Int. J. Econ. Environ. Geol. Vol. 12(2) 72-79, 2021

Journal home page: www.econ-environ-geol.org

Open Access

ISSN: 2223-957X

Prevention and Mitigation Management of Tunnel Collapse and Failure during Construction-A Review

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Received: *05 March, 2021* ***Accepted:*** *31 May, 2021*

Abstract: Empirical and numerical methods of design play a vital role in assessing rock mass behaviour quantitatively and qualitatively for the design of underground structures and support systems. The purpose of this research is to review the techniques used for the management and prevention of failures that occur in rock mass for safe, stable, efficient, and economical design of support system for underground structures especially tunnels in diverse rock mass conditions. Failure of tunnels in rocks can occur during construction as well as during service; however, the former is very common. The most challenging task in tunnel construction is the rehabilitation and remedial process of the failed tunnel section. Unfortunately, due to differences in nature, shape, and type of failure, each case needs to be treated discretely and independently. The risk of failure can be minimized by implementing prior preventive measures, while the success of rehabilitation is based on better management of rehabilitation work. However, both prevention and rehabilitation need ample investigative knowledge that can be learned from case histories. The current work is related to the prevention and mitigation methods of tunnel failure and collapses that occur during the early stages of tunnel designing.

Keywords: Tunnel, prevention, excavation, support, design.

Introduction

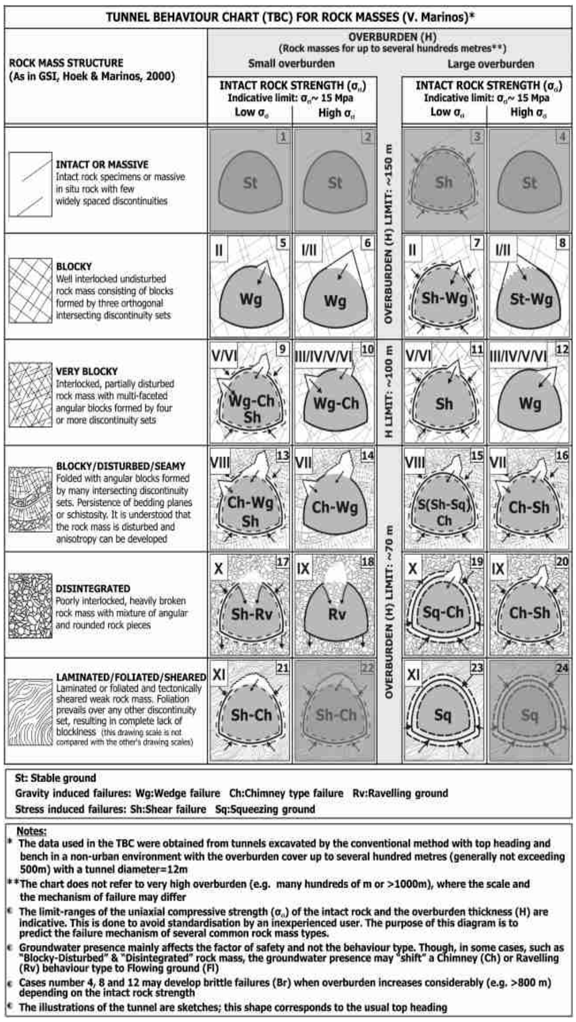
Tunneling has become the top option not only for transportation through hard mountainous regions but also has an increasing trend to be constructed for city metro buses, metro trains, sewerage, and utilities. The design and construction of unground structures involved certain potential risks due to the nature and characteristics of their spatial variation, rock mass behaviour, and level of knowledge. (Rehman, et al., 2019).

The main factors of failure during construction include an abrupt change in rock mass strength, deformation of surrounding strata, blasting, groundwater, tunnel lining, and delay in installing support (Liping et. al., 2014). Failure of the tunnel may occur due to a lack of ground investigations either with geological or/and geotechnical perspective before excavation (Karlsurd, 2010). The failure of the tunnel occasionally occurs in construction due to lack of proper management and careless mistakes during excavation, and sometimes compromise of safety over expense and time (Tun and Singal, 2016; Sajjad, et. al., 2016). Sejnoha et. al. (2009) categorized tunnel failure according to their nature and consequences as *1)* cave in, *2)* significant exceeding of expected deformation of the tunnel tube, *3)* exceeding of acceptable progress of subsidence trough, and *4)* disturbance of water regime in the surrounding. Based on the extent, failure of tunnels can be categorized as *a)* complete collapse, *b)* cave in with cavity, and *c)* rockfall. Based on the location of occurrence, (Tun and Singal, 2016) differentiated failures are *a)* at or around the tunnel portal, *b)* along the finished length of the tunnel and *c)* at the tunnel face or crown portion. The design of tunnels in disturbed and sheared flysch presents a significant challenge to engineers. Due to the complex structure, they cannot easily be classified in terms of the commonly used characterization schemes. The possible type of instability and failure related to the rock mass structure in flysch can be obtained from Tunneling Behavior Chart (TBC) given in Fig. 1 (Marinos, 2012).

The prevalence of tunnel failure during construction can be minimized through proper and reliable geotechnical investigation, effective ground stabilization, and monitoring techniques. The most problematic task in tunnel construction is the rehabilitation and remedial process of the failed tunnel section. Unfortunately, due to variances in nature, shape, and type of failure, each case needs to be treated discretely and independently. Similarly, the rehabilitation process for failed tunnel sections in hard rock is different from soft rock tunnels. To device a remedial methodology, one should not skip the importance of the product material of tunnel failure. Completely crushed hard rock is to be treated as soil or soft rock. Another important factor that should be considered before proposing a methodology is the height of the overburden above the failed section of the tunnel.

Material and Methods

More often, tunnel failure occurs when safety is compromised at any stage of the planning, design, and execution. Tun and Singal, 2016 have described few effective techniques to be adopted during construction to prevent the collapse of tunnels.



St: Stable ground
Gravity induced failures: Wg:Wedge failure Ch:Chimney type failure Rv:Ravelling ground
Stress induced failures: Sh:Shear failure Sq:Squeezing ground

Notes:

* The data used in the TBC were obtained from tunnels excavated by the conventional method with top heading and bench in a non-urban environment with the overburden cover up to several hundred metres (generally not exceeding 500m) with a tunnel diameter=12m

**The chart does not refer to very high overburden (e.g. many hundreds of m or >1000m), where the scale and the mechanism of failure may differ

- The limit-ranges of the uniaxial compressive strength (σ_{ci}) of the intact rock and the overburden thickness (H) are indicative. This is done to avoid standardisation by an inexperienced user. The purpose of this diagram is to predict the failure mechanism of several common rock mass types.
- Groundwater presence mainly affects the factor of safety and not the behaviour type. Though, in some cases, such as "Blocky-Disturbed" & "Disintegrated" rock mass, the groundwater presence may "shift" a Chimney (Ch) or Ravelling (Rv) behaviour type to Flowing ground (Fl)
- Cases number 4, 8 and 12 may develop brittle failures (Br) when overburden increases considerably (e.g. >800 m) depending on the intact rock strength
- The illustrations of the tunnel are sketches; this shape corresponds to the usual top heading

Fig. 1 The modified tunnel behaviour chart (TBC) from Marinos (2012) with projections of the principal failure mechanisms for the rock mass types of flysch-1 (Marinos, 2012).

Some of the common and effective techniques are a) advanced geological and geotechnical investigation using borehole logging, exploratory adits and seismography etc, b) modeling the mechanics of potentially unstable blocks especially at crown, c) assignment of activities to experienced and skilled workers, d) monitoring of various sections and tunnel face regularly e) preparation of peripheral mapping of each advance along the tunnel alignment f) advance long drilling at face to investigate any anomalous geology and water source g) installation of pre-excavation support such as fore-polling and long polling at collapsed potential areas h) adopting multiple rift or ring cutting methods, control blasting and proper scaling of rock surfaces i) proper type and time of support installation i.e. rock bolts, wire mesh and steel arch, shotcrete etc j) proper drainage of groundwater using drainage pipe system k) consolidation and plugging of loose and water-bearing strata using grouting Common prevention methods that can lead to successful excavation in difficult ground conditions and construction as shown diagrammatically in Fig. 2. A detailed description is provided in the following sections.

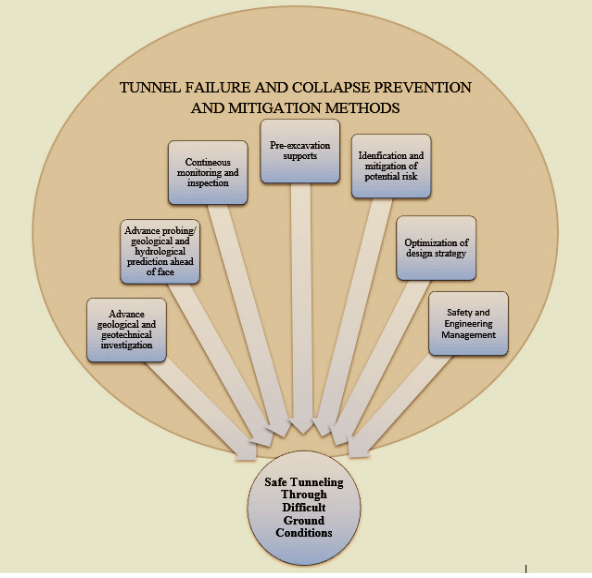


Fig. 2 Concept of safe tunneling in difficult ground conditions.

In this paper, the critical review of the existing prevention techniques for tunnel collapse, failure and relevant case studies are presented in respective prevention techniques section for easily understating to the end users. Furthermore, some important guidelines are derived to minimize the risk of tunnel collapse and failure during construction.

Results and Discussion

This section discusses the results of the reviewing the existing prevention techniques for tunnel collapse and failure and set essential guidelines for the safe and stable execution of tunneling project.

Prevention through Advance Investigations

For any tunneling project, geological and geotechnical expertise are very important before commencing the excavation and construction work. A comprehensive prediction method is required to identify potential hazards and reduce risks. Geotechnical involvement should occur throughout the life of the project. The involvement of preliminary investigations depends on the size as well as the type of project. The cost of geotechnical investigations of a project may vary from 0.1% to 5 % of the total project cost (Look, 2007). However, any disaster during construction enhances the project cost up to double. Besides the quantity of the investigations, the quality of the investigation is also of crucial importance for successful tunneling work. The extent of investigation depends upon the type of structure; however, for tunneling, it should be extended up to 3 m below the invert level or 1 diameter of the tunnel below the invert, whichever is deeper (Sajjad, et al., 2018). Case studies show that one of the possible causes of failure as investigated in Rorvikskaret Road Tunnel, Norway (Karlsurd, 2010), Nikkure-Yama

Tunnel, Japan and soul metro line 5, Phase -2, Korea (Shin et. al., 2006; Lee and Cho, 2008) was insufficient ground investigations.

The primary investigation before tunneling design may incorporate the record of rainfall in the area and the hydraulic conductivity of the rock. One of the possible reasons identified in the Xinkailing tunnel, China collapse was heavy seepage from the surface due to continuous rainfall (Wang et. al., 2012).

Prevention through Advance Probing/Geological Prediction

To prevent a possible collapse of tunnel crown as well as to forecast other unforeseen problems, probe drilling longer than normal, since drilling for blasting is carried out in every cycle of a mining operation. Generally, probe holes (non-core) are drilled in the crown of the tunnel. Such types of holes are used to forecast geological conditions, rock quality, water source, rock class (Ostberg, 2013), lose material, clay pockets, and distance from the face to the observed phenomenon (NGI, 2010). An optical tele viewer (OPTV) can be used as an alternative to core logging in non-core boreholes to record frequency, dip, strike, and aperture of fractures cutting the borehole. Probe drilling should be overlapped to enhance the accuracy of forecasting conditions further. Case studies show that one of the possible causes of failure investigated in Rorvikskaret Road Tunnel, Norway (Karlsurd, 2010) and Moda Collector Tunnel, Turkey (Clay and Tahacs, 1997) was that the tunneling was carried out without performing probe drilling.

Advanced geological prediction methods, i.e. Tunnel Seismic Prediction (TSP), Transient Electromagnetic Method (TEM), Ground Penetration Radar (GPR), and Induced Polarization Method (IP) can be used for the prediction of water fissures in tunnels. These methods are successfully applied in various sections of Jigongling Tunnel, China (Shi, et al., 2017). The schemes used for the geological forecast of tunnels are shown in Fig. 3.

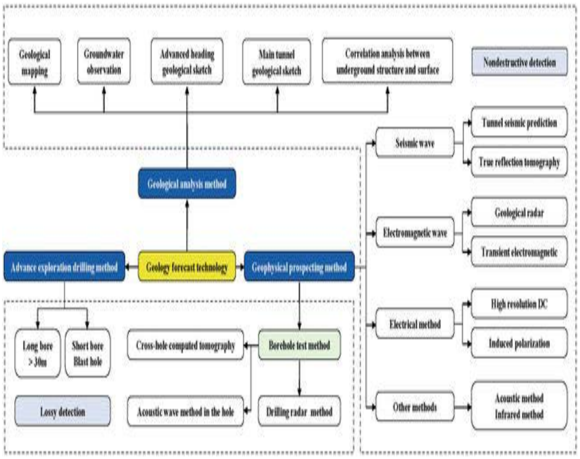


Fig. 3 Common methods for geology forecast of tunnels (Shi, et al., 2017).

Prevention through Monitoring and Inspection

Tunneling through poor rock mass and fault zones may cause problems in construction, the risk of failure can be minimized through continuous monitoring and inspection of the behaviour of the rock mass and support structure. The timing, location of the monitoring station, and type of monitoring system play key roles. Monitoring data can be used in establishing early warning systems against incipient ground collapses or damage to structures at the ground surface (Kavvadas, 1999).

The occurrence of big deformation in tunneling can lead to stability issues such as rock support failure, reduction in tunnel section, working face collapse, and roof fall. To verify the effectiveness of the adopted procedure, successions of field monitoring are required. The monitoring system includes physical face and wall observation as well as convergence measurement, rock-shotcrete interaction, stresses in steel arches, strain in the lining, and determination of allowable deformation. 3D optical measurements with reflector benchmarks of standard surveying instruments/ total station (Kavvadas, 1999) can also be used to measure deformation in difficult ground conditions. (Kavvadas, 2003) has discussed some ground deformation measurements commonly used in tunneling in detail. Presetting bigger deformation can result in stable conditions, as noted in Dongsong Hydropower Station, China (Chen et. al., 2013).

Predictions of rock burst is a worldwide challenge in geotechnical engineering. In deep hard rock tunnels, rock and deformation localization heterogeneity is the key precursors of rock burst. Micro-cracking exists before most rock bursts, which could be captured by the Micro-seismic monitoring system as reported in Jinping - II Hydropower Station, China (Tang et al., 2010) and Seismic monitoring in South African Gold mines (Koldas, 2003) Acoustic Emission and Far Infrared monitoring (Liang et. al., 2013).

Prevention through Pre-excavation Support

When the self-bearing capacity of the fractured host rock is low, it decreases fast after excavation. The deformation pressure will quickly change into loose pressure, thus converting the rock into the loose status and shifting to instability status. Pre-excavation support can enhance the self-bearing capacity (Zhu et. al., 2017). The selection of a pre-excavation support system depends upon the type of rock mass surrounding the tunnel, groundwater condition, size, and depth of the tunnel. The most important support methods are a) bolting, b) umbrella arch, c) injection, d) jet grouting, and e) Freezing (NGI, 2010).

Grouting is one of the key methods used to prevent water and mud inrush in underground structures and tunnels. (Li et. al., 2016) summarized the latest control and prevention methods for water and mud control with relevant modern theories and key techniques for controlling water inrush. Jet grouting with variety is a relatively recent method being used to stop water and increase the bearing capacity of a rock. Pre –excavation grouting increases seismic velocity, deformation modulus, and stability; it also decreases permeability and support requirements. Grouting can be carried out at different modes, i.e., compaction, hydro fracture, and soil fracture etc. Local geological conditions of the given project make the basis for the selection of grouting mode. Nature and characteristics of grouting material, soil type, and stress are other factors affecting the mode of grouting (Zhang et. al., 2014). The selection of grout ingredients, water-cement ratio, length, and density of boreholes depends upon rock type, joints concentration, joints condition, and filling material (Linstrom and Kveen, 2005).

In modern tunneling, drainage is one of the common practices in difficult ground conditions. However, in situations where water recharge is significant, jet and or pre-excavation grouting treatment is critically important for successful operation as reported in Pinglin Pilot Tunnel, Taiwan (Tseng et al., 2001), Kuhrang Tunnel Project, Cheshmeh Langan Tunnel Project, Qomroud Tunnel Project, Alboraz Tunnel Project Semnan Tunnel Project and Nasirabad Tunnel Project, Iran (Zarei et. al., 2010), Xiang'an subsea Tunnel, China (Zhang et. al., 2014).

Arch support methods or umbrella arch methods are economical tunnel excavation methods in rocks that are liable to failure to increase excavation front stability. The selection of specific umbrella methods, as shown in Fig. 4, is related to the geological conditions, lithology of the rock mass, structural defects, depth of overburden and water condition, etc. A pipe firepole is successfully installed at the fault zone section of Nathpa Jhakri Hydro Electric's Headrace Tunnel (Hoek, 2012). Pre-excavation methods, selection, and installation procedures being described in NGI, 2010.

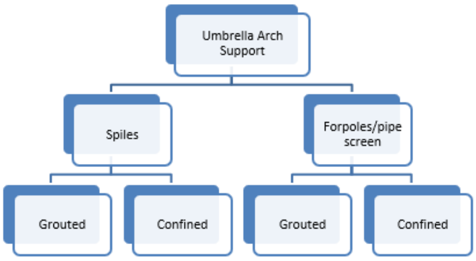


Fig. 4 Umbrella Arch Methods (NGI, 2010).

(Oke et. al., 2014) informs the nomenclature of Umbrella Arch support and its selection criteria under various geological conditions. In the last two decades, the umbrella arch method has been successfully applied in numbers of projects around the world including Ghazvin –Rasht Railroad Tunnel no. 10 (Armen and Mojtabai, 2017), Platamon tunnel, Greece, San Fadele tunnel, Switzerland, Maiko Tunnel, Japan, Driskos Tunnel, Greece and Golovic Tunnel, Slovenia (Oke et. al., 2014), City line Tunnel, Sweden (Alvarez et. al., 2016), Koralm Tunnel KAT-1, Austria (Wanger, 2015) to prevent failure while passing through difficult failure-prone zones.

Prevention through Identification and Mitigation of Potential Risk

One of the main problems associated with deep mines and tunnels in hard rock is to prevent rock burst. The phenomenon is uncommon in tunnels. Rock burst may strain burst due to the existence of mine opening, pillar, and abutment or Fault slip due to the existence of structural features (faults, dykes, shears, and contacts, etc.). In some cases, this may be due to the combined effect of strain burst and fault slip. Rock bursts can be controlled through *a)* artificial ground support, *b)* alternative mining method and mining sequence, and *c)* ground pre-conditioning. In tunneling, ground pre-conditioning is commonly used in a situation where local stress concentration increases rock burst potential. Stress release is one of the effective preventive techniques in such situations. Using the stress release scheme, the rapid stress release method was selected through numerical simulation in Jinping Hydro Power Station, China, to prevent rockburst (Wang and Zhou, 2013).

Predictive evaluation of collapse risk is necessary to ensure safety during construction. In this method, the controlling factors of collapse are accessed, existed collapse risks are measured, and risk evaluation models are prepared. (Daohong et al., 2014) established a high precision risk evaluation model based on the "efficacy coefficient method" in conjunction with the geological forecast of the Kiaochow Bay subsea tunnel in Qingdao, China.

(Cai and Champaigne, 2009) have given a few basic and easy-to-understand principles based on field experiences regarding excavation in a rock burst-prone and rock mass environment. (Kaiser and Cai, 2012) summarized these principles into graphical form as shown in Fig. 5.

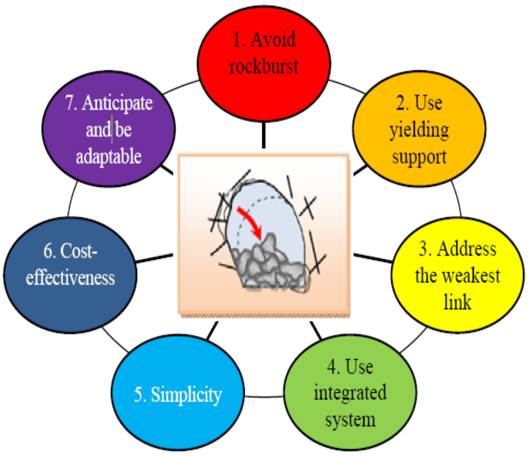


Fig. 5 Summary of rock burst support design principles (Kaiser and Cai, 2012).

Prevention through Optimization of Design Strategy

In hard rock, major failure occurs either due to high-stress conditions i.e., rock burst, rock cracking, and other stress-induced collapses, or due to faulting, cracking slabbing, and dislocation of rock mass i.e., massive collapse. Sometimes the failure of tunnels may occur due to the presence of ground and development of high groundwater pressure, i.e., water and mud outburst. Adopting a good design strategy, the potential risk during tunneling can be minimized. (Feng et. al., 2016) highlighted some methods to implement an excellent global design strategy in hard rock. The methods include *a)* numerical method, rock mass classification method, artificial intelligence method and comprehensive integration methods.

Tunnels in squeezing ground condition happen when the combined effect of ground properties and induced stress extensive yielding. The deformation of the tunnel may continue for a long resulting in the risk of a complete collapse of tunnels. In such a situation, the risk of failure can be mitigated by optimizing design strategies in combination with other mitigation methods. In weak rocks, both the tunnel itself and the tunnel face experience the same pattern of risk of collapse. Typical methods including multiple headings, heading and benching, and full-face with a specially designed support system are commonly used. The choice of exaction system, either full-face or partial and tunnel section type depends upon the rock type and tunnel size. (Yu and Chern, 2007) provided general guidelines for empirical determination of excavation method based on span size and the ratio of uniaxial compressive strength (UCS) to vertical stress on the tunnel.

In modern tunneling, the full-face excavation method is the most successful method due to certain advantages over other methods (Barla, 2005). For face stabilization, while adopting the full-face excavation method, the most effective way is to install fibre reinforce dowels, either smooth, corrugated, or flat structural elements. For the tunnel itself, light and heavy types of support systems are used. The Saint Martin La Porte access tunnel, Italy, is successfully constructed using a Light yielding support system incorporating a Lining stress controller (LSC) and high deformable concrete (HiDCon) (Thut et. al., 2006). Heavy support system with sliding gape (Yielding support) is successfully applied in Yacambu-Quibor Tunnel, Venezuela, to overcome squeezing (Hoek and Guevara, 2009)

Prevention through Safety and Engineering Management

Like other geotechnical structures, the risk of fall during the execution of tunneling operations can be minimized through good safety and engineering risk management. Safety management includes a safety risk management plan, control of unsafe human behaviour, technological innovation in safety risk management, and design of safety risk management regulations, etc. (Qian and Lin, 2016). Safety risk management may be utilized throughout the life span of the tunneling project either to eliminate or mitigate the potential risk. A comprehensive program must be available to analyze the potential risks involved. Analysis of the failure of Singapore MRT shows that the failure to implement risk management is one of the key factors leading to a failure (SG, 2005).

A non-technical aspect of collapse prevention within the scope of management and safety is the feedback procedure for safety improvement. Skilled workforce related to tunneling and construction management is the key management factor responsible for successfully completing a tunneling project (SSCO, 1998).

Another aspect of tunnel failure prevention is the engineering management and coherence with engineering design.

Factors Causing Tunnel Failure

The design of tunnels in heterogeneous rock mass conditions is a very challenging task. The design and construction of underground structures involve certain potential risks due to the nature and characteristics of their spatial variation, rock mass behaviour, and level of knowledge.

Certain factors need to be considered while tunneling. Some of the factors causing failure during construction are presented in table 1.

Table 1. Factors causing tunnel failure during construction (Liping, et al., 2014).

S.No	Factors
1	Changes in the strength of rock mass
2	Deformation behaviour of surrounding rock mass
3	Blasting
4	Groundwater condition
5	Tunnel Lining
6	Delay in support system installation

The failure and collapse of tunnels have become one of the most burning and common problems in tunnel construction throughout the world. 82 tunnels were investigated for the above-stated factors and from the analysis, it is revealed that 12.2% were caused by deformation of surrounding rock, 61% were impacted in varying degrees by groundwater, 25.6% collapsed due to tunnel lining and not being installed in a timely way. This shows that strata deformation, groundwater, and lining have largely affected the normal tunnel construction (Liping, et al., 2014).

Different researchers have characterized the collapse and failure of tunnels during construction presented in table 2.

Table 2. Characterization of Tunnel Failure and Collapse (Tun and Signal, 2016; (Sejnoha et. al., 2009).

S. No.	Types of Failure based on nature and consequences	Types of Failure based on Extent	Types of Failure based on occur: location
1	Cave in	Complete collapse	At or around the tunnel portal
2	Significant exceeding of expected deformation of the tunnel tube,	cave in with a cavity	along the finished length of the tunnel
3	Exceeding of acceptable progress of subsidence trough and	rockfall	at the tunnel face or crown portion
4	Disturbance of water regime in the surrounding.	-	-

(Marinos, 2012) investigated 12 tunnels driven in flysch, and concluded that geological and geotechnical information greatly contribute to analyze the behaviour of the ground and its correlations with other factors; thus formulation behaviour and temporary support is required. Flysch formations are generally characterized by strong heterogeneity in the presence of low strength and tectonically disturbing structures.

To identify potential hazards, the risk comprehensive prediction method is required to be adopted during construction tunnels. Geotechnical involvement should occur throughout the life of the project. The involvement of preliminary investigations depends upon the size as well as the type of project.

Conclusion

Tunnel designing in heterogeneous rock mass conditions is a challenging task and requires thorough geological and geotechnical investigations. The involvement of preliminary investigations depends upon the size, shape, and type of project. The prevalence of tunnel failure during construction can be minimized through proper and reliable geotechnical investigation, effective ground stabilization, and monitoring techniques. Once a failure occurs in tunnels, the most difficult task is the rehabilitation and remedial process of the failed tunnel section. However, each case needs to be treated discretely and independently due to differences in nature, shape, and type of failure. It is very difficult to provide a unique design strategy for re-excavation and construction of a collapsed section of a tunnel due to the factors like mode, type, and extent of failure. Keeping in view the delay and cost factor consequent upon failure, each approach must be adopted to mitigate the risk of failure.

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