

# Safety Challenges in Metro Tunnel Construction While Using TBM/NATM for Tunnel Excavation

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## Abstract

Metro tunnel construction is one of the most complex and hazardous forms of underground infrastructure development. Modern metro systems are generally excavated either by Tunnel Boring Machine (TBM) or by the New Austrian Tunnelling Method (NATM), depending upon the geological condition, tunnel geometry, urban constraints, and project economics. Although both methods improve construction efficiency, they introduce numerous safety challenges related to geology, machinery, occupational health, structural instability, and environmental impacts. The risks are more severe in metro projects because tunnels are usually excavated beneath densely populated urban areas where failure can affect workers, nearby structures, utilities, and public safety.

This paper examines the principal safety challenges associated with TBM and NATM tunnel excavation in metro construction. It identifies all possible hazards, compares the risk profile of both methods, discusses accident mechanisms, and proposes preventive and mitigation measures.

**Keywords:** Metro tunnel, TBM, NATM, tunnel safety, excavation hazards, occupational safety, underground construction, tunnel collapse.

## 1. Introduction

Rapid urbanization and increasing traffic congestion have encouraged many countries to develop underground metro rail systems. Metro tunnels are commonly excavated through soft soil, mixed ground, weathered rock, hard rock, or water-bearing strata. Two major methods are generally adopted:

1. Tunnel Boring Machine (TBM)
2. New Austrian Tunnelling Method (NATM)

TBM excavation is preferred for long, circular tunnels in relatively uniform ground conditions. NATM is generally used where tunnel shapes vary, station caverns are required, or geological conditions are highly variable.

Despite technological improvements, tunnel construction remains a high-risk activity due to the confined underground environment, limited escape routes, continuous machine operation, unstable ground, poor ventilation, and interaction with water, gas, dust, and heavy equipment.

The major objective of this paper is to analyze the safety challenges and hazards in metro tunnel excavation using TBM and NATM and to suggest suitable control measures.

## 2. Tunnel Boring Machine (TBM) Method

A TBM is a mechanized excavation system that excavates the tunnel face while simultaneously installing the tunnel lining. Different types of TBMs are used according to ground conditions:

- Earth Pressure Balance TBM (EPB-TBM)
- Slurry TBM
- Hard Rock TBM
- Mixshield TBM

### 2.1 Advantages of TBM

- High excavation speed
- Reduced surface settlement
- Lower vibration and noise in urban areas
- Better working environment compared to blasting
- Continuous and uniform tunnel profile

### 2.2 Major Safety Challenges in TBM Excavation

#### 2.2.1 Geological Uncertainty

One of the greatest hazards in TBM tunnelling is unexpected geology. Even detailed geotechnical investigations cannot completely identify hidden faults, cavities, mixed-face conditions, weak zones, boulders, or water-bearing strata.

Possible hazards include:

- Sudden face collapse
- Machine entrapment or jamming
- Excessive cutter wear
- Shield deformation
- Tunnel misalignment
- Large ground settlement at surface

#### 2.2.2 Face Instability

The tunnel face must remain stable during excavation. If the pressure at the face is lower than the surrounding ground pressure, collapse may occur.

Hazards:

- Sudden collapse of soil or rock at the tunnel face
- Burial of workers and equipment
- Excessive settlement affecting nearby buildings and roads
- Sinkholes at the ground surface

#### 2.2.3 Water Ingress and Flooding

TBM tunnels often encounter underground water, rivers, pressurized aquifers, or fractured rock.

Possible consequences:

- Flooding of the tunnel
- Electrical short circuits
- Drowning risk to workers
- Loss of face pressure and tunnel collapse
- Machine stoppage and damage

Water ingress is especially dangerous when combined with loose sand or silt because it may create a quicksand condition.

#### **2.2.4 High Gas Pressure and Toxic Gases**

Underground excavation may encounter methane, hydrogen sulfide, carbon monoxide, carbon dioxide, radon, or low-oxygen conditions.

Hazards include:

- Explosion and fire
- Toxic inhalation
- Suffocation
- Reduced worker alertness and fatigue

#### **2.2.5 Mechanical Failure of TBM**

A TBM consists of thousands of moving components such as cutter heads, conveyors, hydraulic cylinders, motors, electrical systems, and segment erectors.

Possible failures:

- Cutter head breakdown
- Hydraulic system failure
- Conveyor belt accidents
- Segment erector malfunction
- Failure of guidance system
- Overheating of motors and transformers

These failures may expose workers to crushing, entanglement, electric shock, burns, or struck-by accidents.

#### **2.2.6 Cutter Replacement Hazards**

Cutter replacement is one of the most dangerous TBM activities because workers may enter the cutter head chamber under compressed air conditions.

Associated hazards:

- Decompression sickness
- Falling objects
- Entrapment in cutter head
- Loss of air pressure
- Severe injury due to rotating parts

### 2.2.7 Electrical Hazards

TBM systems operate with high-voltage power supply.

Potential hazards:

- Electric shock
- Arc flash
- Cable damage due to moisture
- Fire due to short circuit

### 2.2.8 Fire in TBM Tunnel

A fire in a tunnel is highly dangerous because smoke accumulates quickly in the confined space.

Potential causes:

- Electrical short circuit
- Hydraulic oil leakage
- Conveyor belt friction
- Welding or hot work

Consequences:

- Smoke inhalation
- Panic and delayed evacuation
- Damage to tunnel lining and machinery
- Fatalities due to lack of escape route

### 2.2.9 Occupational Health Hazards in TBM

TBM construction exposes workers to:

- Silica dust
- Diesel particulate matter
- Excessive noise
- Whole-body vibration
- Heat stress and humidity
- Poor lighting
- Musculoskeletal disorders

Long-term exposure may cause:

- Silicosis
- Respiratory diseases
- Hearing loss
- Fatigue and mental stress

### 3. New Austrian Tunnelling Method (NATM)

NATM is based on the principle that the surrounding ground itself becomes part of the support system. Excavation is generally performed in stages using drilling and blasting or mechanical excavation, followed by immediate support such as shotcrete, rock bolts, steel ribs, and wire mesh.

#### 3.1 Advantages of NATM

- Flexible for varying tunnel shapes and sizes
- Suitable for large caverns and station boxes
- Adaptable to changing geology
- Lower equipment cost compared to TBM

#### 3.2 Major Safety Challenges in NATM Excavation

##### 3.2.1 Tunnel Face Collapse

Unlike TBM, NATM often exposes a larger unsupported face during excavation. This increases the probability of sudden collapse.

Hazards:

- Falling rock and soil
- Burial of workers
- Damage to equipment
- Chain reaction collapse in unsupported zones

##### 3.2.2 Roof Fall and Sidewall Failure

The crown and sidewalls of NATM tunnels may become unstable if support is delayed or insufficient.

Possible causes:

- Weak rock mass
- Delay in shotcrete application
- Inadequate rock bolts
- Over-excavation

Consequences:

- Fatal injury due to falling rocks
- Progressive tunnel collapse
- Blockage of escape routes

##### 3.2.3 Hazards from Blasting Operations

Blasting is commonly used in NATM for hard rock excavation.

Major hazards:

- Premature detonation
- Fly rock

- Misfire of explosives
- Blast vibration affecting nearby structures
- Toxic fumes after blasting

Workers may also be injured during charging, wiring, or handling explosives.

### **3.2.4 Dust and Toxic Fumes**

Blasting and excavation generate large amounts of dust and gases.

Common harmful substances:

- Silica dust
- Nitrogen oxides
- Carbon monoxide
- Diesel exhaust

These may result in:

- Respiratory disease
- Eye irritation
- Poisoning
- Reduced visibility and higher accident probability

### **3.2.5 Failure of Temporary Support**

NATM relies heavily on temporary support systems.

Possible failures include:

- Shotcrete cracking
- Collapse of steel ribs
- Pull-out of rock bolts
- Failure of lattice girders

Consequences:

- Tunnel deformation
- Collapse of excavation
- Worker entrapment

### **3.2.6 Water Seepage and Groundwater Inflow**

Water ingress is a common problem in NATM tunnels, especially in fractured rock and water-bearing formations.

Hazards:

- Erosion of tunnel face
- Softening of surrounding ground
- Sudden collapse
- Slip and fall accidents
- Damage to electrical equipment

### 3.2.7 Surface Settlement and Building Damage

NATM tunnels are often constructed under roads, railways, and buildings. Inadequate support may lead to ground settlement.

Possible effects:

- Cracking of nearby structures
- Damage to underground utilities
- Road collapse
- Public safety risk

### 3.2.8 Limited Ventilation

Ventilation is more difficult in NATM because excavation and support activities occur simultaneously.

Inadequate ventilation may cause:

- Low oxygen concentration
- Heat stress
- Accumulation of blast fumes
- Poor visibility

### 3.2.9 Ergonomic and Human Factor Hazards

NATM work is highly labour-intensive. Workers are exposed to repetitive manual tasks, awkward posture, fatigue, and poor communication.

Possible problems:

- Human error
- Delayed response during emergency
- Unsafe behavior
- Increased accident rate during night shifts

## 4. Comparative Hazard Assessment: TBM vs NATM

Safety Aspect	TBM	NATM
Tunnel Stability	Face Better controlled but vulnerable to sudden pressure loss	More exposed and higher risk of collapse
Geological Uncertainty	Can cause machine jamming and misalignment	Can cause face failure and overbreak
Water Ingress	High risk in pressurized ground	High risk in fractured rock and loose soil
Fire and Explosion	Mainly due to machinery and gases	Mainly due to blasting and gases
Worker Exposure	Lower direct exposure but more mechanical hazards	Higher exposure to dust, blasting, and rockfall

Occupational Health	Noise, vibration, dust, confined space	Dust, blast fumes, manual handling
Surface Settlement	Usually lower	Usually higher if support is delayed
Emergency Evacuation	Difficult because of long tunnel distance	Difficult due to unstable excavation and blocked routes

## 5. Major Possible Hazards in Metro Tunnel Construction

The following hazards may occur in both TBM and NATM tunnel construction:

1. Tunnel collapse
2. Face instability
3. Roof fall
4. Sidewall collapse
5. Surface subsidence
6. Water ingress and flooding
7. Gas leakage
8. Fire and explosion
9. Electrical shock
10. Machinery entanglement
11. Falling objects
12. Confined space hazards
13. Poor ventilation
14. Dust inhalation
15. Noise-induced hearing loss
16. Vibration-related disorders
17. Heat stress
18. Slips, trips, and falls
19. Crane and lifting accidents
20. Transportation accidents involving locomotives and dumpers
21. Improper handling of explosives
22. Structural failure of temporary support
23. Psychological stress and fatigue
24. Communication failure during emergency
25. Inadequate evacuation and rescue facilities

## 6. Risk Mitigation and Safety Measures

### 6.1 Geological Investigation

- Detailed borehole investigation
- Seismic survey and ground probing
- Real-time monitoring ahead of the face
- Identification of weak zones, faults, and groundwater

### 6.2 Monitoring and Instrumentation

- Settlement markers
- Convergence monitoring
- Groundwater pressure sensors
- Gas detectors

- TBM parameter monitoring
- Real-time alarm systems

### 6.3 Ground Support Measures

For TBM:

- Proper face pressure control
- Grouting ahead of the face
- Strong segment lining
- Regular cutter inspection

For NATM:

- Immediate application of shotcrete
- Adequate rock bolting
- Steel ribs and wire mesh
- Sequential excavation with limited unsupported span

### 6.4 Ventilation and Air Quality Control

- Forced mechanical ventilation
- Dust suppression by water spraying
- Continuous gas monitoring
- Use of respirators where necessary

### 6.5 Fire Prevention

- Fire-resistant cables and hydraulic oil
- Fire extinguishers and suppression systems
- Hot work permit system

## 7. Conclusion

Tunnel excavation using TBM and NATM is associated with significant safety challenges due to complex geology, confined working conditions, heavy machinery, groundwater, gas, dust, and unstable ground. TBM generally provides better control and lower disturbance to the surface, but it introduces risks related to machine failure, face pressure loss, fire, and confined-space operations. NATM offers greater flexibility, but workers are more exposed to hazards such as collapse, blasting accidents, rockfall, dust, and support failure.

The most serious hazards in both methods include tunnel collapse, flooding, gas explosion, fire, electrical accidents, occupational illness, and surface settlement. Effective tunnel safety therefore requires a combination of thorough site investigation, proper design, real-time monitoring, adequate ventilation, strong temporary support, emergency planning, and continuous worker training.

A safe metro tunnel project is not achieved only by selecting the correct excavation method; it depends on anticipating all possible hazards and implementing preventive measures throughout the project lifecycle.

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