Challenges associated with the construction of vertical and inclined shafts in the Himalayan Region

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ABSTRACT: In the Nepal Himalayas, hydropower projects having an installed capacity of over 10 MW usually consist of underground waterways. Most of these underground waterways consist of vertical or inclined pressure shafts, which are part of the headrace system of a hydropower project. Excavation of these shafts requires special techniques, and the performance is dependent on the quality of rock mass. Therefore, the selection of an efficient construction method for shaft excavation is most challenging work.

This manuscript evaluates the challenges associated with the construction of shafts for three hydropower projects in the Nepal Himalayas. The achieved construction progress of each method is compared with actual geological conditions. It is concluded that the major challenges associated with the excavation of pressure shafts through the Himalayan rock mass conditions are frequent overbreak, water inflow, debris flow, difficulties in surveying and control of shaft alignment, ventilation, poor visibility, and pilot hole deviation.

Keywords: Vertical/inclined Shafts, Construction methods, Himalayan rock mass, Overbreak.

1 INTRODUCTION

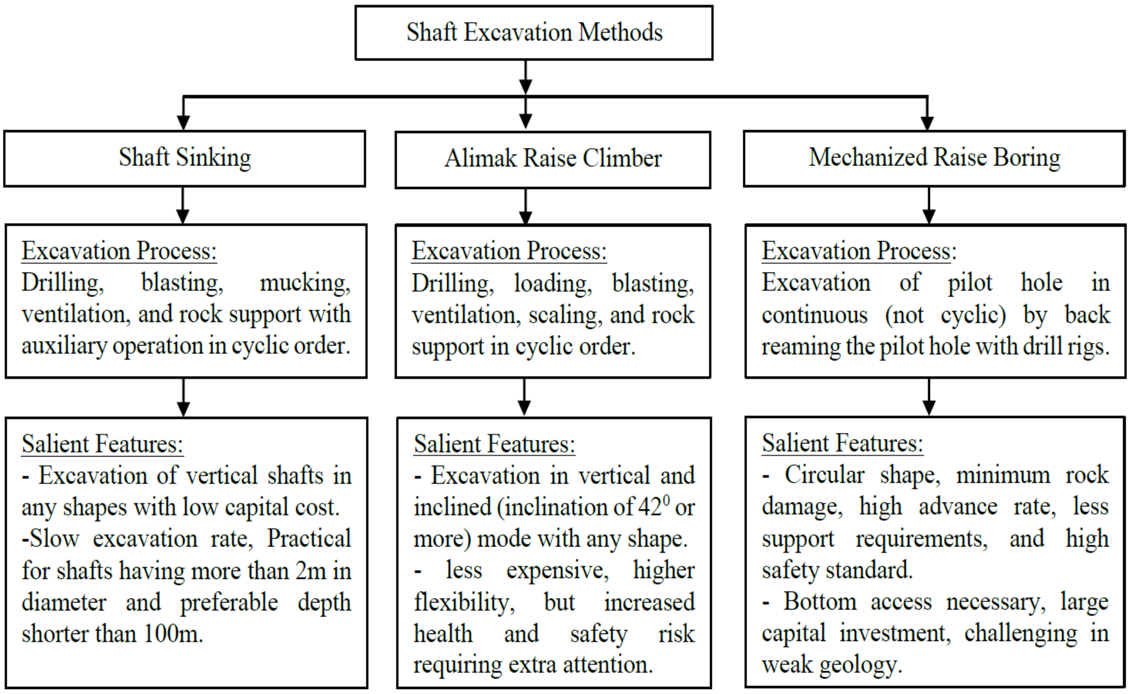
Natural events such as rock-soil failure, high rainfall, landslide, tunnel collapses, etc. cause challenges associated with the development of hydropower projects. Appropriate and viable underground excavation methods should be used to address these problems (Panthi 2006). In hydropower projects, unlined or lined underground pressure shafts are constructed either vertically or inclined to carry water from the headrace tunnel to the powerhouse. In the Nepal Himalaya, most of the hydropower plants with installed capacities over 10 MW consist of underground pressure shafts as penstock water conveyance systems.

The construction of shaft with length (depth) greater than 200 m is a challenging task due to uncertainties in the underground excavation (Sunuwar 2016). These uncertainties are categorized as geological factors associated to weak rock mass quality, high weathering, faulting and fracturing of rock mass, rock stress, and groundwater effect; and non-geological uncertainties associated to the level of skill, expertise, and the technology in use. The stepwise geological investigation is crucial to minimize the uncertainties in underground excavation work (Panthi 2006 and Panthi 2007).

In this manuscript, three shafts of hydropower projects from the Nepal are selected to present the case histories of the shaft excavation and challenges faced during the excavation of these shafts. In addition, applied remedial measures are also discussed.

2 SHAFT EXCAVATION METHODS IN THE HIMALAYAS

The geology-specific (rock mass quality, rock type, and groundwater), project-specific (length, shape, size, and inclination), and contract-related (time, cost, and risk) factors significantly influence the selection of appropriate shaft construction methods. In Nepal usually, Shaft Sinking, Alimak Raise Climber, and Mechanical Raise Boring Methods have been used for the construction of shafts. The major features of shaft excavation methods are illustrated in Figure 1.



Excavation Process:
Drilling, blasting, mucking, ventilation, and rock support with auxiliary operation in cyclic order.

Salient Features:
- Excavation of vertical shafts in any shapes with low capital cost.
-Slow excavation rate, Practical for shafts having more than 2m in diameter and preferable depth shorter than 100m.

Excavation Process:
Drilling, loading, blasting, ventilation, scaling, and rock support in cyclic order.

Salient Features:
- Excavation in vertical and inclined (inclination of 42^0 or more) mode with any shape.
- less expensive, higher flexibility, but increased health and safety risk requiring extra attention.

Excavation Process:
Excavation of pilot hole in continuous (not cyclic) by back reaming the pilot hole with drill rigs.

Salient Features:
- Circular shape, minimum rock damage, high advance rate, less support requirements, and high safety standard.
- Bottom access necessary, large capital investment, challenging in weak geology.

Figure 1. Use Description of shaft excavation methods.

SHAFT SINKING METHOD (SSM): The shaft sinking method is applied to excavate the vertical or nearly vertical shafts from top to bottom. Dewatering, ventilation, shaft centering, and lighting operation are simultaneously conducted as auxiliary operations during the excavation process. Normally, circular shapes are constructed with a diameter of 2-8m (Zou 2017).

ALIMAK RAISE CLIMBER METHOD (ARCM): In 1957 Swedish Alimak company propose a shaft excavation method consisting of long lengths used in driving blind rises termed as Alimak Raise Climber (Zou 2017). This method has been used with a shaft inclination of 42^0 or more and a length of up to 1200m with a 20-30m weekly advance rate (Nilsen & Thidemann 1993).

MECHANIZED RAISE BORING METHOD (MRBM): The first Raise boring machine was tested in Canada in 1960s, which was reliably used to construct 1.8 m diameter and 250 m long shaft (Lyle 2020). The raiser machine is set up at the starting location and it requires access to the breakthrough point (Liu & Meng 2015). A pilot hole (280-450mm dia.) is drilled first and then installation of reaming head (maximum up to 8m size) is carried out, and excavation with back reaming is made. Nowadays, this method is considered an effective method of shaft excavation a circular diameter of up to 8 m and shaft length (depth) of up to 1500 m (Lyle 2020).

3 BRIEF ABOUT TO SELECTED PROJECT CASES

Three pressure shafts from three hydropower project case histories are presented in Table 1. In addition, the project specific salient features are presented in the table.

Table 1. Salient features of selected Hydropower projects.

Projects/ Backgrounds	Chameliya (Basnet 2013 and Shah 2014)	Upper Tamakoshi (Basnet & Panthi 2019 and Gurung 2022)	Super Dordi (Peoples Hydropower Company (P) Ltd. 2022)
Capacity	30 MW	456 MW	54 MW
Pressure Shaft: Length (L) Diameter (D)	Vertical Shaft: L=72 m & D=4.9 m Horizontal Penstock: L=300 m & D=4.9 m	Upper Vertical Shaft: L=310 m & D= 4.4 m Lower Vertical Shaft: L=373 m & D=4.4m	Upper Vertical Shaft: L=227 m & D=2.6 m Lower Inclined Shaft: L=463 m & D=2.6 m Inclination=48^0
Geological region	Lesser Himalayan	Higher Himalayan	Higher Himalayan
Types of rock	Dolomite and Phyllite intercalated with Slate	Gneiss/Schist with foliation (Figure 3a)	Schist and Gneiss (Figure 4a)
Excavation Method	Shaft Sinking and Raise Boring	Shaft Sinking and Alimak Raise Climber	Shaft Sinking and Alimak Raise Climber

4 CHALLENGES ASSOCIATED WITH SHAFT EXCAVATION

4.1 Chameliya Hydroelectric Project (CHEP)

Firstly, a pilot hole with a 20 cm diameter was drilled from top to bottom. After that, the upward reaming by raise boring was made to enlarge the pilot hole up to 1.4 m in diameter. Finally, the required shaft size of 4.9 m diameter was excavated from top to bottom by shaft sinking method using drill and blast techniques as shown in Figure 2a (Shah 2014 and Sunuwar 2016).

During the widening of the pilot hole, debris of about 1700 m^3 flowed into the penstock shaft bottom consisting of crushed material of rocks as shown in Figure 2b. This debris which created a large cavity as shown in Figure 2d was then cleared. During the inspection, it was observed that the bedrock was fully exposed in the cavity area shown in Figure 2c. Further, it was identified that this cavity area was due to the collapse of fully saturated rock mass of the shared zone (Shah 2014).

Figure 2. a) Vertical shaft; b) Large debris flow in vertical shaft; c) Cavity formation in the vertical shaft; d) Detail sketch of pressure shaft (Modified after Shah 2014).

To mitigate this challenge, the initially designed concrete lining concept of the shaft was revised with steel penstock lining. Firstly, debris that came down into the shaft were cleared which created a conical shape cavity (see Figure 2d). The water inflow in the cavity was then sealed with chemical grouting and a geo-membrane layer was used to make watertight and concrete lining. Mortar grouting was done to backfill the whole cavity area and 2 m thick concrete was applied to seal the entrance of the large hole. Finally, the pressure shaft was supported with steel penstock lining (Shah 2014).

4.2 Upper Tamakoshi Hydroelectric Project (UTHP)

Initially, the Mechanized Raise Boring method was selected to excavate the upper vertical shaft based on predicted good quality rock mass condition (see Figure 3a). Even though this method has a good potential with respect to safety and easiness of shaft construction at Tamakoshi. A pilot hole drilled from the top of the shaft deviated and the contractor was unable to connect the planned top and bottom points despite of seven different attempts. After that, the project management team decided to change the construction method where a 2.1 m pilot hole was excavated from bottom to top by using Alimak Raise Climber (Sunuwar 2016 and Gurung 2022). Likewise, the Shaft Sinking method was used to enlarge the pilot hole up to the designed diameter as shown in Figure 3b (Gurung 2022).

During excavation, vertical shaft encountered challenges associated to high-water inflow, and ventilation. The water inflow problem was controlled by using Enkadrain (C20) mat, which was applicable to capture and safely discharge water towards the bottom of the shaft (Gurung 2022).

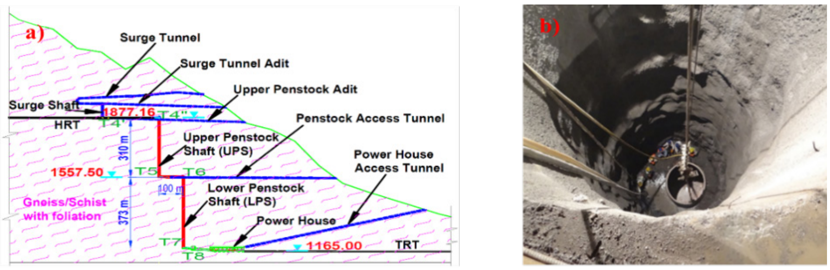


Figure 3. a) Longitudinal Section of shaft in UTHP; b) Vertical shaft excavation (Gurung 2022).

4.3 Super Dordi Hydropower Project (SDHEP)

The 53 m vertical pressure shaft was excavated from the top by using Shaft Sinking (SS) method. Similarly, the 50 m length inclined penstock shaft was also excavated manually from the bottom by using Handheld Drill Jack Hammer (HDJH) and 70 m from top to bottom by using the Shaft Sinking method. The vertical shaft (see Figure 4a) excavation encountered water inflow, where the rock mass quality was observed as weathered with rock mass class type (V) as shown in Table 2. The excavation advance rate by using the SS method was relatively low. Therefore, to meet the planned target project management team decided to excavate both vertical and inclined shafts by using Alimak Raise Climber Method (ARCM) shown in Figure 4b.

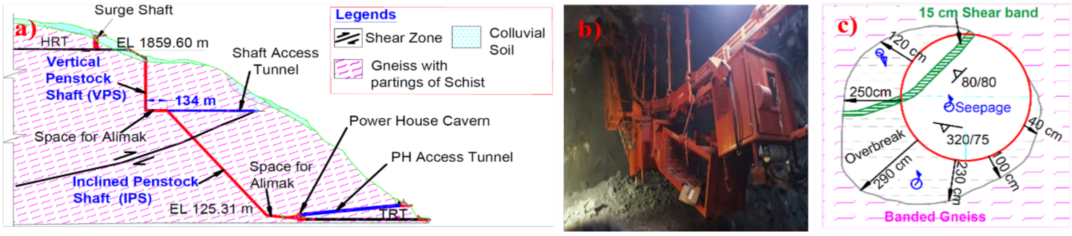


Figure 4. a) Longitudinal section of Shaft; b) Alimak Raised Climber Machine; c) Typical Overbreak section.

During the excavation, it was observed that the rock mass quality along the vertical shafts mostly contains poor quality rock mass (Class V). High water inflow and overbreak were frequently encountered in vertical shaft, which reduced the progress rate of the vertical shaft excavation as shown in Table 2. Also, Figure 4c illustrates the typical overbreak section at 90 m chainage of vertical shaft. The high-water inflow caused difficulties in surveying and fixing the alignment.

As a mitigation measure, safety shotcrete and spot bolting were applied after excavation. Additional rock support consisting of seven rock bolts having 25 mm diameter and 2 m length were installed with equal spacing in a circumferential direction and 1 m spacing in a vertical direction and 10 cm thick shotcrete was applied. However, temporary supports were not applied during the excavation of the penstock shaft with the ARCM method.

Table 2. Rock mass class and overbreak conditions in vertical and inclined shaft of SDHEP.

Shaft	Rock Class	Rock Class (%)	Advance Rate (m/day)	Excavation Methods	Overbreak (cm)
Vertical Penstock Shaft (VPS)	IV	2	0.385	SS	5-40
	V	77	0.940	ARCM	10-300
	V	21	0.437	SS	0-150
Inclined Penstock Shaft (IPS)	II	11	0.724	HDJH	No
	III	17	1.046	ARCM	0-60
	IV	52	0.992	ARCM	10-100
		2	0.455	SS	10-90
	V	5	0.6	ARCM	90-150
		13	0.511	SS	10-80

5 DISCUSSIONS AND COMPARISONS

Identification and mitigation of geological challenges associated with the excavation of shafts are crucial to minimizing cost overrun and timely completion of the shaft excavations which in general fall under the critical path of hydropower projects. The major challenges associated with shaft excavation and applied mitigation measures are summarized in Table 3.

Table 3. Challenges associated with shaft excavation and its mitigations.

Challenges	Mitigation/Lessons learn
1. Complex and Uncertain Geology	- Predict geological conditions using more investment in the engineering geological investigation.
2. Alignment Fixing	- Apply state-of-art technology and improve visibility in the shaft.
3. Overbreak	- Control blasting and immediate use of shotcrete and bolting.
4. Debris Flow	- Use pre-injection grouting to improve the quality of rock mass.
5. Water inflow	- Use pre-injection grouting, if possible, if not use Enkadrain (C20) mat to drain the water.
6. Health and Safety	- Provide adequate ventilation, visibility, and working space. - Transportation and installation of rock support within stand-up time.
7. Pilot hole deviation	- Use of automated rig to tackle difficult geology.

The advance rate results of UTHP show that the excavation of shaft by the SS method after the excavation of pilot hole increased considerably (see Figure 5a). The advance rate and overbreak due to different excavation methods in the case of SDHEP are illustrated in Figure 5b. The results of ARCM method show that the excavation through the better quality of rock mass gives a higher excavation progress rate with less overbreak. Figure 5c illustrates the achieved advance rate at both UTHP and SDHEP. The results indicate that the advance rate of SS and ARCM methods at UTHP is higher than at the SDHEP. This is mainly due to the presence of better rock mass quality along the UTHP shaft alignment. It is noted here that, the SDHEP project is located near to the boundary of the Main Central Thrust (MCT), which has direct influence on the quality of rock mass.

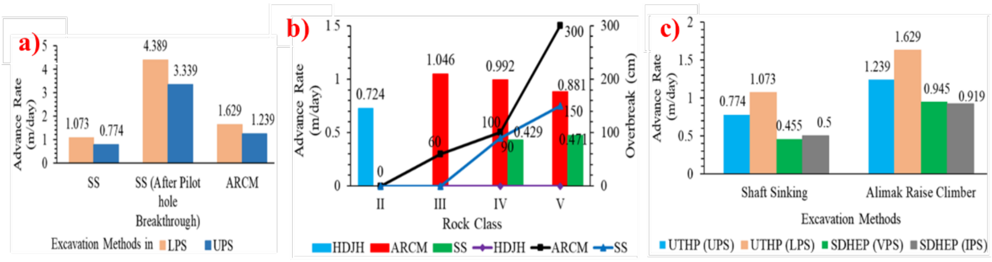


Figure 5. Advanced rate comparison with excavation methods in a) UTHP; b) SDHEP; c) UTHP & SDHEP.

6 CONCLUSIONS

Underground pressure shaft excavation in the Himalayan regions has been a challenging task due to uncertainties associated to geology and insufficient investment in geological investigations. In addition, the complex geology brings challenges associated to alignment fixing. If the alignment is not in proper location, it will lead to unusual overbreak, water ingress, and increased risk on health and safety. The main lesson learned from the excavation of these three pressure shafts is that sufficient investment should be made in the engineering geological investigations during planning and design phases to increase the reliability of geological characterization made.

The main challenges of SS methods are linked to mucking and drainage of water inflow. The ARCM method has challenges with working space, ventilation system, and visibility. However, this method is less expensive and highly flexible. Likewise, the raised boring method increases the progress rate, reduces the overbreak, and improves the safety standard considerably. However, the major challenge of MRBM is the possibility of pilot hole deviation if the shaft lengths are longer than 100 m.

Therefore, the selection of proper shaft excavation methods, experienced manpower, and appropriate technology plays a significant role to minimize excavation challenges and timely completion of shaft excavation in the Himalayan region as well as in other parts of the world.

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REFERENCES

Basnet, C. B. 2013. Evaluation on the Squeezing Phenomenon at the Headrace Tunnel of Chameliya Hydroelectric Project, Nepal. Master's thesis. *Norwegian University of Science and Technology (NTNU)*.

Basnet, C. B. & Panthi, K. K. 2019. Evaluation on the minimum principal stress state and potential hydraulic jacking from the shotcrete-lined pressure tunnel: a case from Nepal. *Rock Mechanics and Rock Engineering*, vol. 52, pp. 2377-2399. https://doi.org/10.1007/s00603-019-1734-z

Gurung, B. 2022. Construction of two penstock vertical shafts of Upper Tamakoshi Hydroelectric Project. Presentation notes at *Nepal Tunnelling Conference*, 22-23 December, 2022.

Liu, Z. & Meng, Y. 2015. Key technologies of drilling process with raise boring method. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 7(4), pp. 385–394.

Lyle, R. R. 2020. Experience with large diameter raise boring in the hard rock of the Canadian Shield. In: *Proceedings of ISRM International Symposium - EUROCK 2020*. Trondheim, Norway, 14-19 June, 2020.

Nilsen, B. & Thidemann, A. 1993. Rock Engineering. *Norwegian Institute of Technology, Division of Hydraulic Engineering*. Hydropower vol. 9, ISBN 82-7598-017-8

Panthi, K. K. 2007. Underground space for infrastructure development and engineering geological challenges in tunneling in the Himalayas. *Hydro Nepal: Journal of Water, Energy and Environment*, vol. 1, pp.43-49.

Panthi, K. K. 2006. Analysis of Engineering Geological Uncertainties Related to Tunnelling in Himalayan Rock Mass Conditions. Ph.D. Theses at NTNU 2006:41. *Norwegian University of Science and Technology*. ISBN 82-471-7825-7

Peoples Hydropower Company (P) Ltd. 2022. Progress Report. Super Dordi Hydropower Project, pp.1-55.

Shah, S. 2014. Underground excavation at Chameliya Hydroelectric Project: Case study. Presentation notes at *Nepal Tunnelling Conference*, 19-20 December 2014.

Sunuwar, S. C. 2016. Challenges of shaft excavation in Nepal Himalaya: case study from hydropower projects. *Journal of Nepal Geological Society*, vol. 50(1), pp. 31–37.

Zou, D. 2017. Theory and technology of rock excavation for civil engineering. *Springer*, ISBN 978-981-10-1989-0. https://doi.org/10.1007/978-981-10-1989-0