundwater inflows, and ensuring worker safety. Complex geological setup of Himalaya has a significant influence on its excavation and stability [1]. The stability of an underground excavation depends on the structural state of the rock mass, its degree of weathering, and the relationship between rock stresses and rock mass strength. While planning underground excavation it may not be always possible to avoid weakness or fault zones due to topographic limits and other project specific issues. Construction of underground structures in such situation becomes a more challenging task, considering limited investigations and the use of modern technologies. Therefore effective planning, designing, and excavation of shafts ensuring safety and efficiency with respect to geological, topographical, and stress conditions are critical for successful cost effective underground projects. Different methods have been practiced so far for the excavation of vertical or inclined shafts. In context of Nepal, the most popularly used equipment and methods are Raise climber (Alimak), Shaft sinking and Raise boring techniques [2]. Shaft sinking was the most popular method adopted in the past, but these days use of Raise Climber (Alimak) is most commonly used in Nepal for its ease of use and safety of the worker [2]. Selection of these excavation methods, equipment, and their working methodology not only depends on the geological conditions of the area but also on the size and height of the shaft, space available for installation of the equipment, and most importantly cost and timeline of the project. This paper presents the case study of Mathillo Mailung Khola Jalvidhyut Aayojana where the construction of two vertical penstock shafts is studied. Selection of excavation methods, their working methodology, and excavation progress concerning the geological condition, topographical and functional requirements have been studied, evaluated and compared.

2. Study Area

2.1 Mathillo Maillung Khola Jalvidhyut Aayojana

MMKJA is a run-off-river type hydropower project with an installed capacity of 14.3 MW with 3.53 m3 /s design discharge and 486.5 m net head. The project is located in ward no. 1 of Uttargaya Rural Municipality, Rasuwa District, which is about 115 km from Kathmandu via Galchi-Battar road, and 105 km via Tokha-Chhahare-Battar. The license boundaries of the project area are: Latitude 28005'56" N to 28008'00" N, and Longitude 85011'000 E to 85013'00" E. The project diverts Mailung River with a watershed area of 72 km2 at the proposed intake. The headworks of the project lies at Rahare village of Uttargaya Rural Municipality. The Powerhouse area lies at 2.5 km downstream from the headworks along the

Mailung River. The project comprises of both surface and underground structures. Major surface structures of the project include a Diversion Weir, Intake, Settling Basin, and Powerhouse. Underground structures, the Headrace tunnel has been designed as a free-flow tunnel with a total length of 1736 m and a 2.8m span. An underground forebay (cavern) is located at the end of the headrace tunnel with a size of 11 m x 5 m X 8.3 m (LxBxH). A penstock tunnel (combination of horizontal tunnel and vertical shaft) of 1173 m length has been designed to convey the discharge from the forebay to the surface powerhouse.

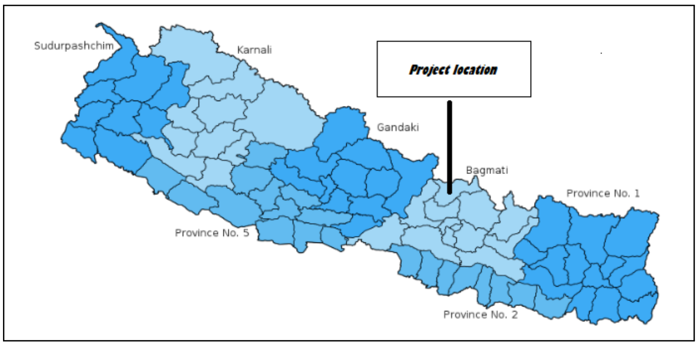

Figure 1: Project Location map

2.2 Geological Settings

The rocks of Central Nepal are divided into the Nawakot Complex and Kathmandu complex by Mahabharat Thrust (Main Central Thrust). The Nawakot Complex represents the Lesser Himalayan overlying Kathmandu Complex belonging to the Higher Himalayan crystallines and Tethyan Himalayan sequence. The Nawakot Complex represents sedimentary to low-grade metamorphic rocks comprising shales, slates, schist, phyllites, metasandstone, and other carbonate rocks [3]. The Nawakot Complex is further differentiated into Lower Nawakot Group and Upper Nawakot Group. Lower Nawakot Group represents the oldest rock sequence in the Lesser Himalaya of Nepal [4]. The Regional map of the project area is depicted in Figure 2.

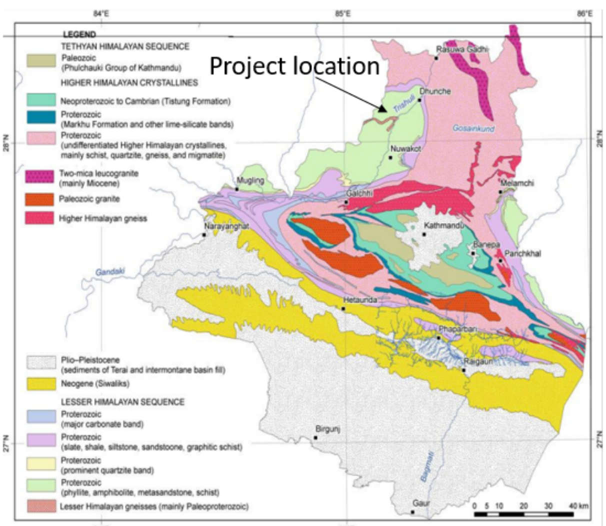

Figure 2: Geological map of Bagmati-Gosaikunda region [3]

The geological conditions around the projects are often characterized by a significant presence of folds, faults, joints, and interbedding of different types of rock strata [5]. The Project area lies in the Kuncha Formation of the Lower Nawakot Group of Nawakot Complex of Lesser Himalaya comprising Phyllite, laminated Metasandstone with few inter-fingering of Augen Gneiss. Geology in the study area is the intercalation of Meta-sandstone and Phyllite. Phyllites in the area are found as parting to about 10 to 15 cm thick, which are medium strong to strong, slightly weathered with healing joints (joints occasionally filled with quartz veins/lens). The Project area is dominated by Metasandstone. Geological Profile of the study area is shown in Figure 3.

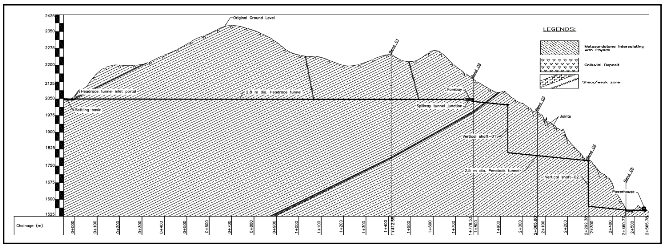

Figure 3: Geological Profile of project area

The rock units are well exposed along the left bank of Mailung River and the foot trail section around the project area. The overall color of the formation is light grey. The phyllite is argillaceous, more or less silty or quartzitic, and includes extremely fine-grained to dense, laminated, siliceous varieties whereas the metasandstone is grey, medium-grained, laminated, widely foliated to massive, strong to very strong [4]. The rocks in the study area dip predominantly towards NE-NW varying from 30° to 55°. The general strikes of the foliation plane (FP) have been found to vary from N50°E to N70°E. Mainly three sets of joints have been found along the study section. Figure 4 presents the joint rosette plotting from joint set informations at different locations.

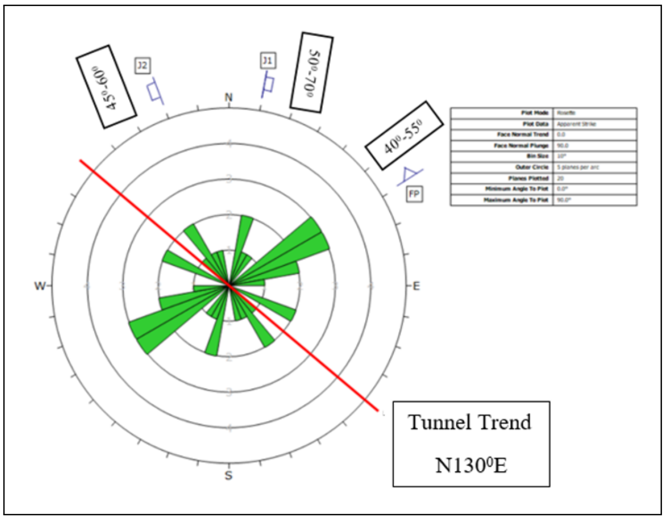

Figure 4: Rosette plotting of joint sets from project area

3. Excavation of Vertical Penstock Shaft

MMKJA comprises two vertical penstock shaft VS1 (Upper Vertical Penstock Shaft) and VS2 (Lower Vertical Penstock

Shaft) of length 224m and 189m respectively. VS1 is located at 0+151.33 m and VS2 lies at 0+449.75 m from forebay. The diameter of both vertical shafts is 2.25m.

3.1 Excavation of VS1

The upper underground vertical pressure shaft with 224 m height and 2.25m diameter was excavated by using Raise Climber and Conventional Shaft Sinking method. Both of these methods involve Drill and Blast procedure in the shaft excavation.

- First stage: Full face 2.25m diameter excavation by Conventional Shaft Sinking from top face (Mucking out from top)

- Second stage: 2.25m diameter full face excavation using Raise Climber from bottom face (Mucking out from bottom via Adit tunnel)

Breakthrough at 59.3 m depth from the top face of the shaft completes the excavation of VS1.

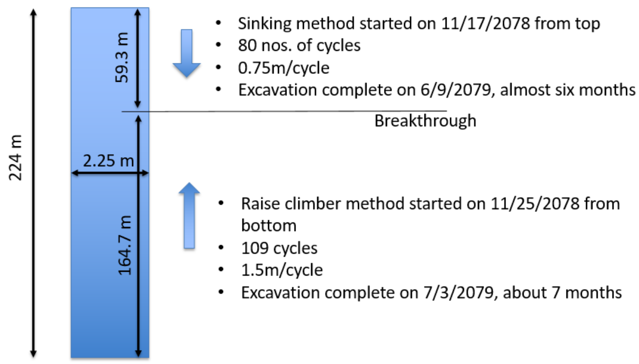

Figure 5: Schematic representation of VS1 excavation sequence

3.1.1 Raise Climber Method

A 70m long adit tunnel and 300m horizontal Pressure tunnel (HT02) were excavated to reach the bottom of the VS1. First, a cavern (11.64m x 4.10m x 4.36m) was excavated at the downstream side to set up the working space for Alikraft and about 4 m of manual excavation along the shaft from the bottom was done to fit the Alikraft's body. Guide rails were then installed on the rock surface using expansion bolts from the nest to the shaft bottom. After installation, Alikraft was operated where raise climber raised the cage up to the required elevation for excavation from the bottom. Since the geology of the shaft was dominated by Metasandstone and also Phyllite in the area were found medium-strong to strong, with joints occasionally filled with quartz veins, guide rails and entire Alikraft body was able to hold into the rock surface by expansion bolts provided by the Alikraft suppliers.

164.7m section of VS1 from the bottom face of shaft was excavated using Alikraft Raise Climber. The excavation of VS1 by using Alikraft was started on 11/25/2078 BS. The average pull length of Alikraft was approximately 1.5m/cycle

Figure 6: Vertical shaft excavation by using Rock climber method

depending on geological conditions.A maximum pull length of 2m was achieved in few sections due to better geological conditions. On average 2 cycles of Alikraft were performed in a day depending on the encountered rock mass quality thus excavation progress of 3 m/day was recorded. In some cases project also achieved excavation progress rate of 6 m/day by carrying out a maximum of 4 cycles in day and night shifts where sound metasandstone was encountered. Altogether Alikraft performed a total of 109 cycles for excavation until break-through point was achieved. The excavation period of VS1 using Raise Climber was ended on 7/3/2079 after the breakthrough of shaft excavation. The Raise Climber(Alikraft) follows Drill and blast principle for shaft excavation, incorporation of the following steps together makes up a cycle as shown in Figure 8.

Figure 7: Raise Climber installation cavern

An Alikraft rail with a working platform is used to excavate as well as transport equipment, rock support materials, and workers at the working face. Drilling on the face was done using Pneumatic Stoppers from the working platform. The average drilling length adopted was 1.5-2m. Wedge cut drilling pattern was adopted with an average of 35 nos of drilled holes per section. Spacing provided between drill holes was 20-50

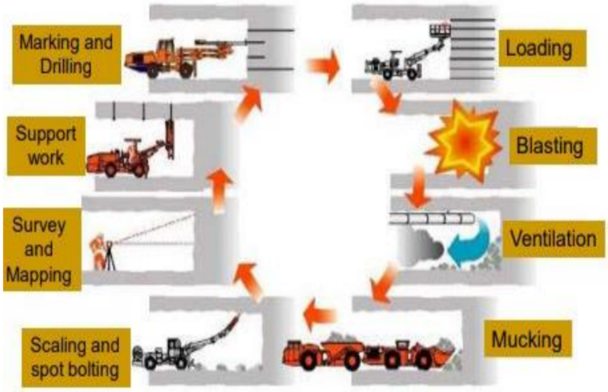

Figure 8: Various steps undertaken in an excavation cycle

cm with burden generally 10-15 cm. Drilling was followed by loading and charging of Superpower cartridge emulsion explosives in the drilled holes. Loading was also done from the platform. An average of 30 kg of explosives was consumed in a cycle. For blasting purposes both electric and non-electric detonators were used. An average of 3 nos of electric and 32 nos of non-electric detonators were consumed. The longer Deto Cord and non-electrical detonators were used considering the safety of the worker. After basting, the blasted rock materials were allowed to fall down at the bottom of the shaft. Noxious gases and dust created by the blast are cleared by providing sufficient ventilation from guide rails. Then guide rails were added and scaling of the loosened chunks of rocks was done manually. Mucks were usually cleared after three to four blasts. Mini-muck-loader was used as hauling equipment. Better geological conditions on this section have left the excavated portion without any rock support. Rock support was provided only at sections comprising weak zones. 7.5cm thick reinforced shotcrete and 1.5m length of rock bolts of 20mm diameter at 1m c/c spacing were provided to stabilize the weak zones. After support work drilling and blasting operations were repeated for the next cycle, raising the shaft. Table 1 gives the Raise Climber cycle time in VS1 excavation.

Table 1: Raise Climber Cycle time in VS1 excavation

Operations	cycle time (hrs)
Survey	0.5
Face Drilling	3-4
Charging	0.5-1
Blasting	0.5
Defuming	1-1.5
Rail leg Fixing and scaling	2
Mucking	-
Support work	-
Total Cycle time	7.5-9.5

Alikraft raise climber consumed about 7 months for 164 m length of vertical excavation although average progress rate of excavation of 1.5m/cycle was achieved. The main reason for the delay was the breakdown of Alikraft, an encounter of multiple weakness zones, the shortage of explosives and their accessories in the international market and due to several other factors, work had been stopped for a month.

3.1.2 Conventional Shaft Sinking Method

Conventional Shaft sinking method was also used for the excavation progress of VS1. Conventional Sinking also follows the Drill and Blast procedure from the top face of the shaft towards the bottom. First, a dome-shaped structure (5m x 6m x 5m) was excavated at the top to create the working space and arch distribution of overburden load as well. Working space was created to allow a hoisting mechanism for mucking out purpose from the top.

Figure 9: Hoisting platform (right) and Mucking out using Bucket (left)

Figure 10: Vertical shaft excavation by using Rock climber method

A 59.3m length section from the top face of the shaft of VS1 was excavated using the Conventional Shaft Sinking method. The excavation of VS1 by using the Sinking method was started on 11/17/2078 BS. The average pull length obtained by this method was only 0.75m/cycle. On average 1-2 cycles were performed in a day. Altogether Sinking method performed a total of 80 cycles for the excavation of VS1 until the break-through point was achieved. The Conventional Sinking method involves a Drill and blast cycle for shaft excavation from the top face. Drilling on the face was done manually using Jack hammer. The average drilling length adopted was about 1m. Wedge cut drilling pattern was adopted on the Cut holes section with an average of 35 nos of drilled holes per section. Spacing provided between drill holes was 20-50 cm with burden generally 10-15 cm. Superpower cartridge emulsion explosive was charged in drilled holes. An average of 23 kg of explosives was consumed in a cycle. For blasting purposes both electric and non-electric detonators were used.

An average of 1 no. of electric and 34 nos. of non-electric detonators were consumed. Shaft sinking is generally carried out in closed, dead-end spaces therefore forced air ventilation was provided to remove noxious and harmful gases and dust for the safety of the workers. After basting and sufficient ventilation, the blasted rock materials were cleared out using the bucket from the face of the excavated shaft to the top of the shaft. Then only mucks were hauled using a hauling equipment tractor. The mucking mechanism was performed through a hoisting platform using a bucket, winch, steel ropes, and pulley. Scaling of loosened chunks of rocks was done manually. As the rock mass encountered was fair to good quality without any geological problems, no rock support was provided in this section. The above operations or cycles were repeated to sink the shaft. Table 2 provides the cycle time of conventional shaft sinking method used in VS1 excavation.

Table 2: Conventional Sinking Cycle time in VS1 excavation

Operations	cycle time (hrs)
Survey	0.5
Face Drilling	3-4
Charging	1-1.5
Blasting	0.167-0.25
Defuming	0.5-1
scaling	0.25-0.33
Mucking	6-7
Support work	-
Total Cycle time	11.5-14.5

A maximum of 2 cycle of excavation had been carried out in a shift during the initial stage of excavation but later on as shaft was sinking down only 1 cycle of excavation was achieved per shift because of tedious mucking out issues from the top. The sinking method consumed about Six months for a 59.3 m length of vertical excavation including delays due to various reasons.

3.2 Excavation of VS2

189 m high and 2.25m diameter underground vertical pressure shaft was excavated from the bottom with full face excavation using Raise Climber from the bottom to the top face of the shaft, mucking out from the bottom via Horizontal tunnel 03 (HT03).

The cycle time of Alikraft in the excavation of VS2 was found 9-11.5 hrs as presented in Table 3. The excavation progress of VS2 was computed a little slower as compared to VS1 due to various reasons including the issues related to COVID-19.

Table 3: Raise Climber Cycle time in VS2 excavation

Operations	cycle time (hrs)
Survey	0.5-1
Face Drilling	4-5
Charging	0.5-1
Blasting	0.5
Defuming	1.5-2
Rail leg Fixing and scaling	2
Mucking	-
Support work	-
Total Cycle time	9-11.5

The excavation of VS2 was started on 03/04/2077 BS. The total progress rate of Alikraft in VS2 was calculated to be approximately 9-11.5 hrs per cycle. A maximum of 2 cycles of excavation had been carried out in a day. Excavation had been carried out in 2 shifts Day and Night. No major rock support was installed during and after excavation besides the weak section at the bottom and a few at the middle, where 5 cm thick reinforced shotcrete and spot bolts were used. Minor geological overbreaks and seepage were the minor issues encountered during the excavation.

4. Post Excavation Activities

After completion of the excavation, the installation of penstock was carried out. Penstock pipes to be installed were transported to the working station. Using a hoisting platform they were lowered down into an excavated shaft. Equipment such as a winch, steel cable, and pulley were used for the hoisting mechanism. Installation of pipes was followed by backfill concreting around the installed penstock pipe for water tightness.

Figure 11: Transportation of penstock pipe to working station

4.1 Pipe Installation

For penstock pipes fitting and installations, 1.2m diameter Penstock pipes were lowered down into the 2.25 m diameter shaft by hoisting mechanism using 16mm and 20mm steel ropes with hoist capacity of 5 tons and 10 tons.

5 m long pipe was lowered down the shaft with a hoist of capacity 10 tons at VS1. First, two 2.5m long penstocks were welded together and then transported to the working station. Two pipes were lowered for one cycle installation. Lowered pipes were fitted together with previously lowered pipes by welding. After installation, testing of pipe and joints was done using an Ultra-sonic Test. For pipe installation at VS2, 2.5m long penstocks were lowered using 16mm steel ropes with a hoist of 5 ton capacity. Here four pipes were lowered and installed for one cycle. Pipes were installed for 10 m height of penstock in both shafts for one cycle of installation.

4.2 Concrete Backfill

After welding and testing of installed pipes backfilling of concrete operation was performed at 10m height. In both shafts, concreting (C15) was done from top face discharging concrete through PE pipes. Volume of concreting was recorded 4-6 m3 per cycle.

The Cycle Time of post-excavation activities was recorded as 4 days in VS1 and around 5-6 days in VS2 excavation. One complete cycle comprises installation, welding, testing, and backfilling operations.

Figure 12: Post excavation activities: Lowering of penstock pipe (right) and Placing of PE pipe for backfilling (left)

5. Challenges on construction

The rock mass encountered during the construction was recorded mostly fair to good. In few sections of VS1 clay band of 5-10 cm were encountered during excavation. Prediction of such weakness zones, faults or shear zones, and groundwater condition have been a major challenge in shaft excavation while common challenges and georisks includes water ingress, overbreak, collapse, and flowing ground [2]. A few major challenges faced during the construction of the vertical penstock shaft at MMKJA are:

- Multiple weakness zones were encountered during the excavation of VS1 at a few elevations from the bottom. The weak zone comprises of clay band of 5-10 cm with highly weathered detached rock mass i.e, metasandstone resulting in ravelling ground condition.
- High water ingression (about 10 to 20 ltrs per sec) was encountered at about 20m downstream from the junction of VS1 and Horizontal Pressure tunnel (HT02), the ingress extended up to the working platform of Alikraft (Niche) and about 10 m downstream of vertical shaft. Water ingression resulted in an overbreak of rock and with flow ground condition at downstream side from the junction in HT02.
- Minor geological over breaks and water ingression at few chainages in excavation of VS2
- Difficulty in support installation at required elevations on time because of deep and small size shaft
- Frequent breakdown of Alikraft machine delaying the excavation progress rate of VS1
- Limited working space and capacity of hoisting platform at top of VS2 encompassed many other challenges in post-excavation activities and safety of workers
- Poor visibility created by the insufficient ventilation after dry shotcreting, fitting, and welding of penstock pipe reduced the working efficiency of the workers delaying the progress
- Breakdown of steel cable during lowering of penstock pipe in VS1. (no casualties were reported)
- Communication between working parties during the concrete backfilling work

6. Rock Support

The main principle of a support system is to utilize the self-supporting capacity of the rock mass. In the case of competent rock mass where induced tangential stress is less than the rock mass strength ground support becomes an option [6]. In the case of jointed rocks, the support system is the key element for utilizing the residual strength of the rock mass. The geological report is the main leading factor for the support system design while excavating the tunnels through weak geological conditions as this would address the best method for a cost-effective support design [7].

In VS1 excavation, the encountered weakness zone comprising an open joint filled with rock fragments and clay band of 5-10 cm was stabilized by 7.5cm thick fibre shotcrete and 1.5m length of rock bolts of 20mm diameter at 1m c/c spacing as rock mass encountered was poor. Rock support designed for the Vertical shaft is depicted in Figure 12. Rock supporting was done at multiple required locations. Besides the sections of the weakness zone, no rock support was installed in VS1 as the rock mass was found to be fair to good with tight joint aperture and dry to damp groundwater conditions. The encountered water ingression at downstream of the junction of VS1 and HT02 was managed by using steel plates and steel lagging, overbreak was filled by C15 concrete followed by 1:1 ratio cement grout which changed the water ingress direction towards niche. Thus,

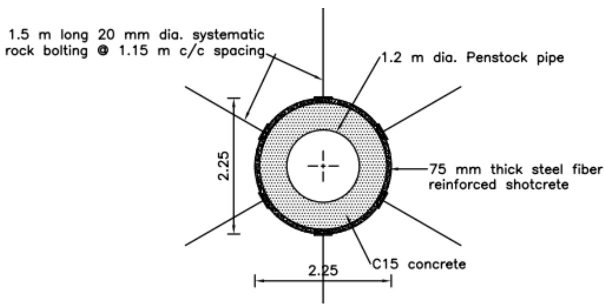

Figure 13: Rock support designed for Vertical Shaft

after stabilizing the crown of HT02, heading and benching was carried out to reach the junction area of VS1 and HT02, Class V support i.e. 20 cm thick wire-mess shotcrete (with weep holes @ 50 c/c), 2 m long rock bolts @ 1 m c/c and ISMB (Steel ribs) @ 50 cm were provided to strength the area.

Similarly in VS2 excavation, rock support was installed at weak sections at the bottom and a few at the middle, where 5 cm thick reinforced shotcrete and spot bolting were done. Few geo risks comprising minor geological overbreaks and seepage did not affect the excavation much. Therefore, Spot bolting and 5cm thick fibre shotcrete were provided at the required locations as fair rock mass was encountered.

7. Conclusion and Discussion

On the basis of the study on vertical shaft construction at MMKJA following conclusions are made:

- Selection of shaft excavation methods primarily depends on geology, length, and size of excavation. The raise climber method is efficient (1.5m/7.5-9.5 hrs of a cycle) for long blind shaft excavation of smaller diameter for rock mass quality from poor to good. The one great advantage of using the Alikraft method is allowing the muck to slide down itself reducing mucking time. Conventional sinking is a bit laborious and tedious involving great mucking time (0.75m/11.5-14.5 hrs of a cycle) and is therefore done for shorter excavation depth. The sinking method is usually suitable for larger-size shaft excavation.

- For deep shaft excavation combining the raise climber method from the bottom and the sinking method from the top has a great influence on project cost and time. Excavation of shaft combining these two methods at MMKJA is found 1.5 times more effective in excavation rate compared to Alikraft alone.

- At MMKJA 224m and 189m long shaft of 2.25m diameter is excavated without installing rock support besides few sections comprising weak zones. It is only possible due to good geological conditions to utilize the self supporting capacity of rock. So it can be concluded that geology is the major factor for the stability and cost considerations of a project.

- Proper ventilation and lighting inside the shaft are very necessary to carry out pre and post-excavation activities ensuring the safety of the workers and running the project efficiently. Also to ensure the safety of the workers, hoisting platforms with equipment of sufficient capacity is prime important for the construction of shafts.

- Besides geo-factors and excavation methodologies there exist other several factors affecting the progress rate of the project. Machine breakdown, worker unavailability, delays in delivering construction materials, shortage of explosives and accessories in the international market, and social problems like COVID-19 are few other factors affecting the progress rate of VS2 to a great extent at MMKJA.

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