Shao Zhizhong | CRCHI - China Railway Construction Heavy Industry Corporation Limited

RESEARCH AND APPLICATION OF TBM TECHNOLOGY FOR 50° UPWARD INCLINATION TUNNELING

With the global energy transition and rapid development of pumped storage, hydropower, and deep underground engineering, the demand for mechanized tunneling technology in ultra steep inclined shafts is increasing. Traditional drill and blast and conventional TBM technologies face bottlenecks such as low safety, low efficiency, poor quality, and inability to adapt to variable diameters and small vertical curves. This presentation introduces the world's first variable diameter TBM for ultra steep inclined shafts developed by China Railway Construction Heavy Industry (CRCHI).

The equipment achieves three core technological breakthroughs:

1. In situ stepless variable diameter technology in narrow tunnels, realizing diameter conversion from 6.53 m to 8.03 m.
2. Ultra steep incline and small curve safe tunneling technology, supporting 50° maximum inclination and R50 m vertical turning radius.
3. Intelligent perception and high precision collaborative control technology, with attitude error ≤ ±5 mm and penetration accuracy up to millimeter level.




The technology has been successfully applied in the Pingjiang Pumped Storage Power Station China and other key projects. It significantly improves construction efficiency, reduces costs, enhances safety, and provides a new solution for global pumped storage and underground engineering. This report will share design concepts, key innovations, engineering applications, performance verification, and future development trends.

Research and Application of TBM Technology for 50° Upward Inclination Tunneling

中国铁建

中国铁建重工集团股份有限公司

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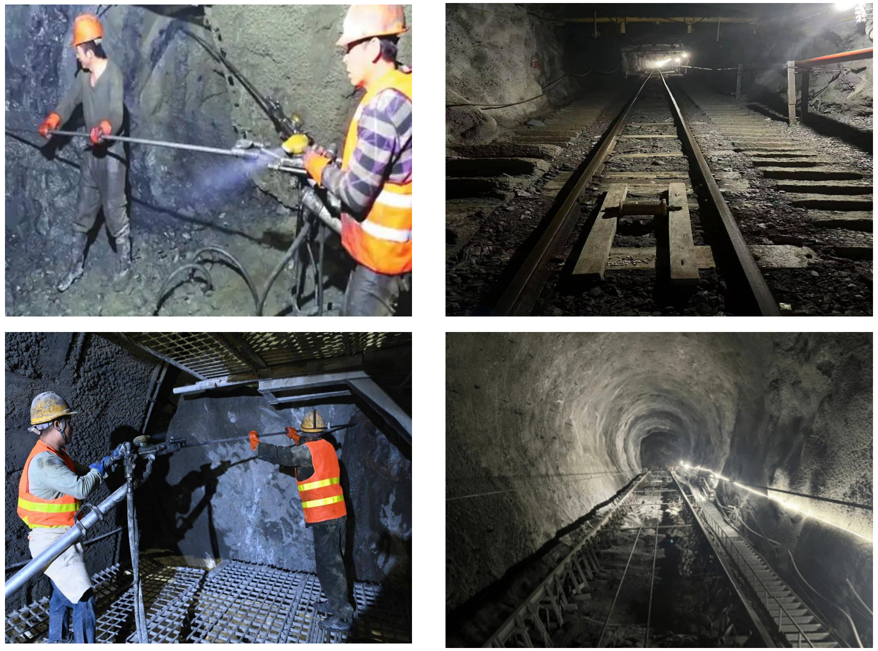
1.1 Development Status of Pumped Storage Power Stations

- The demand for mechanized tunneling technology in ultra-steep inclined shafts is increasing.
- Since the 14th Five-Year Plan, China's installed pumped storage capacity has ranked first in the world for 9 consecutive years.
- Underground caverns mostly use drill-and-blast: high labor input, low efficiency, high safety risks.

Pumped Storage Power Stations



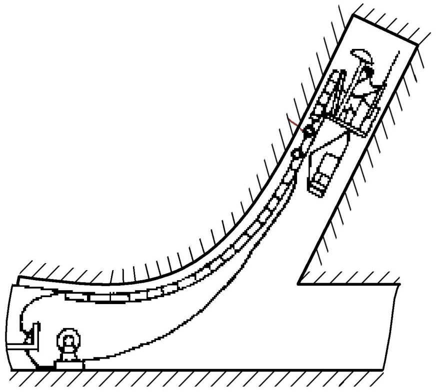
Drill-and-blast construction site

1.2 Conventional Excavation Methods for Diversion Shafts

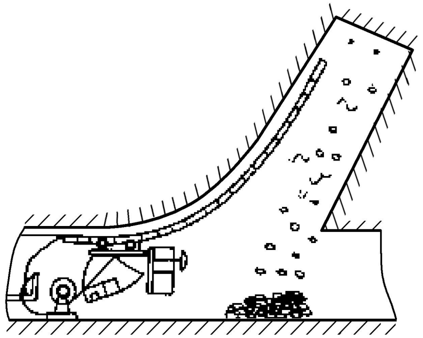
- Conventional alimak raise climber: poor ventilation, harsh conditions, poor safety control.

Alimak climber in protective position

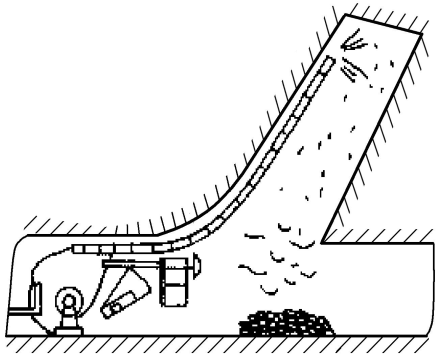
Alimak climber in working position



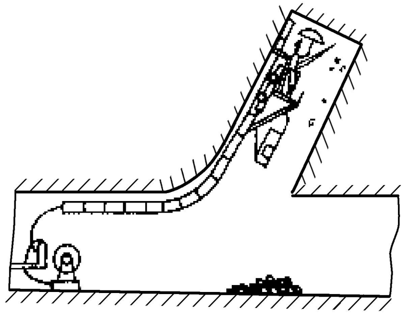
(a) Drilling and Charging



(b) Blasting



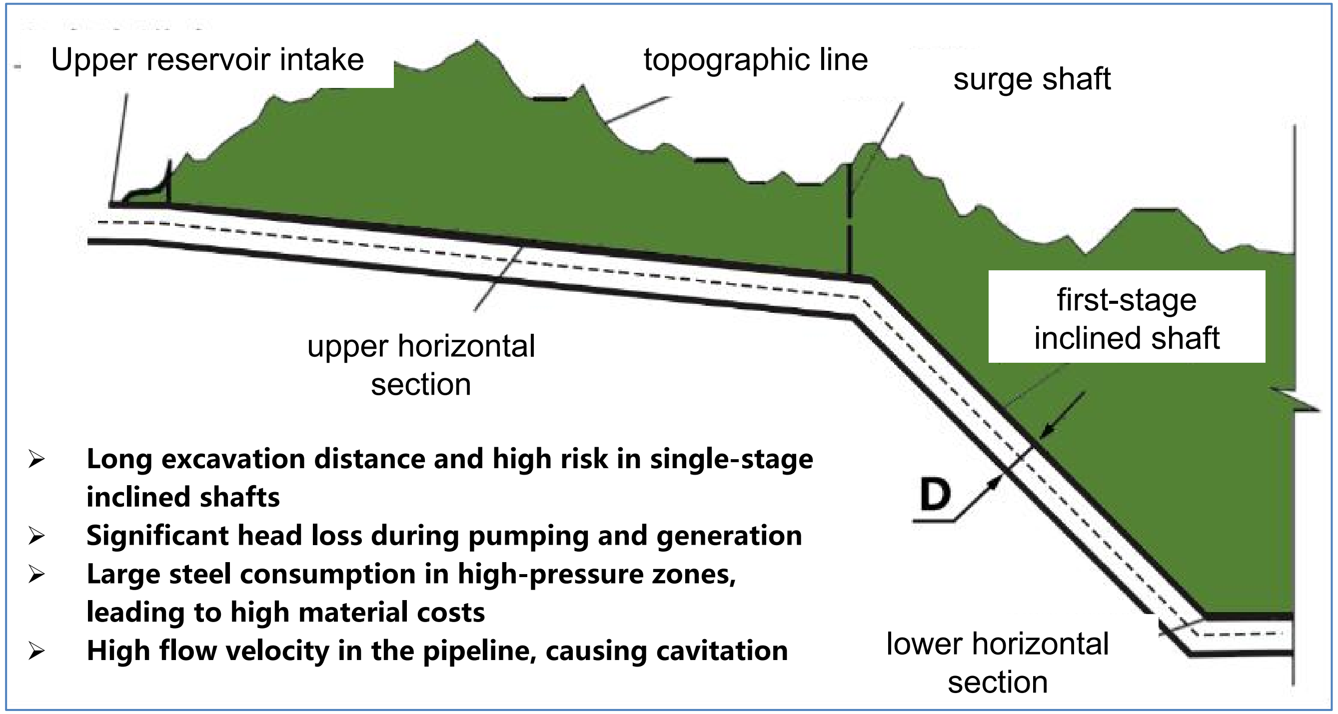
(c) Ventilation and Smoke Exhaust



(d) Loose Rock Removal

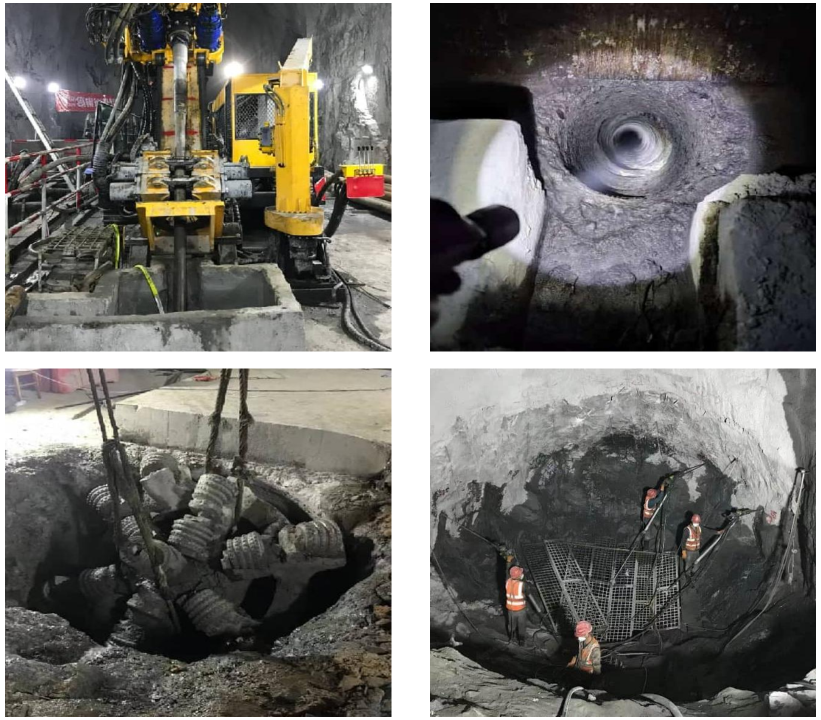
1.2 Conventional Excavation Methods for Diversion Shafts

- Traditional pumped storage water diversion inclined shafts used steep single-stage designs, suffering from large excavation volume, significant head loss, and cavitation.
- The common directional drilling + raise boring + drill-and-blast reaming process also faces issues like inaccurate positioning, crooked holes, and poor forming quality.



- **Long excavation distance and high risk in single-stage inclined shafts**
- **Significant head loss during pumping and generation**
- **Large steel consumption in high-pressure zones, leading to high material costs**
- **High flow velocity in the pipeline, causing cavitation**

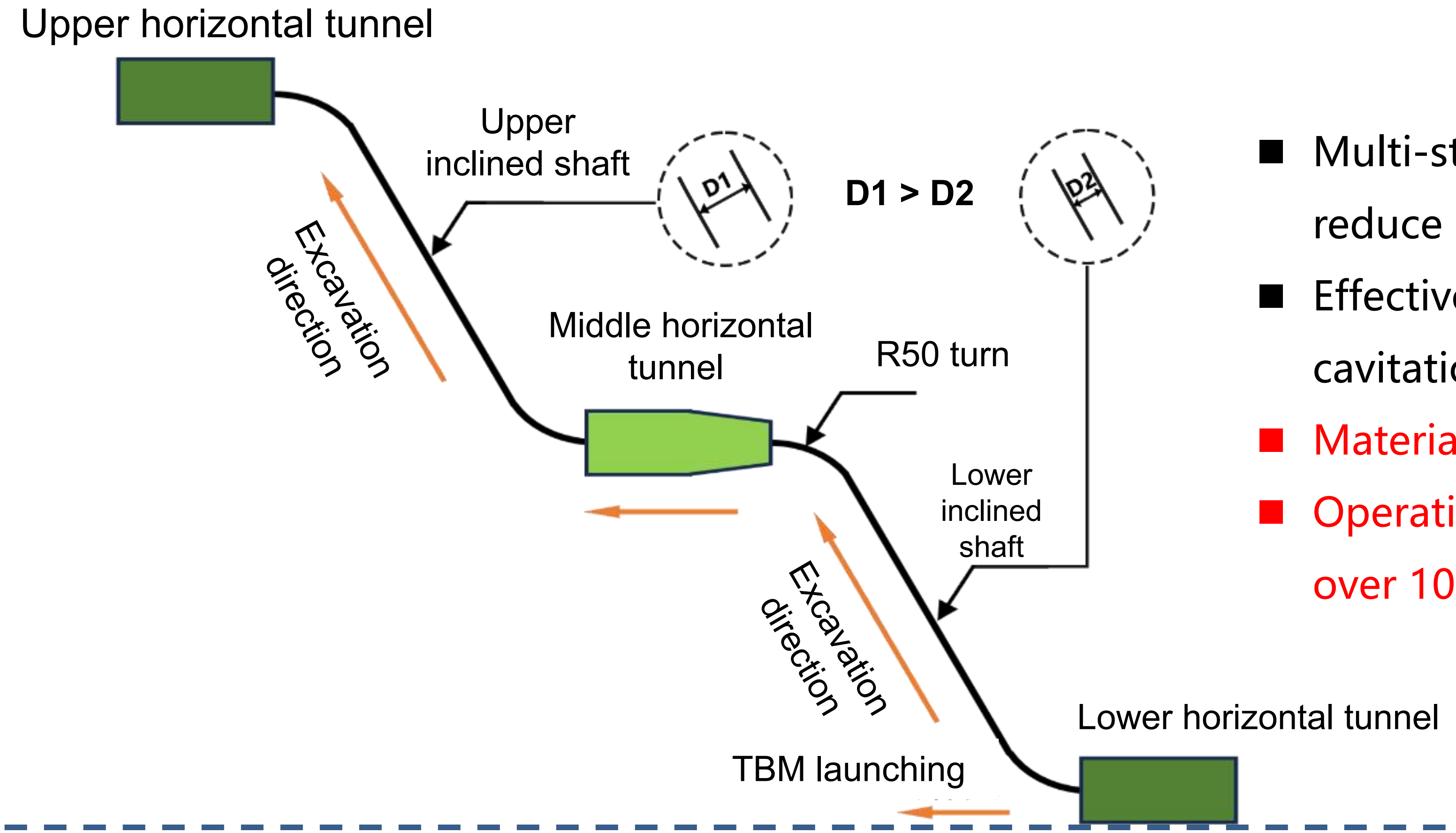
Single-stage inclined shaft



Directional drilling + raise boring + drill-and-blast reaming process

1.3 Characteristics of Multi-Stage Variable-Diameter Diversion Shaft

Multi-stage variable-diameter inclined shaft diagram

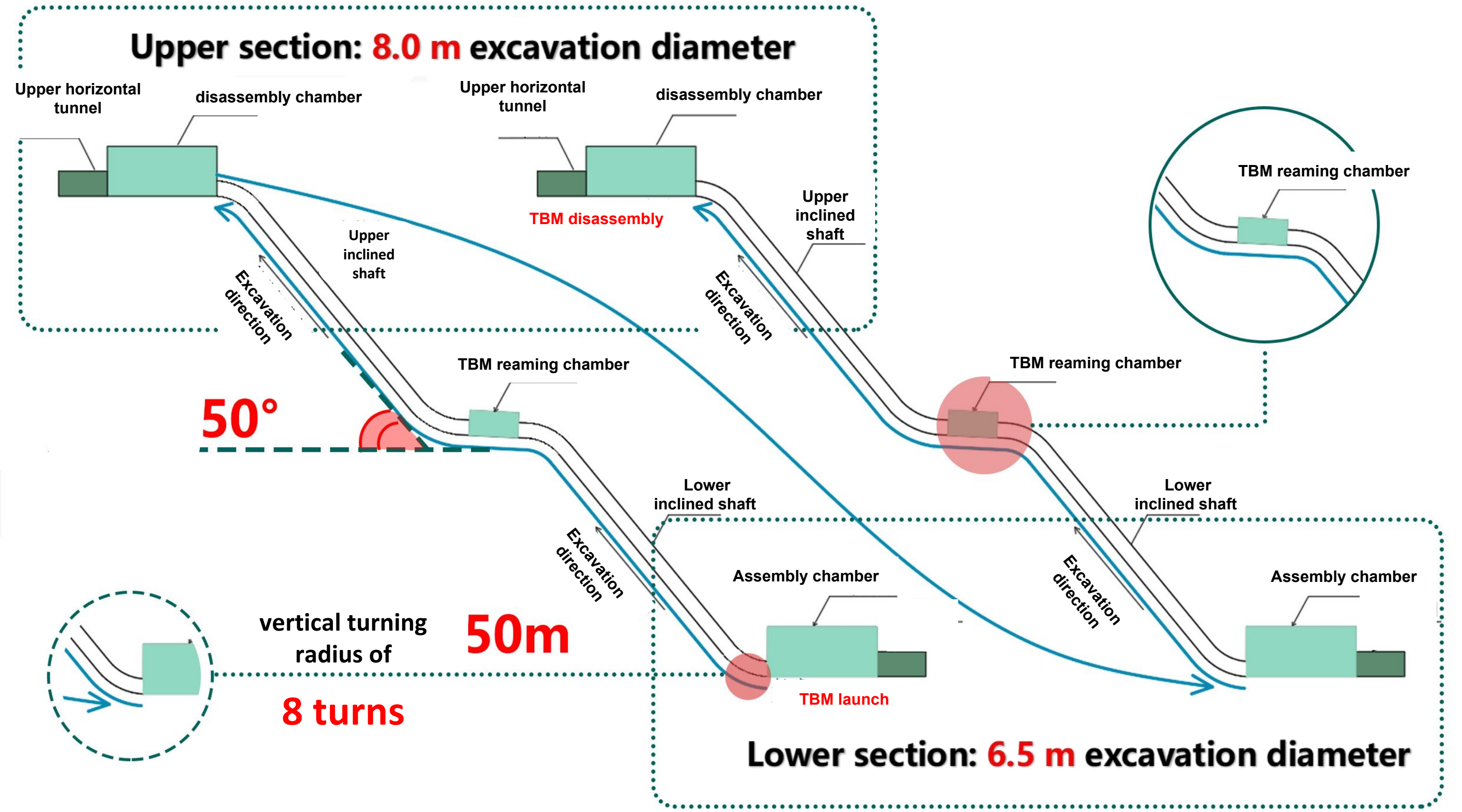


- Multi-stage variable-diameter shafts significantly reduce excavation volume.
- Effectively control flow velocity and reduce cavitation.
- Material cost savings exceed 30%.
- Operation and maintenance costs reduced by over 10%.

Significant technical, economic and social benefits.

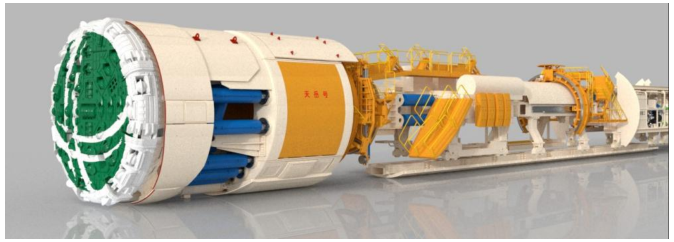
1.4 Challenges for TBM Application in Multi-Stage Variable-Diameter Shafts, Pingjiang Project

- TBM method: high excavation efficiency, no over-break/under-break, low disturbance to surrounding rock, fully mechanized construction, and excellent safety performance.



Two-stage inclined shaft layout of Pingjiang Pumped Storage Power Station

Three major challenges for TBM application:



1. Ultra-steep slope safety
2. Horizontal-inclined transition
3. Large diameter variation

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2.1.1 Large-Scale In-Situ Variable-Diameter Design

- **The diameter is adjustable from 6.5m to 8m, with a variation range of 1.5 meters, equivalent to 23%.**

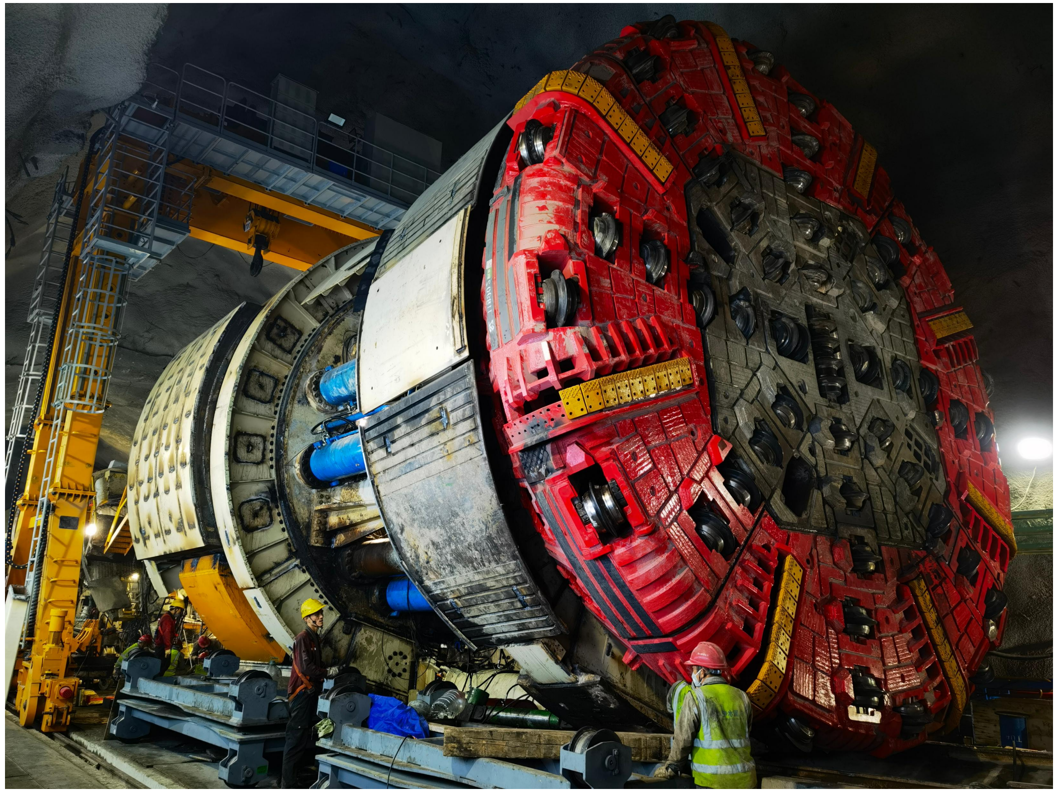
Modular Cutterhead Variable-Diameter Design

Telescopic Stepless Shield Variable-Diameter Design

Modular stepless variable-diameter principle

2.1.1 Large-Scale In-Situ Variable-Diameter Design

- **The diameter is adjustable from 6.5m to 8m, with a variation range of 1.5 meters, equivalent to 23%.**

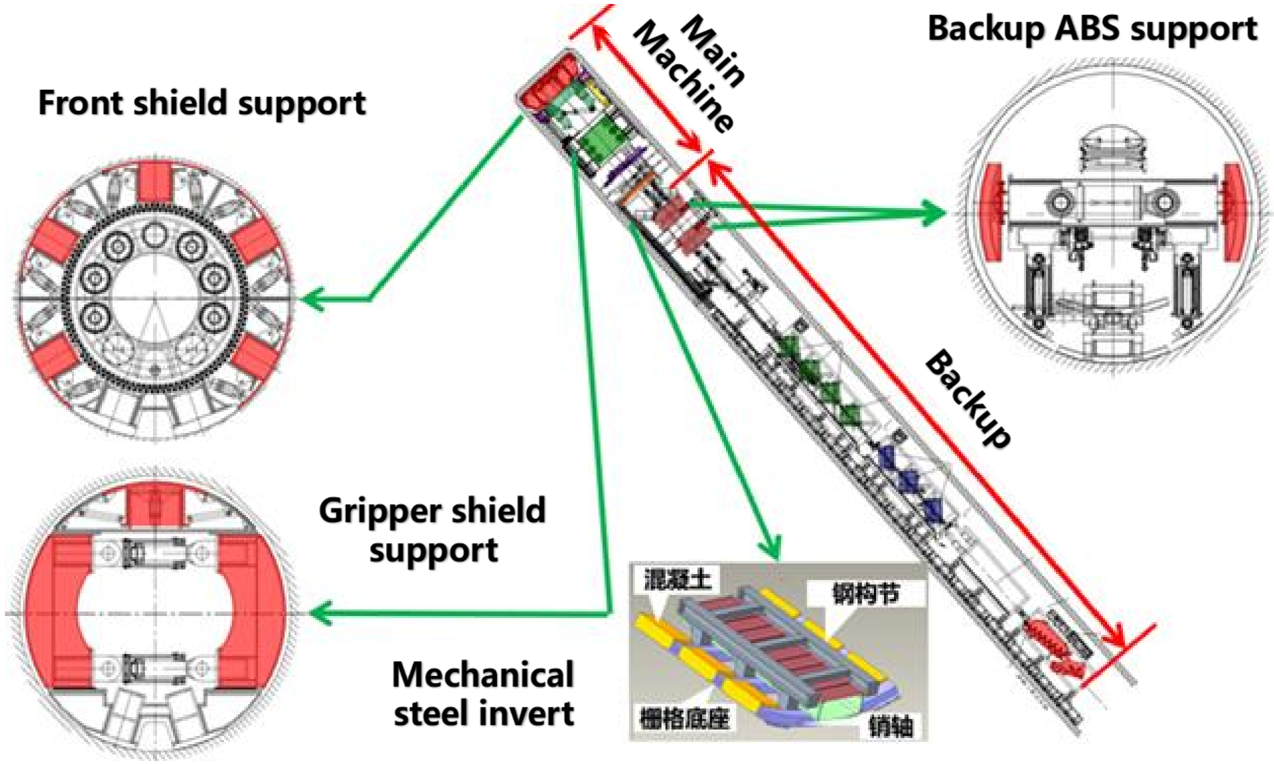


Integrated drive, support and thrust systems

Modular stepless variable-diameter principle

2.1.2 Ultra-Steep Slope Anti-Slip System

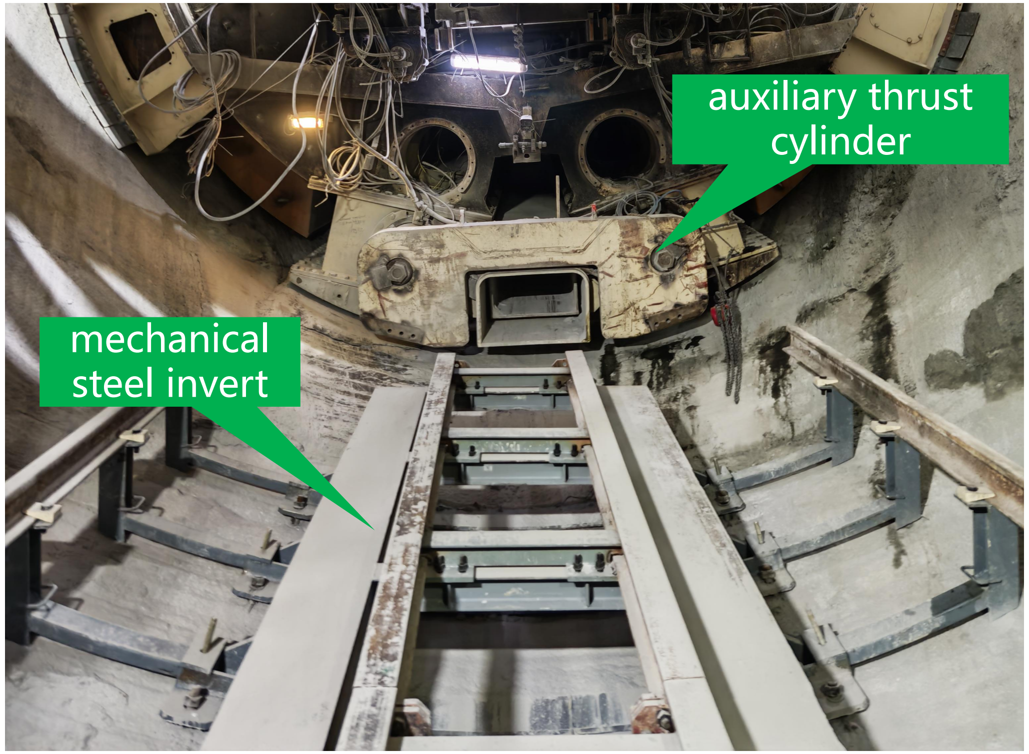
- **Full safety at 50° inclination，calmly cope with tunneling, stepping, unfavorable geological conditions and power failure scenarios.**

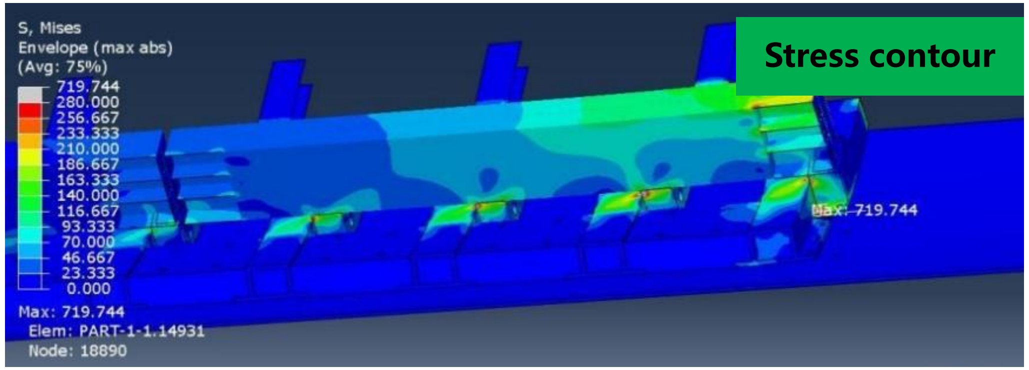


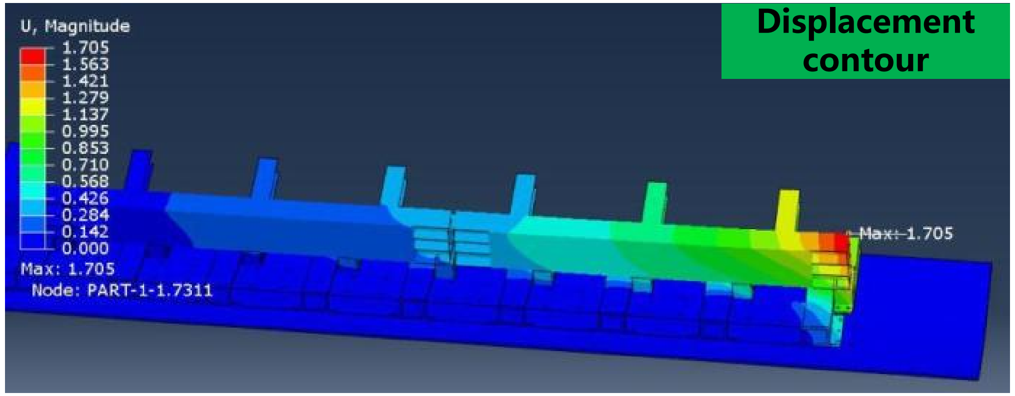
Multi-anti-slip + mechanical steel invert realize continuous steady tunneling and anti-slip safety during shutdown

2.1.2 Ultra-Steep Slope Anti-Slip System

- **Full safety at 50° inclination, calmly cope with tunneling, stepping, unfavorable geological conditions and power failure scenarios.**





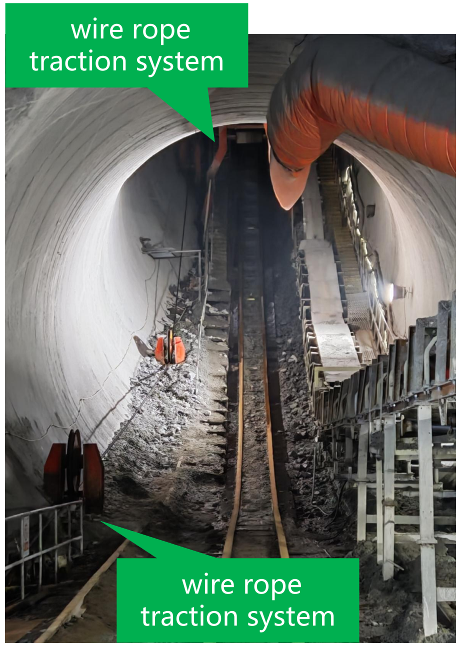


Original mechanical steel segment anti-backward structure, with dual-insurance safety redundancy far exceeding European standards, ensuring safety even during long-term shutdown and power outages

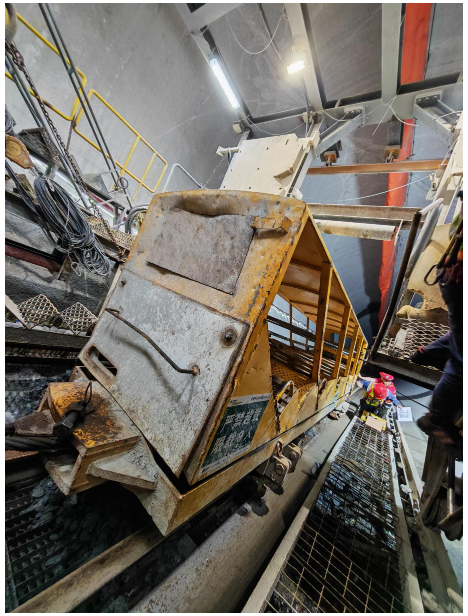
Multi-anti-slip + mechanical steel invert realize continuous steady tunneling and anti-slip safety during shutdown

2.1.2 Ultra-Steep Slope Anti-Slip System

■ **For the first time solved the safety transportation problem of 50° raise shaft**



Winch wire rope traction system technology adaptable to vertical curves



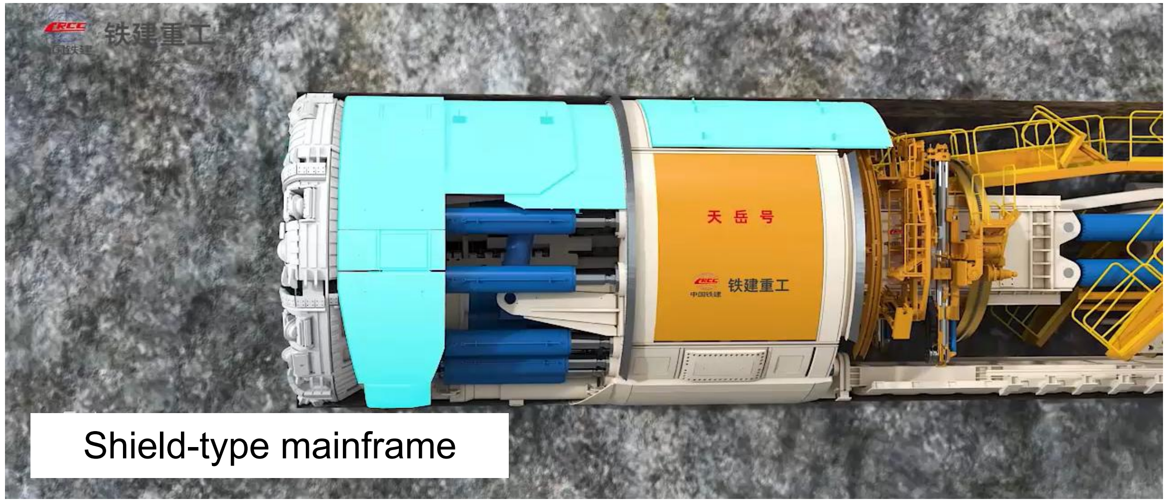
Over-speed braking on special-shaped rails with independent personnel/material separation transportation

On-line non-destructive testing (NDT) of wire ropes

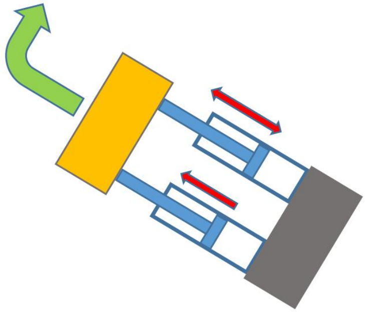
Safe personnel/material transport at 50° slope

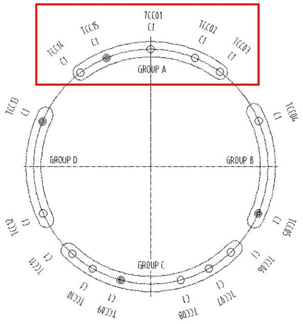
2.1.3 Ultra-Small Radius Spatial Turning Design

- **Vertical turning: from R800m to R50m**



Shield-type mainframe





Variable-zone stepless back-pressure regulating propulsion system, enabling in-situ vertical turning in "tank mode"

World’s first continuous R50m vertical curve tunneling

2.1.3 Ultra-Small Radius Spatial Turning Design

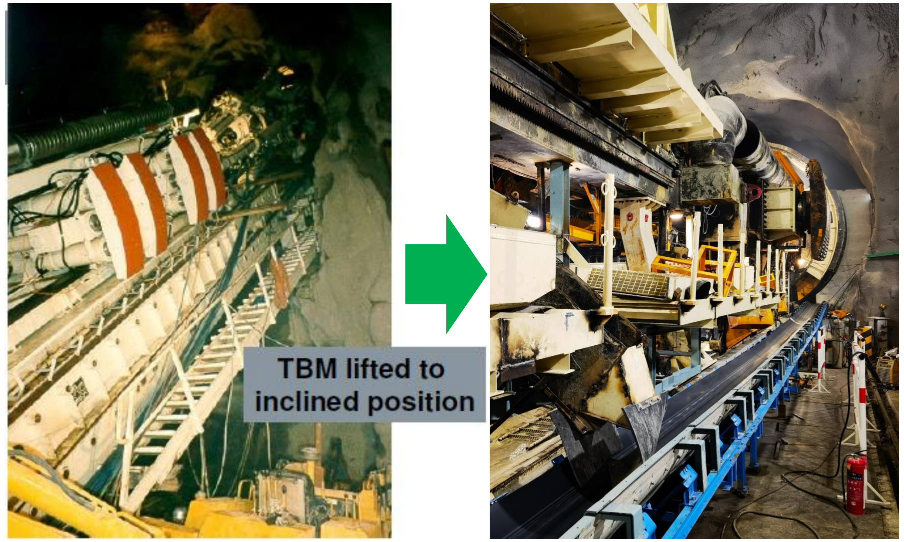
- **Vertical turning: from R800m to R50m，greatly improving TBM flexibility, better matching flow channel design, and reducing auxiliary cavern excavation**

First-ever realization of TBM adapting to R50m spatial curves in inclined shafts, meeting extreme engineering design requirements and reducing construction costs

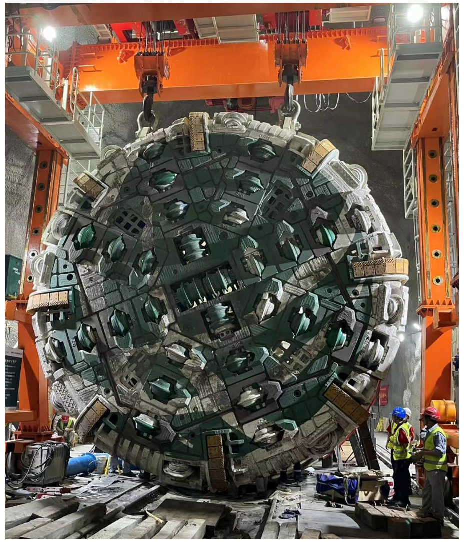
World’s first continuous R50m vertical curve tunneling

2.2.1 Rapid assembly/disassembly in confined space

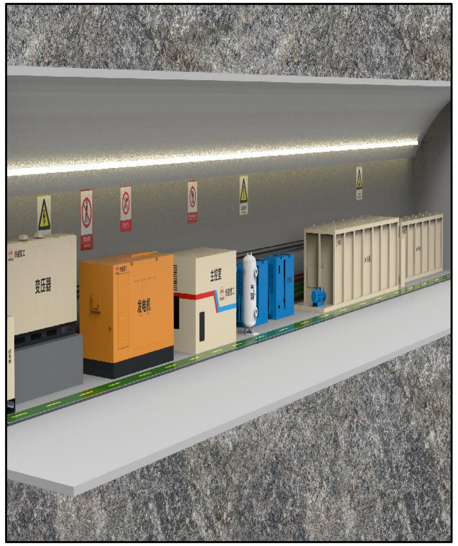
- **Compared with conventional assembly methods, the assembly chamber size is reduced by 50%**
- **The assembly time of the inclined shaft TBM is shortened from 60~90 days to 40 days**
- **The transition and diameter change time is shortened from 60 days to 30 days.**



Horizontal tunnel assembly and turning launch technology



Hydraulic jack-up gantry crane



Remote control technology & variable-head fluid conveying technology

TBM synchronous jacking and diameter changing technology

Rapid assembly, disassembly and transition of multi-stage inclined shaft TBM in compact spaces

2.2.1 Rapid assembly/disassembly in confined space

- **Solved the high-difficulty disassembly problem in ultra-short 20m-class receiving chamber(with back-up system still inside the inclined shaft during disassembly)**

Split disassembly technology for main machine and back-up system in inclined shafts

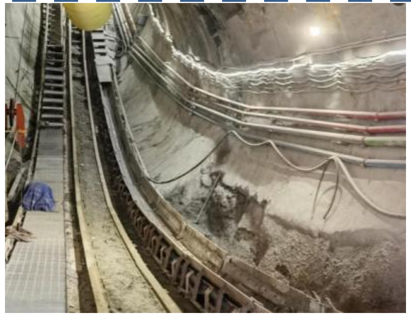
External cylinder + winch-assisted traction disassembly technology

Rapid assembly, disassembly and transition of multi-stage inclined shaft TBM in compact spaces

2.2.2 Horizontal-inclined continuous mucking

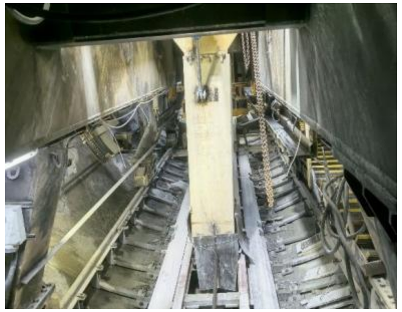
- **Solved the technical challenge of continuous mucking under full working conditions (horizontal → downward curve → inclined shaft → upward curve → horizontal), ensuring efficient TBM tunneling**

① Launch to the bottom of the inclined shaft



② Tunneling in the downward curve section

③ Tunneling in the 50° inclined shaft



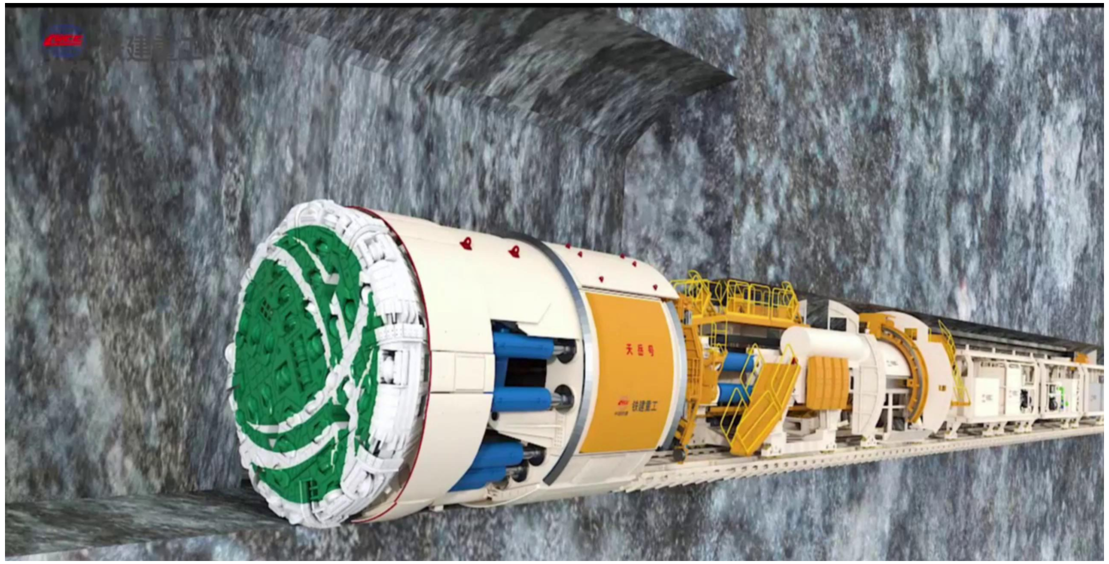
④ Tunneling in the upward curve section

Multi-stage inclined shaft full-condition mucking mode

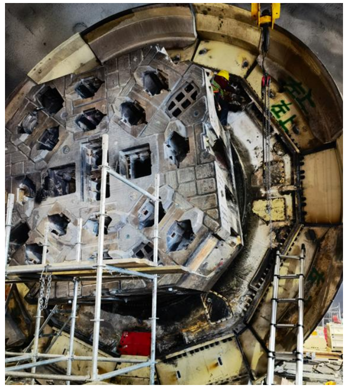
Combined chute + belt conveyor mucking design, enabling rapid mucking conversion in horizontal, curved and inclined sections

2.2.3 In-tunnel variable-diameter process

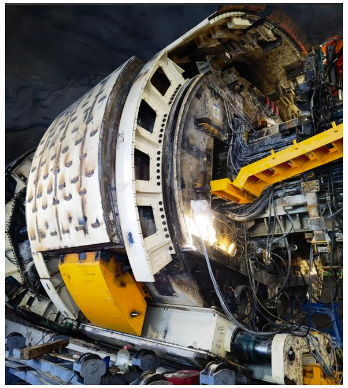
- **Solved the problems of difficult material handling and hoisting, and long construction period for large-scale in-situ TBM diameter change in compact horizontal tunnels**



TBM diameter changing process

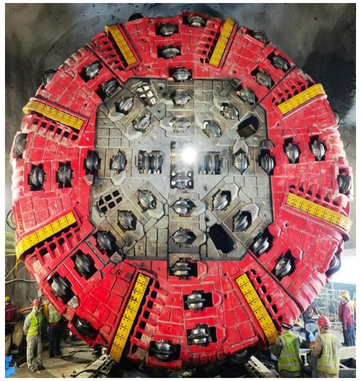


① Front shield diameter change



② Gripper shield diameter change

③ Telescopic shield diameter change



④ Cutterhead diameter change

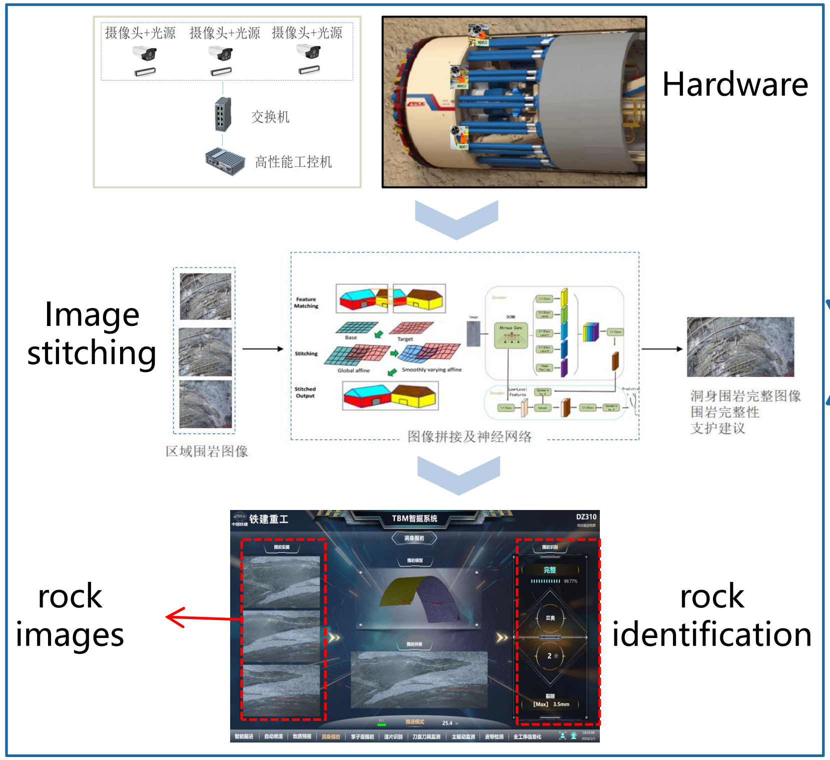
⑤ ABS diameter change

⑥ Back-up system diameter change

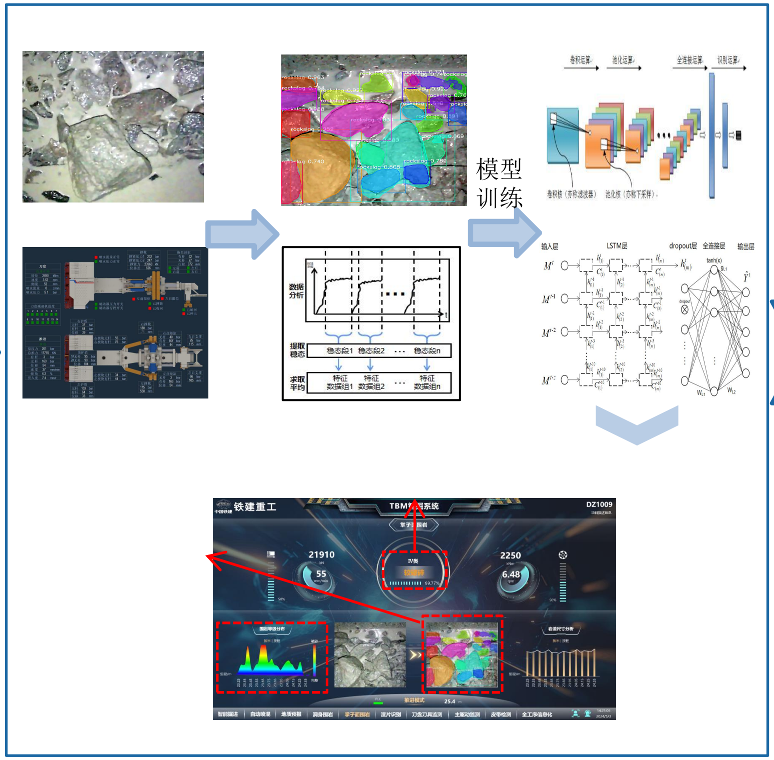
6.5→8.0 m one-machine dual use

2.3.1 Multi-source Fusion Perception and Graded Early Warning Technology for Advance Risk

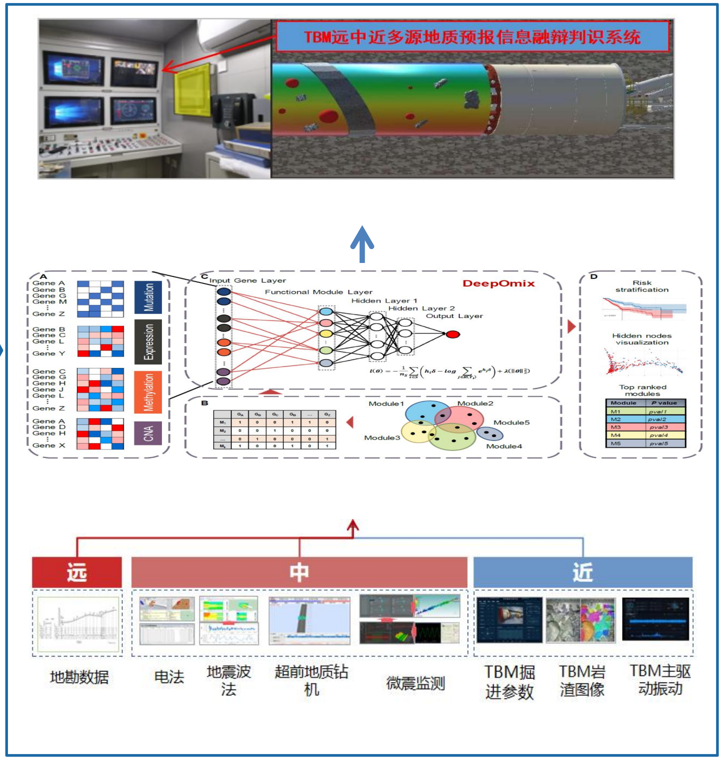
- **Integrating multi-source geological and operational data, we built a deep learning and evidence theory-based online identification system with three-level early warning, enabling active risk perception and graded warning for TBM in ultra-steep inclined shafts.**



Surrounding rock information collection in tunnel



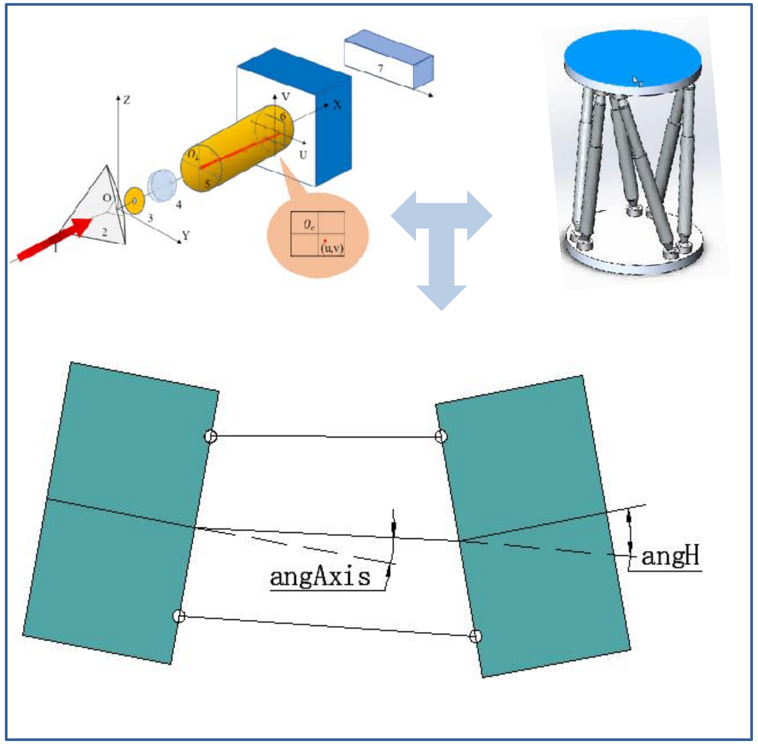
Surrounding rock prediction based on multi-sensor fusion



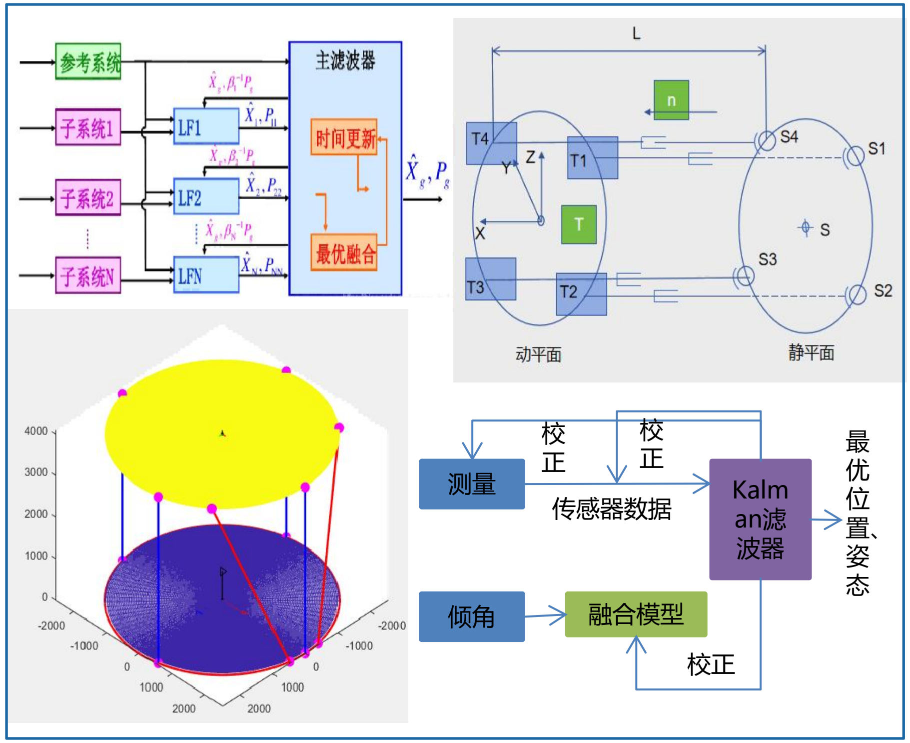
Far-middle-near graded geological prediction

2.3.2 High-Precision Pose Measurement Technology for TBM Turning in Complex Spatial Curves

- **By solving coordinate transformation and parallel robot kinematic pose solving, developing multi-sensor fusion algorithms, and proposing a horizontal-inclined cross cylinder solution, this technology addresses unmeasurable front shield pose issues in ultra-small radius vertical curves, achieving millimeter-level pose perception in dynamic environments.**



Coordinate transformation and kinematic model

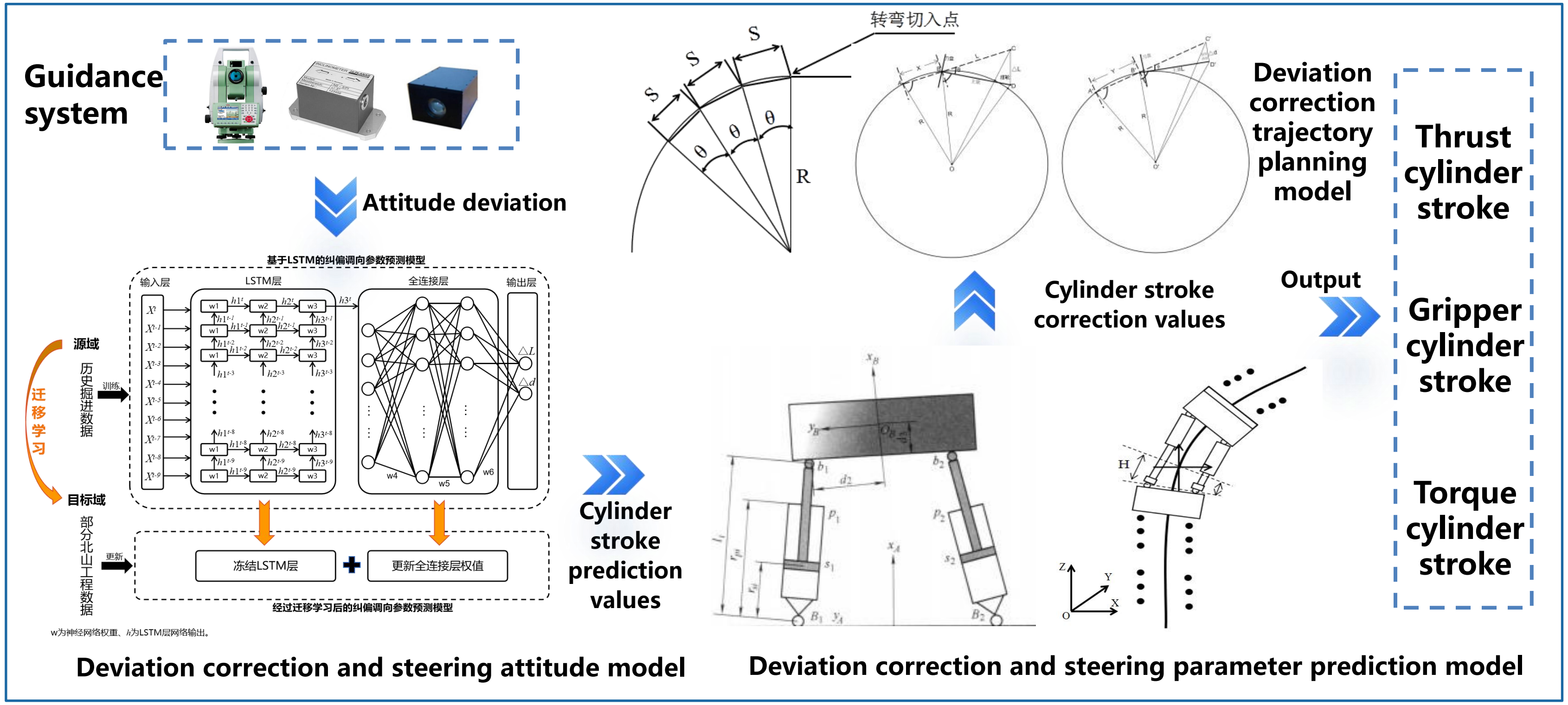


High-precision pose measurement technology

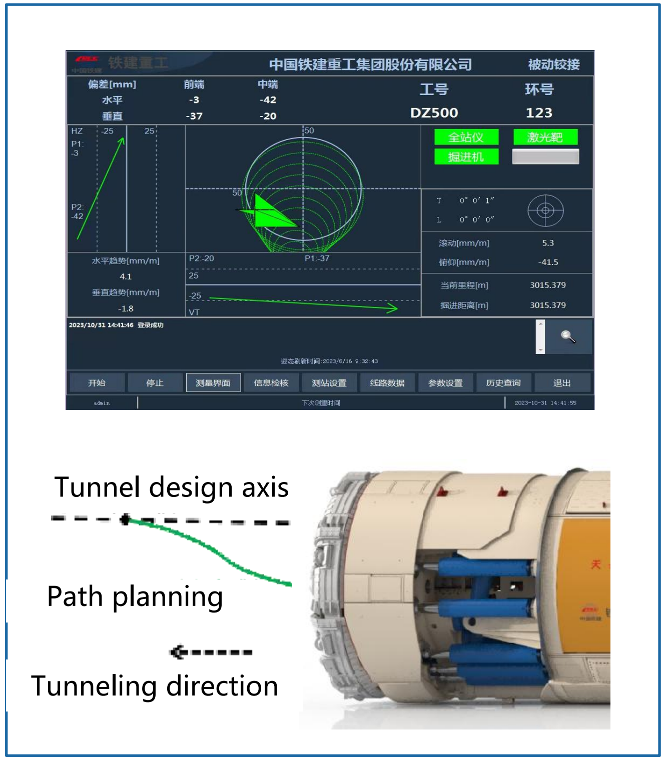
Horizontal-inclined cross stroke measuring cylinder

2.3.3 Adaptive Deviation Correction Control Technology for TBM Turning in Complex Spatial Curves

- **This technology explores the mechanism of deviation correction and steering parameter prediction based on LSTM and transfer learning, constructs a dynamic trajectory planning method incorporating minimum turning radius constraints and a segmented cylinder coordinated control strategy, realizing adaptive high-precision deviation correction and improved trajectory fitting for TBM under complex spatial curve conditions.**



Design of TBM adaptive deviation correction and steering model



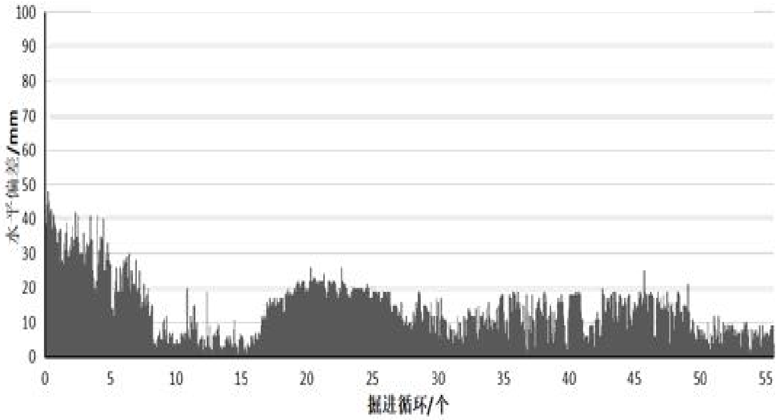
Control effect

Breakthrough 3: Intelligent Perception & Coordinated Control

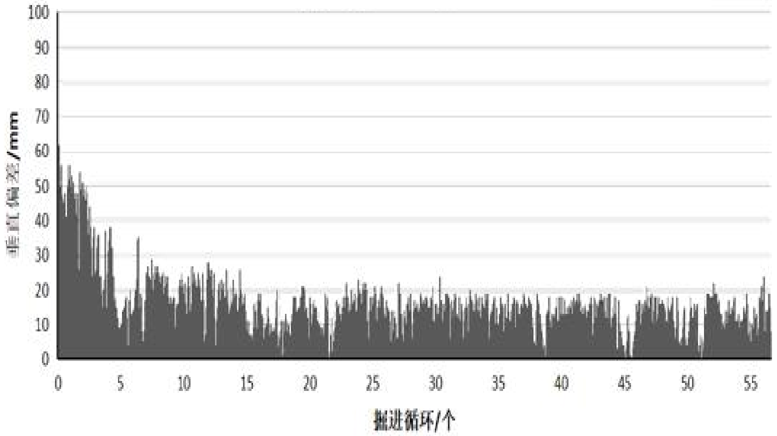
- **Under ultra-steep and complex spatial curve conditions, this technology achieves active risk warning and adaptive deviation correction for TBM. It triples survey station-switching distance, cuts survey time by 70%, and delivers ±5mm positioning and ±20mm attitude control accuracy—over 50% better than peers. It achieved 2mm breakthrough accuracy in the Pingjiang 50° inclined shaft.**

Active deviation correction control system for inclined shaft TBM

Horizontal deviation

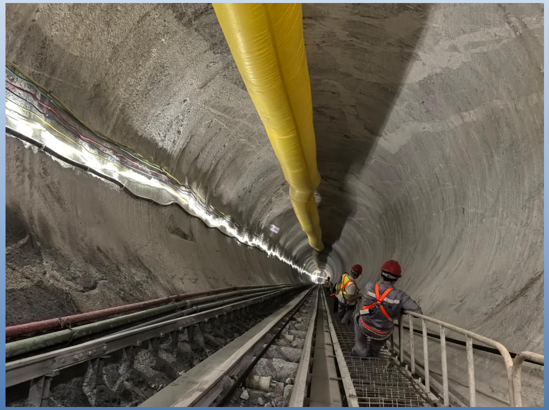


Vertical deviation



Deviation correction and steering control effect

Application in Hunan Pingjiang Pumped Storage Power Station Project

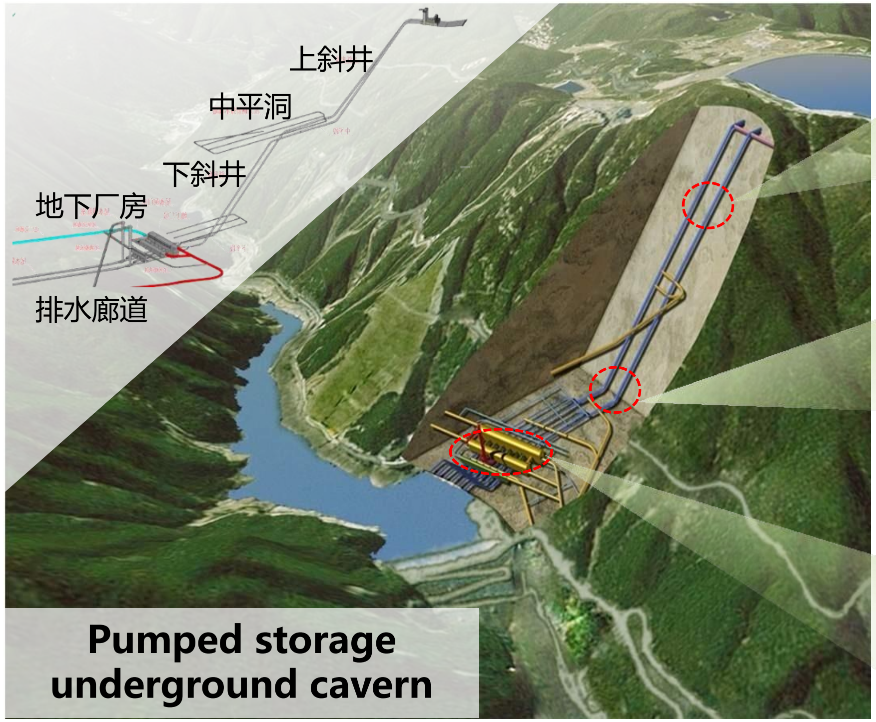


Excavation diameter **6.5/8m**	Turning radius **50m**	Maximum gradient **50°**	Single tunneling length **1150m**	Lithology **Granite**

Adopting multi-anti-slip, large-range non-destructive diameter changing, and ultra-small turning (R50m) technologies, the TBM at Pingjiang Pumped Storage Power Station’ s No.1 inclined shaft achieved 1,150 m of continuous advance with a peak monthly rate of 172 m, and completed breakthrough on June 6, 2025.

CONTENTS

■ **Challenges in large-scale power station construction include complex alignments, steep gradients, and varied cavern sections, requiring construction technologies and equipment with high safety, reliability and efficiency.**

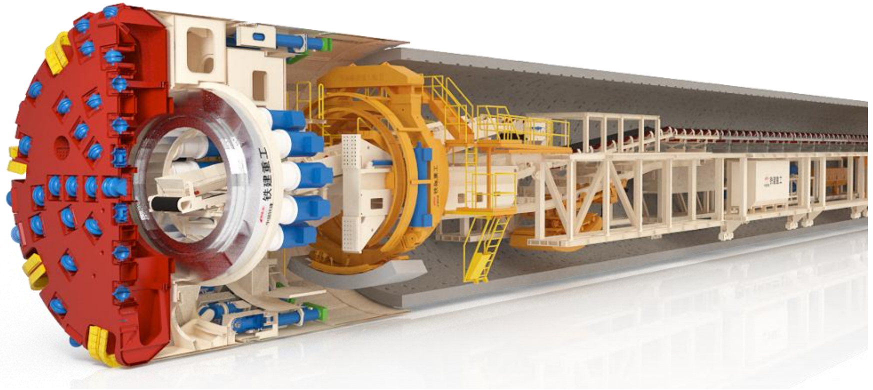


Pumped storage underground cavern

gradient ≥55°

Vertical turning radius ≤ R20m

Tunnel diameter variation ≥ Φ2m



High safety risks

Ultra-large powerhouse extremely tight curves

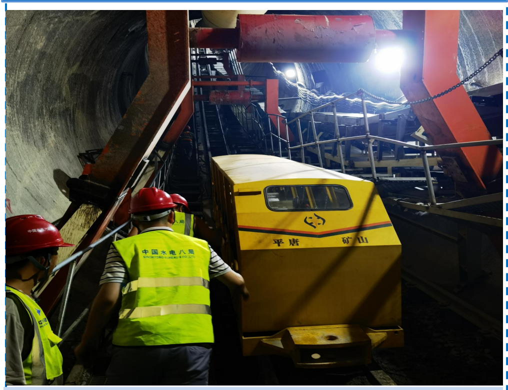
Larger diameter variations in-tunnel

Frequent transitions in short chamber

(1) Inclined-vertical Integrated Reaming TBM

While there is development and construction experience with three types of TBM—full-face raise boring TBM, full-face vertical shaft TBM, and reaming-type vertical shaft TBM—the following industry challenges remain:

Intrinsic Safety

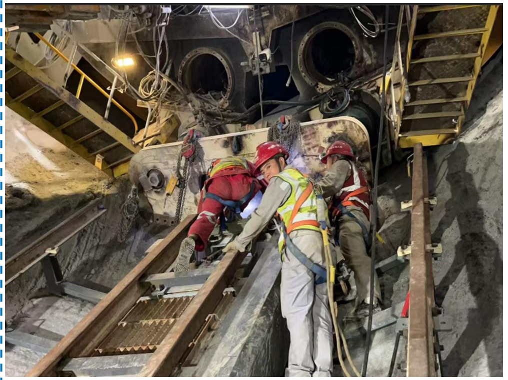


Large number of personnel working in the shaft

Limited Application Scenarios

Incompatibility with large auxiliary caverns, large auxiliary platforms, and large auxiliary equipment

Complex Work Procedures

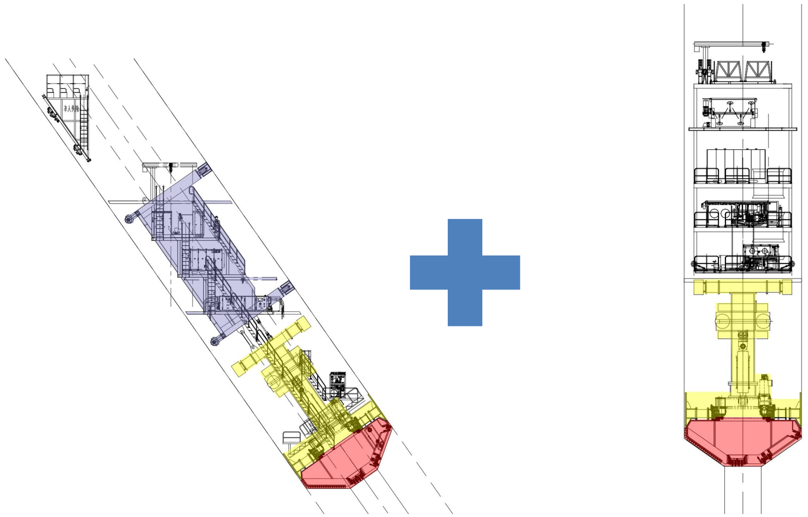


Long duration of mucking, support and other procedures, limiting tunneling efficiency

Development of New-Generation Inclined and Vertical Shaft TBM Equipment

(1) Inclined-vertical Integrated Reaming TBM

- **Application scenarios: Diversion tunnels, ventilation shafts and other projects. Easy assembly, quick breakthrough, and rapid transition.**
- **Equipment features: Inclined-vertical integration, reaming-type downward mucking, variable diameter (1.5m), and horizontal assembly and launch.**
- **Design parameters: Pilot tunnel diameter 1.5-2.5m, gradient ≥55°, turning radius down to R20m level.**



Inclined shaft **Vertical shaft**

(2) Mobile TBM

- **Application scenarios: Projects with varying diameters, scattered locations, and different lengths.**
- **Equipment features: Tracked mobility, variable diameter capability, quick retraction, with "fast assembly, fast tunneling, fast demobilization" characteristics.**
- **Design parameters: Overall length ＜30m, turning radius ＜ 30m.**

Branch network tunnels

Underground powerhouse and drainage tunnels

Thank you!