

# Management of Hydropower Tunnels to Prevent Collapse and Remedial Measures

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**Abstract:** Tunnels are important structures in hydropower projects as they reduce the length of the water conductor system. However, tunnels also pose the possibility of collapse during construction which may cause significant time and cost overruns. Moreover, collapsing tunnels pose threats to workers and machinery. Systematic control and understanding of tunnel physics is key to preventing these dangers. In this paper, we explore the most effective means for constructing tunnels for hydropower projects.

**Keywords:** Hydropower tunnels, tunnel collapse, construction management

## Introduction

Tunnels are very important for developing hydropower as they provide various appurtenant underground structures in hydropower projects such as power tunnels, river diversion during construction of dams, tunnels for grouting and inspection of dams, service tunnels, gate shafts, surge chambers, underground powerhouses, free flow water conveyance tunnels, and spillway tunnels. However, during tunnel construction, these structure occasionally collapse because of geological conditions, lack of proper management and careless mistakes made during construction. In most cases, tunnel engineers can predict whether a tunnel will collapse or not during the next excavation circle based on geological conditions and probe drilling data at the open tunnel face. More often than not, tunnels collapse because tunnel engineers prioritize expense and time over safety as extra support works such as pipe-poling, umbrella fore-poling and pre-grouting, are very costly and time-consuming. However, nothing is as important as safety in tunnels. Therefore, the necessary arrangements and techniques have to be managed to avoid potential human and project harm.

Tunnel collapse can be differentiated in three portions based on where the collapse takes place:

- At or around the tunnel portal,
- Along the finished length of the tunnel, and
- At the tunnel face or crown portion.

Ground stabilization techniques are most effective to prevent collapse. They are as follows:

- Regular inspection of the tunnel portal and tunnel interior;
- Probe-drilling at each segment;
- Fore-poling, pipe-poling (up to 5 m), and long pipe-poling (5~10 m);
- Multiple rift or ring cutting methods control blasting and scaling by experienced skilled labor;
- Rock-bolting, wire-mesh, shotcreting and steel arch supporting,
- Installation of drainage pipes to lower ground water, and
- Grouting.

## Literature Review

In this study, a detailed literature review has been undertaken on the types of tunnel collapse, the causes

of these collapses, and the possible remedial measures (Table 1).

Based on the above literature review, tunnel collapses occur in one of three places along the tunnel. Those locations and the potential causes of collapse in those areas are summarized in Figure 1.

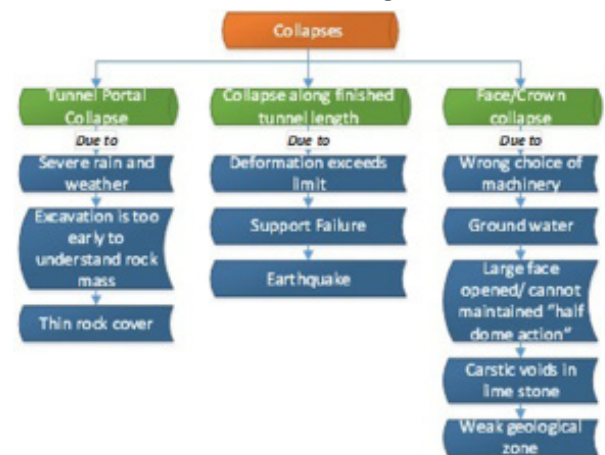


Figure 1: Major portions with types and causes of collapse

## Prevention of Tunnel Collapses and Remedial Measures

To prevent and mitigate tunnel collapse, the following measures need to be conducted along with the application of ground stabilization techniques.

### • Regular Inspection of the Tunnel Portal and Tunnel Interior

To prevent collapse at the portal and along the finished tunnel portion, regular inspections should be carried out.

If the tunnel portal or any place along the tunnel collapses, all personnel working inside the tunnel could be seriously injured. Therefore, regular inspection for abnormal conditions at the portal, and throughout the tunnel must be carried out, and immediate remedial actions undertaken:

- (a) Ground survey: leveling must be checked regularly to insure proper support for the tunnel,
- (b) Convergence measurements and deformation tests must be conducted inside the tunnel and suspected cracked areas must be strengthened with extra

Ref No.	Types of Collapse	Causes of collapse	Remedial measures
1.	(i) Collapse at Jointed and faulted sections. (ii) Surface settlement and deformation along the alignment	Wrong selection of tunnel boring machines (TBM) due to insufficient geological investigation during bidding stage.	Replace by Shielded Road Header instead of TBM.
2.	Face Collapse	Presence of sandy with clay layer, in upper heterogeneous and lower homogeneous type above the tunnel face and ground water.	Longer fore-piles and lowering ground water.
3.	Collapse of tunnel portal slope	Due to severe rain storm and abnormal weather.	Continuous maintenance is executed in accordance with danger classes.
4.	Face collapse and portal collapse	Due to instability (that cannot be maintained "half dome action").	Excavation is carried out multi stage instead of full face.
	Tunnel portal, Overall mass slide	(a) Rock masses are highly discontinuous and low quality due to weathering	Umbrella arch method, diaphragm of piles, stability and reinforcement techniques of rock slopes.
	Upper slope slide	(b) Excavation effects the stability of natural or man-made slope	
	Outer rib slide	(c) At portal regions, in situ stresses may be highly non-uniform	
	Upper slope subsidence/collapse	(d) Over-break is high due to poor quality rock	
	Crown face over-break	(e) Seismic	
	Internal crown/rib failure	(f) Portal excavation is too early to understand about the rock mass.	
	Invert failure		
	Seal rupture		
5.	Various tunnel collapse pattern	Condition of shear zone, discontinuity conditions nearby shear zone, geometry of joint with tunnel, water inflow, face condition, excavation method, the effect of configuration in earth, rock mass structure, rock mass classification, rock type, overburden, tunnel depth, tunnel geometry, RQD, joint condition and joint spacing.	Developed prediction module for potential tunnel face failure, using the data obtained from 20 sites in Korea, with the help of GIS-based intelligent management system, named (Intelligent Tunnel Information System).
6.	Face collapse	Excessive over-break	Initial strength and stiffness of shotcrete linings.
7.	Collapse at tunnel face and shaft	Water inflow is too high, and also draw-down due to head difference (3~5 m) which can cause blow-out and collapse.	Prevent the water inflow by grouting.
8.	Cave-in occurred during tunneling under a caustic void, creating crater	Difficult to define	Stiff support system, steel sets, pre-reinforcement, by pre-investigation of probe drilling.
9.	Huge collapse	Deformation exceeds the limit	Systematic rock-bolting.
10.	Roof settlement, displacement converged	Support failure	Backfill to avoid collapse of settlement area, and stiff support was installed.
11.	Portal collapse	Thin rock cover	Jet grouting, and supporting by reinforced concrete.
12.	(1) Collapse during enlargement of pilot tunnel (2) Tunnel deformation, Settlement of crown and convergence.	Loosing of the ground	Long and middle span fore-piling techniques.

13.	Crown collapse	Loosening zone	Long fore-poling
14.	Top heading collapse	Geological faults zone	Jet grouting
15.	Collapse of 400m long section	The main causes of seismically induced failures in tunnels are liquefaction, fault rupture and strong seismic shaking.	For a proper seismic design, both the strength and flexibility of the tunnel should be considered.
16.	Complete Collapse	Following the earthquake; concrete crushing, shear cracking and offset displacement of the lower footing	Higher design earthquake resistance (2000 year return period).
17.	Tunnel-arch collapse	Construction without the ground stabilization method	Ground stabilizing method.
18.	Face instability, displacement above roof	Shallow overburden	Engineering Record and checking engineer within safety management.
19.	Cave-in/collapse incident, buried or trapped the workforce	- not mentioned	shielded drives (segments, pipe-jacking) with pre-cast lining. A threat posed to the excavation crew To secure the roof in advance by means of suitable measures (e.g. reinforcement matting and anchors) in order to protect the head.
20.	Face and crown immediate collapse	Brittle fracture zone	Long face reinforcing method
21.	Large deformation and collapse	Weakness zone such as heavily jointed and faulted zone	Convergence analysis

Table 1: Types and Causes of Tunnel Collapse with Remedial Measures.

supports immediately. The deformation can be tested with strain gauges, or by manual measurements with steel measuring tape, or precise surveying, and/or

(c) Drainage weep-hole pipes must be installed immediately in areas where underground water is accumulating, causing overload stress on the tunnel.

• **Preparing for the most Terrible Situation by Installing Quality Steel Pipes of Air and Water Supply**

If collapse occurs behind the working face, it is extremely important to supply air, water and nutrients to persons possibly trapped inside. At normal working condition, air and water supply pipes are used for drilling and other tunnel works. These same pipes can be used to supply water, air and nutrients to personnel while working to access the trapped area. These supply pipes must be 75 to 100 mm diameter quality steel pipes as illustrated (Figure 2). This type of accident occurred earlier this year in Bhutan at the Punatsangchu Hydropower Project. Six people died (<http://www.kuenselonline.com/six-men-buried-alive-inside-p-i-chamber/>.[22]).

In the case of an emergency, communication with those trapped inside is vital. Therefore, all workers must have two-way radios and safety equipment, such as torch helmets, safety shoes, reflective wear, safety glass goggles, and dust masks. Quality electric cables should also be used inside the tunnel for reliable electric supply in any condition.

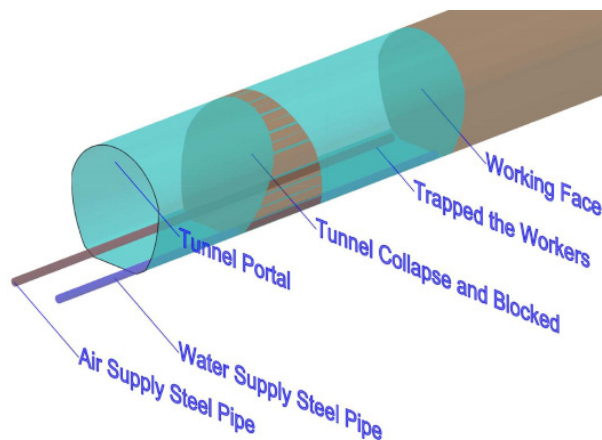


Figure 2: Tunnel collapse behind the working face.

• **Checking by “Probe Drilling” in Every Circle**

This type of check is done to prevent face collapses and crown collapses. Probe-holes are drilled to forecast geological conditions, rock quality, water leakage, and rock class [23]. Generally, tunnel collapses occur in the crown portion. Therefore, in every circle, the rock condition of 3 to 4 m ahead of the tunnel is estimated by “probe-drilling” on the periphery of crown portion. The forecast of ahead conditions is achieved by evaluating the color of rock powder or flush water, recording the penetration per minute, noting the sound of drilling, and observing the quantity of water coming out from the aquifer strata. It is an easy, accurate and inexpensive method to foresee tunnel conditions for the next excavation circle.

- **Pre-supports**

To avoid crown collapses, pre-supports should be provided. There are two primary styles of pre-supports.

- *Umbrella fore-poling* is aimed at limiting the decompression in the crown immediately ahead of the face. In this type of pre-support, longitudinal bars are installed ahead of the tunnel from the periphery of the face, typically over the upper third or quarter of the excavated profile (Figure 3) [24].

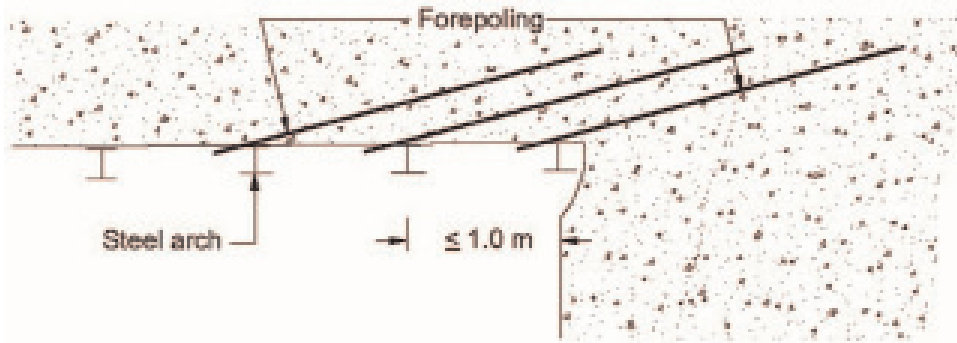


Figure 3: Arrangement of umbrella fore-poling [24].

- *Pipe poling* is a stronger modified method as combination of fore-poling and pre-grouting. The pipe-poling method is used ahead of the tunnel face for advanced length. But this method is costly and time consuming. Therefore, it is used only in very weak geological zones (Figure 4).

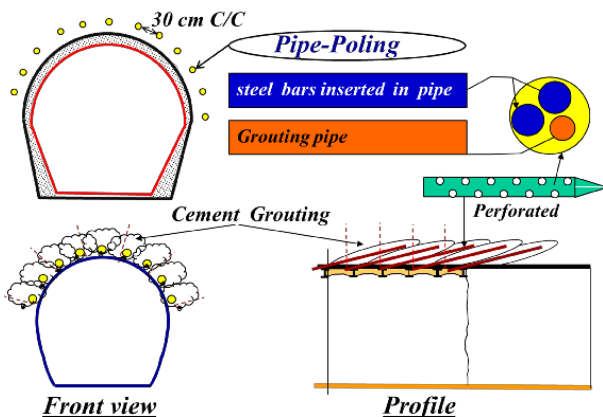


Figure 4: Arrangement of pipe-poling.

- **Multiple Drift Cutting Method, Control Blasting and Scaling**

Where the tunnel section is large and geological conditions are very weak, ring cutting or the multiple drift method is found to be the safest method. Even if collapse does occur, ring cutting will not cause severe damage because the centre core is an immediate support for the collapsed area. In ring cutting a large tunnel is divided into upper and lower portions, and benching would follow after heading is done. Since this method is used only in weak geological areas, scaling must be done by experienced skilled labour with great

care to prevent falling rock (Figure 5 and 6) [25][26].

- **Rock-bolting, Wire-mesh, Shotcreting and Steel Arch Supporting**

These are extra support methods for ground stabilization to prevent collapse. Based on pre-investigation, if the tunnel engineer suspects collapse, then steel arch sets, shotcrete with steel fibres, and wire-mesh are kept to be ready for immediate support. The steel arch set is the strongest and must be pre-fabricated. A steel arch fabrication workshop is shown in Figure 7.

If after blasting the rock cracks, the rock fragments between these cracks will fall. Gradually, the cracks will become larger and looser and weaker in binding strength, which will exacerbate the collapse. To prevent loose rock

fragments from falling, and to provide immediate early support, shotcreting mixed with steel fibers should be used. These steel fibers will improve the crack resistance capacity and serve as multidirectional reinforcement (Figure 8). To provide stronger reinforced concrete, ready-made wire-mesh should be placed on the affected area just before shotcreting.

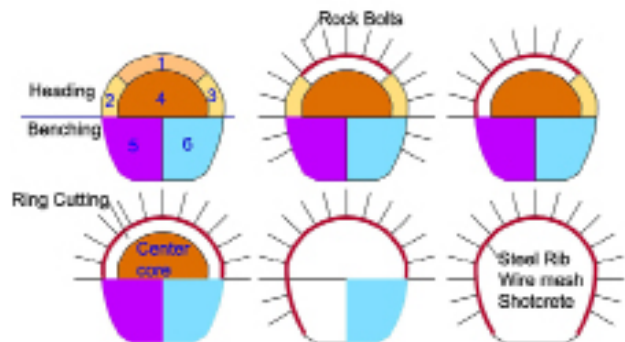


Figure 5: Multiple drift or ring cutting method.

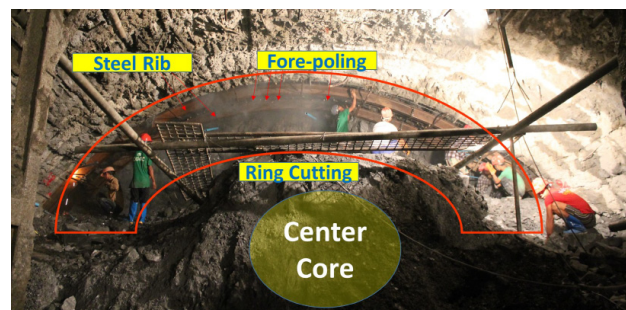


Figure 6: Multiple drift or ring cutting method used at Tahtay HPP in Myanmar.



Figure 7: Steel rib fabrication workshop



Figure 8: Steel fiber shotcrete [27]

• **Installation of Drainage Pipes and Lowering Ground Water and Dewatering Facilities**

To prevent crown collapse along the tunnel, installation of weep-hole drainage pipes are important because tunnel collapse primarily occur when water extrudes from the tunnel face. Drainage can prevent over stress due to accumulating ground water, and improve the ground stability. Moreover, shotcrete cannot be applied to the surface while water is coming out from the surface. If perforated weep-hole drainage pipes are inserted, water will drain out and the surface area will dry sooner. For dewatering facilities inside the tunnel, submersible pumps are the most favored piece of equipment.

• **Get Ever Ready of Enough Skilled Workers and Machinery**

In tunnel works, experienced labour is key. For example, experienced workers are needed for drilling, shotcrete, and mucking. Generally, tunneling works occurs around the clock. In one tunnel circle, when the drilling work is finished, then drilling workers return to

base camp. After shotcreting, shotcrete workers return, and machine operators go back after mucking, and so on. But tunnel collapse can occur at any time. Because of this all skilled workers, machinery, and machine operators must be ready on standby. Of course, this is a difficult thing to demand of workers which is why they need to be satisfied with proper incentives for the work.

Many companies construct temporary buildings near the front of the tunnel where workers can rest and entertain themselves (television, movies, snooker, chess) while on standby. This will help diminish the long-term fatigue that many workers experience during tunneling work.

• **Safety**

When a tunnel collapses, the safety of all personnel is the highest importance. Therefore, all workers must be on alert inside the tunnel, and they must be fresh and not overtired. Therefore, they should not work for more than three hours continuously inside the tunnel. A skillful team leader must be on hand to direct action in case of a collapse. Figure 9 illustrates a typical division of labor for a tunneling team.

The safety of the machinery is also important because they are very expensive. Machine operators must be alert and the machine must not be left inside the tunnel, if this can be safely avoided. In weak geological zones, some machinery like a Drilling Jumbo, should not be used if possible.

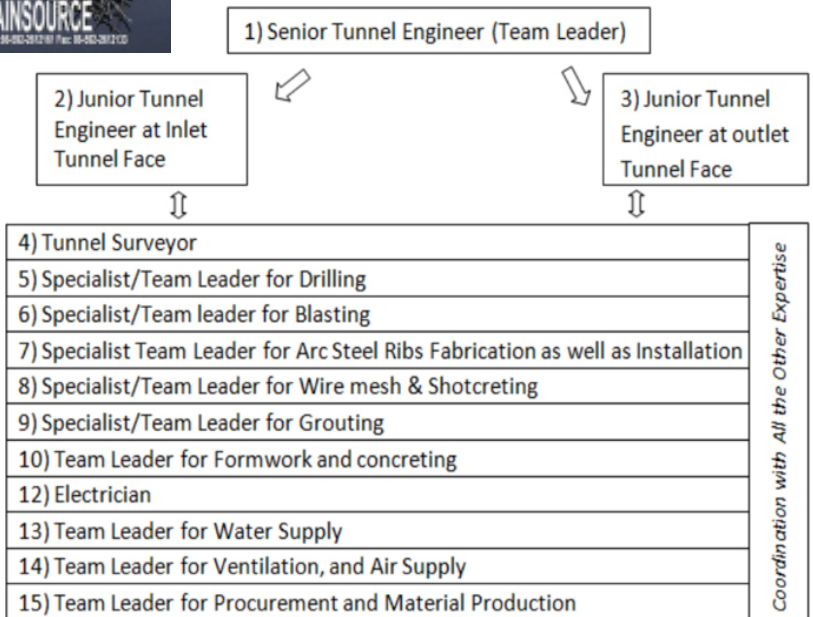


Figure 9: Tunneling team division of labour

• **Remedial Measures after Tunnel Surprise**

When tunnel collapse occurs at the crown portion of the tunnel face, the collapsing materials must not be mucked out. If they are mucked out, the collapse will continue (Figure 10)



Figure 10: Huge collapse at crown because of mucking out the dropped material [28].

If a tunnel starts to collapse uncontrollably, construction teams must wait until the slope of collapsed material is stable. Rock boulders can be backfilled to block and prevent continuous collapse, so that the collapsed material or backfilled material supports itself and blocks the collapsed hollow itself.

In this condition, drain pipes must be installed in all directions to reduce underground water. The collapse hollow can be back-filled by grouting. After backfill is complete, collapse materials can be mucked out, and forward supports placed ahead of the face by pipe-poling combined with pre-grouting. After that, the excavation of the tunnel can safely proceed (Figure 11).

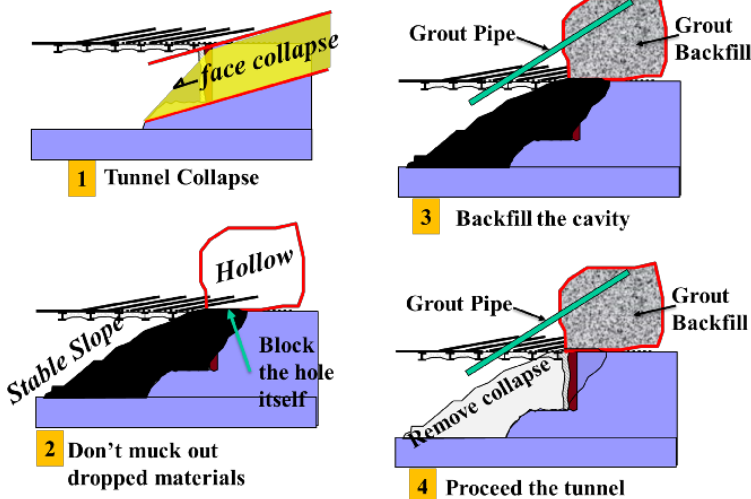


Figure 11: Procedures for remedial measure after surprise

### • The Last Solution for the Most Terrible Tunnel Surprises

In the most severe collapse situations, deviation from the original alignment should be made to the new one. Although, this type of situation may not happen if the above procedures for remedial measures are followed. To go with the new alignment is only the final solution. After excavating the new alignment of tunnel, the previous collapsed void in old alignment must be backfilled by pressure grouting, because the old alignment, at which the weakest area exists, is very near to

the new alignment.

### Conclusions

In this study, an attempt has been made to review the causes of tunnel collapse and the preventive as well as remedial measures that can be used in the case of tunnel collapse. By following these procedures and

management techniques, severe tunnel collapse can be avoided.

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### Acknowledgments

The authors would like to thank Indian Technical and Economic Cooperation (ITEC) programme, Ministry of External Affairs, Govt. of India for sponsoring to carry out Master of Technology in Alternate Hydro Energy Systems at Indian Institute of Technology, Roorkee, India.

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