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Technical innovation in the “Beishan No. 1” hard rock tunnel boring machine for high-gradient spiral tunnels

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1 Project overview

The “Beishan No. 1”, the world’s first-ever hard rock Tunnel Boring Machine (TBM) tailored for high-gradient spiral tunnels, constitutes a pivotal element within the Beishan Underground Research Laboratory (URL) initiative in China. Beishan URL, the first URL for geological disposal of high level radioactive waste (HLW) in China, is a national key construction project listed in the “13th Five-Year Plan”. In 2019, subsequent to receiving approval from the China Atomic Energy Authority, the Beijing Research Institute of Uranium Geology (BRIUG), serving as the project’s owner, initiated its construction. This underground facility, categorized as a “third generation” URL for HLW disposal, i.e., area-specific URL, was located in Beishan, Jiuquan City, Gansu Province, China, following more than three decades of rigorous research on site selection.

The underground infrastructure of the Beishan URL incorporates a structural design consisting of spiral ramps complemented by three vertical shafts and two levels of experimental tunnels (Fig. 1). The spiral ramp stretches over a distance of approximately 7.0 km, featuring a circular cross-section with a diameter of 7.03 m. It

encompasses a horizontal turning radius of 255 m and a vertical curve radius of 380 m, characterized by a maximum gradient of 10% and an average gradient of 9%. In order to minimize damage on the surrounding rock during the excavation, and taking into consideration the engineering geological conditions of the selected site, such as the presence of an intact rock mass, absence of large fault zones, low rock burst proneness, and minimal water ingress, the BRIUG research team systematically conducted a feasibility research on the excavation of the Beishan URL’s spiral ramp using TBM technology. Finally, the comprehensive plan of using TBM for the ramp excavation with small-radius turns, high gradients, and long distances in extremely hard rock geological conditions has been put forward.

The geological condition of extremely hard rock and engineering design of spiral descending posed technical challenges for the TBM design and construction. To overcome these challenges, the BRIUG, in collaboration with construction organization, TBM manufacturer, and research institutes such as the China Railway 18th Bureau Group Tunnel Engineering Co., Ltd., China Railway Construction Heavy Industry Co., Ltd., Beijing University of Technology, Central South University, and Huludao Litan Heavy Industry Machinery Co., Ltd., among others, conducted comprehensive and creative research. This collaborative research resulted in significant breakthroughs in several key technologies, including efficient rock fragmentation in extremely hard rock with high integrity, effective excavation capabilities with small-radius turn, proficient transportation of rock mucks with continuous unidirectional small-radius turns, safety insurance for construction and *in situ* testing on steep gradients, and precise three-dimensional (3D) control of the spiral excavation direction. These advancements ultimately led to the successful development of the “Beishan No. 1”, the world’s pioneering hard rock TBM tailored for high-gradient spiral tunnels (Fig. 2). This machine not only furnishes essential excavation equipment for the construction of an internationally advanced URL but also

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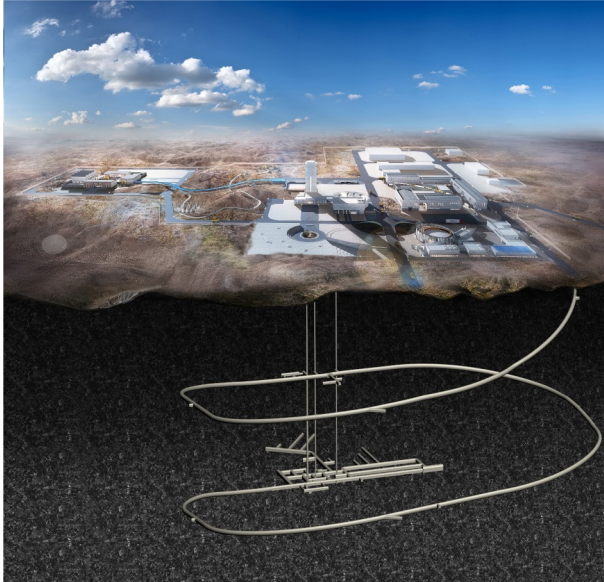


Fig. 1 Overall layout design of Beishan Underground Research Laboratory (sourced from Wang et al. (2023)).

provides a Chinese solution and pivotal technical equipment for global HLW disposal projects.

2 Technological innovations in the development of the “Beishan No. 1” TBM equipment

The “Beishan No. 1” TBM has an excavation diameter of 7.03 m and spans a total length of approximately 95 m. The cutterhead torque is 5160 kN·m, cutterhead speed ranges from 0 to 10 revolutions per minute, and the excavation stroke is more than 1.8 m. The development of this TBM equipment marked notable technological breakthroughs in several critical areas, including efficient rock fragmentation in extremely hard rocks, proficient excavation capabilities in small-radius turns, effective muck

removal in continuous small-radius curves, and precise control of the 3D spiral excavation direction. Furthermore, to facilitate scientific experiments during the construction of the Beishan URL, the TBM is equipped with several advanced research instruments.

2.1 Efficient rock fragmentation technology in extremely hard rock

The rock mass of Beishan URL shows very high integrity in terms of rock quality designation (RQD) data obtained from the borehole cores in the site, and the proportion of rock mass classified as “extremely good” is greater than 86%. The average uniaxial compressive strength (UCS) of the rock mass is 172 MPa, and the max UCS value is 235 MPa. To solve the efficient rock fragmentation issue in extremely hard rock, the equipment design of the “Beishan No. 1” TBM incorporated several technical innovations.

(1) Pioneering design on cutterhead design. In the design of the cutterhead, the comparative analysis was conducted, evaluating the rock fragmentation performance and suitability for extremely hard rock with different types of cutterhead, i.e., flat, conical, and spherical cutterheads. Detailed investigations on the rock fragmentation and muck removal efficiency of conical cutterheads with different cone angles were conducted (Fig. 3), and an optimal angle for the conical cutterhead and the rock fragmentation mode of free-surface cutting are proposed. Research findings indicate that this novel cutterhead design triples the efficiency of rock fragmentation when compared to conventional cutterhead.

(2) Design on high-capacity and large-diameter cutters and compact cutter spacing. The design implementation integrates high-capacity bearings and 20-inch diameter cutters, with each cutter demonstrating a load-bearing capacity of up to 375 kN, constituting a noteworthy 19% enhancement in comparison to 19-inch cutters. Furthermore, these cutters facilitate a 23% increase in allowable

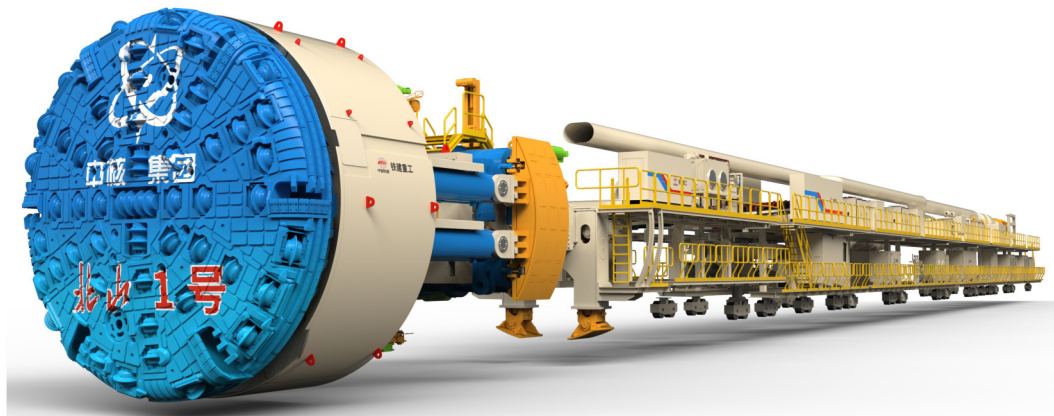


Fig. 2 Hard rock tunnel boring machine “Beishan No. 1”.

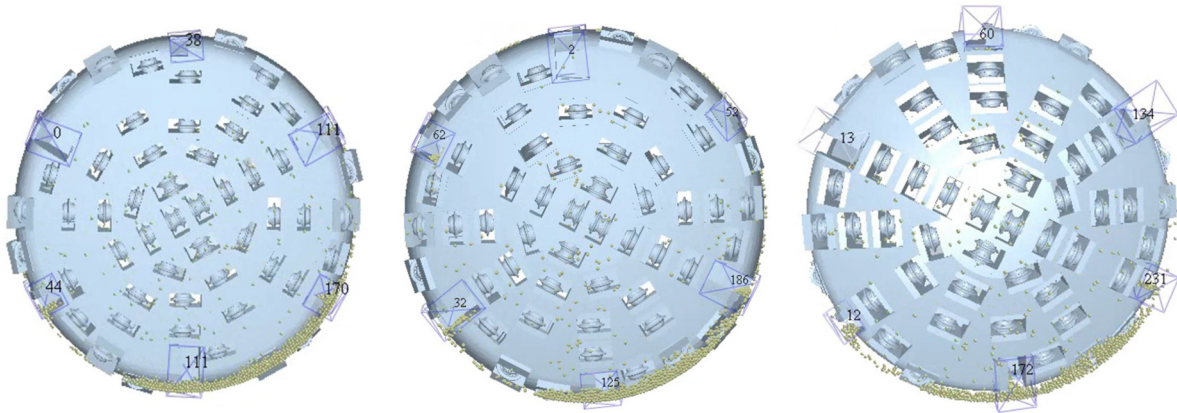


Fig. 3 Performance analysis of conical cutterheads with different cone angles.

wear. Based on rock cutting test and modelling analysis, an optimal configuration featuring closely spaced cutters was proposed. This cutter selection and layout significantly amplifies rock fragmentation efficacy.

(3) Design on high-thrust and high-speed, accompanied by a high-performance main drive. This configuration provides a sufficient power for the efficient rock fragmentation.

(4) Innovative design for rock fragmentation assisted by artificial fractures. Trial test at the TBM construction site of the Jilin Yinsong Water Supply Project demonstrated the effectiveness of rock fragmentation facilitated by artificial fractures. The *in situ* test revealed that within tunnel segments where controlled blasting was applied to create artificial fractures in advance, the TBM achieved an average increase in excavation speed ranging from 17.8% to 42.3%. Based on these insights and considering the geological characteristics of the Beishan URL project, further refinement of an artificial fracture assisted rock breaking system was conducted. The “Beishan No. 1” is equipped with an advanced drilling system for pre-drilling (Fig. 4), accommodating a diverse array of circumferential blast hole arrangements.

2.2 Efficient tunnelling technology for small-radius turns

In addressing the challenge posed by the 255-meter small-radius curve, the “Beishan No. 1” TBM incorporates a series of rigorously optimized design features. Combined with the engineering geological conditions characterized by hard rock, a design strategy focused on short shield and compact machine configuration was implemented. This strategic approach resulted in a reduction of the shield length from the conventional 5 to 3 m and a decrease in the main machine’s length from 25 to 16 m. Additionally, the adoption of large-stroke, double gripper cylinders was pivotal in ensuring the steadfast adherence of the grippers to the tunnel walls during turning operation. The back-up system adopted a double-layer design

with short length and large safety spacing (Fig. 5), thus significantly amplifying its adaptability to tunnelling in small-radius curves.

2.3 Efficient muck transportation technology for continuous small-radius turns

Belt conveyors, employed for muck transportation, offer several advantages, including high and uninterrupted transportation efficiency, low failure rate, low cost, and eco-friendly to environment. Nevertheless, the complex design challenge of accommodating seven consecutive small-radius curves in the same direction of the Beishan URL necessitated innovative solutions for the belt conveyor transportation system. Through dedicated design research efforts, a pioneering technique was developed to ensure efficient muck transportation using belt conveyors within continuous and unidirectional small-radius curves.

The specially designed conveyor system encompasses several key innovations, including the rigorous selection of optimized rubber belts, a multi-point collaborative drive design, and precise belt orientation control during turns, as well as complemented by limit wheels, press wheels, automatic deviation correction mechanisms, and anti-flip belt configurations. All these components underwent rigorous testing within a controlled factory environment (Fig. 6). Notably, the test conveyor, featuring a horizontal turn radius of 200 m and a turning angle of 185°, demonstrated stable performance, and verified the feasibility and reliability of the continuous belt conveyor technology for muck transportation within continuous small-radius spiral ramp of Beishan URL.

2.4 Precise control of 3D spiral excavation direction

To navigate the complex 3D spiral descending path of the ramp, a sophisticated multi-cylinder position-adaptive propulsion system comprised of main thrust cylinders,

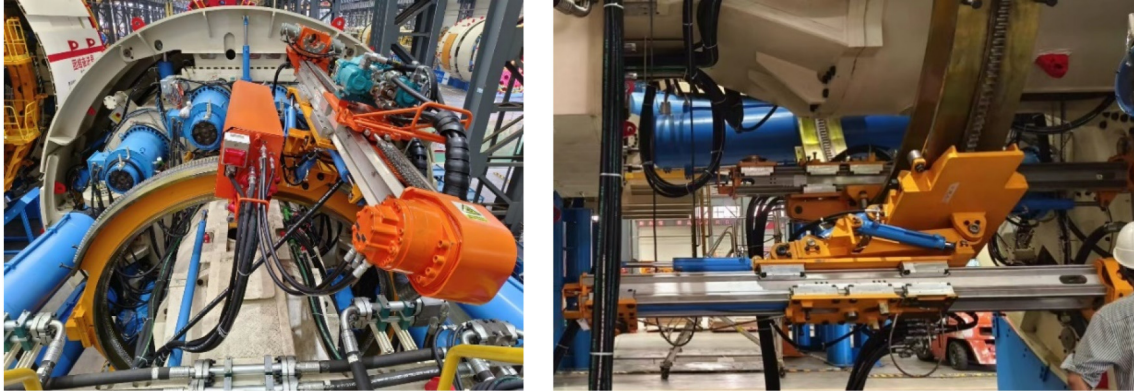


Fig. 4 Drilling system for hole making.

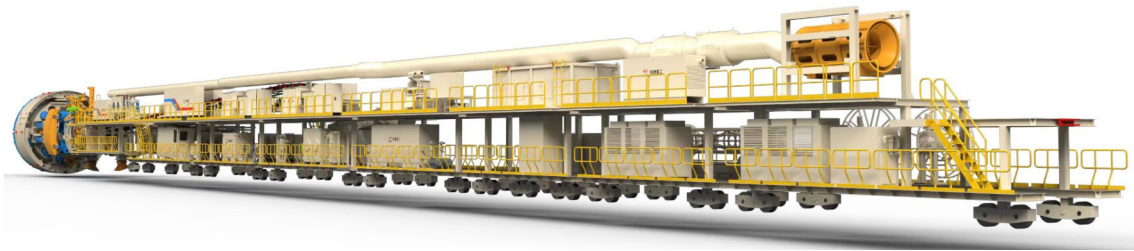


Fig. 5 Back-up system with double-deck layout design.



Fig. 6 Specialized conveyor system for muck transportation in factory test.

double gripper cylinders, and torque cylinders, and an integrated correction and steering mechanism along with its associated control methodology were devised. To further enhance precision and efficiency, the “Beishan No. 1” TBM is outfitted with an advanced mobile station-style laser guidance system. This system incorporates a total station directly mounted on the TBM, eliminating the need for frequent repositioning in turning sections. Continuous, real-time, and highly precise guidance is achieved through the simple adjustment of the rear-view prism’s orientation. Additionally, a guidance system featuring directional control and early warning technology, in conjunction with an auxiliary driving automatic

cruise system, was collaboratively developed. These innovative solutions empower the TBM to rigorously trace a spiral curve within construction routes characterized by small-radius turning and steep gradients.

2.5 Research equipment mounted on the “Beishan No. 1” TBM

To support scientific experiments conducted during the URL construction, the “Beishan No. 1” TBM is outfitted with several specialized tools and systems. These include an advanced core drilling rig, a tunnel-wall core drilling rig, and an automated circumferential wall cleaning

system, all of which are instrumental in geological mapping and the evaluation of the quality of the engineering rock mass. Moreover, the TBM is equipped with a series of intelligent monitoring equipment, such as a cutterhead condition monitoring system, a muck analysis system, and a vibration monitoring system. This comprehensive suite of advanced experimental apparatuses provides robust support for the research focused on intelligence and efficiency of TBM tunnelling technology.

3 Conclusions

The “Beishan No. 1” TBM embarked on its journey from Changsha, China on September 4, 2022, and arrived at the construction site of the Beishan URL on November 1, 2022. By November 18, 2022, equipment assembly was successfully completed, paving the way for its stepping commencement (Fig. 7). On December 30, 2022, it initiated the excavation process, and on May 29, 2023, the TBM successfully finished the excavation of the first turn of the spiral ramp. This achievement not only verified the performance of this pivotal equipment but also marked a significant milestone in the application of this TBM technology innovation in China.

By the end of October 2023, the excavation of the ramp within the Beishan URL had reached 2540 m, successfully tunnelling through the extremely hard rocks, two 255-meter small-radius turns, a steep with gradient of -10% , and alternating slopes ranging from -10% to -3% (Fig. 8). These achievements marked the commencement of a rapid construction phase for the Beishan URL.

Being the world’s first hard rock TBM designed for high-gradient spiral tunnels, the triumphant development of the “Beishan No. 1” TBM represents a pivotal milestone. It furnishes essential and critical equipment for the construction of the Beishan URL, as a national key project and world-class URL. This successful application of “Beishan No. 1” provides a robust foundation for the advancement of TBM excavation technology in spiral, high-gradient, long-distance and extremely hard rock tunnels. The “Beishan No. 1” TBM is poised to make its mark on the global stage, contributing vital equipment technology for key international projects in HLW disposal field.



Fig. 7 The “Beishan No. 1” TBM stepping into the ramp (sourced from Wang et al. (2023)).

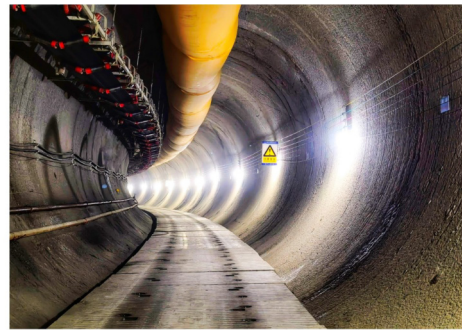


Fig. 8 Internal view of the spiral ramp with small-radius turn and steep gradient excavation (sourced from Wang et al. (2023)).

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