Advanced technologies and equipment used in underground construction

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Abstract: This article analyzes innovative technologies applied in modern underground construction. In particular, high-performance Tunnel Boring Machines (TBM), intelligent digital monitoring systems, automated control technologies, and new-generation construction materials (high-strength concretes, geosynthetic materials, and grouting compounds) are examined in terms of their technical, economic, and operational advantages. The study substantiates, through scientific analysis, the role of these advanced technologies in reducing construction time, improving safety levels, and extending the service life of underground structures. The findings demonstrate that the implementation of innovative approaches significantly enhances the efficiency, reliability, and sustainability of underground infrastructure projects. The article is intended for civil engineers, researchers, design specialists, and practitioners working in the field of underground construction and geotechnical engineering.

Keywords: underground structures, tunnel construction, TBM technology, geotechnical reinforcement, shotcrete, BIM modeling, digital monitoring, robotic systems, artificial intelligence, smart tunnels

1. Introduction

Today, the process of urbanization is developing rapidly on a global scale. The growth of the population in large cities, the increase in traffic flow, and the rising demand for infrastructure are leading to the limitation of surface areas [1]. Consequently, placing transport tunnels, subways, road and rail overpasses, and engineering communications (water supply, sewerage, electricity, and communication networks) underground is becoming a strategic necessity (Figures 1 and 2).

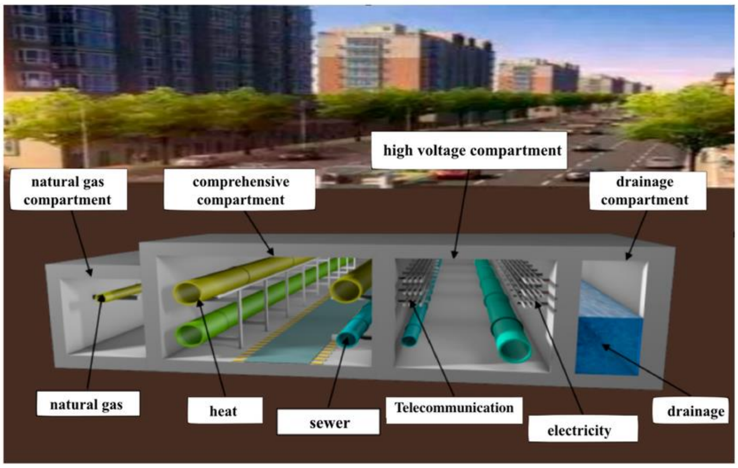


Figure 1

The construction of underground engineering structures is carried out in complex geomechanical conditions. Factors such as various compositions of soil layers, high groundwater levels, location in seismically active areas, and the risk of deformation in dense urban construction conditions significantly affect the design and construction process. The soil-structure interaction, redistribution of stresses, and settlement processes require constant scientific analysis [2].

Figure 2

In modern underground construction, safety, economic efficiency, and environmental sustainability are considered the main criteria. Traditional excavation and reinforcement methods may not provide high efficiency in all cases. Therefore, Tunnel Boring Machines (TBM), digital geotechnical monitoring, automated control systems, innovative construction materials, and BIM technologies are being widely implemented.

Scientific research shows that the use of advanced technologies:

- ✓ Reduces construction time by 20-35%;
- ✓ Reduces the risk of accidents by 30-40%;
- ✓ Extends the service life of the structure by up to 25%;
- ✓ Significantly lowers operational costs.

In this regard, the application of innovative technologies in the construction of underground structures is one of the priority areas of modern engineering science. This article analyzes the scientific and technical foundations of advanced technologies and equipment in this field.

2. Tunnel Boring Machines (TBM)

The most efficient and safest modern tunneling method is TBM (Tunnel Boring Machine) technology. Compared to traditional drilling-and-blasting or open excavation methods, TBM provides higher precision, lower noise levels, and minimal vibration (Figures 3, 4, and 5).

Especially in densely built urban environments, TBM technology is highly advantageous because it minimizes the impact on surface buildings and existing infrastructure [3].

Figure 3. TBM Cutterhead

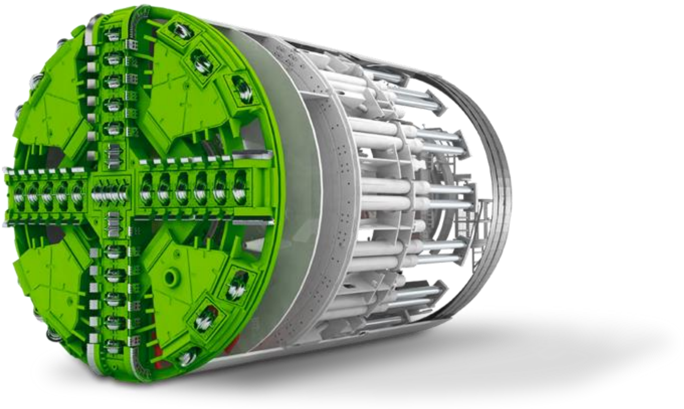


Figure 4. EPB Shield TBM

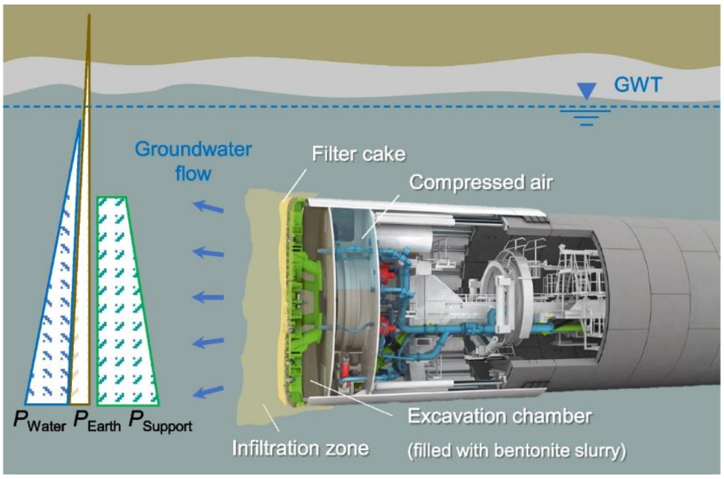


Figure 5. Slurry Shield TBM

2.1. General Operating Principle of TBM Technology

A TBM system consists of the following main components:

- ✓ Cutterhead - excavates and fragments the soil or rock;
- ✓ Shield - temporarily supports the excavated cavity;
- ✓ Pressure balance system - controls ground pressure at the tunnel face;
- ✓ Segment erection system - installs precast reinforced concrete lining segments;
- ✓ Control and automation module - monitors operational parameters in real time.

During excavation, the balance between soil pressure and applied face pressure is maintained according to:

$$\sigma_{face} \approx \sigma_{earth} + \sigma_{water}$$

Where:

- ✓ σ_{face}- pressure at the cutting face;
- ✓ σ_{earth}- earth pressure;
- ✓ σ_{water}- groundwater pressure.

Proper pressure control significantly reduces surface settlement (S).

2.2. EPB (Earth Pressure Balance) Shield

The EPB Shield is applied in soft, plastic, and water-bearing soils. It maintains pressure equilibrium by retaining excavated soil in a pressurized chamber at the tunnel face, thus reducing surface deformation [4].

Advantages:

- Limits settlement to 10-15 mm;
- Construction rate: 12-20 m/day;

- Reduces additional grouting operations;
- Safe for urban environments.

Surface settlement in EPB tunneling is commonly estimated using the empirical formula:

$$S_{max} = \frac{V_l}{\sqrt{2\pi} \cdot i}$$

Where:

✓ V_l- ground loss ratio;
✓ i- radius of the influence zone.

2.3. Slurry Shield

The Slurry Shield method is used in water-saturated, sandy, and unstable soils. In this system, the tunnel face is stabilized by bentonite slurry, which provides hydrostatic pressure support.

Key Features:

✓ Hydrostatic pressure control;
✓ Soil-slurry separation system;
✓ Suitable for large-diameter tunnels (6-15 m).

Advantages:

✓ High stability in water-bearing soils;
✓ Reliable performance in areas with high groundwater levels;
✓ Minimal surface settlement.

In Slurry Shield technology, face pressure is determined by:

$$P = \gamma_{slurry} \cdot h$$

Where:

✓ γ_{slurry}- slurry density;
✓ h- pressure head.

2.4. Scientific and Practical Efficiency

Research indicates that TBM technology reduces accident probability from 10^{-3} to 10^{-5}. Moreover, it enables tunnel structures to be designed with a service life of up to 100 years (Table 1).

Table 1.

Scientific and Practical Efficiency

Indicator	Conventional Method	TBM (EPB/Slurry)
Construction rate	3-6 m/day	12-25 m/day
Surface settlement	30-50 mm	10-15 mm
Safety index β	2.5-2.8	3.5-3.8
Noise & vibration	High	Low

TBM technology represents an innovative stage in underground construction. EPB and Slurry Shield systems enable stable and safe tunnel construction under various geological conditions.

Real-time monitoring of geomechanical processes and precise pressure balance control ensure high structural quality, improved safety, and significant economic efficiency.

3. New Methods for Strengthening Underground Structures

During the construction of underground structures, ground improvement and rapid stabilization of lining systems play a decisive role in ensuring structural reliability and long service life.

Modern geotechnical technologies are aimed at:

✓ Improving the physical-mechanical properties of soil;
✓ Controlling filtration processes;
✓ Limiting deformations and settlements;

- ✓ Increasing overall structural safety and durability.

3.1. Jet Grouting

Jet grouting is a ground improvement method in which cement or цемент-sand grout is injected into the soil under high pressure (20-40 MPa), forming cylindrical soil-cement columns in situ (Figures 6, 7, and 8).

Figure 6. Jet Grouting Drilling Stage

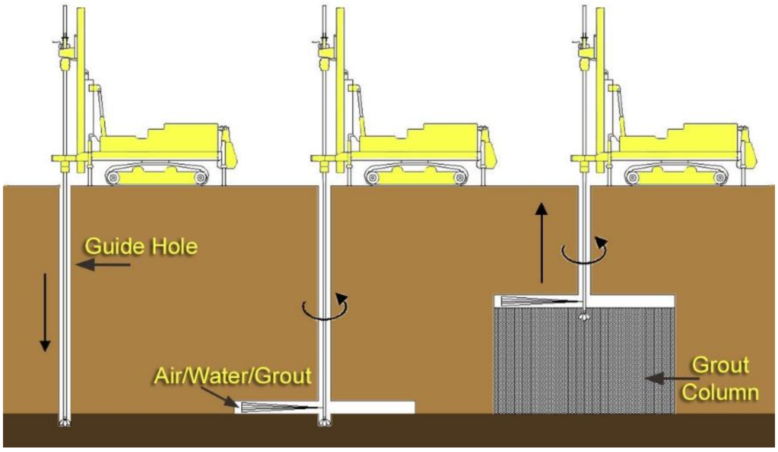
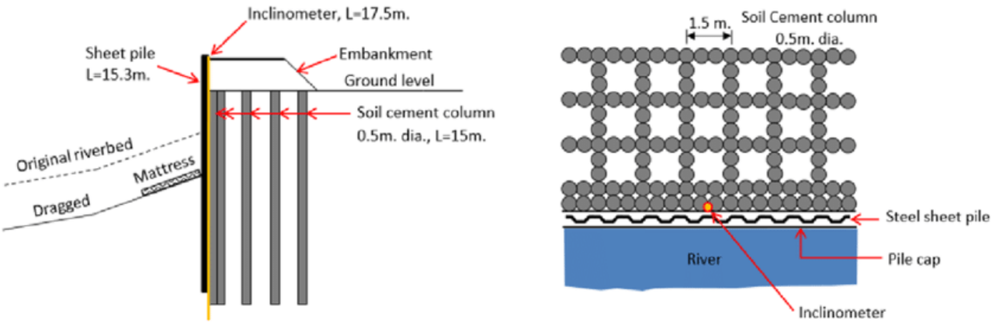


Figure 7. High-Pressure Injection Process



a) Typical Section b) Typical Plan

Figure 8. Soil-Cement Columns

Technological Stages:

1. Drilling;
2. High-pressure injection (rotational and upward movement);
3. Soil-cement mixing reaction;
4. Hardening and strengthening [5].

Scientific and Practical Indicators:

- ✓ Column diameter: 0.6-2.0 m;
- ✓ Compressive strength (fc): 2-10 MPa;
- ✓ Permeability reduction: 5-10 times;
- ✓ Settlement reduction: 30-50%.

The increase in soil shear strength is evaluated using:

$$R = c' + \sigma' \tan \varphi'$$

Where:

- ✓ c'- improved cohesion;
- ✓ σ'- effective stress;
- ✓ φ'- internal friction angle.

Jet grouting is particularly effective in areas with high groundwater levels and for stabilizing the tunnel face before excavation.

3.2. Shotcrete

Shotcrete is a method of rapidly stabilizing tunnel walls and crowns by spraying concrete under high pressure. It is widely applied in the New Austrian Tunnelling Method (NATM) (Figures 9, 10, and 11).

Figure 9. Shotcrete Application in Tunnel

Figure 10. Robotic Shotcrete Equipment

Figure 11. Fiber-Reinforced Shotcrete Surface

Modern Features:

- ✓ Robotic spraying systems;
- ✓ Polymer- and fiber-reinforced concrete;
- ✓ Rapid-setting additives.

Technical Parameters:

- ✓ Layer thickness: 5-30 cm;
- ✓ Compressive strength: 25-50 MPa;
- ✓ Setting time: 3-10 minutes;
- ✓ Crack resistance increase: ≈40%.

Internal stresses in shotcrete lining are evaluated by:

$$\sigma = \frac{M \cdot y}{I}$$

Where:

- ✓ M- bending moment;
- ✓ y- distance from the neutral axis;
- ✓ I- moment of inertia.

Fiber-reinforced shotcrete limits crack propagation and increases the structural reliability index (β) to 3.2-3.8.

3.3. Innovative Strengthening Materials

The following advanced materials are widely implemented in underground construction:

- ✓ Geosynthetic membranes - waterproofing and seepage control;
- ✓ Fiber-reinforced concrete - enhanced crack resistance;
- ✓ Polymer injection compounds - sealing of water inflow;
- ✓ Self-healing concrete - automatic repair of microcracks.

These materials can extend structural service life by 20-30%.

Jet grouting and shotcrete technologies play a crucial role in ensuring the geotechnical stability of underground structures [6].

The integration of:

- ✓ Robotic construction equipment,
- ✓ Real-time monitoring systems,
- ✓ Innovative composite and self-healing materials, significantly accelerates construction processes, improves safety, and enhances long-term эксплуатацион efficiency.

4. Digital Technologies and BIM in Underground Construction

Digitalization in modern underground construction plays a decisive role in quality control, safety enhancement, and resource management.

Building Information Modeling (BIM) technology enables the creation of a Digital Twin, integrating design, construction, and operation phases within a unified information environment (Figures 12, 13, and 14).

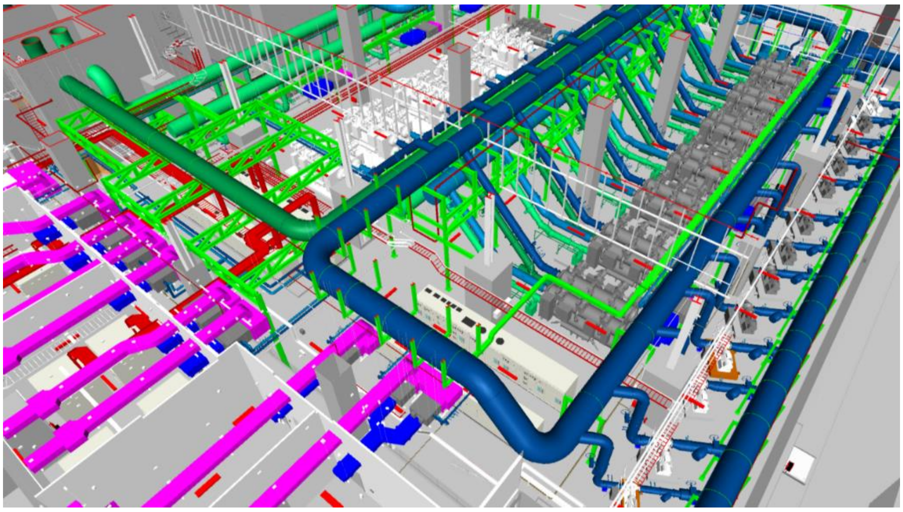


Figure 12. BIM 3D Model of Underground Infrastructure

Figure 13. Digital Twin Concept in Infrastructure

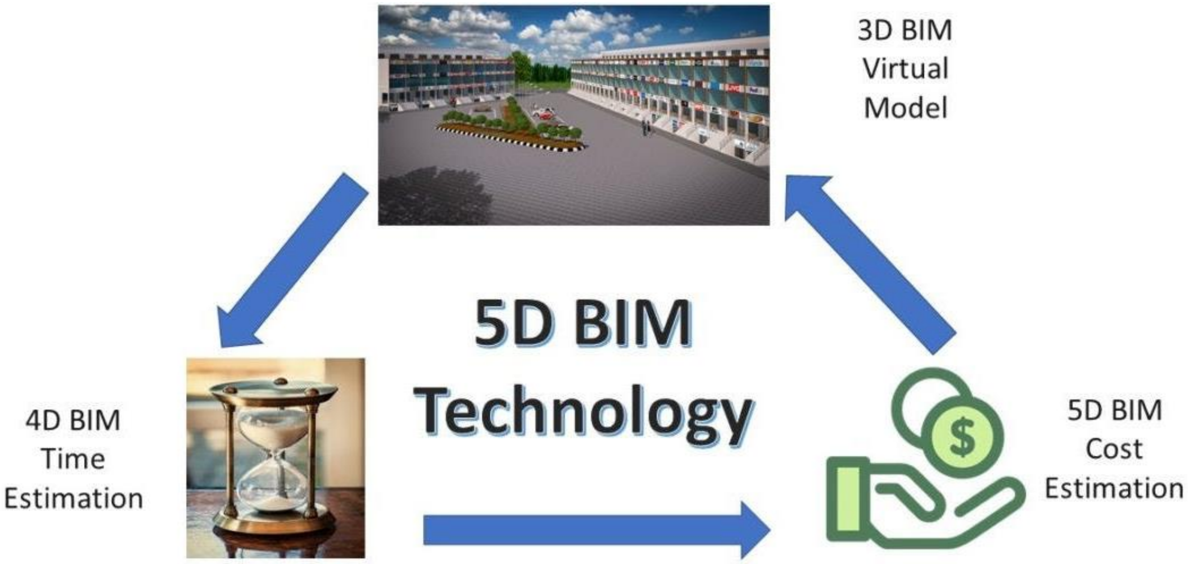


Figure 14. BIM-Based Construction Management

4.1. Importance of BIM Technology

Within the BIM environment, the following tasks are performed:

- ✓ 3D modeling of geological and hydrogeological data;
- ✓ 4D (time) and 5D (cost) construction analysis;
- ✓ Calculation of stresses and deformations;
- ✓ Prediction of operational expenditures.

The Digital Twin model is continuously updated using real-time sensor data. This enables dynamic assessment of:

- ✓ Probability of failure (Pf)
- ✓ Reliability index (β)

Such integration significantly improves decision-making accuracy during both construction and operation phases.

4.2. Geological Monitoring

To monitor soil movement and settlement processes in underground structures, the following instruments are used:

- ✓ Inclinometers;
- ✓ Piezometers;
- ✓ Deformation sensors;
- ✓ IoT-based smart sensors.

Settlement over time is evaluated using:

$$S(t) = S_0(1 - e^{-kt})$$

Where:

- ✓ $S(t)$- settlement at time *t*;
- ✓ k- soil consolidation coefficient;
- ✓ t- time.

Real-time monitoring reduces geotechnical risk by approximately **35-40%**, enabling early intervention and preventive strengthening.

4.3. LiDAR Scanning

LiDAR (Light Detection and Ranging) technology uses laser pulses to measure tunnel geometry with high precision (±2-3 mm).

Advantages:

- ✓ Verification of excavated cross-section compliance with design;
- ✓ Early detection of deformation;
- ✓ Automatic volume calculation.

LiDAR is especially important for geometric control in tunnels excavated using Tunnel Boring Machine (TBM) and New Austrian Tunnelling Method (NATM) technologies.

4.4. Application of Advanced Technologies

Table 2.

Application of Advanced Technologies

Technology Type	Main Advantage	Application Field
Microtunneling	No surface excavation	Urban utilities
Fiber-reinforced concrete	High flexibility	Tunnel linings
Autonomous drilling	Enhanced safety	Mining and metro construction
BIM & Digital Twin	Integrated management	Large infrastructure projects
LiDAR scanning	Geometric precision	TBM and NATM tunnels

The implementation of BIM and digital monitoring systems in underground construction:

- ✓ Ensures information transparency;
- ✓ Detects geotechnical risks at early stages;
- ✓ Reduces construction time by 15-25%;
- ✓ Improves operational efficiency and life-cycle performance.

BIM and digital monitoring systems are transforming underground construction into an intelligent and sustainable infrastructure paradigm.

Through real-time data integration, predictive analytics, and advanced visualization tools, underground structures become safer, more durable, and economically optimized throughout their entire life cycle [7].

5. Conclusion and Future Prospects

Modern underground construction has entered a qualitatively new stage of development through the implementation of advanced technologies - Tunnel Boring Machines (TBM), geotechnical strengthening methods, BIM-based digital modeling, and robotic systems [3, 8].

Scientific analysis demonstrates that digitalization and automation play a decisive role in:

- ✓ Reducing construction risks;
- ✓ Minimizing the influence of the human factor;
- ✓ Enhancing structural stability and durability;
- ✓ Optimizing life-cycle performance.

The integration of robotic equipment and artificial intelligence in underground construction significantly reduces direct human involvement in hazardous environments. Autonomous drilling systems, robotic shotcrete units, and sensor-based monitoring platforms enable real-time process control. As a result, the probability of failure (Pf) decreases, while the reliability index (β) may increase to 3.5-4.0.

In the near future, the concept of the Smart Tunnel is expected to become widely implemented. Such infrastructure systems will possess the following capabilities:

- ✓ Self-diagnostics;
- ✓ Automatic detection of deformations and cracks;
- ✓ Intelligent control of ventilation and lighting systems;
- ✓ Energy-efficient operational modes;
- ✓ Predictive maintenance planning.

A Digital Twin model created within the BIM environment integrates all sensor data during the operational phase and continuously analyzes structural conditions. This allows a transition from reactive to preventive maintenance strategies, reducing operational costs by 25-35%.

Equipping underground structures with intelligent management systems leads to:

- ✓ Extension of service life by 20-30%;
- ✓ Significant improvement in safety levels;
- ✓ Reduction in energy and material consumption;
- ✓ Contribution to sustainable urban infrastructure development.

The introduction of innovative technologies, robotics, and artificial intelligence in underground construction not only enhances technical efficiency but also ensures human safety and long-term economic sustainability.

The evolution toward fully digitalized and intelligent underground infrastructure represents a global trend in urban development. The integration of:

- ✓ BIM and Digital Twin technologies;
- ✓ Real-time monitoring systems;

- ✓ AI-based predictive analytics;
- ✓ Autonomous construction equipment;

will transform underground engineering into a smart, adaptive, and resilient infrastructure domain.

In the long term, the Smart Tunnel paradigm will become an integral component of global smart-city ecosystems, ensuring reliability, sustainability, and technological advancement in underground urban systems.

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